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Sustainable Dairy Farming: Evaluating the Economic Impacts of Greenhouse Gas Mitigation Strategies Using Simulation Models.

A Thesis

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Table of Contents

TABLE OF CONTENTS.....	I
LIST OF TABLES	II
LIST OF FIGURES	II
ACKNOWLEDGMENTS.....	III
ABSTRACT	IV
I. INTRODUCTION	1
1. CATEGORIZING EMISSION SOURCES AND DEFINITIONS	3
2. SCOPE 3 EMISSIONS OVERVIEW	5
II. LITERATURE REVIEW	8
1. RESEARCH MODELING	11
2. WHOLE SYSTEM MODELS.....	12
3. PARTIAL SYSTEMS RESEARCH	18
III. MATERIALS FOR LCA MODELING.....	23
1. IFSM REPORTING OVERVIEW	25
IV. METHODS FOR USING IFSM MODELING.....	30
1. COW CHARACTERISTICS	31
2. MANURE CHARACTERISTICS	32
3. FEEDING AND PASTURE CHARACTERISTICS	34
4. CROP CHARACTERISTICS	35
5. ECONOMIC CHARACTERISTICS	36
V. IFSM RESULTS SUMMARY OF MODELS 1–7	38
1. ECONOMIC TRENDS ACROSS IFSM MODELS	39
2. CARBON FOOTPRINT TRENDS IN IFSM MODELS	42
3. IFSM MODELED SCENARIOS RESULTS SUMMARY.....	46
4. ANAEROBIC DIGESTION SYSTEM GHG EMISSIONS TRENDS USING IFSM	51
VI. DISCUSSION	56
1. LIMITATIONS OF FINDINGS AND IFSM SOFTWARE.....	60
2. IMPLICATIONS	62
VII. CONCLUSION FOR IFSM MODELING	64
VIII. REFERENCES.....	67
IX. APPENDICES	74

List of Tables

TABLE 1. IFSM MODELS AND ASSUMPTION DESCRIPTIONS.....	31
TABLE 2. COW ASSUMPTION CHARACTERISTICS USED IN MODELING ACROSS ALL FARMS.	32
TABLE 3. MANURE ASSUMPTION CHARACTERISTICS USED IN MODELING ACROSS ALL FARMS.....	33
TABLE 4. FEED AND PASTURE ASSUMPTION CHARACTERISTICS USED IN MODELING ACROSS ALL FARMS.....	35
TABLE 5. CROP ASSUMPTION CHARACTERISTICS USED IN MODELING ACROSS ALL FARMS.	36
TABLE 6. ECONOMIC ASSUMPTION CHARACTERISTICS USED IN MODELING ACROSS ALL FARMS.	37
TABLE 7. QUICK REFERENCE OF THE IFSM MODELS AND THEIR ASSUMPTION DESCRIPTIONS.....	38
TABLE 8. CHANGE IN MILK PRODUCTION TO TOTAL COST IN MODEL 2 COMPARED TO BASELINE MODEL 1.....	40
TABLE 9. PERCENT CHANGE IN REDUCTION IN FEED AND BEDDING COSTS.....	40
TABLE 10. THE TOTAL CARBON FOOTPRINT OF MILK INCLUDING BIOGENIC CO ₂	43
TABLE 11. EMISSIONS REDUCTIONS FROM PASTURELAND USE	44
TABLE 12. PERCENT CHANGE IN TOTAL MILK PRODUCTION FROM BASELINE MODEL 1.	47
TABLE 13. MANURE OUTPUT AND PERCENT CHANGES FROM BASELINE ON FARMS FOR MITIGATION OPTIONS.	49
TABLE 14. PRIMARY EMISSION CHANGES FOR INCREASED PASTURE AND CROP MODELS.....	52
TABLE 15. CARBON FOOTPRINT REDUCTION WITH AD SYSTEM USE COMPARED TO BASELINE MODEL 1.	54
TABLE 16. RETURN TO MANAGEMENT CHANGE WITH AD SYSTEM USE COMPARED TO BASELINE MODEL 1.	56

List of Figures

FIGURE 1. IFSM SYSTEM’S FLOW DIAGRAM (USDA, 2020).	24
FIGURE 2. IFSM SOFTWARE INTERFACE WITH SUMMARY REPORT AND ANIMAL CHARACTERISTICS (USDA, 2020). .	29
FIGURE 3. PERCENT CHANGE IN RETURN TO MANAGEMENT FOR MODELS 1-7.	39
FIGURE 4. AD SYSTEM PERCENT CHANGE IN RETURN TO MANAGEMENT COMPARED TO BASELINE MODEL 1.	42
FIGURE 5. PERCENT CHANGE IN TOTAL GHG EMISSIONS.....	44
FIGURE 6. MODELS BY FARM FOR TOTAL LBS. CO ₂ E PER LBS. FPCM INCLUDING BIOGENIC CO ₂	46
FIGURE 7. PERCENT CHANGE CARBON FOOTPRINT INCLUDING BIOGENIC CO ₂ REDUCTIONS.....	46
FIGURE 8. PERCENT CHANGE IN TOTAL GHG EMISSIONS FOR AD SYSTEM INSTALLATION.	53
FIGURE 9. PERCENT CHANGE IN RETURN TO MANAGEMENT FOR MODELS 1–7 FOR AD SYSTEM INSTALLATION.	55

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Abstract

The dairy industry's commitment to achieving net zero greenhouse gas (GHG) emissions by 2050 has placed significant pressure on dairy farms, as emissions from field-to-farm gate account for the majority (78%–83%) of total emissions. This research employed the Integrated Farm System Management (IFSM) software modeling tool using Life Cycle Analysis (LCA) methodology to analyze field-to-farm gate emissions associated with various mitigation options across five heterogeneous dairy farms. A total of 70 economic models were estimated with the goal of informing stakeholders and policymakers on maintaining dairy farm economic viability while reducing GHG emissions. The IFSM modeling indicates that dairy farms have multiple mitigation options available, with the most significant reduction in GHG emissions achieved through adding pasture grazing and changing feed requirements with carbon footprint reductions from 2.7% to 26.7%. When employed alongside anaerobic digestion (AD) systems, these mitigation options resulted in a reduction in emissions ranging from 16.0% to 37.3%, albeit with a corresponding decrease in return to management (RTM) of 0.4% to 14.8%. In contrast, the most profitable approaches without utilizing AD systems, such as the use of larger Holsteins for increased milk production or increased cropland utilization, were found to yield higher profits ranging from 1.3% to 19.5% but showed a limited reduction in the carbon footprint of milk by 0.0% to 6.7%. Results demonstrate that the largest consistent increase in dairy farm profitability did not result in significant reductions in the carbon footprint of milk, and the largest mitigation options did not provide a guarantee of being cost-neutral or better.

I. Introduction

As climate change remains a significant global concern due to greenhouse gas (GHG) emissions, attention from governments and researchers has been given to the agriculture sector which globally contributes between 11% and 17% of all GHG emissions (WRI, 2019, FAO, 2020). These agriculture emissions, known as *field-to-farm gate* emission, includes emissions from cropping, livestock, related land-use needs, and the power to operate machinery. On a global basis, these emissions have decreased by an estimated 24% since the 2000s (FAO, 2020). The most recent EPA estimate from 2022 is that the U.S. agriculture sector accounts for 10.6% of all U.S. emissions, an upward revision from their 2017 estimate of 8.7% (EPA, 2017, EPA 2022). According to the EPA's sector categorization, agriculture is the fourth largest GHG emitter (10.6%) after transportation (27.2%), electric power industry (24.8%), industry (23.8%), and followed by commercial (7.1%), residential (6.1%), and U.S. Territories (0.4%) (EPA, 2022a).

When exclusively examining agriculture-related emissions, the EPA excludes CO₂ fossil fuel combustion emissions of 0.7%, and the remaining emissions from agriculture represent 9.9% of total emissions (EPA, 2022a). This estimate includes agricultural activities such as soil management, enteric fermentation, manure management, rice cultivation, urea fertilization, liming, and field burning. Methane emissions from enteric fermentation represent 26.9% of emissions, followed by manure management at 9.2% (EPA, 2022a). The agriculture sector's contribution to emissions has led to discussions to identify strategies to reduce U.S. agricultural emissions to limit climate change and achieve net-zero goals.

Estimates of the U.S. dairy sector's contribution to total U.S. GHG emissions vary, ranging from 1.5% (Rotz et al., 2021) to 1.9% (Thoma et al., 2013), to 2% (Innovation Center for U.S. Dairy, 2020), and as high as 2.7% (Malliaroudaki et al., 2022). Based on the EPA's estimate of 10.6% of the agriculture sector's contribution to U.S. GHG emissions, these estimates imply that dairy production accounts for anywhere between 14.2% to 25.5% of agriculture's contribution to U.S. GHG emissions. According to the 2010 Food and Agriculture Organization of the United Nations (FAO) report, global dairy production contributes 2.7% of GHG for milk, and when the meat from cull cows is included, this percentage increases to 4.0% (FAO, 2010).

The dairy industry's contribution to GHG emissions includes methane (CH₄), nitrous oxide (N₂O), and carbon dioxide (CO₂) being the primary GHGs associated with this sector. These gases are converted into carbon dioxide equivalent (CO₂e) and measured per unit of fluid milk or by tonnage. Research by Rotz and Thoma (2017) found GHGs to be between 0.8 and 1.2 kg CO₂e per kg of milk, and research by Thoma et al. (2013) found them to be between 1.77 and 2.4 kg CO₂e per kg of milk with an average of 2.05 (90% confidence limits) (Rotz and Thoma, 2017; Thoma et al., 2013). GHG emissions also vary based on the size of the dairy operation and production system used with baseline carbon footprints of 0.99 kg CO₂e per kg of milk for 1500-cow operations, and 1.1 kg CO₂e per kg of milk for 150-cow operations which are comparable to previous research (Veltman et al., 2020). The FAO (2010) reported global estimates of 2.4 CO₂e per kg, with industrialized regions such as the U.S., Canada, Europe, and Australia being between 1.0 and 2.0 CO₂e per kg of milk. Therefore, the dairy sector is a significant contributor to GHG emissions and should be considered when developing strategies to mitigate climate change.

To address climate change and its negative impacts, world leaders at the UN Climate Change Conference 2021 (COP21) in Paris agreed on the Paris Climate Accords which set goals to limit global warming to 2°C and to further strive to limit them to 1.5°C by mid-century (UNFCCC, 2022). To achieve this, many industries, including the dairy sector, need to achieve net-zero emissions (also known as being carbon-neutral) by 2050. Many companies, including the dairy processing sector, are voluntarily taking the initiative to reduce their emissions. The dairy processor sector includes cooperatives, privately held companies, and publicly traded companies. They also range from companies whose sole focus is dairy processing to companies that own a wide range of consumer-brand food products outside of being dairy focused. Several dairy processors, regardless of their ownership structure or focus, are setting goals to achieve net zero by 2050, which are communicated in *sustainability reports* (e.g., Dairy Farmers of America, 2021; General Mills, 2022; Chobani, 2019; Organic Valley, 2021; Glanbia Nutritionals, 2021). However, many of the top fifty dairy processors in North America lack substantive goals in their sustainability reports (e.g., Agropur, 2020; Conagra, 2020; Schreiber Foods, 2020), and many others do not publish sustainability reports currently.

1. Categorizing Emission Sources and Definitions

The dairy sector has widely adopted the industry standard of GHG emissions accounting created by the World Resource Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). These standards, which are used by the EPA and the Innovation Center for U.S. Dairy, are organized into three main areas called Scopes 1, 2, and 3 (EPA, 2021). This allows large-scale processors within the dairy sector to measure their practices that contribute

to GHG emissions and communicate with common terminology. By utilizing these standards, the dairy sector can determine where reductions in GHG emissions need to be made within a business's supply chain. According to the EPA:

- **Scope 1** emissions are direct greenhouse gas (GHG) emissions that occur from sources that are controlled or owned by an organization (e.g., emissions associated with fuel combustion in boilers, furnaces, and vehicles).
- **Scope 2** emissions are indirect GHG emissions associated with the purchase of electricity, steam, heat, or cooling. Scope 2 emissions physically occur at the facility where they are generated, and they are accounted for in an organization's GHG inventory because they are a result of the organization's energy use.
- **Scope 3** emissions are the result of activities from assets not owned or controlled by the reporting organization, but that the organization indirectly impacts in its value chain. Scope 3 emissions include all sources not within an organization's Scope 1 and 2 boundaries. The Scope 3 emissions for one organization are the Scope 1 and 2 emissions of another organization. Scope 3 emissions, also referred to as value chain emissions, often represent the majority of an organization's total GHG emissions.

Many dairy processors with informative sustainability reports have measured the percentages of their Scope 1, 2, and 3 emissions for their supply chain. For instance, Dairy Farmers of America (DFA), the largest processor in the U.S., calculates that their entire *cradle-to-grave* supply chain contribution to Scope 1 and Scope 2 each account for 1% of their total emission. Scope 3 emissions account for the remaining 98% of emissions and can be categorized

into on-farm and downstream emissions. DFA breaks down the contributing processes for their associated Scope 3 emissions which make up 81% of GHGs from on-farm processes, while the remaining 17% is from downstream processes such as *Transportation & Distribution* and *Use & End-of-Life of Sold products*.

According to DFA (2022), the on-farm emissions in the dairy sector's contribution to total supply chain emissions are categorized into enteric (28%), manure (26%), feed (23%), and on-farm energy (4%). Downstream emissions are composed of transportation & distribution (9%) and use & end-of-life of solid products (8%). The transportation & distribution emissions are typically owned by the processor or contracted through a third party, and responsibility for emissions is not clearly defined. For the *Use & End-of-Life of Sold products* category, packing choices (e.g., compostable vs plastic) are the responsibility of the processor, while recycling and home energy use are the consumers' responsibility. However, the dairy farmer is responsible for the remaining 81% of on-farm emissions, even if they purchase feed from a crop farmer.

2. Scope 3 Emissions Overview

The focus of this thesis analysis is on Scope 3 emissions, which refer to emissions generated by dairy farms from the field-to-farm gate stage. To achieve processors' commitments and reduce the dairy industry's GHG emissions, dairy farms will be responsible for directly addressing processors' Scope 3 emissions, which are the Scope 1 and 2 emissions of the dairy farmer. The reported percentages of Scope 3 emissions vary by processor depending on their processing needs. Dairy processors report their Scope 3 emissions such as Glanbia Nutritionals (86%), Emmi (97%), and Bel Brands (96.5%). Similarly, companies with a broader product line

report similar percentages of Scope 3 emissions including Kraft Heinz (95%), General Mills (95.7%), and Danone (95.6%). However, most dairy-focused processors currently do not provide this information to the public. These numbers are consistent with the FAO (2010) findings of a global average of 93%, with North America, Western Europe, and Oceania being estimated to be lower between 78% and 83% (FAO, 2010). Dairy farmers, like processors, also have Scope 3 emissions defined as pre-farm sources, which are lumped into the processor's definition of processor's Scope 3 emissions (e.g., feed sourced from crop growers). This highlights that if processors want to achieve their net-zero targets, it is necessary to establish who is responsible for the reductions and the associated costs to achieve these dairy processors' Scope 3 emissions mitigations.

As of 2020, dairy processors accounting for 74% of all U.S. milk production committed to net-zero goals by 2050 through the Innovation Center for U.S. Dairy and their U.S. Dairy Stewardship Commitment (Innovation Center for U.S. Dairy, 2022). Because Scope 3 emissions account for all the emissions that farmers have responsible over, this implies that a vast majority of mitigation will need to happen at the field-to-farm gate. Contributing sources to Scope 3 emissions include energy use for animal comfort, milk cooling, sanitation needs, crop production for homegrown feed, purchased feed production, animal welfare needs, manure emissions, as well as natural ruminant enteric metabolic biogenic emissions. Scope 3 percentages also vary by region and farming system used (e.g., grazing vs conventional). Given that 78% to 83% of all dairy-related emissions occur at the farm level, these commitments by processors put a substantial burden on U.S. dairy farmers to address GHGs emissions within

their operations. These net-zero pledges by processors and the burden that will fall on farmers to meet these commitments establish this thesis, which addresses the question:

What strategies are available to ensure that dairy farmers of diverse sizes and regions can minimize the dairy industry's Scope 3 GHG emissions while maintaining economic viability?

To answer these questions this thesis explored various options for GHG mitigation while maintaining economic viability for dairy farmers. The options needed to reduce the three primary sources of emissions in dairy farming include enteric, manure, and feed. To fulfill these requirements Life Cycle Analysis (LCA) modeling tool was used. The Integrated Farm System Model (IFSM) is a widely used LCA software tool that simulates the long-term performance, environmental impact, and economics of production systems including a dairy farm's return to management (RTM).

To capture regional differences, five farms of various sizes across the country were compared using IFSM software. They include a farm with 280 lactating cows in Idaho, a 1000-cow farm in New York, a 1200-cow farm in Texas, and a 300-cow and 5000-cow farm in Minnesota. In total, fourteen distinct model scenarios were run for each of the five farms for a total of 70 models.

For modeling the economics and carbon footprint of milk in IFSM three broad categories of assumptions characteristics were adjusted. They include changes that affect enteric emissions, manure, and feed, but as an LCA modeling tool, these categories interact with one

another. The assumptions underlying each modeling tool can be found in the Materials and Methods sections.

The research presented in this thesis aims to contribute to the current body of research by providing insights on how GHG mitigation strategies can be implemented in the dairy processing industry as it moves towards achieving its net-zero by 2050 goals. The answers to these thesis questions may provide researchers, farmers, governments, and other stakeholders with perspectives that have not yet been addressed. The stakeholders need these perspectives as the net zero commitments that dairy processors are making, and the actions that governments may take to mitigate climate change will have significant impacts on the evolution of the U.S. food system. In the coming years, processors may require that dairy farmers reduce their carbon footprint for those processors to reduce their Scope 3 emissions. With many processors needing to report their emissions every five years starting in 2025, it leaves little time for stakeholders to act on mitigation strategies. It is in this context that this thesis hopes to shed light on these strategies to add to the current body of literature.

II. Literature Review

The world is facing the challenge of mitigating climate change for a more sustainable future, and the dairy sector is no exception. As the dairy sector contributes 1.9% to 2.7% of all GHG emissions in the U.S., it is important to focus on this area (Thoma et al., 2013; Malliaroudaki et al., 2022). Much of the responsibility to reduce dairy emissions will likely fall on dairy farmers to achieve the Scope 3 reductions pledged by processors, and it is essential to

study and understand Best Management Procedures (BMPs) at the dairy farm level. However, if these BMPs have high entry costs, decrease profitability, or jeopardize milk or crop yields, they are unlikely to be adopted by farmers (Veltman et al., 2020). As the economics of the dairy GHG mitigation change, it is important to update the literature regularly to avoid leading to incorrect conclusions (Capper and Cady, 2020).

In Rotz's (2018) meta-analysis review he analyzed a range of dairy farm models developed using different software and underlying assumptions. One of the key outcomes of this study was the distribution of GHG emissions, with the highest emission rate being 1.2 CO₂e per kg of milk from an 80-cow grazing and free-stall farm in Ireland, and the lowest emission rate of approximately 0.72 CO₂e per kg of milk observed on a 1000-cow free-stall farm with anaerobic digester in use in New York.

The focus solely on the percentages of GHG emission sources can lead to an incomplete understanding of the distribution of GHG emissions from dairy farms. Rather, it is necessary to translate these percentages into CO₂e values for a complete picture of the carbon footprint of milk. For instance, the farm with the largest CO₂e emissions in Ireland had a small fraction of GHGs originating from manure due to the grazing system in place. In contrast, a 300-cow free-stall farm in Pennsylvania, which had lower overall emissions of approximately 0.95 CO₂e per kg of milk, had manure contributing a significant proportion of the farm's GHG emissions. Therefore, when comparing percentages of GHG-contributing sources, it is important to consider the influence of factors such as farm location, feed system, manure handling, animal housing, and herd size on GHG emissions to address mitigation options.

Rotz (2018) echoes previous research indicating that CO₂ is a relatively small component of farm GHG emissions, accounting for only about 5% (Rotz and Thoma, 2017). This is due to the closed-loop nature of biogenic GHG emissions, wherein only anthropogenic emissions contribute to the overall atmospheric GHG emissions. Biogenic emissions, as defined in IFSM, have negative values and thus, when included in the total emissions, reduce the overall total. This point is relevant to the upcoming results section. The carbon in biogenic emissions comes from the atmosphere through plant fixation and is returned to the atmosphere via respiration, leading to no long-term change in atmospheric carbon quantities (Rotz, 2018). Biofuels derived from algae, for instance, are considered net-zero because they remove carbon from the atmosphere and release CO₂ back into the atmosphere upon burning, resulting in no net effect on overall global atmospheric carbon levels. It is important to note that while a significant portion of CO₂ is emitted from dairy production systems through plant, animal, and microbial respiration, this should not be conflated with the need to reduce animal and manure CH₄ and N₂O emissions, and anthropogenic CO₂ emissions.

Meta-analyses from academic research indicate that GHG emissions can be reduced by focusing on specific areas such as manure management and feed intake (Rotz, 2018). The use of anaerobic digesters has been shown to produce the lowest GHG emissions with 25% less emissions than other confinement production systems (Rotz, 2018). However, in the United States, the cost of implementing anaerobic digesters may vary by region. In addition, the choice of manure storage system also plays a role in GHG emissions, as anaerobic environments allow for more CH₄ and N₂O to form. The rapid removal of manure, such as in free-stall barns, has a

smaller GHG footprint compared to bedded pack barns where manure accumulates on the floor for months (Rotz, 2018).

In terms of feed, grazing operations have been shown to reduce emissions per cow by 15% by using smaller-sized cows that require lower feed intake. However, grazing operations also have lower milk production per cow and higher N₂O emissions, leading to a 10%–20% greater GHG footprint compared to confinement systems (Rotz, 2018). According to Rotz (2018), feed additives and diet present a significant opportunity to mitigate CH₄ emissions. More research is needed in this area. Whole systems modeling has identified areas in manure and feed where reductions can be made. Despite the need for better data, improved modeling processes, and standardized accounting for accurate comparisons, each mitigation strategy must make financial sense for farmers based on their region, operation style, and herd size.

1. Research Modeling

Extensive research and modeling have been conducted within the dairy industry to identify the processes responsible for GHG emission generation within the dairy industry and potential mitigation strategies. This work can be broadly categorized into two groups: (1) whole system modeling and (2) partial system modeling. These systems modeling tools are often made up of software programs, a few of which were examined for this thesis and will be discussed below.

Whole system modeling in the dairy industry has predominantly utilized LCA methods as seen by Thoma et al. (2013), Naranjo et al. (2020), Uddin et al. (2022), Van Middelaar et al. (2014), Liang et al. (2017), and Capper and Cady (2020). A more targeted approach, the

Integrated Farm System Model (IFSM), is used to focus on emissions that dairy farmers have control over, specifically those from the field-to-farm gate, as reported by Veltman et al. (2018). These models often build upon and expand on existing partial systems analysis within the literature.

In contrast, partial systems research has focused on mitigation techniques implemented in specific aspects of the farming system, such as manure management, feed requirements and substitutes, or water use. Partial systems research has often been used to build components of whole system modeling and can be used to answer detailed questions, as seen in studies by Adom et al. (2012), Van Middelaar et al. (2014), Dutreuil et al. (2014), Wightman and Woodbury (2015), Aguirre-Villegas and Larson (2017), and Scott and Blanchard (2021). These studies employ a variety of research techniques, including panel data, survey data, and tools or methods from LCA and IFSM research. Researchers have gained valuable insights into the complex interactions of the dairy ecosystem, the processes contributing to dairy GHG emissions, and potential mitigation strategies.

2. Whole System Models

LCA modeling is a well-established methodology for assessing the environmental impact of a product's system boundaries, from raw material extraction to end-of-life disposal. Commonly referred to as "cradle-to-grave" emissions, this approach considers the full system boundaries associated with a particular product (Science Direct, 2022). In an LCA model, cradle-to-grave emissions would go beyond Scope 3 measures and account for emissions associated with retail grocery stores or other institutions, retail consumers, and end-of-life disposal.

However, not all dairy LCAs use cradle-to-grave models and instead are limited to the field-to-farm gate. Regardless, LCAs aim to quantify the environmental impact associated with resource extraction, manufacturing processes, transportation requirements, and often the consumer use and final disposal of a given product (Science Direct, 2022).

Within the dairy-focused academic literature, LCAs are utilized as a tool that employs industry-specific terminology. Notably, the Energy Corrected Milk (ECM) metric serves to establish pricing structures that account for specific fat and protein percentages that may vary within milk, ultimately influencing the premiums paid to farmers. While the measurement is standardized, the reporting of it within the literature is not. For example, Thoma et al. (2013) and U.S. Dairy Stewardship Commitment (2022) define ECM as Fat and Protein Corrected Milk (FPCM) with 4% fat and 3.3% protein per kilogram, while Rotz (2018) defines it as 4% fat and 3.5% protein. Although CO₂e estimates are corrected, it is necessary to consider these variations when comparing different models.

In assessing LCA's CO₂e models, it is necessary to consider the system boundaries and assumptions used in the calculations. For instance, Thoma et al. (2013) reported that the GHG footprint of milk ranged from 1.77 to 2.4 CO₂e per kg of milk, with an average of 2.05 kg CO₂e, based on their cradle-to-grave model. The authors identified enteric emissions (25%), manure (25%), feed (19%), transportation (17%), retail (6%), consumption (5%), and farm energy (4%) as significant contributors to GHG emissions. These findings are generally consistent with DFA's (2022) cradle-to-grave sustainability report, which identified enteric emissions (28%), manure (26%), feed (23%), transportation and distribution (9%), use and end-of-life of solid products (8%), and energy (4%) as the main sources of GHG emissions in dairy production. However,

most dairy LCAs that were examined were field-to-farm gate models. For example, Naranjo et al. (2013) estimated GHG emissions to be between 1.12 and 1.16 CO₂e per kg of milk in 2014, while Rotz and Thoma (2017) found them to be between 0.8 and 1.2 CO₂e, and Uddin et al. (2022) estimated them to be between 1.02 and 1.26 CO₂e depending on the region, with a national average of 1.14 CO₂e per kg of milk in 2022. According to Uddin et al. (2022), the main sources of CO₂e emissions were enteric (39.5%), manure (36%), feed (20%), and farm energy (5.3%). Capper and Cady (2020) found that when they combined manure measurements with enteric emissions, these accounted for 80% of GHGs per unit of milk, followed by cropping input CO₂ at 7.6%, fertilizer application at 5.3%, and other areas on the farm accounting for the remaining emissions.

Although the dairy sector in the U.S. still contributes significantly to GHG emissions, the industry has made remarkable strides over the past half-century (Capper and Cady, 2020; Naranjo et al., 2013). In a 50-year study of California dairy farms, Naranjo et al. (2013) used two separate models and found that GHG emissions per kg of milk decreased from 2.11 CO₂e in 1964 to 1.12 and 1.16 CO₂e in 2014, representing a reduction of 45% to 46.9%, depending on the model used. In 2007–2017, before the Paris Accords, U.S. dairy farmers produced the same amount of milk while using 21% less land, 30% less water, and emitting 19% less GHG, thanks to the adoption of new technologies and advancements in science and innovation such as enhanced cow genetics and efficiencies from machinery use (Capper and Cady, 2020). Naranjo et al. (2013) also reported a significant decrease in enteric methane emissions, with 54.1% to 55.7% less emission per kg of ECM from 1964 to 2014, accounting for the greatest reduction.

The dairy sector has made significant progress in reducing GHG emissions through technological advancements in various subcategories that have improved field-to-farm gate emissions. The subcategories encompass a wide range of emissions, comprising those resulting from manure management and enteric methane sources, as well as emissions stemming from anthropogenic sources like farm management and crop production. According to Naranjo et al. (2020), the dairy sector has reduced emissions over 50 years (1964 to 2014) due to efficiency gains. Cow housing and milking emissions were reduced by 57.7% to 59.2%, crop production emissions by 62.6% to 63.9%, GHG emissions from manure management decreased by 8.73% to 11.9%, and production of 1.0 kg of ECM led to a 54.1% to 55.7% reduction in enteric methane emissions. In 1964, a cow consumed about 1.93 kg of feed to produce 1 kg of ECM (normalized to a lifetime basis), whereas in 2014, the feed conversion ratio was 0.79–0.81 kg of feed per kg of ECM (Naranjo et al., 2020).

Efficiency gains in the dairy sector have continued in recent years, as highlighted by Capper and Cady (2020) through their estimates comparing the resource used to produce the same 1.0 kg of ECM between 2007 and 2017. Despite fewer cows in 2017 producing more milk than ever, U.S. dairy farmers used 74.8% of the cattle, 82.7% of the feedstuffs, 79.2% of the land, and 69.5% of the water to produce the same 1.0 kg of ECM. GHG emissions per 1.0 kg of ECM produced in 2017 were 80.8% of equivalent milk production in 2007. They also found that since 2007, U.S. ECM production has increased by 24.9%, yet total GHG emissions from dairy production only increased by 1.0% (Capper and Cady, 2020).

LCAs estimate the environmental impact of a product over its lifespan but may not target the necessary stage for mitigation efforts. GHG emissions per unit of milk have decreased

over time, but monitoring environmental impacts is time-consuming and leads to quickly outdated point-in-time estimates. To avoid relying on outdated research, it is preferable to use current models, and expanding literature to avoid the use of dated assumptions that can be difficult to detect within models.

One modeling tool that uses LCA methodology for dairy farms is IFSM. According to the USDA (2020), IFSM is “Unlike most farm models, IFSM simulates all major farm components on a process level. This enables the integration and linking of components in a manner that adequately represents the major interactions among the many biological and physical processes on the farm.” This type of modeling is particularly useful for dairy and beef production, given the complexity of processes involved, such as crop production, pasture grazing, feed storage, and manure handling (USDA, 2020). This scope of modeling proves to be beneficial, particularly when considering that around three-quarters of dairy emissions arise during the field-to-farm gate. Several LCA studies have limited their scope to the farm gate (Naranjo et al., 2013; Rotz and Thoma, 2017; Capper and Cady, 2020; Uddin et al., 2022), which coincides with the dairy processor's Scope 3 emissions.

Veltman et al. (2020) conducted a study on Best Management Practices (BMP) for dairy farms to identify areas where farms should focus to reduce GHG emissions and other environmental impacts. The study serves as the first step in identifying contributing processes that require attention, as dairy farms need to know how to allocate their time and resources efficiently. This also allows for cost analysis, which is necessary for farms to conduct to adapt to new systems or technologies. The authors note that "BMPs that jeopardize production (milk, crop yield), and/or are associated with high initial implementation costs and a decrease in long-

term profitability are unlikely to be adopted by farmers and as such cannot generally be considered sustainable" (Veltman et al., 2020). The results from Veltman et al. (2020) are consistent with previous LCAs, which show that enteric CH₄ emissions are the primary contributor to GHG emissions (approximately 45%), followed by CH₄ emissions from manure (approximately 16%), and those associated with pre-farm sources emissions (approximately 13%). Veltman et al. (2020) found that the greatest GHG reductions can be achieved by investing in manure management (4% to 20% reduction) followed by dietary manipulations (0% to 12% reduction). However, the most cost-effective measures were found to be in-feed strategies, while manure strategies were not cost-effective. Dutreuil et al. (2014) used IFSM tools to examine feeding strategies and manure management in Wisconsin. They estimated mitigation costs for three types of dairy farms (conventional, grazing, and organic) when implementing these strategies. To find that GHG emissions reductions can be achieved, but profitability depends on the strategy taken. When conventional farms used grazing, they saw a 27.6% decrease in total GHG emissions (0.16 kg of CO₂e per kg of ECM) and a 29.3% increase in net return to management (+\$7,005 per year) when milk production was assumed constant. On grazing and organic farms, increasing feed concentrate to forage ratios reduced GHGs when milk yields increased by either 5% or 10%. However, the 5% level was not sufficient to maintain the net return to management, while the 10% level was (Dutreuil et al., 2014).

Dutreuil et al. (2014) also examined changes in manure management. They found a 13.7% decrease in GHG emissions of 0.08 kg of CO₂e per kg of ECM on conventional farms when changing manure management by incorporating the daily application of manure and adding a 12-month covered storage tank. However, these same changes led to a 6.1% (0.04 kg of CO₂e

per kg of ECM) and 6.9% (0.06 kg of CO₂e per kg of ECM) increase in GHG emissions in the grazing and organic farms, respectively.

3. Partial Systems Research

The literature on partial system modeling delves into subcategories of the broader LCA and IFSM models. These subcategories may examine feeding strategies for enteric emission reductions or manure management for reduced CH₄ emissions. They may also focus on regional differences or be region-specific. As Rotz (2018), points out, "Detailed process simulation models provide vital research tools, whereas simpler models are normally most useful in a decision support role."

The literature that takes on the role of decision support tends to concentrate on the measurement and mitigation of GHG emissions on dairy farms without considering the cost of mitigation strategies. However, some of the literature is starting to address the issue of estimating the cost of mitigation. Given that several major dairy processors are committing to net zero, it is important to investigate the financial costs associated with the GHG mitigation that dairy farmers are responsible for in future research. A few examples of such literature are presented below.

The production of feed for cows involves emissions during production and digestion. Crop production used to feed animals includes anthropogenic energy emissions from machinery, production input resources emissions such as fertilizer & chemical use, and direct & indirect and use changes. Factors such as crop variations and region can impact these emissions. Adom et al. (2012) found that CO₂e emissions vary based on geographical location within the

U.S., due to factors such as synthetic fertilizer use and soil composition. As a result, the Southeast dairy region has higher GHG emissions due to inputs used in feed production. The authors suggest the precise application of fertilizers as a potential solution, though they do not specify the extent to which this approach would reduce GHGs (Adom et al., 2012).

Feed strategies have an impact on enteric emissions, as the composition of a cow's diet influences the fermentation processes in its digestive system, leading to enteric methane emissions through belching (AP News, 2019). Different feed rations are used on farms, with varying combinations of corn, soybean, alfalfa, hay, supplements, and grass from grazing. These feeds may be produced on or off-site, or a mixture of both, and must meet specific dietary requirements for the health of the animals and target milk production levels. The ratio of forage-to-grain intake also affects fiber intake and digestion, leading to differences in enteric fermentation CH₄ emissions. Feed processing can also impact emissions, such as cutting corn stalks shorter to increase silage yields, which also increases the fiber content in the corn silage. These decisions affect milk production, yields, farm economics, and GHG emissions.

Van Middelaar et al. (2014) assessed the cost-effectiveness of three feeding strategies on Dutch dairy farms to reduce enteric CH₄ emissions from field-to-farm gate. However, implementing any of these strategies would reduce farm income, which limits the likelihood of adoption, as profitability is typically a key driver for decision-making. As stated by Van Middelaar et al. (2014), "Reducing the maturity stage of grass and grass silage was the most cost-effective (€57/t of CO₂e), followed by supplementation of dietary nitrate (€241/t of CO₂e) and supplementation of an extruded linseed product (€2,594/t of CO₂e)." In this case, the

lowest cost option at €57/t of CO₂e is 45 times less expensive to implement than the most expensive mitigation option.

Manure management is a promising area for GHG mitigation in dairy farming. Wightman and Woodbury (2015) evaluated confined dairy operations in New York and found that capturing methane and then burning it by flaring can be a cost-effective means of mitigating GHGs, reducing GHG emissions between 40% to 62% of manure GHGs. Implementing this approach requires a change in the manure management system and profitability is conditional on carbon credits. It is important to note that this method is only applicable to certain styles of confined dairy farming operations, where high-density cow populations make it easier to collect methane for flaring.

The concentration of cows and the methods employed in dairy farming practices are contingent upon farm size. According to Horacio et al. (2016), small and medium-sized dairy farms commonly manage their manure in solid form and utilize tie stalls for housing their cows, while larger dairy facilities handle slurry and liquid manure and utilize free stalls. These farm size differences determine which mitigation strategies are viable and the feasibility of recuperating their expenses. Wightman and Woodbury (2015) observed that a significant initial investment was necessary to cover manure storage for flaring, but this cost was recuperated over the lifespan of the infrastructure. They estimated that this change would add \$0.05 per liter of milk (Wightman and Woodbury, 2015).

Wightman and Woodbury (2015) highlight an additional consideration in the context of manure management. Historically, manure use involved year-round application on cropland as fertilizer, which posed environmental concerns due to potential water contamination. To

address these concerns, long-term storage of manure became a prevalent practice causing anaerobic conditions, which can lead to increased CH₄ emissions. Wightman and Woodbury (2015) found that if manure storage practices in 2012 had been similar to those in 1992, CH₄ emissions from such storage would have been only 37% of what they were. This finding underscores the importance of assessing the entire system when seeking to address environmental concerns. While the shift to long-term manure storage improved water quality, it had an unintended GHG cost that must also be considered.

A more recent and promising mitigation strategy for manure is the use of anaerobic digestion (AD) systems. As previously mentioned, Rotz (2018), found that the lowest emissions modeled farm reduced GHGs by 25% when using AD systems, while Aguirre-Villegas and Larson (2017) concluded that AD systems were the most effective way to reduce GHG emissions from both energy use and manure perspectives. However, they recognized that the technology is expensive to implement, and different farm sizes and manure management practices create additional challenges.

Aguirre-Villegas and Larson (2017) found that the farm percentages with AD systems were plug-flow (43%), modified plug-flow (29%), and complete mix (29%) digesters. They show that 70% of small farms handle solid manure, and most of their GHG emissions occur during manure land application as fertilizer. On the other hand, nearly 80% of the large facilities handle liquid manure, and this storage method creates most of their GHGs due to the anaerobic conditions of storage. This also creates a greater risk to water quality due to its liquid form. Moreover, differences in dairy size and access to water create variations in the type of AD system that can be implemented, with certain systems having higher capital costs. Collection

and application of manure also vary by the size of the farm, with more energy-efficient automated methods usually done by larger operations, and they are more likely to land-apply manure in the spring and fall instead of weekly or daily. If storage is done for longer periods, this allows for the anaerobic conditions that create more methane.

According to Aguirre-Villegas and Larson (2017), small farms primarily emit GHGs through manure land application. In their low-emission scenario, small farms could reduce GHG emissions by 9%, but they could increase GHG emissions by up to 35% if they transitioned away from daily land application to manure storage. On the other hand, large farms could reduce emissions by 47% by using anaerobic digesters. However, methods to reduce ammonia (NH_3) by 39% with land injection increased overall GHG emissions by 4%. The study emphasizes the unintended consequences of mitigation strategies that only consider certain gases without evaluating the whole system (Aguirre-Villegas and Larson 2017).

In summary, whole systems modeling and partial system modeling are both important in contributing to the literature. As noted by Rotz (2018), "Models provide important tools for quantifying emissions, identifying opportunities for reduction, and evaluating mitigation strategies." When updating these models, it is increasingly important to accurately define the data, better understand mitigation techniques, standardize model procedures, and account for both mitigation costs and responsibility. This will help in defining responsibility and feasibility for mitigation. Regional differences must also be considered as an important variable in future research. Reductions are still possible as the dairy industry has become more efficient over the decades, but this is often overlooked (Naranjo et al., 2020; Capper and Cady, 2020). However, research is needed to understand the limits of possible reductions and whether achieving net-

zero emissions is possible when so many system emissions are biological. While it is important to understand and quantify these models for net-zero goals, it is equally important to understand the costs and responsibility of mitigation at the farm level. If dairy farms must bear most of the costs for the dairy industries' overall GHG mitigation and if they do not find it profitable, GHG mitigation systems will not be adopted.

III. Materials for LCA Modeling

Life Cycle Analysis (LCA) modeling is widely used in applied economics research. LCA modeling tools are often used to evaluate the environmental impacts of a product or system throughout its entire life cycle, from raw material extraction to disposal. LCA modeling tools provide a framework to quantify and compare the environmental impacts of different products or systems, based on various metrics such as greenhouse gas emissions, energy use, economic costs, and resource depletion. The results of LCA modeling can inform decision-making by identifying areas of high impact and opportunities for improvement. LCA modeling tools are widely used in sustainability assessments, and policymaking to support the transition towards more sustainability.

The Integrated Farm System Model (IFSM) is a widely used LCA simulation tool that predicts the long-term performance, environmental impact, and economics of dairy and beef production systems (Dutreuil et al., 2014; Horacio et al., 2017; Rotz, 2018; Rotz et al., 2021; Veltman et al., 2018). As an LCA modeling tool, IFSM focuses on the field-to-farm gate and is

particularly useful for evaluating dairy processors' Scope 3 emissions, which account for over three-quarters of all milk-related emissions (USDA, 2020).

IFSM is a sophisticated simulation tool that considers the interactions of all major physical and biological components of farm systems to produce economic, biological, and environmental outcomes (USDA, 2020). The model allows researchers to select a wide range of characteristics, from small-scale soil pH composition to large-scale total acres of crops planted, to represent real-world farm systems. The model variables are categorized into crop and soil, grazing, machinery, tilling and planting, harvesting, storage, animal and feeding, manure, and economics (input and output costs). Figure 1 depicts the interconnections of these variables as a system within the IFSM model, where modifying a single parameter affects the entire system, and the system adapts accordingly as additional variables are modified (USDA, 2020).

Note: Yellow arrows indicate connected farm processes and small black arrows indicate system inflows and outflows.

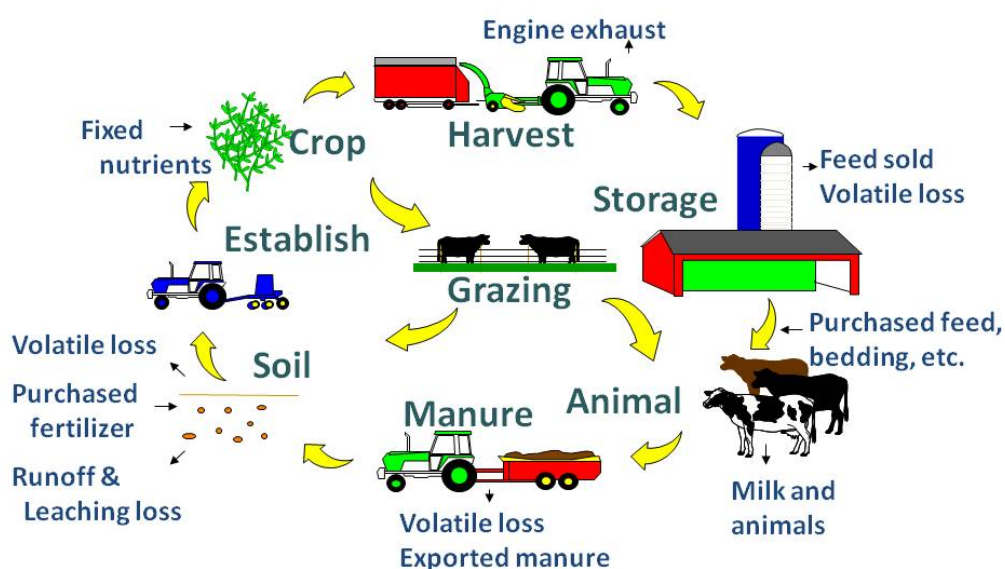


Figure 1. IFSM System's Flow Diagram (USDA, 2020).

IFSM generates extensive data sets of environmental and economic impacts resulting from the interactions within the system. These data sets can be used to estimate the carbon emissions and carbon footprint of dairy milk. To conduct the simulations, IFSM utilizes local weather data over a specified period of multiple years, typically 20, to generate average estimates of these variables. The simulations are typically performed on pre-defined example farms and machinery model sets, which can be customized to meet the user's requirements.

These simulations enable users to compare the effects of different GHG mitigation strategies on the entire farm system, which can aid in evaluating best practices. However, few studies have compared multiple mitigation options on farms of various sizes and regions in the same study. This analysis aims to address this gap and examine the available mitigation options for dairy farms to achieve net-zero targets set by processors, while also considering differences in farm size and region. This thesis aims to answer the primary question: What strategies are available to ensure that dairy farmers of diverse sizes and regions can minimize the dairy industry's GHG emissions while maintaining economic viability? IFSM will provide economic and GHG emissions data for modeling various mitigation approaches on heterogeneous farms to answer these questions. This study's findings will help inform policy discussions among stakeholders concerning dairy processors' net-zero pledges and their impact on dairy farms.

1. IFSM Reporting Overview

The farm system simulation report covers three main areas: emission sources, input and output quantities, and economics. Emission sources are presented in CO₂e and include emissions from animal (enteric), manure, direct and indirect land use, biogenic, anthropogenic,

and production of resource inputs. IFSM also generates detailed reports on other GHGs contributing to CO₂e, such as ammonia, hydrogen sulfide, ozone, methane, and nitrous oxide. These detailed reports allow for a comprehensive evaluation of the environmental impact of dairy and beef production and facilitate the identification of potential areas for improvement.

The emissions calculated by IFSM are influenced by the choices made by the user when inputting parameters into the software. Some of these factors are mostly out of the control of the dairy farm, such as weather and soil composition, while others are within their control, such as herd size and machinery. IFSM generates reports on the input and output quantities of several categories that are under the farm's control, including manure, milk, culled beef, crops, purchased feed, and water use.

In addition to emissions, the simulations generated by IFSM provide detailed information on the economic aspects of inputs and outputs on dairy farms. The user can adjust many of these variables, such as income from and expenses for equipment, machinery, energy (diesel, natural gas, electricity), labor, seed, fertilizer & chemicals, land, feed & bedding, animals, taxes, and milk sales. The combination of these three reporting categories makes IFSM a powerful tool for examining the entire dairy farm system, from the field to the farm gate.

IFSM allows for the adjustment of the variables to estimate the potential effects of GHG emissions mitigation options for the three primary sources of emissions in dairy farming: enteric, manure, and feed. Since these mitigation variables interact with one another, it is not possible to isolate the effects of a single source. IFSM models consider all interactions between the numerous variables and their parameters, as set by the user. For example, increasing alfalfa cropland may affect both the feed category and enteric emissions, as IFSM prioritizes the use of

farm-grown products first. Harvesting the alfalfa crop will result in anthropogenic emissions, but these could be lower than from other feed options. This change will also affect economic outcomes as less feed needs to be purchased, which may or may not reduce overall expenses.

Pastureland utilization also impacts manure emissions and reduces the need to purchase feed. User choices in pastureland, feed type, protein mixes, and hay-to-grain ratio influence feed system effects. Milk production is determined by the animal component, which is directly affected by the quantity and quality of available feed. Increasing milk production targets will require more feed and will affect both feed and enteric emissions. Ultimately, modifying variables related to cow management will have direct and indirect impacts on the three primary emissions categories on dairy farms. The interactions between the numerous variables and their parameters are accounted for in IFSM models, allowing for the estimation of the potential effects of GHG emissions mitigation options for enteric, manure, and feed sources.

In this thesis, IFSM was utilized to assess the economic feasibility of implementing GHG emissions mitigation methods on five dairy farms, located in four different states, and were based on IFSM-provided example farms and machinery configurations. The IFSM example farms serve as comprehensive operational templates that can be used without modification to run simulations or customized to meet the specific requirements of the user. In this research, the farm size and location were kept consistent using the available IFSM example farms, which were selected to represent a range of typical dairy operations. The chosen locations encompass a significant geographic span across the United States, while the selection of four states is based on their inclusion in the top ten for total dairy production volume. The farms ranged from a farm with 280 lactating cows in Idaho, one in New York with 1000 lactating cows, one in Texas

with 1200 lactating cows, and two in Minnesota with 300 and 5000 lactating cows. Seven different models were tested for each farm, with and without the inclusion of an anaerobic digester, resulting in a total of fourteen scenarios per farm, and a total of seventy distinct models across all farms.

The mitigation scenario models assess the effects of changing various categories, such as cows, manure storage, feed options, grazing options, and crops grown. These models are labeled as Models 1–7, with Model 1 serving as the baseline assumption model. An AD system was also integrated into these seven models, resulting in the corresponding models being labeled with an *AD* before the model number (e.g., AD Model 1). The AD system was the only variable that differed between the AD and non-AD models, while all other variables remained constant across the two versions of each model. The capital costs of the anaerobic digestion system, electrical pricing, ETCE, and other variables were based on research using an Excel-based AD system capital cost modeling tool named Anaerobic Digester Economic Spreadsheet (ADES) courtesy of the University of Minnesota.

To improve the accuracy of comparisons between farms and to account for the variability of farming practices, many characteristics of the IFSM example farm models were standardized, such as cow characteristics, manure storage, feed options, grazing options, crops grown, and economics (input and output prices). This allows for local conditions to affect the results while keeping other variables constant. The simulations generate comprehensive summary reports that describe the mean and standard deviation based on 20 years of randomized local weather data. Figure 2 shows the software interface with a portion of the summary output data and an open tab for adjusting assumption characteristics for animal and

feed information. More details on the standardized characteristics are provided in the Methods section.

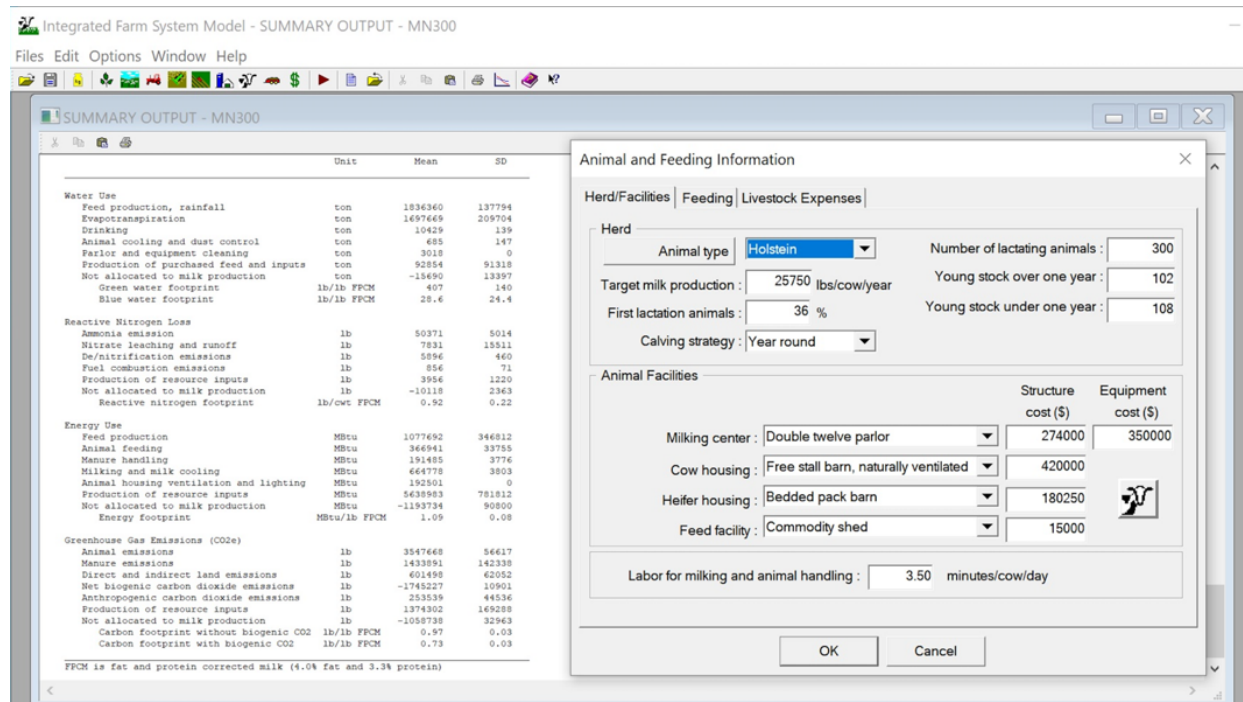


Figure 2. IFSM Software Interface with Summary Report and Animal Characteristics (USDA, 2020).

The thesis reports the results of each model in two main categories: economics and emissions. The primary financial metric used is the Return to Management (RTM), which is the derived profits from dairy, crop, and animal sales revenues minus the sum of all costs of production, with capital investments being amortized over their life expectancy. Simulations are performed on an annual time step with farm processes performed under 365 days of weather data. Then the next year of weather data is read until the requested number of simulated years is met. To report RTM and other variables and account for yearly variations, values for the mean and standard deviation are provided based on the overall number of simulated years (USDA,

2020). GHG emissions are measured in pounds (lbs.) of carbon dioxide equivalent (CO_2e), with the primary carbon footprint measure being CO_2e lbs. per lbs. of fat and protein-corrected milk (FPCM). This is referred to as the “carbon footprint of milk” in this thesis. FPCM is an industry-standardized content measurement for commodity milk that adjusts the fat and protein percentages of milk to 4% and 3.3%, respectively, enabling uniform product trading and comparison of research effects. Two carbon footprint measures are reported, one including biogenic processes and the other excluding them. Biogenic emissions are a closed-loop process, with CO_2 emissions from enteric or manure processes coming from plant fixation, which results in no net increase in atmospheric CO_2 emissions. The RTM and carbon footprint of milk metrics will be discussed in more detail later, including their subcomponents. RTM and carbon footprint of milk metrics were chosen for this study as they directly relate to how dairy farmers will be assessed in achieving net zero emissions and what changes in the farm's profitability may occur.

IV. Methods for Using IFSM Modeling

Emissions are influenced by various factors such as the characteristics that define the cows, manure, feed, crops, and economics. Although all combinations of variables cannot be modeled, the main objective of this study is to analyze how the economics of mitigation options are affected by regional and farm size differences. Most regional differences base assumptions were kept such as soil conditions, weather, farm equipment, storage, crop mixes, and crop acreage. For comparison, farming choices were adjusted such as cow size and feed ratio for consistency, while state commercial electrical pricing was updated (e.g., Table 2 to Table 6). One

of the critical regional differences that can impact the annual models is the local weather. In the IFSM software, only the parameters for the base assumptions can be modified, and the formulas cannot be modified. Some of these formula assumptions may have a significant impact on overall outcomes. Furthermore, IFSM does not update all variables when it updates the example farm models, and it does not specify which variables were updated. Table 1 provides a concise overview of the seven primary base models that were simulated across all five farms.

Table 1. IFSM Models and Assumption Descriptions.

IFSM Models	Assumption Description
Model 1	Original Baseline Assumption for Comparison Against
Model 2	Large Holsteins with Increased Milk Production (27,000 lbs./cow/year FPCM)
Model 3	Feed Changes (Forage-to-Grain Ratio Set to Low)
Model 4	Pastureland Grazing Included (1 Acre / Lactating Cow)
Model 5	Alfalfa Crop Increased (1 Acre / Lactating Cow)
Model 6	Corn Crop Increased (1 Acre / Lactating Cow)
Model 7	Soybean Crop Increased (1 Acre / Lactating Cow)

Note: For models including AD systems they are identified with an AD before the model number (e.g., AD Model 1).

1. Cow Characteristics

The use of cow breeds, the sizes of lactating cows, and all cow-type ratios in IFSM farms can affect the outcomes. To maintain consistency, cow-type ratios were standardized and referred to using IFSM terms. Other cow types consist of 36% young stock under one year old of the cumulative lactating and dry cow numbers. They have a 6% mortality loss rate for calves before they become heifers which roughly translates to 34% of the lactating cow population. Further mortality of bred heifers and milking cows is accounted for in IFSM, but that is an unchangeable variable and is generally low at 5%. IFSM also assumes a 15% dry-cow ratio,

which cannot be modified. Table 2 presents the variables used for cow characteristics. The original dairy milking facilities in the farm models were retained, as there are several systems in use, and they often depend on the dairy herd size. Changing these assumptions primarily affects Model 2, which increased the size of Holsteins to 1,673 lbs. and raised the target milk production to 27,000 lbs./cow/year.

Table 2. Cow Assumption Characteristics Used in Modeling Across All Farms.

Cow Assumption Characteristics	Variable Used
Animal Type	Holsteins
Target Milk Production (lbs./cow/year)	25,750
Percent of herd in First Lactation (%)	36
Calving Strategy	Year Round
Mature Cow Body Weight (lbs.)	1521
Average Milk Fat (%)	3.5
Genetic Fiber Intake Capacity (%)	1
Dry Cows (IFSM assumed %)	15
Young Stock Over One Year (6% loss of Calve Stock) (% of lactating)	≈34
Young Stock Under One Year (% of lactating)	36

Notes: Characteristics labeled as in IFSM (USDA, 2020). There is no option to adjust the protein percentage of milk.

2. Manure Characteristics

Farm manure methods and handling were standardized, except for the storage size and cost, which are a function of the number of animals on the farm. The primary manure handling method and a secondary method can lead to significant differences in results if not adjusted. Therefore, all secondary manure handling methods were set to zero use as seen in Table 3. Not using a secondary manure method meant that storage size adjustments were necessary for some farms, which were increased to cover only the annual average requirements.

Table 3. Manure Assumption Characteristics Used in Modeling Across All Farms.

Manure Assumption Characteristics	Variable Used
Manure Collection Methods	Scraper with Slurry Pump
Manure Type	Slurry (8-10% DM)
Manure Incorporation by Tillage (otherwise field spread)	None
Storage Period (months)	6
Storage Type	Covered Tank or Basin
Storage Size Adjustments if Needed	Farm Specific
Bedding	Straw
Bedding Amount Used per Mature Animal (lbs./day)	3
Second Manure Handling	None
Exports of Manure (%)	0
AD Initial Costs (Digester and Generator)	Herd Size Dependent*
Biogas Leakage Rate (%)	1
Volatile Solids Conversion Efficiency (%)	30
Annual Repair and Maintenance Costs (hrs./week)	5
Electrical Generation Capacity	Herd Size Dependent*
Electrical Generation Efficiency	Herd Size Dependent*
Run Time Efficiency (%)	92
Biogas Used for Water Heating (%)	0

*Notes: Asterix indicates AD System farm size dependent variables based on calculations from Anaerobic Digester Economic Spreadsheet courtesy of the University of Minnesota. Characteristics labeled as in IFSM (USDA, 2020).

AD systems include digester storage cost, generator cost, volatile solids conversion efficiency, generator kW size, electrical generation efficiency, and run time. These were based on research done with an Excel-based AD system capital cost modeling tool named Anaerobic Digester Economic Spreadsheet (ADES) courtesy of the University of Minnesota. However, IFSM does not separately specify the life expectancy of AD systems compared to other machinery and infrastructure and this will affect the finances of these large capital investments. Models that use AD systems are primarily affected by changing these assumptions. Manure changes affect all models, with pronounced changes in Model 2 due to the larger Holsteins, Model 3 due to feed

changes, Model 4 due to cows excreting manure while grazing on pastureland, and all the anaerobic digester models are labeled AD Models 1 through AD Model 7.

3. Feeding and Pasture Characteristics

Feeding options for cows are a crucial factor in determining simulation results. The type of feed used can vary significantly across farms, depending on the availability of alternative options in the local area. Variables that affect the results due to feed include the quantity, quality, type, cost, and availability of pasture. Feed assumptions were standardized, but many variables are optimized by the software program as it runs scenarios to account for regional conditions. Feed options must be standardized as they can have a significant impact on economic outcomes, as costs will vary locally for the same feed items and will depend on the feed mix choices. Table 4 shows the variable characteristics used for feed and pastureland. Pastureland was assumed to be seeded and require labor, which increases costs, but other costs such as fencing were not included as they will vary by farm if needed. IFSM reduces grain and silage feed by the pasture nutrient availability while cows are out to graze. Feed options also consist of a forage-to-grain ratio which in IFSM modifies the linear program used to formulate feed rations. A high forage-to-grain ratio uses as much forage as possible in the lactating cow's diet. A low forage-to-grain ratio minimizes the use of forage to maintain a minimum amount of dietary fiber (USDA, 2020). Feed affects all models as larger cows will require more feed, and increasing the crops grown will change feeding ratios. However, changes in the feed will primarily affect Model 3 by lowering the forage-to-grain ratio and increasing the minimum hay

percentage from 0% to 25%. Changes in pastureland will affect Model 4 by increasing land available for grazing by one acre per lactating cow, which in turn will reduce feed requirements.

Table 4. Feed and Pasture Assumption Characteristics Used in Modeling Across All Farms.

Feed and Pasture Assumption Characteristics	Variable Used
Minimum Dry Hay in Cow Rations (%)	0
Protein and Phosphorus Feeding Levels (%)	100
High Relative Forage to Grain Ratio	High
Crude Protein Supplement	Soybean Meal 44%
Undegradable Protein of Distiller's Grain	Distiller's Grain
Energy Supplement	Grain & Animal/Veg Oil
Grazed Forage Yield Adjustment Factor (%)	70
Labor for Grazing Management (hrs./100 lactating cows)	6.82
Pasture Utilization Efficiency (%)	60
Grazing Period (months)	5
Animals Grazed	All Cows
Time on Pasture	Half Days

Notes: Characteristics labeled as in IFSM (USDA, 2020).

4. Crop Characteristics

Cropping characteristics were generally similar across farms, but there were variations in the types of crops grown, land availability, machinery used, and planting and harvest options based on regional differences and herd sizes. For example, some farms may grow wheat, while others did not grow alfalfa. Additionally, some farms rented some land while others owned all their land, and each farm had its own harvesting schedule for baling or producing field-wilted silage. Crop assumptions include how the crop is harvested such as rolled at the chopper, necessary moisture content at harvest, and intended use such as roasting and cash crop, as seen in Table 5. As a result, each example model farm in IFSM has unique characteristics that

result in differences in the estimated three primary emission sources of enteric, manure, and feed which all help determine the overall economic cost for GHG emissions mitigation.

To increase cropland, each farm required individual adjustments to their machinery needs in order to have the appropriate ability to plant, harvest, and transport the crops. If additional machinery was needed it was increased based on farming practices done on that farm and based on the already available equipment. All costs and revenues associated with the machinery were included in the analysis. Adjustments for alfalfa included the transport of feed, mowing, tedding, baling, racking, forage chopping, feed mixing, silo filling, primary manure handling, and drill seeding. For Corn, adjustments were also needed in plowing, field cultivation, and row crop planting. Changing these assumptions primarily affects Models 5 through 7, which increase the specified crop by one acre per lactating cow.

Table 5. Crop Assumption Characteristics Used in Modeling Across All Farms.

Crop Assumption Characteristics	Variable Used
Corn Maximum Moisture Content at Harvest (%)	68
Corn Silage Cutting Hight (inches)	6
Corn Silage Processing	Rolled at the Chopper
High Moisture Corn Type	Grain w/ Little Cob & Husk
Soybean and Small Grain Primary Use	Cash Crop
Soybean Roasting Cost (\$/ton DM)	50

Notes: Characteristics labeled as in IFSM (USDA, 2020).

5. Economic Characteristics

Many economic variables are locally dependent, such as the cost of electricity, land rental prices, and bedding prices. Local electricity prices were adjusted to match state

commercial rates, while diesel and natural gas used the most recently updated IFSM averages (see Table 6). The Mailbox Price of milk was updated using USDA data in December 2022 state averages (USDA, 2022c). The assumed economic life of machinery and buildings is 12 years and 30 years, respectively. These values would normally differ depending on the type of machinery such as an anaerobic digesters generator, a tractor, or a combine, and hence may affect financial results. Other economic variables include cropping, feed, products, and custom operations, but these were not changed from the last IFSM update and can be regionally specific. Economic assumptions were not specifically changed for any of the primary seven models, but all changes for model scenarios have economic consequences. However, the inclusion of an AD system in AD Model 1 through AD Model 7 adds a large capital cost to each farm.

Table 6. Economic Assumption Characteristics Used in Modeling Across All Farms.

Economic Assumption Characteristics	Variable Used
Diesel Fuel (\$/gal)	3.229
Natural gas (\$/therm.)	0.641
Electricity	State Average
Labor Wage (\$/hr.)	12
Land Rental	Farm Specific
Property Tax (%)	2.3
Machine Economic Life (years)	12
Structure Economic Life (years)	30
Machinery Salvage Value (%)	30
Structure Salvage Value (%)	0
Interest Rates Mid and Long-Term (%)	4
Milk Pricing (Mailbox in \$/cwt)	State Average

Notes: Characteristics labeled as in IFSM (USDA, 2020).

V. IFSM Results Summary of Models 1–7

This research employs a comparative analysis to assess GHG mitigation strategies for five dairy farms. A total of seven different models were utilized to evaluate fourteen distinct scenarios, each of which was tested with and without the investment of an anaerobic digester system. The findings indicate that there are potential mitigation options that have greater return to management outcomes than other options when looking at their milk carbon footprint. The carbon footprint is a function of the pounds of fat and protein corrected milk production to the total emissions from all sources required to produce the FPCM. Although some scenarios resulted in higher GHG emissions, they also yielded greater milk production, thereby lowering the carbon footprint per pound of FPCM. Conversely, other scenarios decreased milk production but generated greater revenue and reduced GHG emissions. Variables in Appendix A through Appendix S are color coordinated where green denotes economic results, salmon for GHG emissions results, and blue for general results. Table 7 is a review of the IFSM models and assumption descriptions before further discussion.

Table 7. Quick Reference of the IFSM Models and Their Assumption Descriptions.

IFSM Models	Assumption Description
Model 1	Original Baseline Assumption for Comparison Against
Model 2	Large Holsteins with Increased Milk Production (27,000 lbs./cow/year FPCM)
Model 3	Feed Changes (Forage-to-Grain Ratio Set to Low)
Model 4	Pastureland Grazing Included (1 Acre / Lactating Cow)
Model 5	Alfalfa Crop Increased (1 Acre / Lactating Cow)
Model 6	Corn Crop Increased (1 Acre / Lactating Cow)
Model 7	Soybean Crop Increased (1 Acre / Lactating Cow)

Note: For models including AD systems they are identified with an AD before the model number (e.g., AD Model 1).

1. Economic Trends Across IFSM Models

All farms had a positive mean return on management across the 20 years of simulations in the baseline Model 1. When the target milk production was increased by using larger Holsteins in Model 2, all farms benefited, but the percentage of benefits depended on local farm conditions (see Figure 3). The MN-300 farm saw much smaller returns than the similarly sized ID-280 farm. All farms experienced an increase in total costs but were compensated by the increased milk production as seen in Table 8 which shows the change in milk production and total cost in Model 2 from baseline Model 1. The increase in costs in Model 2 was primarily due to the dietary requirements of larger and more productive cows, but milk productions grow by 0.4% to 17.7% which overcompensated for these added expenses at the current milk selling price.

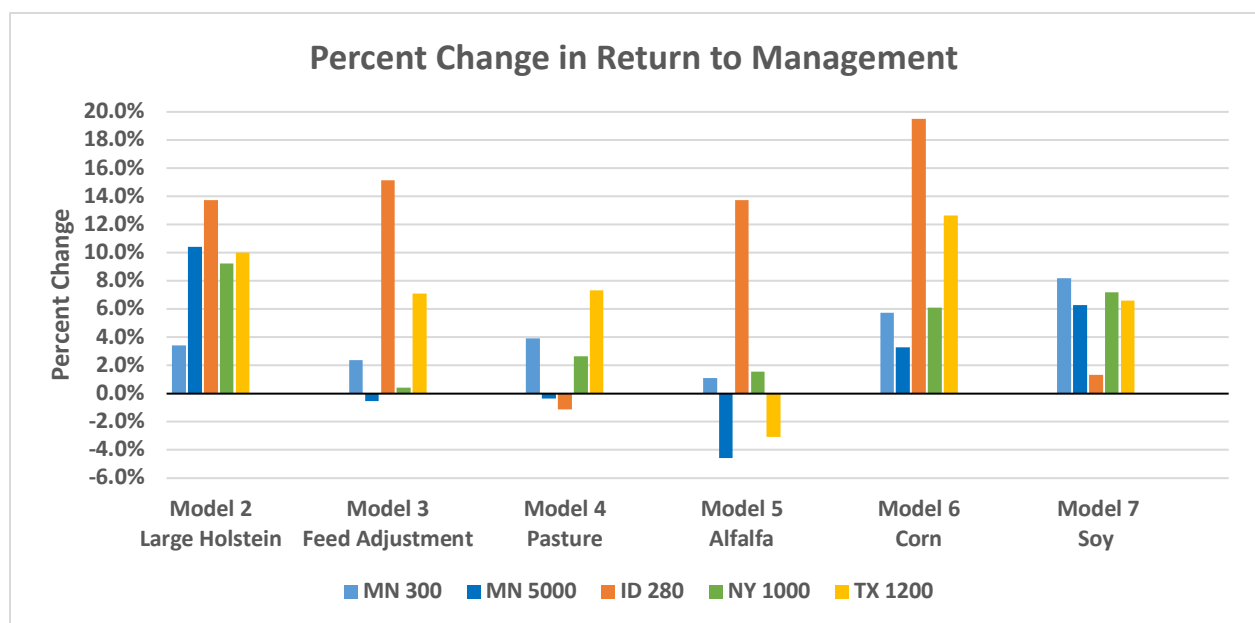


Figure 3. Percent Change in Return to Management for Models 1-7.

Table 8. Change in Milk Production to Total Cost in Model 2 Compared to Baseline Model 1.

Farms	Model 1 FPCM Milk Production (lbs./yr.)	Model 2 FPCM Milk Production (lbs./yr.)	Change in Milk Production (%)	Model 1 Total Cost (\$/yr.)	Model 2 Total Cost (\$/yr.)	Change in Total Costs (%)
ID 280	5,947,200	6,486,200	9.1	1,040,071	1,101,595	5.9
MN 300	6,372,600	7,022,100	10.2	825,196	882,708	7.0
NY 1000	22,053,000	24,032,000	9.0	2,747,640	2,978,807	8.4
TX 1200	26,043,600	28,383,600	9.0	3,736,400	4,032,107	7.9
MN 5000	110,830,000	120,805,000	9.0	14,365,093	15,393,897	7.2

The reduction of feed and bedding category costs was one of the largest cost decreases for most farms in Models 3–7 as seen in Table 9, which shows the changes in feed and bedding costs from baseline Model 1 for Models 2–7 and range from an increase of up to 64% and a decrease as low as 221.8%. It is worth noting that the MN-300 farm was the only farm that produced more feed than it needed annually, which reduced its annual total costs in Models 1–3 even before increasing the cropland. Increasing pasture and cropland in Models 5–7 tended to increase costs for the *Seed, Fertilizer, and Chemicals* category, as well as the *Energy* category. These cost increases were offset by reductions in feed and bedding costs but varied depending on the farm.

Table 9. Percent Change in Reduction in Feed and Bedding Costs.

Farms	Model 2 Large Cows (%)	Model 3 Feed Change (%)	Model 4 Pasture (%)	Model 5 Alfalfa (%)	Model 6 Corn (%)	Model 7 Soy (%)
MN 300	64.0	-10.6	-29.8	-138.6	-221.8	-201.9
MN 5000	28.2	7.6	-11.4	-27.9	-88.5	-88.5
ID 280	33.3	12.2	-39.2	-131.4	-173.0	-55.3
NY 1000	47.9	-2.3	-25.8	-109.6	-160.3	-137.9
TX 1200	14.3	0.5	-4.4	-18.1	-49.3	-25.2

The installation of an AD system had a negative economic impact on all farms in AD Model 1, except for the larger MN-5000 and NY-1000 farms. The TX-1200 farm experienced relatively modest declines in Return to Management (RTM), while the two smallest farms, MN-300 and ID-280, saw significant declines as seen in Figure 4, which illustrates the changes in RTM from baseline Model 1 when an AD system is included in the primary seven models. The IFSM analysis does not incorporate the capacity to capture the resale of electricity to the grid, rendering it unwise to exclusively rely on it for a comprehensive economic evaluation of an AD system. However, it can be useful in evaluating how much income an AD system would need to generate to achieve a positive RTM. Based on these simulations, both the MN-300 and ID-280 farms would require their AD system to generate over a hundred thousand dollars more annually to become profitable. In summary, despite the implemented mitigation methods, most farms increased their RTM by increasing the size of their operation before installing the AD system.

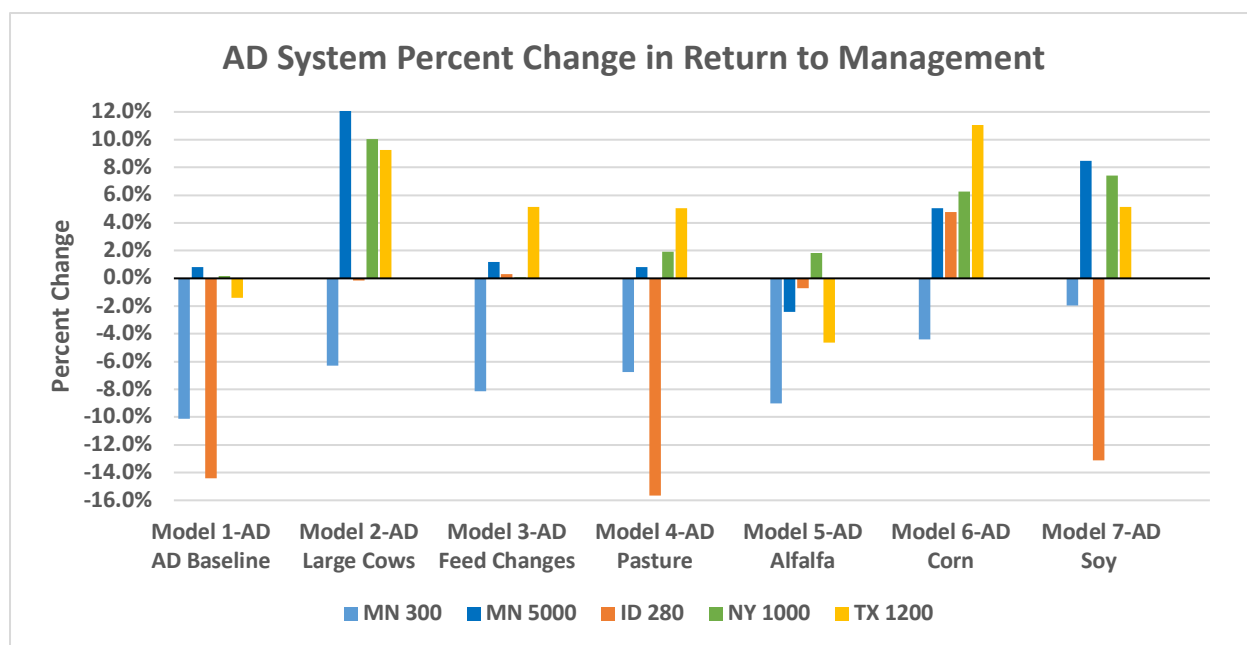


Figure 4. AD System Percent Change in Return to Management Compared to Baseline Model 1.

2. Carbon Footprint Trends in IFSM Models

The mitigation of GHG emissions varied across farms, with some achieving greater reductions than others, despite using the same mitigation methods. The total carbon footprint of milk, including biogenic CO₂, ranged from 0.55 to 0.83 lbs. CO₂e/lb. FPCM as seen in Table 10, which displays the carbon footprint of FPCM for Models 1-7. The MN-5000 and NY-1000 farms already had the smallest carbon footprint, while the TX-1200 farm had the largest. The MN-5000 and NY-1000 farms both started with a 22.8% smaller footprint than the TX-1200 farm in baseline Model 1 before models were simulated. The gap between the farms' maximum and minimum carbon footprints was the largest with pastureland at 29.0% and the smallest with increased corn acreage at 18.2%. Overall, farms began with significant differences in their carbon footprints that could be increased or reduced depending on the model.

Table 10. The Total Carbon Footprint of Milk Including Biogenic CO₂.

Farms	Model 1 Baseline (lbs. CO ₂ e / lb. FPCM)	Model 2 Large Cows (lbs. CO ₂ e / lb. FPCM)	Model 3 Feed Changes (lbs. CO ₂ e / lb. FPCM)	Model 4 Pasture (lbs. CO ₂ e / lb. FPCM)	Model 5 Alfalfa (lbs. CO ₂ e / lb. FPCM)	Model 6 Corn (lbs. CO ₂ e / lb. FPCM)	Model 7 Soy (lbs. CO ₂ e / lb. FPCM)
ID 280	0.75	0.74	0.55	0.73	0.72	0.7	0.73
MN 300	0.73	0.71	0.64	0.64	0.73	0.72	0.72
NY 1000	0.66	0.65	0.57	0.59	0.65	0.65	0.65
TX 1200	0.83	0.83	0.68	0.79	0.83	0.78	0.82
MN 5000	0.66	0.66	0.59	0.59	0.66	0.66	0.66
Difference Btw Max & Min Carbon Footprint (%)	22.8	24.3	21.1	29.0	24.3	18.2	23.1

In Model 2, increasing cow size and milk production led to an increase in total emissions ranging from 7.6% to 9% as the cows required more feed (see Figure 5). The most significant reduction in emissions was achieved by changing feed from high forage-to-grain ratio, with no minimum hay percentage, to a low forage-to-grain ratio and 25% minimum hay, resulting in reductions ranging from 8% to 13.1%. The addition of pasture in Model 4 was the second-largest area of reduction.

While pasture use reduced emissions across farms, the reductions were not correlated with the farm size. The largest reduction was observed in anthropogenic and land use, followed by manure emissions, ranging from 4.3% to 33.8% as seen in Table 11, which shows that using pastureland reduced emissions in these three categories. Cropland changes in Model 5–7 showed modest reductions in total emissions, ranging from 0% to 4.1%. These changes varied by emissions category and farm, indicating that regional factors, farm size, and/or individual farm practices may impact the success of pastureland use.

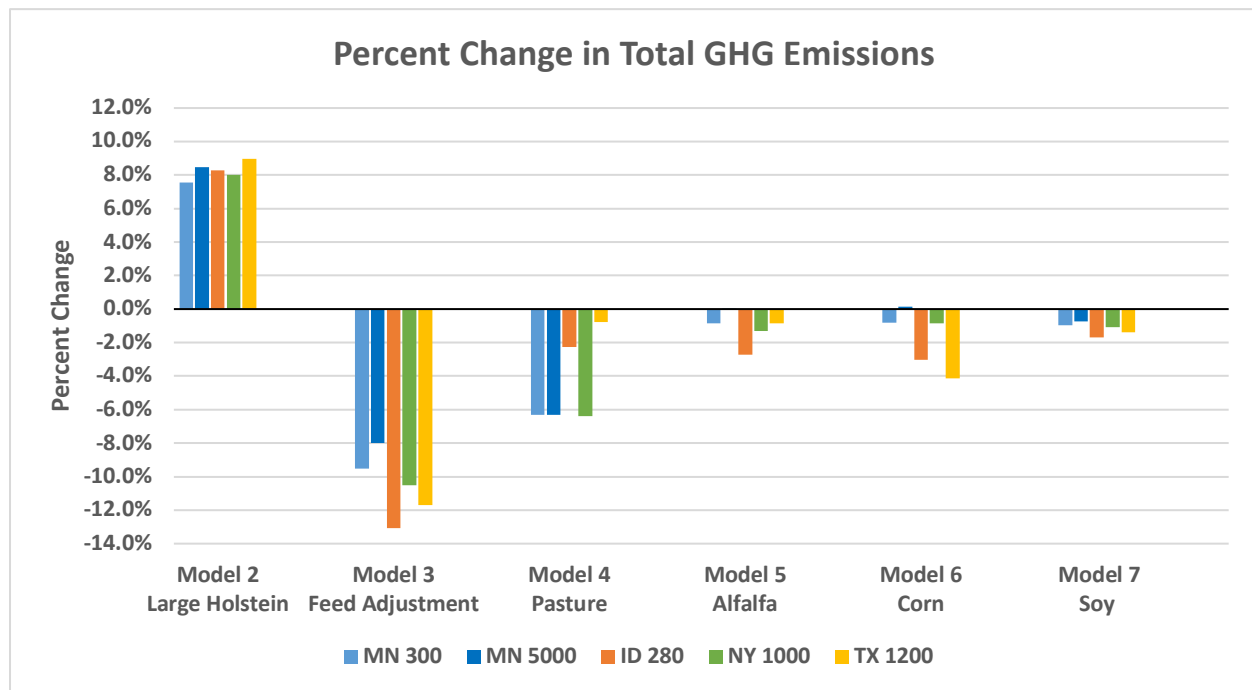


Figure 5. Percent Change in Total GHG Emissions.

Table 11. Emissions Reductions From Pastureland Use

Farms	% Δ Manure Emissions (lbs. CO ₂ e)	% Δ Direct and Indirect Land Emissions (lbs. CO ₂ e)	% Δ Anthropogenic (lbs. CO ₂ e)
ID 280	-4.3	-18.1	-22.7
MN 300	-8.4	-21.9	-26.6
NY 1000	-7.5	-12.0	-13.4
TX 1200	-7.4	-12.0	-11.7
MN 5000	-5.8	-23.2	-33.8

Measuring the carbon footprint of dairy farms based on total emissions per unit of milk provides a more comprehensive assessment of its carbon emissions. This allows for easy comparisons of emissions per pound of milk produced. The results of the models show that feed changes and pastureland use were the most significant methods for reducing carbon

footprints (see Figure 6 and Figure 7). Figure 6 presents the carbon footprint of dairy farm models in terms of pounds of CO₂e per pound of FPCM, including biogenic CO₂ with ranges from as high as 0.83 lbs. CO₂e/lb. FPCM to as low as 0.55 lbs. CO₂e/lb. Biogenic CO₂ refers to carbon emissions from cows where the carbon originated from plant CO₂ photosynthesis fixation and has no net impact on total atmospheric CO₂. Biogenic emissions, as defined in IFSM, have negative values and thus, when included in the total emissions, reduce the overall total. Excluding biogenic CO₂ artificially increases the carbon footprint of dairy by 21.7% to 35.8% in the models. Although Figure 6 helps illustrate the emissions reductions achieved by the mitigations used in this study, it highlights the challenge of achieving net zero emissions, as substantially greater reductions will be required. Figure 7 illustrates the percentage reduction from the baseline model for each farm mitigation method with ranges from no change of 0% to as low as a 26.7% decrease. When comparing the figures, it becomes apparent that relying solely on percentage changes can be misleading, as it may create the impression that achieving net zero emissions is a straightforward task. However, as Figure 6 demonstrates, while the mitigations used in this study do result in emission reductions, meeting the goal of net zero emissions will prove to be a challenging task, as significantly larger reductions will be necessary.

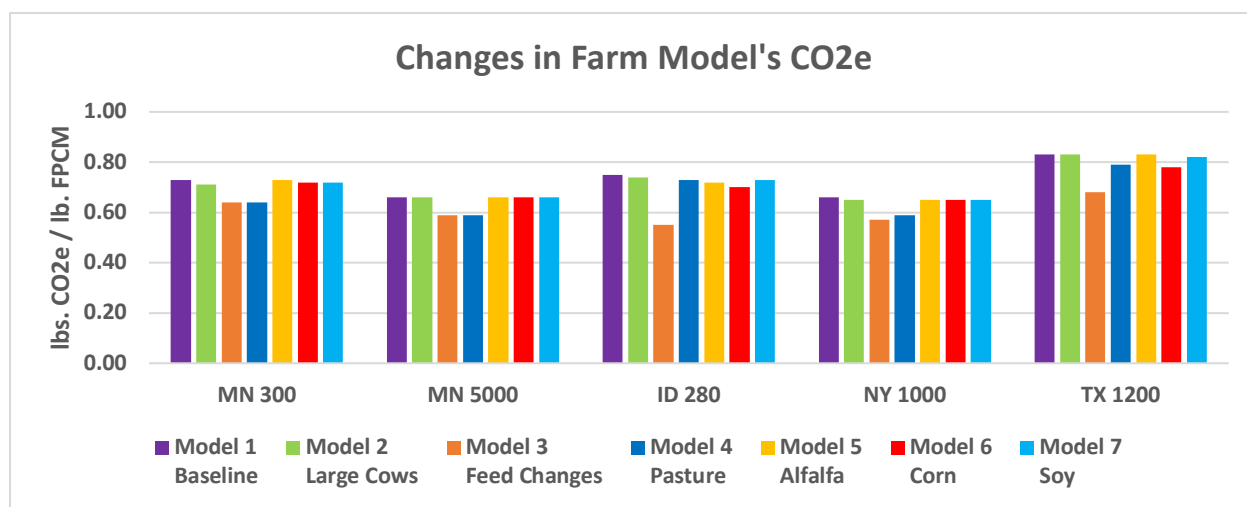


Figure 6. Models by Farm for Total lbs. CO₂e per lbs. FPCM Including Biogenic CO₂.

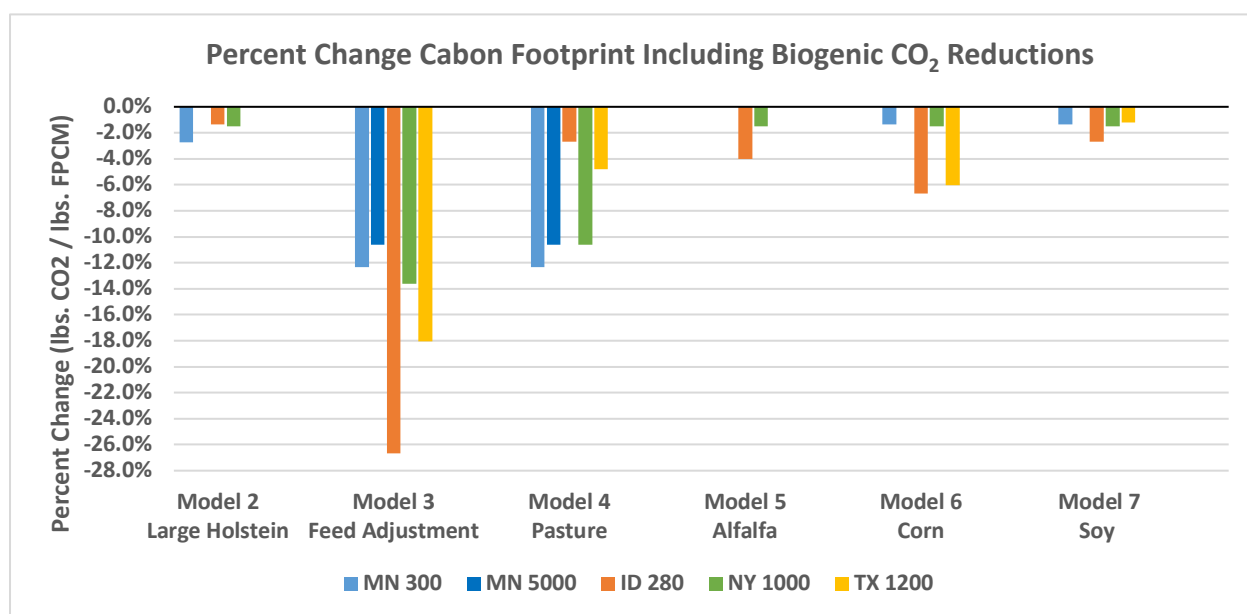


Figure 7. Percent Change Carbon Footprint Including Biogenic CO₂ Reductions.

3. IFSM Modeled Scenarios Results Summary

The increase in milk production with larger cows in Model 2 did not guarantee a significantly smaller carbon footprint per unit of milk. To assess the effects, milk production was

specifically targeted to observe its effects on GHG emissions. Table 12 shows the percent changes in total milk production from the baseline Model 1 with all farms showing increases between 9.0% to 10.2%. However, the table reveals that four scenarios showed declines in production, and another three were neutral.

Table 12. Percent Change in Total Milk Production from Baseline Model 1.

Farms	Model 2 Large Cows (%)	Model 3 Feed Change (%)	Model 4 Pasture (%)	Model 5 Alfalfa (%)	Model 6 Corn (%)	Model 7 Soy (%)
ID 280	9.1	7.6	0.0	0.1	1.3	0.2
MN 300	10.2	0.5	4.8	-0.4	0.1	0.0
NY 1000	9.0	-0.1	3.2	0.2	0.1	-0.2
TX 1200	9.0	3.1	4.1	-0.3	0.3	0.1
MN 5000	9.0	0.3	2.4	0.2	0.7	0.0

The simulations also showed that the larger cows produced more manure than the baseline model, with an average increase of around 10%, except for the MN-5000 farm, which decreased by 0.4% as seen in Table 13, which shows the manure output and percent changes from baseline Model 1 on farms for mitigation options. In IFSM, manure production averaged between 150 to 190 lbs./cow/day. Because they are the averages for all cows this means that the lactating cows would presumably be producing well above these amounts. These amounts may be high compared to other research which ranged from 106 to 150 lbs./cow/day for lactating cows. (Penn State Extension, 2002; Washington State University 2007; University of Minnesota Extension, 2012; USDA, 2014; USDA, 2022).

The simulations also found that milk production and manure are two of the primary variables affecting the carbon footprint of milk, and therefore major determiners of the models

presented. For the MN-5000 and TX-1200 farms, increased milk production led to a neutral carbon footprint, despite increased manure production. In contrast, for the other farms, increased milk production compensated for the increased manure emissions, resulting in a net reduction in emissions.

Feed adjustments in Model 3 resulted in the largest decrease in carbon footprint, ranging from 10.6% to 26.7%, while milk production slightly increased on all farms. Specifically, feed adjustments decreased manure production by approximately 7%–11%, resulting in a net reduction in the carbon footprint. The primary reason for this reduction is the decrease in fiber intake in the cow's diet from using more grain as it has less fiber than forage. As a result, emissions were reduced due to lower methane production associated with the decrease in fiber digestion.

The addition of pastureland in Model 4 showed the second-largest reduction in carbon footprint, with milk production being neutral at 0% or increasing by up to 4.8%, and manure production increasing by roughly 10% on all farms as shown earlier in Table 13 and Table 12. The reduction in carbon footprint was primarily due to the decreased emissions from manure, which is lower due to manure being left in the field where it emits less CH₄ than in holding tanks. These manure emissions were a significant contributor to the overall reduction. However, manure and milk production are not the only primary areas affecting the carbon footprint of milk, as further discussed below. Overall, the use of pastureland resulted in reduced emissions for all farms.

Table 13. Manure Output and Percent Changes from Baseline on Farms for Mitigation Options.

Models	Total Manure Handled (tons)	Manure per All Cows Average (lbs.) *	Change from Baseline (%)
ID 280			
Baseline	14,059	162	-
Large Holstein	15,617	180	11.1
Feed Adjustments	12,463	143	-11.4
Pastureland	13,688	158	-2.6
Alfalfa	13,927	160	-0.9
Corn	13,212	152	-6.0
Soy	13,918	160	-1.0
AD System Baseline	13,721	158	-2.4
MN-300			
Baseline	16,041	172	-
Large Holstein	17,657	190	10.1
Feed Adjustments	14,328	154	-10.7
Pastureland	14,275	153	-11.0
Alfalfa	16,135	173	0.6
Corn	15,961	171	-0.5
Soy	16,041	172	0.0
AD System Baseline	15,658	168	-2.4
NY 1000			
Baseline	53,070	171	-
Large Holstein	58,493	189	10.2
Feed Adjustments	48,035	155	-9.5
Pastureland	47,036	152	-11.4
Alfalfa	53,605	173	1.0
Corn	53,125	171	0.1
Soy	53,477	173	0.8
AD System Baseline	51,801	167	-2.4
TX 1200			
Baseline	63,522	171	-
Large Holstein	70,509	190	11.0
Feed Adjustments	57,030	153	-10.2
Pastureland	55,849	150	-12.1
Alfalfa	61,911	166	-2.5
Corn	61,381	165	-3.4
Soy	62,775	169	-1.2
AD System Baseline	62,005	167	-2.4
MN-5000			
Baseline	252,141	163	-
Large Holstein	251,109	162	-0.4
Feed Adjustments	233,950	151	-7.2
Pastureland	233,950	151	-7.2
Alfalfa	251,111	162	-0.4
Corn	249,982	161	-0.9
Soy	252,446	163	0.1
AD System Baseline	246,115	159	-2.4

* Note: The manure average includes excretion from all cow types (lactating, dry, heifer, and calf).

The addition of alfalfa cropland in Model 5 showed limited changes in milk production ranging from -0.4 to 0.2 CO₂e lbs. / lb. FPCM across farms as seen earlier in Table 12. The carbon footprint of milk was neutral or decreased from 0.0% to 4.0% across farms as seen earlier in Figure 7. The reductions in carbon footprint were only seen on the ID-280 and NY-1000 farms, which were the fewest for any crop increase. Changes in RTM ranged from -3.1% to 13.7% as seen earlier in Figure 3. Alfalfa was the least profitable crop to be increased except for the ID-280 farm where it was the most profitable option.

The addition of corn cropland in Model 6 showed increases in milk production on all farms ranging from 0.1 to 1.3 CO₂e lbs. / lb. FPCM as seen earlier in Table 12. The carbon footprint of milk was neutral (0.0%) to a decrease of 6.7% across farms as seen earlier in Figure 7. All farms except the MN-5000 farm saw reductions in their carbon footprint. All farms saw increases in RTM ranging from 3.13% to 19.5% as seen earlier in Figure 3. Increasing corn was the most profitable crop option for the ID-280 and NY-1000 farms.

The addition of soybean cropland in Model 6 showed limited changes in milk production ranging from -0.2 to 0.2 CO₂e lbs. / lb. FPCM across farms as seen earlier in Table 12. The carbon footprint of milk was neutral or decreased from 0.0% to 2.7% across farms as seen earlier in Figure 7. All farms saw reductions in their carbon footprint except the MN-5000 farm which was carbon neutral. All farms saw increases in RTM ranging from 1.3% to 8.2% as seen earlier in Figure 3.

The increase of land used for either pastureland or cropland had heterogeneous outcomes due to several contributing emissions factors. In addition to milk production and manure emissions, the simulations identified three other primary emissions source categories

affecting the models: *direct and indirect land use changes, anthropogenic sources, and the production of resource inputs*. The changes in these areas ranged from a reduction of 20.7% to an increase of 50.3% as seen in Table 14, and Table 12 which shows these three major emissions categories and how they changed in Models 4–7, with the areas with the most significant change above 10% have been highlighted. Each farm showed different emissions changes for different land use increases, making it difficult to generalize the leading areas that contribute to the overall reduction trends for Models 5–7 in earlier examined Figure 5. However, pastureland primarily reduced emissions due to manure emissions reductions, while in cropland, the carbon footprint was reduced or neutral due to other emissions areas working in tandem with increased milk production amounts.

4. Anaerobic Digestion System GHG Emissions Trends Using IFSM

In IFSM, there are two main components to consider when installing an AD system: the return to management and the carbon footprint of milk. All farms in each model experienced significant decreases in total GHG emissions as well as in the carbon footprint per unit of milk (see Figure 8). Figure 8 illustrates the percent change in total GHG emissions for AD System installation with the carbon footprint of milk decreasing by 12.3% to 37.3%. Among the farms, the MN-5000 farm consistently showed the highest reductions, followed by the NY-1000 farm.

Table 14. Primary Emission Changes for Increased Pasture and Crop Models.

Farms and Variables	Model 4 Pasture (% Δ)	Model 5 Alfalfa (% Δ)	Model 6 Corn (% Δ)	Model 7 Soy (% Δ)
ID 280	Increases in Acreage from Baseline: 55.2% (From 507 to 787 acres)			
Land Use	-11.3	-13.6	1.7	-7.1
Anthropogenic	-10.1	-20.7	50.3	-3.6
Production of Resource Inputs	-3.6	-3.6	-9.3	-3.1
MN-300	Increases in Acreage from Baseline: 28.8% (From 1,039 to 1,338 acres)			
Land Use	-0.2	0.1	-9.2	-3.8
Anthropogenic	0.0	-1.4	15.1	-7.8
Production of Resource Inputs	-8.5	-4.9	-2.7	-2.0
NY 1000	Increases in Acreage from Baseline: 41.7% (From 2,397 to 3,397 acres)			
Land Use	-7.1	4.4	-4.1	0.8
Anthropogenic	1.4	28.0	-1.3	-14.2
Production of Resource Inputs	-10.6	-11.9	-2.1	-1.9
TX 1200	Increases in Acreage from Baseline: 176.5% (From 680 to 1,880 acres)			
Land Use	10.6	22.0	13.4	2.9
Anthropogenic	-3.1	7.1	0.9	-6.0
Production of Resource Inputs	-1.1	-8.4	-19.8	-4.6
MN 5000	Increases in Acreage from Baseline: 71.0% (From 7,043 to 12,043 acres)			
Land Use	-8.7	2.6	-10.6	-0.2
Anthropogenic	-9.1	5.2	22.8	-12.0
Production of Resource Inputs	-6.6	-2.0	-0.9	-1.9

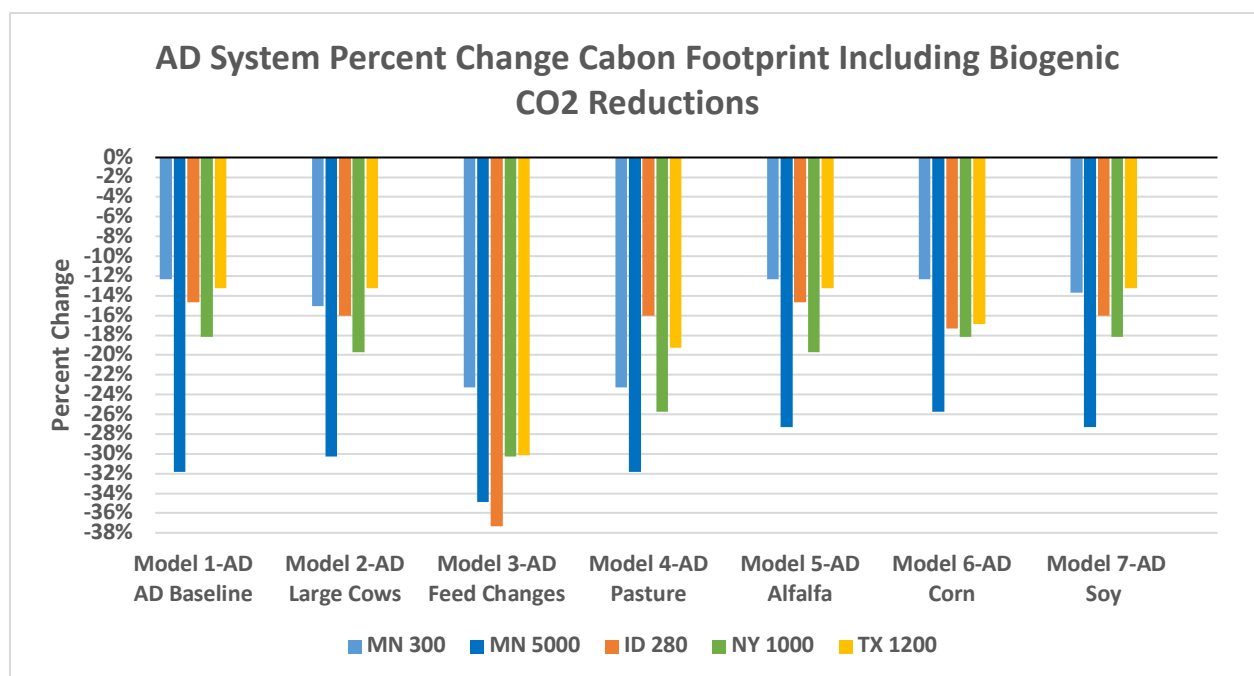


Figure 8. Percent Change in Total GHG Emissions for AD System Installation.

The installation of an AD system in AD Model 1 resulted in emissions reductions ranging from 12.3% to 31.8% compared to the baseline Model 1, with the MN-5000 farm again showing the largest reductions as seen in Table 15, which shows the difference between the emissions reductions in the original models and the reductions once an AD system was used. The results presented in Table 15 demonstrate that the implemented mitigation strategies are in addition to, and complement the reductions achieved prior to the installation of an AD system. This effect leads to an overall improvement in the environmental performance of the dairy farm, highlighting the insufficiency of relying solely on one method or the other to achieve meaningful emissions reductions.

Table 15. Carbon Footprint Reduction with AD System Use Compared to Baseline Model 1.

AD Farm System	AD Model 1 AD Baseline	AD Model 2 Large Cows	AD Model 3 Feed Changes	AD Model 4 Pasture	AD Model 5 Alfalfa	AD Model 6 Corn	AD Model 7 Soy
ID 280	-14.7%	-14.7%	-10.7%	-13.3%	-10.7%	-10.7%	-13.3%
MN 300	-12.3%	-12.3%	-11.0%	-11.0%	-12.3%	-11.0%	-12.3%
NY 1000	-18.2%	-18.2%	-16.7%	-15.2%	-18.2%	-16.7%	-16.7%
TX 1200	-13.3%	-13.3%	-12.0%	-14.5%	-13.3%	-10.8%	-12.0%
MN 5000	-31.8%	-30.3%	-24.2%	-21.2%	-27.3%	-25.8%	-27.3%

The three larger farms generally experienced greater emissions reductions, ranging from 10.8% to 18.2%. The MN-5000 farm, once again, experienced the largest reduction benefits, ranging from 21.2% to 30.3%. The use of larger cows with increased milk production with an AD system was not found to be more effective than using standard cow size, except for the MN-5000 farm where there was a slight increase in the carbon footprint. The difference between the models on the smaller and midsized farms was between 1.4% and 4%. However, the MN-5000 farm saw the least benefit from an AD system when pastureland was used, with a 10.6% difference between AD Model 1 and AD Model 4. On all the farms except the Texas farm, reductions with an AD system were better in the baseline AD Model 1 system than they were when pastureland was used in AD Model 4. Overall, AD systems improved emissions reductions, but their effectiveness is generally reduced when pastureland is also used as a mitigation option.

The profitability of the AD system installation, as indicated by the return to management, varied across the different farms. Generally, only the larger farms were profitable while the smaller ID-280 and MN-300 farms were not (see Figure 9). Figure 9 illustrates the return to management with an AD system installation. Specifically, the farm's RTM ranged

broadly from -15.7% for the ID-280 with pastureland to as high as 13.3% for the MN-5000 farm with larger Holsteins. It is important to note again that these profit margins do not consider any sales of excess biogas electricity to the grid, as the IFSM model assumes that excess biogas is flared off. Therefore, these RTM values may be underestimating the actual potential profitability of AD systems.

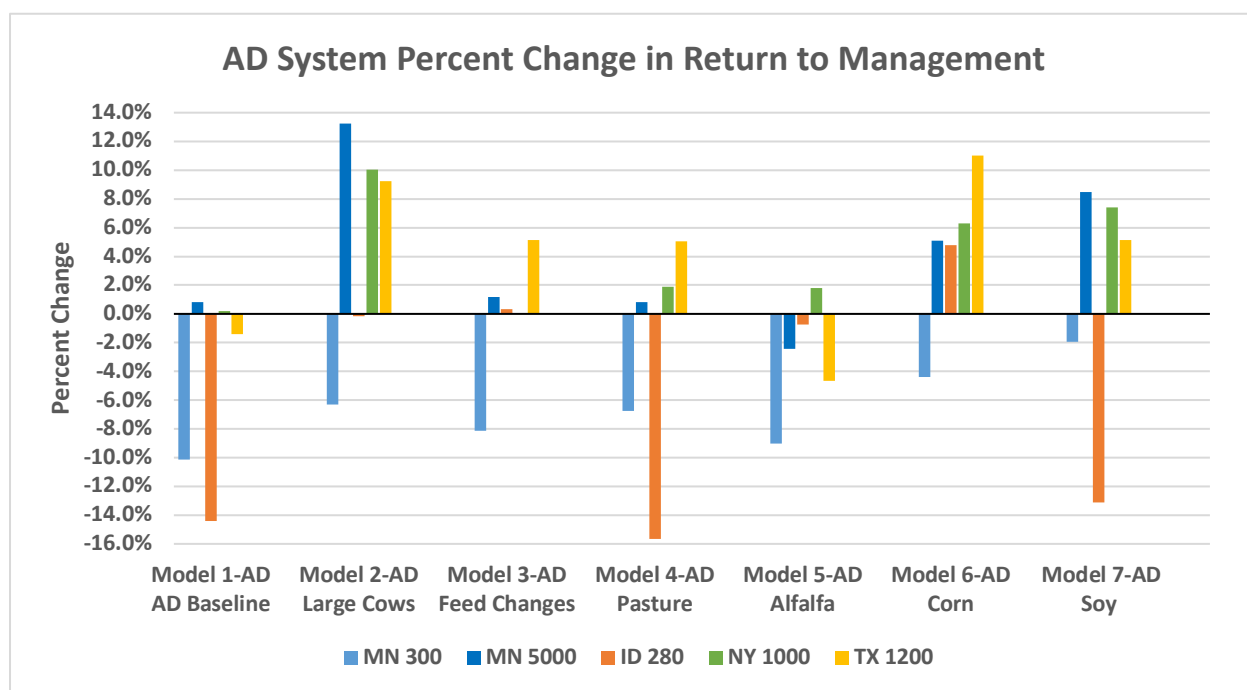


Figure 9. Percent Change in Return to Management for Models 1–7 for AD System Installation.

In the case of the two smaller farms, AD systems led to a loss of the positive RTM they had before installation, except for the ID-280 farm, where added profits from feed changes in AD Model 3 or added corn cropland in AD Model 6 compensated for the added cost of the AD system. On the other hand, the three larger farms saw the best likelihood of profitability with larger Holsteins, increasing corn acreage, or increasing soy acreage, with RTMs increases

ranging from 9.2% to 13.3%. For the larger Holstein with increased milk production scenario, the higher RTM is due to increased milk sales, as biogas is not sold back to the grid. Increasing acreage in corn or soy also made AD systems more feasible, as income from producing these crops offset feed purchases and changed the feasibility of the AD system in those scenarios.

Overall, AD systems generally reduced potential RTM, as low as 14.7% on the ID-280 farm with corn cropland, and increased RTM by just 1.8% on the MN-5000 farm with larger cows (see Table 15). Table 15 shows the difference between the RTM in the original models and the general reductions once an AD system was used. The only two farms that saw increases in RTM due to AD systems were the MN-5000 and NY-1000 farms. In most cases, AD systems reduce profitability compared to the baseline model, assuming that excess biogas will be flared.

Table 16. Return to Management Change with AD System Use Compared to Baseline Model 1.

AD Farm System	AD Model 1 AD Baseline	AD Model 2 Large Cows	AD Model 3 Feed Changes	AD Model 4 Pasture	AD Model 5 Alfalfa	AD Model 6 Corn	AD Model 7 Soy
ID 280	-14.4%	-13.9%	-14.8%	-14.5%	-14.5%	-14.7%	-14.5%
MN 300	-10.1%	-9.7%	-10.5%	-10.7%	-10.1%	-10.2%	-10.1%
NY 1000	0.2%	0.8%	-0.4%	-0.7%	0.3%	0.2%	0.2%
TX 1200	-1.4%	-0.8%	-2.0%	-2.3%	-1.5%	-1.6%	-1.5%
MN 5000	0.8%	2.8%	1.7%	1.1%	2.2%	1.8%	2.2%

VI. Discussion

The simulations demonstrate that there are six out of seven potential mitigation options available to lower total GHG emissions on dairy farms. Two options that stood out were the use of feed with a lower forage-to-grain ratio with GHG emissions reduction ranging from 8.0% to

13.1%, and the use of pastureland with reductions ranging from 0.8% to 8.0%. The exception was increasing milk production with larger Holsteins, which increased total emissions by 7.6% to 9.0%. However, looking at total emissions alone can be misleading if milk production needs to be maintained or increased. In this context, all seven methods were carbon footprint neutral or showed reductions. Despite the increase in total emissions, increased milk production with larger cows offset these emissions and was carbon footprint neutral or reduced emissions by as much as 2.7%.

Adjustments to feed remained the most significant carbon footprint reduction option, resulting in a decrease in the carbon footprint of 10.6% to 26.7%, followed by the use of pastureland, which resulted in reductions from 2.7% to 12.3%. The addition of various cropland was also carbon footprint neutral or led to reduced emissions by as much as 4.7%. The inclusion of AD systems further built upon these mitigations, resulting in a reduction range of 10.3% to 27.8%.

The research simulations suggest that the effects of increasing various crop mixes on the carbon footprint of milk vary across regions, emphasizing the need for tailored sustainability guidelines instead of a generalized, one-size-fits-all approach. This is due to how emissions differ based on soil type, fertilizer needs, climate, typical farming practices, weather variability, and other regional factors. To identify the factors that have an impact on the carbon footprint of milk production and to apply the appropriate recommendations, a regional approach is necessary. However, the results suggest that adding pastureland or reducing the forage-to-grain ratio generally lowers the carbon footprint of milk, while other options vary on a farm-by-farm

basis. This implies that switching from a higher to a lower forage-to-grain ratio may be one of the easiest mitigation methods for farmers to reduce their carbon footprint.

Mitigation methods are more likely to be adopted if they do not decrease the farm's profitability. One consistent way to increase RTM was to use larger cows and increase milk production, resulting in RTM increases ranging from 1.1% to 8.2%. The primary reason for this increase in RTM was the increase in milk sales. Increasing corn or soybean acreage, which reduced the need to purchase feed, was the second and third largest and most consistent method to increase profitability, with increases ranging from 3.3% to 19.5%, and 1.3% to 8.2%, respectively. The increase in RTM for these crops was due to the reduction in costs by replacing purchased grains with self-grown grains.

The installation of AD systems generally decreased RTM, with only the NY-1000 and MN-5000 farms seeing an increase from baseline Model 1 of 0.2% and 0.8%, respectively. When combined with other mitigation options, AD systems generally decreased profitability compared to using the other mitigation options alone. However, the MN-5000 farm, and to a lesser extent, the NY-1000 farm were exceptions to this trend, likely due to the large herd size of the MN-5000 farm and local cost and climate factors for the NY-1000 farm.

To successfully reduce the carbon footprint of milk to meet dairy processors' net zero pledges, mitigation options must be cost-neutral or increase profitability while showing significant mitigation potential. However, no single mitigation option worked for all farms under these criteria. The largest consistent increase in RTM was larger Holsteins producing more milk, but this scenario did not produce significant reductions in the carbon footprint of milk. Changing feed was the most successful mitigation option in terms of total emissions, and

improved RTM on all farms except the largest MN-5000 farm. Adjusting the feed-to-grain ratio is also an easy mitigation option for farms to implement, specifically if they don't already use this ratio. Therefore, this could be one of the quickest and easiest methods to reduce a farm's carbon footprint if they have a high ratio. For larger farms like MN-5000, feed adjustments and the use of pastureland were the best GHG mitigation options. However, they decreased the farm's RTM by 0.6% and 0.3%, respectively. This suggests that very large dairy farms may be less inclined to adopt these more significant mitigation options unless required to do so.

Nonetheless, these two options worked well for MN-300, NY-1000, and TX-1200 farms, which achieved significant reductions while increasing their RTM. The ID-280 was also able to achieve the largest reduction of 26.7% by changing its feed and increasing its RTM by 15.2%. These findings suggest that two of the most significant mitigation options could involve supporting smaller to mid-sized farms to adopt these changes and may help to bridge the GHG mitigation economic gap with very large farms. As many mitigation options are costly to implement and the largest farms tend to reap disproportionate economic benefits, such as with the use of AD systems, these findings imply that counteracting these trends may require these interventions. Further research should be carried out in these areas.

The three mitigation options that were more likely to achieve increased profitability and reductions in carbon footprint were increasing milk production with larger Holsteins or increasing acreage with either corn or soybeans. These three options increased RTM on all farms and are likely to be the measures farms adopt first due to their profitability. However, they require farms to intensify or expand operations, making the farms larger in scope while obtaining lower reductions than other options. Because they are more profitable, these

methods may have more support from farmers to implement. These findings also suggest that specialization may not bring as many benefits to dairy farms as economies of scope.

The last mitigation option was to install an AD system, either alone or in combination with other options. AD systems reduced emissions the most on all farms, ranging from 12.3% to 37.3%. However, they were not profitable on many farms in many models and often reduced RTM when combined with another mitigation method. Overall, only the NY-1000 and MN-5000 farms consistently increased their RTM from an AD system installation.

1. Limitations of Findings and IFSM Software.

IFSM has several limitations that can affect the accuracy of its outcomes. The large number of potential variable changes can lead to missing key differences when comparing across farms. Attention to detail is essential to avoid errors. For example, the use of secondary manure handling or using manure exports can lead to large GHG emissions differences if not matched with intended comparison farms. In research, while differences in specific farms with specific practices may be observed, it may be inaccurate to generalize these findings to all farms of similar size in the same region. In addition, despite the recent update within the past two years, numerous variables appeared to lack discernible correlation with farm size, regional location, or herd composition.

The machinery available on the farm limit how many new acres of cropland can be added, and adjustments were necessary as mentioned previously. IFSM would not estimate models if the equipment was not adequate and does not identify which machinery would be needed, nor instruct the user on how much cropland that added machinery can handle. This

limitation makes it challenging to interpret and adjust the machinery needed to maximize its potential acreage use. For instance, the software may have required a new tractor for an additional 100 acres, but that tractor could potentially handle 500 acres which means it's being underutilized. IFSM also does not specifically separate calculations for emissions related to crop feed, and they seem to be incorporated into the *Land Use* and *Production of Resource Inputs* emissions categories. This can make it difficult to attribute emissions from these sources.

Currently, the IFSM software also does not include the option to incorporate electricity generated and sold back to the grid as revenues for the assessment of AD system viability. This means that any benefits from selling excess electricity back to the grid are not accounted for, and all economic results for AD systems will be affected. As such, the assessment of AD system viability should be treated with caution. This should be a consideration when examining research from other LCA software tools that model AD system economics. Future updates to IFSM and similar software should include this option for a more accurate assessment.

IFSM also calculates the emissions of purchased feed based on an average of feed production across the country but recognizes that emissions varied by up to 50% across simulation conditions. As commodity crops this may be appropriate, but it does not account for if local farms are purchasing local feed. In this context there may be little difference in emission from a dairy farm increasing cropland by 100 acres to use as feed, or if they purchase 100 acres worth of feed from their neighbor. More research is needed in this area.

Lastly, the inability to adjust certain calculations in IFSM may have affected the results. Specifically, IFSM had a higher average manure production compared to other research cited, which could have impacted the economics of AD systems and estimates for GHG emissions, and

certainly would if biogas-generated electricity was sold back to the grid. Further research is required to accurately assess dairy manure production amounts and their impact on the carbon footprint of milk and the economics of mitigation options.

Limitations in this research methodology also need to be addressed. First, the models only simulated the impact of one mitigation option, either alone or with an AD system, while multiple options can be combined to achieve different results. For instance, increasing cow productivity and acreage while also incorporating pastureland could lead to optimal reductions. Future research should combine mitigation options to provide a more comprehensive understanding of their combined impact. Second, the cropland ratio used in this study assumed an increase of one acre per lactating cow. Some farms started with a higher acreage-to-cow ratio of various crops than other farms before the addition of more acreage, and this could significantly impact the results. In conclusion, these limitations hinder the potential analysis of the assumptions being modeled, and their resolution can enhance the accuracy and relevance of IFSM outcomes.

2. Implications

To reduce the carbon footprint of milk, the most profitable options may not necessarily be the methods that result in the largest reductions. This creates a tradeoff between what is best for farmers and what is best for the environment. This research shows that to achieve environmental targets, changes to feed may be one of the first areas that processors will require farmers to address. Feed changes may affect the quality of milk produced or farm operations, and more research in this area should be considered. If farms are already implementing the best

feed practices for GHG emissions, then they will need to explore other mitigation options to reduce their carbon footprint. The next best option will be to introduce their herds to pastureland. However, this will require a significant amount of land use change for cow grazing and should be studied in detail. It raises important questions about whether farmers should be required to make such a change, whether there is sufficient land available, what other practices that land is used for, and what the potential consequences of such a change will be. Further research is needed to understand how large farms, which already have smaller carbon footprints, would manage to add pastureland when they are designed to be efficient through compact and intensive farming practices.

If farmers are not required to choose specific mitigation methods, they will most likely opt for the most profitable options, such as intensifying their operations by increasing milk production or by expanding operations by adding more corn or soybean acreage. This has significant implications for dairy farmers and crop farmers, as dairy farms may need to expand their operations to decrease emissions. This means that the need for dairy farmers to reduce their carbon footprint may impact land rental and ownership prices in their regions. This research suggests that land rental and ownership are areas that require further investigation since pasture and cropland increases were modeled with rented land. The models also considered necessary adjustments to farming equipment to accommodate the increased acreage for crops. Further research could explore what the optimal efficiency in acreage would be and how it will affect dairy farms for this capital-intensive equipment.

The installation of AD systems was found to be the most effective method for reducing the carbon footprint of milk, but it was only profitable for the NY-1000 and MN-5000 farms,

which already had the smallest carbon footprint in baseline Model 1, as shown previously in Figure 4. The results were attributed to both the size and local conditions of these farms. If the most stringent reductions in the carbon footprint are required, it could have implications for the size and location of the dairy farms that are best suited to meet those demands. This may benefit farms that are already located in favorable locations and encourage other farms to increase their size to achieve the most stringent reductions. Stakeholders should be aware of these conditions to meet net-zero pledges.

VII. Conclusion for IFSM Modeling

There are numerous mitigation options available to dairy farmers to decrease their GHG emissions footprint, and many of these options are economically feasible. The literature indicates that a significant portion, 78%–83%, of the carbon footprint of milk, is generated from the field-to-farm gate, and these emissions are classified as dairy processors' Scope 3 emissions. To meet dairy processors' mitigation targets, substantial reductions on farms will be required. This thesis aimed to answer the question regarding dairy processors' net-zero commitments: What strategies are available to ensure that dairy farmers of diverse sizes and regions can minimize the dairy industry's Scope 3 GHG emissions while maintaining economic viability?

This research reveals that many of the most profitable mitigation methods may require dairy farms to become more intensive or extensive operations. For IFSM modeling, the research showed that reducing emissions is best achieved by adding pastureland or reducing the forage-to-grain ratio. Meaningful reductions can also be achieved by increasing dairy farm-grown

forage-based cropland, with corn and soybeans increasing returns to management by offsetting purchased feed expenses. However, increasing milk production by using larger Holsteins did not significantly reduce GHG emissions but did consistently increase returns to management from increased milk sales. Finally, AD systems significantly reduced emissions, but they were only economically viable on farms with favorable state conditions or on farms that were large enough to have economies of scale.

These findings align with previous literature that highlights the significance of manure management, pasture grazing, and feed mix changes in reducing GHG emissions, and AD systems can further enhance these reductions. However, this thesis reveals that the profitability of pasture grazing and changing the forage-to-grain ratio is dependent on the farm where these methods are applied, with positive outcomes for both carbon footprint reduction and return to management possible, but not universally across farms. In terms of best potential profitability, farms may opt to increase milk production using larger Holsteins and/or expand crop acreage. These methods may result in a marginal reduction in emissions and negligible progress toward achieving net-zero targets.

This research has implications for many stakeholders in the dairy industry, particularly those who aim to reduce emissions to achieve net zero pledges. Processors may require dairy farms, either explicitly or implicitly, to take mitigation options. The ease of changing feed mixes, and the potential profitability of increasing milk production and/or adding crop acreage may produce dairy farms that are more intensive or extensive operations, which will have ripple effects across the industry that stakeholders should be aware of. Large land use shifts may also

be necessary if grazing on pastureland is seen as the best traditional option, but it is unclear who will bear the cost of less profitable mitigation options.

To meet processor reduction requirements, AD system use may become necessary, especially for the most stringent reductions. AD systems show the largest reductions in GHG emissions but may not be financially viable for most farms and therefore may require significant government support to be adopted. Without such help, AD system use may only work for the largest dairy farms and for those in the most economically advantageous states.

There are a diverse set of mitigation options available to dairy farms to reduce the carbon footprint of milk, but there will not be a one-size-fits-all approach as farm size and geography will play an important role. By looking at the farm system nationwide, stakeholders can be confident that they can optimize emissions reductions while preserving farm profitability. It is important to understand that mitigation options are not mutually exclusive, and in fact, a combination of methods may be the best approach for many farms. Furthermore, policymakers and industry leaders must consider the economic viability of mitigation options for dairy farmers and offer support and incentives to encourage the adoption of sustainable practices. By taking a holistic approach that balances environmental, social, and economic factors, the dairy industry can make meaningful progress toward achieving net zero emissions by 2050.

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IX. Appendices

Appendix A. Idaho 280 Farm Models in IFSM.

ID-280 Farm	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6		Model 7	
Model Variables	Original Baseline		Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)		Feed Changes (Forage-to-Grain Ratio)		Pastureland Included (1 Acre /Lactating Cow)		Alfalfa Increased (1 Acre /Lactating Cow)		Corn Increased (1 Acre /Lactating Cow)		Soybean Increased (1 Acre /Lactating Cow)	
Land (acres)	507		507		507		787		787		787		787	
Electricity Purchase Price (¢/kWh)	8.2		8.2		8.2		8.2		8.2		8.2		8.2	
Lactating Herd Size (each)	280		280		280		280		280		280		280	
FPCM per Cow, (lbs./cow)	21,240		23,165		22,862		21,232		21,258		21,526		21,279	
FPCM Productions (lbs.)	5,947,200		6,486,200		6,401,360		5,944,960		5,952,240		6,027,280		5,958,120	
Financial Costs (\$)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Equipment	374,625	1,140	375,365	1,136	373,979	1,135	378,431	1,277	396,434	1,672	384,746	1,747	376,598	1,125
Facilities	108,174	201	108,174	201	108,174	201	108,199	203	108,297	209	109,092	0	108,336	213
Energy	48,825	782	51,123	773	48,905	819	49,815	746	59,472	1,278	69,872	3,765	51,533	777
Labor	96,483	447	97,213	439	95,761	443	99,265	722	106,648	763	100,343	536	98,513	461
Seed, Fertilizer & Chemical	70,851	0	70,851	0	70,851	0	77,851	0	92,690	0	146,863	0	91,291	0
Land Rental	19	0	19	0	19	0	54,339	0	54,339	0	54,339	0	54,339	0
Net Purchased Feed & Bedding	158,486	25,284	211,279	24,687	177,839	23,549	96,435	31,422	-49,825	31,225	-115,760	49,377	70,832	29,508
Animal Purchase and Livestock Expense	115,710	0	115,710	0	115,710	0	115,710	0	115,710	0	115,710	0	115,710	0
Milk Hauling and Marketing Fees	54,761	380	59,724	371	58,942	393	54,741	392	54,808	373	55,498	540	54,862	381
Property Tax	12,137	0	12,137	0	12,137	0	12,137	0	12,137	0	12,137	0	12,137	0
Total Costs	1,040,071	-	1,101,595	-	1,062,317	-	1,046,923	-	950,710	-	932,840	-	1,034,151	-
Income from Milk Sales	1,602,789	11,137	1,748,054	10,859	1,725,178	11,515	1,602,200	11,461	1,604,169	10,918	1,624,360	15,805	1,605,761	11,155
Income from Animal Sales	98,293	0	105,402	0	98,293	0	98,293	0	98,293	0	98,293	0	98,293	0
Return to Management	661,010	26,619	751,861	25,677	761,154	28,219	653,571	35,667	751,751	32,364	789,814	47,309	669,901	29,231
Greenhouse Gas Emissions (lbs. of CO ₂ e)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Animal	3,301,261	31,988	3,533,068	30,971	2,315,211	47,810	3,291,324	31,079	3,280,184	32,900	3,181,636	19,418	3,280,798	34,300
Manure	1,255,898	166,247	1,369,038	178,925	1,201,899	171,496	1,237,855	167,721	1,246,485	165,082	1,212,042	166,176	1,246,555	163,886
Direct & Indirect Land	459,573	22,553	522,883	27,046	376,199	15,302	407,816	22,472	396,876	15,495	467,336	21,958	426,764	21,410
Net Biogenic CO ₂	-1,563,856	4,393	-1,712,302	6,103	-1,740,251	35,675	-1,560,156	7,796	-1,560,426	3,871	-1,607,422	42,431	-1,563,856	4,393
Anthropogenic CO ₂	166,743	7,422	191,706	7,861	128,902	5,466	149,860	9,160	132,174	6,910	250,653	32,131	160,723	6,774
Production of Resource Inputs (e.g., Feed)	1,608,612	66,682	1,749,586	66,773	1,809,752	52,727	1,551,046	70,516	1,550,201	65,092	1,459,114	41,964	1,559,428	71,019
Not Allocated to Milk Production	-997,386	23,875	-1,090,937	25,000	-795,706	27,412	-975,147	28,063	-969,240	24,988	-952,154	24,654	-978,298	24,477
Total Emissions Allocated to Milk Production	5,794,701	-	6,275,344	-	5,036,257	-	5,662,754	-	5,636,680	-	5,618,627	-	5,695,970	-
Total Emissions with Biogenic Reductions	4,230,845	-	4,563,042	-	3,296,006	-	4,102,598	-	4,076,254	-	4,011,205	-	4,132,114	-
Carbon Footprint without Biogenic CO ₂ (lb./lb. FPCM.)	0.97	0.02	0.97	0.02	0.79	0.03	0.95	0.03	0.95	0.02	0.93	0.02	0.96	0.02
Carbon Footprint with Biogenic CO ₂ (lb./lb. FPCM.)	0.75	0.02	0.74	0.02	0.55	0.03	0.73	0.03	0.72	0.02	0.7	0.02	0.73	0.02

Appendix B. Changes from Original Base Model, Idaho 280 Farm in IFSM.

ID-280 Farm	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Changes in Model Variables Results	Original Baseline	Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)	Feed Changes (Forage-to-Grain Ratio)	Pastureland Included (1 Acre /Lactating Cow)	Alfalfa Increased (1 Acre /Lactating Cow)	Corn Increased (1 Acre /Lactating Cow)	Soybean Increased (1 Acre /Lactating Cow)
% Δ Land (acres)	-	-51.2	-51.2	-24.3	-24.3	-24.3	-24.3
% Δ FPCM Milk Productions (lbs.)	-	9.1	7.6	0.0	0.1	1.3	0.2
Change in Costs (\$)							
% Δ Equipment	-	0.2	-0.2	1.0	5.8	2.7	0.5
% Δ Facilities	-	0.0	0.0	0.0	0.1	0.8	0.1
% Δ Energy	-	4.7	0.2	2.0	21.8	43.1	5.5
% Δ Labor	-	0.8	-0.7	2.9	10.5	4.0	2.1
% Δ Seed, Fertilizer & Chemical	-	0.0	0.0	9.9	30.8	107.3	28.8
% Δ Net Purchased Feed & Bedding	-	33.3	12.2	-39.2	-131.4	-173.0	-55.3
% Δ Animal Purchase and Livestock Expense	-	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Milk Hauling and Marketing Fees	-	9.1	7.6	0.0	0.1	1.3	0.2
% Δ Property Tax	-	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Total Cost	-	5.9	2.1	0.7	-8.6	-10.3	-0.6
% Δ Income from Milk Sales	-	7.2	0.0	0.0	0.0	0.0	0.0
% Δ Income from Animal Sales	-	13.7	15.2	-1.1	13.7	19.5	1.3
% Δ Return to Management	-	13.7	15.2	-1.1	13.7	19.5	1.3
Change in lbs. CO2e							
% Δ Animal Emissions	-	7.0	-29.9	-0.3	-0.6	-3.6	-0.6
% Δ Manure Emissions	-	9.0	-4.3	-1.4	-0.7	-3.5	-0.7
% Δ Direct and Indirect Land Emissions	-	13.8	-18.1	-11.3	-13.6	1.7	-7.1
% Δ Anthropogenic	-	15.0	-22.7	-10.1	-20.7	50.3	-3.6
% Δ Production of Resource Inputs (e.g., Feed)	-	8.8	12.5	-3.6	-3.6	-9.3	-3.1
% Δ Total Emissions Allocated to Milk Production	-	8.3	-13.1	-2.3	-2.7	-3.0	-1.7
% Δ Total Emissions with Biogenic Reductions	-	7.9	-22.1	-3.0	-3.7	-5.2	-2.3
% Δ Carbon Footprint Without Biogenic CO2 (lb./lb. FPCM.)	-	0.0	-18.6	-2.1	-2.1	-4.1	-1.0
% Δ Carbon Footprint With Biogenic CO2 (lb./lb. FPCM.)	-	-1.3	-26.7	-2.7	-4.0	-6.7	-2.7

Appendix C. Idaho 280 Farm Models in IFSM with AD System.

ID-280 Farm, with AD System	AD Model 1		AD Model 2		AD Model 3		AD Model 4		AD Model 5		AD Model 6		AD Model 7	
Model Variables	AD System Baseline		Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)		Feed Changes (Forage-to-Grain Ratio)		Pastureland Included (1 Acre /Lactating Cow)		Alfalfa Increased (1 Acre /Lactating Cow)		Corn Increased (1 Acre /Lactating Cow)		Soybean Increased (1 Acre /Lactating Cow)	
Land (acres)	507		507		507		787		787		787		787	
Electricity Purchase Price (¢/kWh)	8.2		8.2		8.2		8.2		8.2		8.2		8.2	
Lactating Herd Size (each)	280		280		280		280		280		280		280	
FPCM per Cow, (lbs./cow)	21,240		23,165		22,862		21,232		21,258		21,525		21,279	
FPCM Productions (lbs.)	5,947,200		6,486,200		6,401,360		5,944,960		5,952,240		6,027,000		5,958,120	
Financial Costs (\$)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Equipment	374,189	1,144	374,869	1,140	373,584	1,139	378,006	1,299	395,993	1,680	384,292	1,757	376,147	1,130
Facilities	236,060	201	236,060	201	236,060	201	236,084	203	236,182	209	236,977	0	236,222	213
Energy	14,551	1,086	13,642	1,076	17,324	1,101	16,330	1,178	25,471	1,628	37,366	4,440	17,550	1,121
Labor	98,608	451	99,244	444	97,964	447	101,412	745	108,781	771	102,519	537	100,646	465
Seed, Fertilizer & Chemical	70,851	0	70,851	0	70,851	0	77,851	0	92,690	0	146,863	0	91,291	0
Land Rental	19	0	19	0	19	0	54,339	0	54,339	0	54,339	0	54,339	0
Net Purchased Feed & Bedding	158,482	25,284	211,275	24,687	177,835	23,549	96,413	31,371	-49,829	31,225	-115,568	49,394	70,830	29,507
Animal Purchase and Livestock Expense	115,710	0	115,710	0	115,710	0	115,710	0	115,710	0	115,710	0	115,710	0
Milk Hauling and Marketing Fees	54,761	380	59,724	371	58,942	393	54,741	392	54,808	373	55,498	542	54,862	381
Property Tax	12,137	0	12,137	0	12,137	0	12,137	0	12,137	0	12,137	0	12,137	0
Total Costs	1,135,368	-	1,193,531	-	1,160,426	-	1,143,023	-	1,046,282	-	1,030,133	-	1,129,734	-
Income from Milk Sales	1,602,789	11,137	1,748,054	10,859	1,725,178	11,515	1,602,200	11,461	1,604,169	10,918	1,624,350	15,863	1,605,761	11,155
Income from Animal Sales	98,293	0	105,402	0	98,293	0	98,293	0	98,293	0	98,293	0	98,293	0
Return to Management	565,714	26,228	659,925	25,286	663,045	27,836	557,470	34,953	656,177	31,989	692,509	46,891	574,317	28,865
Greenhouse Gas Emissions (lbs. of CO ₂ e)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Animal	3,301,261	31,988	3,533,068	30,971	2,315,211	47,810	3,291,362	31,100	3,280,184	32,900	3,181,489	19,563	3,280,798	34,300
Manure	944,398	138,329	1,028,372	149,708	914,832	146,486	933,372	138,734	937,483	137,004	916,226	136,558	937,692	135,626
Direct & Indirect Land	461,451	22,553	524,584	26,943	377,926	15,300	409,663	22,510	399,076	15,651	469,062	21,769	429,083	21,342
Net Biogenic CO ₂	-1,563,856	4,393	-1,712,302	6,103	-1,740,251	35,675	-1,560,156	7,796	-1,560,426	3,871	-1,607,603	42,482	-1,563,856	4,393
Anthropogenic CO ₂	164,988	7,330	189,598	7,755	127,624	5,401	148,334	9,054	130,971	6,841	249,397	32,135	159,182	6,698
Production of Resource Inputs (e.g., Feed)	1,163,332	59,710	1,214,526	54,737	1,485,732	46,679	1,172,019	68,428	1,245,115	67,707	1,165,128	28,108	1,168,273	66,111
Not Allocated to Milk Production	-886,249	19,822	-961,155	20,473	-712,391	24,360	-874,749	21,526	-879,259	20,694	-866,692	19,675	-875,782	20,702
Total Emissions Allocated to Milk Production	5,149,181	-	5,528,993	-	4,508,934	-	5,080,001	-	5,113,570	-	5,114,610	-	5,099,246	-
Total Emissions with Biogenic Reductions	3,585,325	-	3,816,691	-	2,768,683	-	3,519,845	-	3,553,144	-	3,507,007	-	3,535,390	-
Carbon Footprint without Biogenic CO ₂ (lb./lb. FPCM.)	0.87	0.02	0.85	0.02	0.7	0.02	0.85	0.02	0.86	0.02	0.85	0.02	0.86	0.02
Carbon Footprint with Biogenic CO ₂ (lb./lb. FPCM.)	0.64	0.02	0.63	0.02	0.47	0.03	0.63	0.02	0.64	0.02	0.62	0.02	0.63	0.02

Appendix D. Changes from Original Base Model, Idaho 280 Farm in IFSM with AD System.

ID-280 Farm, with AD System	AD Model 1	AD Model 2	AD Model 3	AD Model 4	AD Model 5	AD Model 6	AD Model 7
Changes in Model Variables Results	AD System Baseline	Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)	Feed Changes (Forage-to-Grain Ratio)	Pastureland Included (1 Acre /Lactating Cow)	Alfalfa Increased (1 Acre /Lactating Cow)	Corn Increased (1 Acre /Lactating Cow)	Soybean Increased (1 Acre /Lactating Cow)
% Δ Land (acres)	-	-51.2	-51.2	-24.3	-24.3	-24.3	-24.3
% Δ FPCM Milk Productions (lbs.)	0.0	9.1	7.6	0.0	0.1	1.3	0.2
Change in Costs (\$)							
% Δ Equipment	-0.1	0.1	-0.3	0.9	5.7	2.6	0.4
% Δ Facilities	118.2	118.2	118.2	118.2	118.3	119.1	118.4
% Δ Energy	-70.2	-72.1	-64.5	-66.6	-47.8	-23.5	-64.1
% Δ Labor	2.2	2.9	1.5	5.1	12.7	6.3	4.3
% Δ Seed, Fertilizer & Chemical	0.0	0.0	0.0	9.9	30.8	107.3	28.8
% Δ Net Purchased Feed & Bedding	0.0	33.3	12.2	-39.2	-131.4	-172.9	-55.3
% Δ Animal Purchase and Livestock Expense	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Milk Hauling and Marketing Fees	0.0	9.1	7.6	0.0	0.1	1.3	0.2
% Δ Property Tax	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Total Cost	9.2	14.8	11.6	9.9	0.6	-1.0	8.6
% Δ Income from Milk Sales	0.0	7.2	0.0	0.0	0.0	0.0	0.0
% Δ Income from Animal Sales	-14.4	-0.2	0.3	-15.7	-0.7	4.8	-13.1
% Δ Return to Management	-14.4	-0.2	0.3	-15.7	-0.7	4.8	-13.1
Change in lbs. CO2e							
% Δ Animal Emissions	0.0	7.0	-29.9	-0.3	-0.6	-3.6	-0.6
% Δ Manure Emissions	-24.8	-18.1	-27.2	-25.7	-25.4	-27.0	-25.3
% Δ Direct and Indirect Land Emissions	0.4	14.1	-17.8	-10.9	-13.2	2.1	-6.6
% Δ Anthropogenic	-1.1	13.7	-23.5	-11.0	-21.5	49.6	-4.5
% Δ Production of Resource Inputs (e.g., Feed)	-27.7	-24.5	-7.6	-27.1	-22.6	-27.6	-27.4
% Δ Total Emissions Allocated to Milk Production	-11.1	-4.6	-22.2	-12.3	-11.8	-11.7	-12.0
% Δ Total Emissions with Biogenic Reductions	-15.3	-9.8	-34.6	-16.8	-16.0	-17.1	-16.4
% Δ Carbon Footprint Without Biogenic CO2 (lb./lb. FPCM.)	-10.3	-12.4	-27.8	-12.4	-11.3	-12.4	-11.3
% Δ Carbon Footprint With Biogenic CO2 (lb./lb. FPCM.)	-14.7	-16.0	-37.3	-16.0	-14.7	-17.3	-16.0

Appendix E. Minnesota 300 Farm Models in IFSM.

MN-300 Farm	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6		Model 7	
Model Variables	Original Baseline		Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)		Feed Changes (Forage-to-Grain Ratio)		Pastureland Included (1 Acre /Lactating Cow)		Alfalfa Increased (1 Acre /Lactating Cow)		Corn Increased (1 Acre /Lactating Cow)		Soybean Increased (1 Acre /Lactating Cow)	
Land (acres)	1,039		1,039		1,039		1,338		1,338		1,338		1,338	
Electricity Purchase Price (¢/kWh)	11.22		11.22		11.22		11.22		11.22		11.22		11.22	
Lactating Herd Size (each)	300		300		300		300		300		300		300	
FPCM per Cow, (lbs./cow)	21,242		23,407		21,343		22,258		21,148		21,256		21,243	
FPCM Productions (lbs.)	6,372,600		7,022,100		6,402,900		6,677,400		6,344,400		6,376,800		6,372,900	
Financial Costs (\$)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Equipment	178,994	3,575	179,673	3,785	174,160	2,320	178,586	2,910	186,048	4,407	183,559	3,863	183,305	3,814
Facilities	178,159	2,650	178,780	2,896	179,935	3,564	179,735	3,437	181,592	4,460	178,578	2,124	178,158	2,650
Energy	68,531	6,983	70,562	7,156	66,118	6,645	67,798	6,752	74,981	8,006	79,461	10,771	71,670	6,832
Labor	105,695	2,070	106,655	1,947	104,758	2,287	112,704	2,266	109,633	3,127	109,180	2,242	108,906	2,063
Seed, Fertilizer & Chemical	111,193	0	111,193	0	111,193	0	117,493	0	132,452	0	163,813	0	133,093	0
Land Rental	48,627	0	48,627	0	48,627	0	97,826	0	97,826	0	97,826	0	97,826	0
Net Purchased Feed & Bedding	-78,431	149,664	-28,215	153,615	-86,758	143,620	-101,777	140,594	-187,133	179,454	-252,355	188,762	-236,786	167,218
Animal Purchase and Livestock Expense	134,361	0	134,361	0	134,361	0	134,361	0	134,361	0	134,361	0	134,361	0
Milk Hauling and Marketing Fees	60,682	347	63,687	362	60,970	325	63,584	189	60,413	337	60,722	273	60,683	351
Property Tax	17,385	0	17,385	0	17,385	0	17,385	0	17,385	0	17,385	0	17,385	0
Total Costs	825,196	-	882,708	-	810,749	-	867,695	-	807,558	-	772,530	-	748,601	-
Income from Milk Sales	1,654,656	9,466	1,736,585	9,883	1,662,498	8,872	1,733,777	5,142	1,647,314	9,194	1,655,733	7,449	1,654,676	9,574
Income from Animal Sales	104,839	0	112,438	0	104,839	0	104,839	0	104,839	0	104,839	0	104,839	0
Return to Management	934,299	130,964	966,313	134,221	956,586	126,498	970,920	123,828	944,594	155,466	988,041	171,234	1,010,915	148,328
Greenhouse Gas Emissions (lbs. of CO ₂ e)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Animal	3,547,668	56,617	3,776,863	57,597	2,962,792	68,494	3,533,051	34,627	3,555,750	63,193	3,547,356	56,901	3,547,816	56,935
Manure	1,433,891	142,338	1,548,720	154,645	1,313,614	122,111	1,058,848	98,873	1,441,028	138,100	1,427,836	141,284	1,433,896	142,283
Direct & Indirect Land	601,498	62,052	671,803	64,597	470,021	52,806	600,247	71,035	602,043	85,298	546,117	87,712	578,453	64,318
Net Biogenic CO ₂	-1,745,227	10,901	-1,903,940	11,776	-1,752,854	10,554	-1,746,031	11,344	-1,738,428	10,491	-1,746,417	8,877	-1,745,632	11,561
Anthropogenic CO ₂	253,539	44,536	276,903	52,243	186,210	32,389	253,543	42,170	249,956	32,860	291,949	71,917	233,666	41,597
Production of Resource Inputs (e.g., Feed)	1,374,302	169,288	1,480,094	200,199	1,587,082	158,101	1,257,056	172,229	1,306,972	135,785	1,337,277	122,927	1,346,702	164,095
Not Allocated to Milk Production	-1,058,738	32,963	-1,136,479	35,962	-952,827	27,109	-939,235	28,889	-1,055,367	32,537	-1,049,210	34,237	-1,048,395	32,126
Total Emissions Allocated to Milk Production	6,152,160	-	6,617,904	-	5,566,892	-	5,763,510	-	6,100,382	-	6,101,325	-	6,092,138	-
Total Emissions with Biogenic Reductions	4,406,933	-	4,713,964	-	3,814,038	-	4,017,479	-	4,361,954	-	4,354,908	-	4,346,506	-
Carbon Footprint without Biogenic CO ₂ (lb./lb. FPCM.)	0.97	0.03	0.94	0.03	0.87	0.02	0.86	0.03	0.96	0.03	0.96	0.03	0.96	0.03
Carbon Footprint with Biogenic CO ₂ (lb./lb. FPCM.)	0.73	0.03	0.71	0.03	0.64	0.02	0.64	0.03	0.73	0.03	0.72	0.03	0.72	0.03

Appendix F. Changes from Original Base Model, Minnesota 300 Farm in IFSM.

MN-300 Farm	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Changes in Model Variables Results	Original Baseline	Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)	Feed Changes (Forage-to-Grain Ratio)	Pastureland Included (1 Acre /Lactating Cow)	Alfalfa Increased (1 Acre /Lactating Cow)	Corn Increased (1 Acre /Lactating Cow)	Soybean Increased (1 Acre /Lactating Cow)
% Δ Land (acres)	-	0.0	0.0	28.8	28.8	28.8	28.8
% Δ FPCM Milk Productions (lbs.)	-	10.2	0.5	4.8	-0.4	0.1	0.0
Change in Costs (\$)							
% Δ Equipment	-	0.4	-2.7	-0.2	3.9	2.6	2.4
% Δ Facilities	-	0.3	1.0	0.9	1.9	0.2	0.0
% Δ Energy	-	3.0	-3.5	-1.1	9.4	15.9	4.6
% Δ Labor	-	0.9	-0.9	6.6	3.7	3.3	3.0
% Δ Seed, Fertilizer & Chemical	-	0.0	0.0	5.7	19.1	47.3	19.7
% Δ Net Purchased Feed & Bedding	-	64.0	-10.6	-29.8	-138.6	-221.8	-201.9
% Δ Animal Purchase and Livestock Expense	-	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Milk Hauling and Marketing Fees	-	5.0	0.5	4.8	-0.4	0.1	0.0
% Δ Property Tax	-	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Total Cost	-	7.0	-1.8	5.2	-2.1	-6.4	-9.3
% Δ Income from Milk Sales	-	5.0	0.5	4.8	-0.4	0.1	0.0
% Δ Income from Animal Sales	-	7.2	0.0	0.0	0.0	0.0	0.0
% Δ Return to Management	-	3.4	2.4	3.9	1.1	5.8	8.2
Change in lbs. CO2e							
% Δ Animal Emissions	-	6.5	-16.5	-0.4	0.2	0.0	0.0
% Δ Manure Emissions	-	8.0	-8.4	-26.2	0.5	-0.4	0.0
% Δ Direct and Indirect Land Emissions	-	11.7	-21.9	-0.2	0.1	-9.2	-3.8
% Δ Anthropogenic	-	9.2	-26.6	0.0	-1.4	15.1	-7.8
% Δ Production of Resource Inputs (e.g., Feed)	-	7.7	15.5	-8.5	-4.9	-2.7	-2.0
% Δ Total Emissions Allocated to Milk Production	-	7.6	-9.5	-6.3	-0.8	-0.8	-1.0
% Δ Total Emissions with Biogenic Reductions	-	7.0	-13.5	-8.8	-1.0	-1.2	-1.4
% Δ Carbon Footprint Without Biogenic CO2 (lb./lb. FPCM.)	-	-3.1	-10.3	-11.3	-1.0	-1.0	-1.0
% Δ Carbon Footprint With Biogenic CO2 (lb./lb. FPCM.)	-	-2.7	-12.3	-12.3	0.0	-1.4	-1.4

Appendix G. Minnesota 300 Farm Models in IFSM with AD System.

MN-300 Farm, with AD System	AD Model 1		AD Model 2		AD Model 3		AD Model 4		AD Model 5		AD Model 6		AD Model 7	
Model Variables	AD System Baseline		Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)		Feed Changes (Forage-to-Grain Ratio)		Pastureland Included (1 Acre /Lactating Cow)		Alfalfa Increased (1 Acre /Lactating Cow)		Corn Increased (1 Acre /Lactating Cow)		Soybean Increased (1 Acre /Lactating Cow)	
Land (acres)	1,039		1,039		1,039		1,338		1,339		1,340		1,341	
Electricity Purchase Price (¢/kWh)	11.22		11.22		11.22		11.22		11.22		11.22		11.22	
Lactating Herd Size (each)	300		300		300		300		300		300		300	
FPCM per Cow, (lbs./cow)	21,242		23,408		21,343		22,258		21,149		21,258		21,242	
FPCM Productions (lbs.)	6,372,600		7,022,400		6,402,900		6,677,400		6,344,700		6,377,400		6,372,600	
Financial Costs (\$)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Equipment	178,626	3,568	179,246	3,769	173,846	2,306	178,266	2,885	185,663	4,382	183,175	3,847	182,923	3,798
Facilities	308,810	2,652	309,374	2,831	310,588	3,567	310,385	3,436	312,245	4,464	309,225	2,141	308,808	2,651
Energy	30,404	7,062	29,154	7,364	31,454	6,422	34,555	6,491	36,657	7,607	41,496	11,049	33,543	6,903
Labor	107,640	2,056	108,499	1,939	106,811	2,269	114,799	2,244	111,572	3,101	111,126	2,229	110,850	2,048
Seed, Fertilizer & Chemical	111,193	0	111,193	0	111,193	0	117,493	0	132,452	0	163,813	0	133,093	0
Land Rental	48,627	0	48,627	0	48,627	0	97,826	0	97,826	0	97,826	0	97,826	0
Net Purchased Feed & Bedding	-77,924	149,125	-27,881	153,242	-86,368	143,222	-101,144	139,936	-186,551	178,763	-251,582	188,085	-236,211	166,607
Animal Purchase and Livestock Expense	134,361	0	134,361	0	134,361	0	134,361	0	134,361	0	134,361	0	134,361	0
Milk Hauling and Marketing Fees	60,682	347	63,689	364	60,969	324	63,584	189	60,414	338	60,727	269	60,682	350
Property Tax	17,385	0	17,385	0	17,385	0	17,385	0	17,385	0	17,385	0	17,385	0
Total Costs	919,804	-	973,647	-	908,866	-	967,510	-	902,024	-	867,552	-	843,260	-
Income from Milk Sales	1,654,656	9,466	1,736,632	9,926	1,662,463	8,840	1,733,777	5,142	1,647,349	9,208	1,655,863	7,326	1,654,642	9,547
Income from Animal Sales	104,839	0	112,438	0	104,839	0	104,839	0	104,839	0	104,839	0	104,839	0
Return to Management	839,691	130,472	875,422	133,888	858,435	126,432	871,104	123,621	850,162	155,327	893,151	170,722	916,221	147,759
Greenhouse Gas Emissions (lbs. of CO ₂ e)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Animal	3,547,554	56,528	3,781,030	59,091	2,962,399	68,351	3,533,139	34,847	3,555,754	63,255	3,546,952	56,916	3,547,671	57,001
Manure	1,032,187	74,983	1,112,487	81,542	948,559	62,848	755,610	49,535	1,037,762	72,455	1,027,580	74,529	1,032,149	74,873
Direct & Indirect Land	612,610	61,905	684,145	63,581	481,650	52,141	603,172	68,684	615,278	83,886	556,174	86,555	589,929	64,159
Net Biogenic CO ₂	-1,745,227	10,901	-1,903,940	11,776	-1,752,854	10,554	-1,746,031	11,344	-1,738,428	10,491	-1,746,417	8,877	-1,745,632	11,561
Anthropogenic CO ₂	251,571	44,510	273,835	51,308	184,873	32,365	251,714	42,049	248,195	32,808	290,158	71,824	231,920	41,609
Production of Resource Inputs (e.g., Feed)	1,059,971	149,763	1,125,352	181,579	1,367,619	135,898	979,717	143,485	1,026,482	111,566	1,080,175	97,334	1,071,083	151,003
Not Allocated to Milk Production	-954,920	27,500	-1,022,471	30,541	-868,857	18,841	-858,046	22,933	-956,200	24,166	-953,819	28,700	-950,356	27,896
Total Emissions Allocated to Milk Production	5,548,973	-	5,954,378	-	5,076,243	-	5,265,306	-	5,527,271	-	5,547,220	-	5,522,396	-
Total Emissions with Biogenic Reductions	3,803,746	-	4,050,438	-	3,323,389	-	3,519,275	-	3,788,843	-	3,800,803	-	3,776,764	-
Carbon Footprint without Biogenic CO ₂ (lb./lb. FPCM.)	0.87	0.03	0.85	0.03	0.79	0.02	0.79	0.02	0.87	0.02	0.87	0.03	0.87	0.03
Carbon Footprint with Biogenic CO ₂ (lb./lb. FPCM.)	0.64	0.03	0.62	0.03	0.56	0.02	0.56	0.02	0.64	0.02	0.64	0.03	0.63	0.03

Appendix H. Changes from Original Base Model, Minnesota 300 Farm in IFSM with AD System.

MN-300 Farm, with AD System	AD Model 1	AD Model 2	AD Model 3	AD Model 4	AD Model 5	AD Model 6	AD Model 7
Changes in Model Variables Results	AD System Baseline	Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)	Feed Changes (Forage-to-Grain Ratio)	Pastureland Included (1 Acre /Lactating Cow)	Alfalfa Increased (1 Acre /Lactating Cow)	Corn Increased (1 Acre /Lactating Cow)	Soybean Increased (1 Acre /Lactating Cow)
% Δ Land (acres)	-	0.0	0.0	28.8	28.9	29.0	29.1
% Δ FPCM Milk Productions (lbs.)	0.0	10.2	0.5	4.8	-0.4	0.1	0.0
Change in Costs (\$)							
% Δ Equipment	-0.2	0.1	-2.9	-0.4	3.7	2.3	2.2
% Δ Facilities	73.3	73.7	74.3	74.2	75.3	73.6	73.3
% Δ Energy	-55.6	-57.5	-54.1	-49.6	-46.5	-39.4	-51.1
% Δ Labor	1.8	2.7	1.1	8.6	5.6	5.1	4.9
% Δ Seed, Fertilizer & Chemical	0.0	0.0	0.0	5.7	19.1	47.3	19.7
% Δ Net Purchased Feed & Bedding	0.6	64.5	-10.1	-29.0	-137.9	-220.8	-201.2
% Δ Animal Purchase and Livestock Expense	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Milk Hauling and Marketing Fees	0.0	5.0	0.5	4.8	-0.4	0.1	0.0
% Δ Property Tax	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Total Cost	11.5	18.0	10.1	17.2	9.3	5.1	2.2
% Δ Income from Milk Sales	0.0	5.0	0.5	4.8	-0.4	0.1	0.0
% Δ Income from Animal Sales	0.0	7.2	0.0	0.0	0.0	0.0	0.0
% Δ Return to Management	-10.1	-6.3	-8.1	-6.8	-9.0	-4.4	-1.9
Change in lbs. CO ₂ e							
% Δ Animal Emissions	0.0	6.6	-16.5	-0.4	0.2	0.0	0.0
% Δ Manure Emissions	-28.0	-22.4	-33.8	-47.3	-27.6	-28.3	-28.0
% Δ Direct and Indirect Land Emissions	1.8	13.7	-19.9	0.3	2.3	-7.5	-1.9
% Δ Anthropogenic	-0.8	8.0	-27.1	-0.7	-2.1	14.4	-8.5
% Δ Production of Resource Inputs (e.g., Feed)	-22.9	-18.1	-0.5	-28.7	-25.3	-21.4	-22.1
% Δ Total Emissions Allocated to Milk Production	-9.8	-3.2	-17.5	-14.4	-10.2	-9.8	-10.2
% Δ Total Emissions with Biogenic Reductions	-13.7	-8.1	-24.6	-20.1	-14.0	-13.8	-14.3
% Δ Carbon Footprint Without Biogenic CO ₂ (lb./lb. FPCM.)	-10.3	-12.4	-18.6	-18.6	-10.3	-10.3	-10.3
% Δ Carbon Footprint With Biogenic CO ₂ (lb./lb. FPCM.)	-12.3	-15.1	-23.3	-23.3	-12.3	-12.3	-13.7

Appendix I. New York 1000 Farm Models in IFSM.

NY-1000 Farm	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6		Model 7	
Model Variables	Original Baseline		Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)		Feed Changes (Forage-to-Grain Ratio)		Pastureland Included (1 Acre /Lactating Cow)		Alfalfa Increased (1 Acre /Lactating Cow)		Corn Increased (1 Acre /Lactating Cow)		Soybean Increased (1 Acre /Lactating Cow)	
Land (acres)	2,397		2,397		2,397		3,397		3,397		3,397		3,397	
Electricity Purchase Price (¢/kWh)	18		18		18		18		18		18		18	
Lactating Herd Size (each)	1,000		1,000		1,000		1,000		1,000		1,000		1,000	
FPCM per Cow, (lbs./cow)	22,053		24,032		22,029		22,761		22,090		22,073		22,012	
FPCM Productions (lbs.)	22,053,000		24,032,000		22,029,000		22,761,000		22,090,000		22,073,000		22,012,000	
Financial Costs (\$)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Equipment	223,554	2,528	232,681	3,271	217,083	3,751	217,763	2,723	349,629	4,871	252,068	2,977	239,470	3,195
Facilities	503,805	2,392	505,488	3,285	508,328	5,251	507,781	4,845	508,540	2,287	504,638	1,289	504,129	1,695
Energy	264,885	18,202	277,909	18,059	259,501	18,171	258,043	18,382	278,456	15,407	296,110	39,118	271,020	18,355
Labor	317,460	2,541	322,595	2,258	312,310	3,310	333,139	3,190	329,452	3,345	322,555	2,545	329,848	2,961
Seed, Fertilizer & Chemical	344,815	0	344,815	0	344,815	0	401,689	0	433,635	0	552,644	0	447,191	0
Land Rental	12	0	12	0	12	0	121,413	0	121,413	0	121,413	0	121,413	0
Net Purchased Feed & Bedding	375,043	290,226	554,729	295,567	366,467	282,426	278,432	279,567	-35,966	261,208	-226,208	462,186	-142,253	355,400
Animal Purchase and Livestock Expense	415,140	0	415,140	0	415,140	0	415,140	0	415,140	0	415,140	0	415,140	0
Milk Hauling and Marketing Fees	250,837	1,070	273,349	1,217	250,568	1,238	258,888	607	251,259	1,357	251,067	997	250,373	1,085
Property Tax	52,089	0	52,089	0	52,089	0	52,089	0	52,089	0	52,089	0	52,089	0
Total Costs	2,747,640	-	2,978,807	-	2,726,313	-	2,844,377	-	2,703,647	-	2,541,516	-	2,488,420	-
Income from Milk Sales	5,857,446	24,997	6,383,134	28,427	5,851,166	28,916	6,045,453	14,164	5,867,303	31,692	5,862,822	23,285	5,846,606	25,347
Income from Animal Sales	351,591	0	376,984	0	351,591	0	351,591	0	351,591	0	351,591	0	351,591	0
Return to Management	3,461,397	263,985	3,781,312	265,457	3,476,443	242,633	3,552,668	252,404	3,515,247	233,827	3,672,896	425,838	3,709,777	324,106
Greenhouse Gas Emissions (lbs. of CO ₂ e)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Animal	11,573,151	100,806	12,410,382	137,041	9,585,034	85,624	11,302,392	76,948	11,414,107	77,683	11,587,482	104,800	11,571,443	113,269
Manure	2,860,058	354,762	3,093,241	390,637	2,645,166	319,574	2,238,144	263,055	2,883,694	350,267	2,861,697	351,484	2,876,159	345,748
Direct & Indirect Land	2,090,140	244,902	2,329,734	261,791	1,838,894	218,013	1,941,510	196,959	2,182,623	252,333	2,005,366	327,879	2,106,200	250,050
Net Biogenic CO ₂	-6,041,047	27,332	-6,592,795	29,120	-6,055,548	28,986	-5,964,008	107,034	-6,038,848	32,307	-6,043,258	23,782	-6,032,154	28,669
Anthropogenic CO ₂	1,260,315	184,977	1,351,785	207,197	1,090,814	158,106	1,277,497	183,181	1,613,386	194,943	1,243,346	357,609	1,081,313	170,021
Production of Resource Inputs (e.g., Feed)	5,211,840	358,200	5,688,962	431,017	5,420,732	459,169	4,656,947	465,892	4,591,040	258,532	5,100,914	296,044	5,115,396	319,382
Not Allocated to Milk Production	-3,252,247	106,203	-3,550,746	117,646	-2,913,763	95,723	-2,934,770	93,900	-3,202,932	81,121	-3,221,361	111,064	-3,223,457	98,882
Total Emissions Allocated to Milk Production	19,743,257	-	21,323,358	-	17,666,877	-	18,481,720	-	19,481,918	-	19,577,444	-	19,527,054	-
Total Emissions with Biogenic Reductions	13,702,210	-	14,730,563	-	11,611,329	-	12,517,712	-	13,443,070	-	13,534,186	-	13,494,900	-
Carbon Footprint without Biogenic CO ₂ (lb./lb. FPCM.)	0.9	0.03	0.89	0.03	0.8	0.03	0.81	0.03	0.88	0.02	0.89	0.03	0.89	0.03
Carbon Footprint with Biogenic CO ₂ (lb./lb. FPCM.)	0.66	0.03	0.65	0.03	0.57	0.03	0.59	0.03	0.65	0.02	0.65	0.03	0.65	0.03

Appendix J. Changes from Original Base Model, New York 1000 Farm in IFSM.

NY-1000 Farm	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Changes in Model Variables Results	Original Baseline	Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)	Feed Changes (Forage-to-Grain Ratio)	Pastureland Included (1 Acre /Lactating Cow)	Alfalfa Increased (1 Acre /Lactating Cow)	Corn Increased (1 Acre /Lactating Cow)	Soybean Increased (1 Acre /Lactating Cow)
% Δ Land (acres)	-	130.7	130.7	226.9	226.9	226.9	226.9
% Δ FPCM Milk Productions (lbs.)	-	9.0	-0.1	3.2	0.2	0.1	-0.2
Change in Costs (\$)							
% Δ Equipment	-	4.1	-2.9	-2.6	56.4	12.8	7.1
% Δ Facilities	-	0.3	0.9	0.8	0.9	0.2	0.1
% Δ Energy	-	4.9	-2.0	-2.6	5.1	11.8	2.3
% Δ Labor	-	1.6	-1.6	4.9	3.8	1.6	3.9
% Δ Seed, Fertilizer & Chemical	-	0.0	0.0	16.5	25.8	60.3	29.7
% Δ Net Purchased Feed & Bedding	-	47.9	-2.3	-25.8	-109.6	-160.3	-137.9
% Δ Animal Purchase and Livestock Expense	-	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Milk Hauling and Marketing Fees	-	9.0	-0.1	3.2	0.2	0.1	-0.2
% Δ Property Tax	-	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Total Cost	-	8.4	-0.8	3.5	-1.6	-7.5	-9.4
% Δ Income from Milk Sales	-	9.0	-0.1	3.2	0.2	0.1	-0.2
% Δ Income from Animal Sales	-	7.2	0.0	0.0	0.0	0.0	0.0
% Δ Return to Management	-	9.2	0.4	2.6	1.6	6.1	7.2
Change in lbs. CO2e							
% Δ Animal Emissions	-	7.2	-17.2	-2.3	-1.4	0.1	0.0
% Δ Manure Emissions	-	8.2	-7.5	-21.7	0.8	0.1	0.6
% Δ Direct and Indirect Land Emissions	-	11.5	-12.0	-7.1	4.4	-4.1	0.8
% Δ Anthropogenic	-	7.3	-13.4	1.4	28.0	-1.3	-14.2
% Δ Production of Resource Inputs (e.g., Feed)	-	9.2	4.0	-10.6	-11.9	-2.1	-1.9
% Δ Total Emissions Allocated to Milk Production	-	8.0	-10.5	-6.4	-1.3	-0.8	-1.1
% Δ Total Emissions with Biogenic Reductions	-	7.5	-15.3	-8.6	-1.9	-1.2	-1.5
% Δ Carbon Footprint Without Biogenic CO2 (lb./lb. FPCM.)	-	-1.1	-11.1	-10.0	-2.2	-1.1	-1.1
% Δ Carbon Footprint With Biogenic CO2 (lb./lb. FPCM.)	-	-1.5	-13.6	-10.6	-1.5	-1.5	-1.5

Appendix J. New York 1000 Farm Models in IFSM with AD System.

NY-1000 Farm, with AD System	AD Model 1		AD Model 2		AD Model 3		AD Model 4		AD Model 5		AD Model 6		AD Model 7	
Model Variables	AD System Baseline		Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)		Feed Changes (Forage-to-Grain Ratio)		Pastureland Included (1 Acre /Lactating Cow)		Alfalfa Increased (1 Acre /Lactating Cow)		Corn Increased (1 Acre /Lactating Cow)		Soybean Increased (1 Acre /Lactating Cow)	
Land (acres)	2,397		2,397		2,397		3,397		3,397		3,397		3,397	
Electricity Purchase Price (¢/kWh)	18		18		18		18		18		18		18	
Lactating Herd Size (each)	1,000		1,000		1,000		1,000		1,000		1,000		1,000	
FPCM per Cow, (lbs./cow)	22,053		24,033		22,029		22,760		22,090		22,073		22,012	
FPCM Productions (lbs.)	22,053,000		24,033,000		22,029,000		22,760,000		22,090,000		22,073,000		22,012,000	
Financial Costs (\$)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Equipment	221,339	2,551	230,190	3,291	215,208	3,727	216,100	2,824	347,369	4,788	249,961	2,975	237,278	3,295
Facilities	729,773	2,383	731,457	3,273	734,308	5,241	733,740	4,822	734,503	2,278	730,631	1,299	730,107	1,694
Energy	34,238	20,116	27,193	20,827	47,461	18,943	57,737	18,885	45,856	16,846	65,193	40,747	38,870	19,516
Labor	316,711	2,564	321,507	2,294	311,878	3,309	332,898	3,181	328,671	3,363	321,801	2,555	329,075	2,969
Seed, Fertilizer & Chemical	344,815	0	344,815	0	344,815	0	401,689	0	433,635	0	552,644	0	447,191	0
Land Rental	12	0	12	0	12	0	121,413	0	121,413	0	121,413	0	121,413	0
Net Purchased Feed & Bedding	376,497	289,221	556,110	294,502	367,250	281,745	280,142	278,423	-35,429	260,960	-224,155	460,236	-141,047	354,748
Animal Purchase and Livestock Expense	415,140	0	415,140	0	415,140	0	415,140	0	415,140	0	415,140	0	415,140	0
Milk Hauling and Marketing Fees	250,837	1,071	273,353	1,216	250,568	1,238	258,884	610	251,255	1,364	251,067	999	250,369	1,086
Property Tax	52,089	0	52,089	0	52,089	0	52,089	0	52,089	0	52,089	0	52,089	0
Total Costs	2,741,451	-	2,951,866	-	2,738,729	-	2,869,832	-	2,694,502	-	2,535,784	-	2,480,485	-
Income from Milk Sales	5,857,444	24,999	6,383,241	28,406	5,851,166	28,916	6,045,356	14,244	5,867,206	31,863	5,862,822	23,335	5,846,509	25,369
Income from Animal Sales	351,591	0	376,984	0	351,591	0	351,591	0	351,591	0	351,591	0	351,591	0
Return to Management	3,467,584	261,876	3,808,358	262,382	3,464,028	242,232	3,527,114	251,880	3,524,295	233,967	3,678,628	423,284	3,717,614	322,998
Greenhouse Gas Emissions (lbs. of CO2e)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Animal	11,573,804	100,599	12,410,758	137,230	9,585,278	85,810	11,303,795	76,887	11,415,386	78,358	11,587,688	104,619	11,571,983	113,183
Manure	1,245,526	109,921	1,337,740	121,173	1,161,426	98,635	1,014,040	81,367	1,256,191	107,943	1,246,120	108,653	1,251,962	106,360
Direct & Indirect Land	2,099,995	252,799	2,339,773	269,490	1,850,554	223,077	1,958,092	203,215	2,196,028	257,535	2,021,796	332,785	2,123,857	254,322
Net Biogenic CO2	-6,041,047	27,332	-6,592,795	29,120	-6,055,548	28,986	-5,964,008	107,034	-6,038,848	32,307	-6,043,258	23,782	-6,032,154	28,669
Anthropogenic CO2	1,252,160	185,203	1,342,648	207,329	1,084,268	158,180	1,270,116	183,250	1,605,722	194,485	1,237,168	357,541	1,074,548	169,988
Production of Resource Inputs (e.g., Feed)	3,683,179	249,409	3,962,246	315,671	4,170,457	352,771	3,293,351	369,970	3,208,182	234,582	3,917,165	187,796	3,806,509	224,939
Not Allocated to Milk Production	-2,808,006	72,081	-3,053,777	80,321	-2,527,430	67,261	-2,581,661	73,438	-2,778,998	57,540	-2,827,289	86,209	-2,809,547	67,034
Total Emissions Allocated to Milk Production	17,046,658	-	18,339,388	-	15,324,553	-	16,257,733	-	16,902,511	-	17,182,648	-	17,019,312	-
Total Emissions with Biogenic Reductions	11,005,611	-	11,746,593	-	9,269,005	-	10,293,725	-	10,863,663	-	11,139,390	-	10,987,158	-
Carbon Footprint without Biogenic CO2 (lb./lb. FPCM.)	0.77	0.02	0.76	0.02	0.7	0.02	0.71	0.02	0.77	0.02	0.78	0.02	0.77	0.02
Carbon Footprint with Biogenic CO2 (lb./lb. FPCM.)	0.54	0.02	0.53	0.02	0.46	0.02	0.49	0.02	0.53	0.02	0.54	0.02	0.54	0.02

Appendix K. Changes from Original Base Model, New York 1000 Farm in IFSM with AD System.

NY-1000 Farm, with AD System	AD Model 1	AD Model 2	AD Model 3	AD Model 4	AD Model 5	AD Model 6	AD Model 7
Changes in Model Variables Results	AD System Baseline	Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)	Feed Changes (Forage-to-Grain Ratio)	Pastureland Included (1 Acre /Lactating Cow)	Alfalfa Increased (1 Acre /Lactating Cow)	Corn Increased (1 Acre /Lactating Cow)	Soybean Increased (1 Acre /Lactating Cow)
% Δ Land (acres)	-	130.7	130.7	226.9	226.9	226.9	226.9
% Δ FPCM Milk Productions (lbs.)	0.0	9.0	-0.1	3.2	0.2	0.1	-0.2
Change in Costs (\$)							
% Δ Equipment	-1.0	3.0	-3.7	-3.3	55.4	11.8	6.1
% Δ Facilities	44.9	45.2	45.8	45.6	45.8	45.0	44.9
% Δ Energy	-87.1	-89.7	-82.1	-78.2	-82.7	-75.4	-85.3
% Δ Labor	-0.2	1.3	-1.8	4.9	3.5	1.4	3.7
% Δ Seed, Fertilizer & Chemical	0.0	0.0	0.0	16.5	25.8	60.3	29.7
% Δ Net Purchased Feed & Bedding	0.4	48.3	-2.1	-25.3	-109.4	-159.8	-137.6
% Δ Animal Purchase and Livestock Expense	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Milk Hauling and Marketing Fees	0.0	9.0	-0.1	3.2	0.2	0.1	-0.2
% Δ Property Tax	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Total Cost	-0.2	7.4	-0.3	4.4	-1.9	-7.7	-9.7
% Δ Income from Milk Sales	0.0	9.0	-0.1	3.2	0.2	0.1	-0.2
% Δ Income from Animal Sales	0.0	7.2	0.0	0.0	0.0	0.0	0.0
% Δ Return to Management	0.2	10.0	0.1	1.9	1.8	6.3	7.4
Change in lbs. CO2e							
% Δ Animal Emissions	0.0	7.2	-17.2	-2.3	-1.4	0.1	0.0
% Δ Manure Emissions	-56.5	-53.2	-59.4	-64.5	-56.1	-56.4	-56.2
% Δ Direct and Indirect Land Emissions	0.5	11.9	-11.5	-6.3	5.1	-3.3	1.6
% Δ Anthropogenic	-0.6	6.5	-14.0	0.8	27.4	-1.8	-14.7
% Δ Production of Resource Inputs (e.g., Feed)	-29.3	-24.0	-20.0	-36.8	-38.4	-24.8	-27.0
% Δ Total Emissions Allocated to Milk Production	-13.7	-7.1	-22.4	-17.7	-14.4	-13.0	-13.8
% Δ Total Emissions with Biogenic Reductions	-19.7	-14.3	-32.4	-24.9	-20.7	-18.7	-19.8
% Δ Carbon Footprint Without Biogenic CO2 (lb./lb. FPCM.)	-14.4	-15.6	-22.2	-21.1	-14.4	-13.3	-14.4
% Δ Carbon Footprint With Biogenic CO2 (lb./lb. FPCM.)	-18.2	-19.7	-30.3	-25.8	-19.7	-18.2	-18.2

Appendix L. Texas 1200 Farm Models in IFSM.

TX-1200 Farm	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6		Model 7	
Model Variables	Original Baseline		Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)		Feed Changes (Forage-to-Grain Ratio)		Pastureland Included (1 Acre /Lactating Cow)		Alfalfa Increased (1 Acre /Lactating Cow)		Corn Increased (1 Acre /Lactating Cow)		Soybean Increased (1 Acre /Lactating Cow)	
Land (acres)	680		680		680		1,880		1,880		1,880		1,880	
Electricity Purchase Price (¢/kWh)	9.1		9.1		9.1		9.1		9.1		9.1		9.1	
Lactating Herd Size (each)	1,200		1,200		1,200		1,200		1,200		1,200		1,200	
FPCM per Cow, (lbs./cow)	21,703		23,653		22,369		22,583		21,637		21,774		21,722	
FPCM Productions (lbs.)	26,043,600		28,383,600		26,842,800		27,099,600		25,964,400		26,128,800		26,066,400	
Financial Costs (\$)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Equipment	225,960	6,180	236,898	5,536	206,464	7,452	215,089	4,699	470,034	27,658	270,003	14,468	273,462	6,977
Facilities	365,330	1,152	369,035	1,152	365,330	1,152	365,542	1,176	365,911	1,189	384,060	3,391	366,484	1,422
Energy	151,536	4,199	163,941	4,116	146,262	4,624	148,513	3,367	161,292	8,080	167,918	6,709	163,163	4,415
Labor	422,301	5,812	435,495	5,544	405,883	5,691	440,559	4,241	433,997	10,414	430,343	10,536	431,669	6,229
Seed, Fertilizer & Chemical	146,759	0	146,759	0	146,759	0	182,159	0	199,259	0	428,281	0	231,301	0
Land Rental	4	0	4	0	4	0	51,004	0	51,004	0	51,004	0	51,004	0
Net Purchased Feed & Bedding	1,611,753	93,452	1,841,536	96,755	1,619,578	62,941	1,541,102	100,984	1,320,311	221,681	816,390	194,794	1,204,990	145,462
Animal Purchase and Livestock Expense	497,580	0	497,580	0	497,580	0	497,580	0	497,580	0	497,580	0	497,580	0
Milk Hauling and Marketing Fees	282,091	2,606	307,432	2,855	290,745	4,016	293,533	2,918	281,240	2,553	283,010	2,469	282,339	2,640
Property Tax	33,086	0	33,427	0	33,086	0	33,086	0	33,086	0	33,086	0	33,086	0
Total Costs	3,736,400	-	4,032,107	-	3,711,691	-	3,768,167	-	3,813,714	-	3,361,675	-	3,535,078	-
Income from Milk Sales	6,449,030	59,572	7,028,359	65,278	6,646,882	91,822	6,710,624	66,701	6,429,588	58,377	6,470,044	56,444	6,454,704	60,366
Income from Animal Sales	421,609	0	452,080	0	421,609	0	421,609	0	421,609	0	421,609	0	421,609	0
Return to Management	3,134,238	100,026	3,448,334	107,876	3,356,799	121,349	3,364,066	129,942	3,037,482	185,809	3,529,979	182,933	3,341,234	153,876
Greenhouse Gas Emissions (lbs. of CO ₂ e)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Animal	14,042,451	117,813	15,064,636	123,625	10,781,725	350,205	13,471,493	165,559	13,706,839	246,665	13,772,881	148,261	13,930,372	91,972
Manure	8,528,287	2,824,312	9,378,246	3,093,312	7,900,778	2,567,014	8,440,856	2,751,352	8,498,780	2,766,340	8,346,416	2,653,165	8,451,838	2,773,576
Direct & Indirect Land	2,744,810	413,984	3,046,780	480,344	2,415,189	347,723	3,034,814	304,399	3,350,010	550,716	3,111,520	410,255	2,824,426	327,183
Net Biogenic CO ₂	-7,220,505	35,428	-7,853,534	36,428	-7,443,673	80,475	-7,156,524	15,798	-7,049,242	133,065	-7,256,130	31,184	-7,236,770	24,137
Anthropogenic CO ₂	693,642	20,638	752,968	21,395	612,802	18,861	672,470	21,438	742,866	47,610	699,766	66,209	652,266	17,317
Production of Resource Inputs (e.g., Feed)	6,518,034	313,440	7,256,080	321,565	6,877,858	185,653	6,448,954	321,310	5,972,144	527,864	5,229,490	138,317	6,217,712	328,847
Not Allocated to Milk Production	-4,676,336	463,206	-5,150,531	505,079	-3,990,507	444,373	-4,430,600	437,620	-4,652,994	497,836	-4,464,798	422,045	-4,607,587	460,696
Total Emissions Allocated to Milk Production	27,850,888	-	30,348,179	-	24,597,845	-	27,637,987	-	27,617,645	-	26,695,275	-	27,469,027	-
Total Emissions with Biogenic Reductions	20,630,383	-	22,494,645	-	17,154,172	-	20,481,463	-	20,568,403	-	19,439,145	-	20,232,257	-
Carbon Footprint without Biogenic CO ₂ (lb./lb. FPCM.)	1.07	0.11	1.07	0.1	0.92	0.1	1.02	0.1	1.06	0.11	1.02	0.1	1.05	0.1
Carbon Footprint with Biogenic CO ₂ (lb./lb. FPCM.)	0.83	0.1	0.83	0.1	0.68	0.1	0.79	0.1	0.83	0.11	0.78	0.1	0.82	0.1

Appendix M. Changes from Original Base Model, Texas 1200 Farm in IFSM.

TX-1200 Farm	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Changes in Model Variables Results	Original Baseline	Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)	Feed Changes (Forage-to-Grain Ratio)	Pastureland Included (1 Acre /Lactating Cow)	Alfalfa Increased (1 Acre /Lactating Cow)	Corn Increased (1 Acre /Lactating Cow)	Soybean Increased (1 Acre /Lactating Cow)
% Δ Land (acres)	-	-34.6	-34.6	80.9	80.9	80.9	80.9
% Δ FPCM Milk Productions (lbs.)	-	9.0	3.1	4.1	-0.3	0.3	0.1
Change in Costs (\$)							
% Δ Equipment	-	4.8	-8.6	-4.8	108.0	19.5	21.0
% Δ Facilities	-	1.0	0.0	0.1	0.2	5.1	0.3
% Δ Energy	-	8.2	-3.5	-2.0	6.4	10.8	7.7
% Δ Labor	-	3.1	-3.9	4.3	2.8	1.9	2.2
% Δ Seed, Fertilizer & Chemical	-	0.0	0.0	24.1	35.8	191.8	57.6
% Δ Net Purchased Feed & Bedding	-	14.3	0.5	-4.4	-18.1	-49.3	-25.2
% Δ Animal Purchase and Livestock Expense	-	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Milk Hauling and Marketing Fees	-	9.0	3.1	4.1	-0.3	0.3	0.1
% Δ Property Tax	-	1.0	0.0	0.0	0.0	0.0	0.0
% Δ Total Cost	-	7.9	-0.7	0.9	2.1	-10.0	-5.4
% Δ Income from Milk Sales	-	9.0	3.1	4.1	-0.3	0.3	0.1
% Δ Income from Animal Sales	-	7.2	0.0	0.0	0.0	0.0	0.0
% Δ Return to Management	-	10.0	7.1	7.3	-3.1	12.6	6.6
Change in lbs. CO ₂ e							
% Δ Animal Emissions	-	7.3	-23.2	-4.1	-2.4	-1.9	-0.8
% Δ Manure Emissions	-	10.0	-7.4	-1.0	-0.3	-2.1	-0.9
% Δ Direct and Indirect Land Emissions	-	11.0	-12.0	10.6	22.0	13.4	2.9
% Δ Anthropogenic	-	8.6	-11.7	-3.1	7.1	0.9	-6.0
% Δ Production of Resource Inputs (e.g., Feed)	-	11.3	5.5	-1.1	-8.4	-19.8	-4.6
% Δ Total Emissions Allocated to Milk Production	-	9.0	-11.7	-0.8	-0.8	-4.1	-1.4
% Δ Total Emissions with Biogenic Reductions	-	9.0	-16.8	-0.7	-0.3	-5.8	-1.9
% Δ Carbon Footprint Without Biogenic CO ₂ (lb./lb. FPCM.)	-	0.0	-14.0	-4.7	-0.9	-4.7	-1.9
% Δ Carbon Footprint With Biogenic CO ₂ (lb./lb. FPCM.)	-	0.0	-18.1	-4.8	0.0	-6.0	-1.2

Appendix N. Texas 1200 Farm Models in IFSM with AD System.

TX-1200 Farm, with AD System	AD Model 1		AD Model 2		AD Model 3		AD Model 4		AD Model 5		AD Model 6		AD Model 7	
Model Variables	AD System Baseline		Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)		Feed Changes (Forage-to-Grain Ratio)		Pastureland Included (1 Acre /Lactating Cow)		Alfalfa Increased (1 Acre /Lactating Cow)		Corn Increased (1 Acre /Lactating Cow)		Soybean Increased (1 Acre /Lactating Cow)	
Land (acres)	680		680		680		1,880		1,880		1,880		1,880	
Electricity Purchase Price (¢/kWh)	9.1		9.1		9.1		9.1		9.1		9.1		9.1	
Lactating Herd Size (each)	1,200		1,200		1,200		1,200		1,200		1,200		1,200	
FPCM per Cow, (lbs./cow)	21,704		23,653		22,368		22,583		21,638		21,773		21,721	
FPCM Productions (lbs.)	26,044,800		28,383,600		26,841,600		27,099,600		25,965,600		26,127,600		26,065,200	
Financial Costs (\$)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Equipment	221,701	6,098	232,130	5,491	202,663	7,375	211,618	4,608	466,357	27,633	265,836	14,357	269,373	6,895
Facilities	609,034	1,152	612,738	1,152	609,034	1,152	609,246	1,176	609,614	1,189	627,755	3,394	610,188	1,421
Energy	-42,792	3,829	-48,606	3,954	-31,279	4,150	-19,115	3,577	-28,909	9,296	-20,818	3,496	-29,207	3,597
Labor	420,929	5,772	433,711	5,520	404,907	5,673	439,809	4,216	432,729	10,421	429,101	10,454	430,358	6,183
Seed, Fertilizer & Chemical	146,759	0	146,759	0	146,759	0	182,159	0	199,259	0	428,281	0	231,301	0
Land Rental	4	0	4	0	4	0	51,004	0	51,004	0	51,004	0	51,004	0
Net Purchased Feed & Bedding	1,611,688	93,587	1,841,620	96,692	1,619,615	62,950	1,540,864	101,277	1,320,357	221,658	816,567	194,802	1,205,096	145,496
Animal Purchase and Livestock Expense	497,580	0	497,580	0	497,580	0	497,580	0	497,580	0	497,580	0	497,580	0
Milk Hauling and Marketing Fees	282,099	2,612	307,432	2,855	290,735	4,007	293,533	2,918	281,242	2,551	283,006	2,467	282,332	2,634
Property Tax	33,086	0	33,427	0	33,086	0	33,086	0	33,086	0	33,086	0	33,086	0
Total Costs	3,780,088	-	4,056,795	-	3,773,104	-	3,839,784	-	3,862,319	-	3,411,398	-	3,581,111	-
Income from Milk Sales	6,449,209	59,721	7,028,359	65,278	6,646,656	91,614	6,710,624	66,701	6,429,635	58,325	6,469,952	56,394	6,454,547	60,214
Income from Animal Sales	421,609	0	452,080	0	421,609	0	421,609	0	421,609	0	421,609	0	421,609	0
Return to Management	3,090,730	100,764	3,423,644	107,955	3,295,161	121,568	3,292,447	130,015	2,988,925	184,636	3,480,166	186,424	3,295,045	154,024
Greenhouse Gas Emissions (lbs. of CO ₂ e)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Animal	14,042,730	117,507	15,064,718	123,572	10,783,514	349,038	13,471,393	165,752	13,706,895	246,725	13,773,155	148,206	13,930,516	91,735
Manure	7,940,984	1,331,631	8,734,703	1,541,748	7,365,326	1,221,855	7,221,368	1,243,043	7,917,592	1,302,777	7,782,208	1,220,642	7,870,602	1,294,329
Direct & Indirect Land	2,815,922	406,570	3,135,128	470,724	2,470,165	342,648	3,060,099	300,669	3,427,351	547,449	3,152,168	415,609	2,865,076	326,817
Net Biogenic CO ₂	-7,220,505	35,428	-7,853,534	36,428	-7,443,673	80,475	-7,156,524	15,798	-7,049,242	133,065	-7,256,130	31,184	-7,237,068	23,839
Anthropogenic CO ₂	683,138	20,663	741,430	21,396	603,686	18,665	663,343	21,393	732,865	47,533	691,379	65,229	643,486	17,227
Production of Resource Inputs (e.g., Feed)	3,595,352	283,523	4,050,241	296,617	4,347,316	126,860	3,910,625	311,026	3,179,660	442,573	2,933,990	225,380	3,778,932	283,166
Not Allocated to Milk Production	-4,179,770	254,959	-4,602,528	284,144	-3,568,383	262,200	-3,913,341	240,518	-4,175,770	294,490	-4,059,222	200,578	-4,177,808	249,958
Total Emissions Allocated to Milk Production	24,898,356	-	27,123,692	-	22,001,624	-	24,413,487	-	24,788,593	-	24,273,678	-	24,910,804	-
Total Emissions with Biogenic Reductions	17,677,851	-	19,270,158	-	14,557,951	-	17,256,963	-	17,739,351	-	17,017,548	-	17,673,736	-
Carbon Footprint without Biogenic CO ₂ (lb./lb. FPCM.)	0.96	0.06	0.96	0.06	0.82	0.06	0.9	0.05	0.95	0.07	0.93	0.05	0.96	0.06
Carbon Footprint with Biogenic CO ₂ (lb./lb. FPCM.)	0.72	0.06	0.72	0.06	0.58	0.06	0.67	0.05	0.72	0.06	0.69	0.04	0.72	0.06

Appendix O. Changes from Original Base Model, Texas 1200 Farm in IFSM with AD System.

TX-1200 Farm, with AD System	AD Model 1	AD Model 2	AD Model 3	AD Model 4	AD Model 5	AD Model 6	AD Model 7
Changes in Model Variables Results	AD System Baseline	Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)	Feed Changes (Forage-to-Grain Ratio)	Pastureland Included (1 Acre /Lactating Cow)	Alfalfa Increased (1 Acre /Lactating Cow)	Corn Increased (1 Acre /Lactating Cow)	Soybean Increased (1 Acre /Lactating Cow)
% Δ Land (acres)	-	-34.6	-34.6	80.9	80.9	80.9	80.9
% Δ FPCM Milk Productions (lbs.)	0.0	9.0	3.1	4.1	-0.3	0.3	0.1
Change in Costs (\$)							
% Δ Equipment	-1.9	2.7	-10.3	-6.3	106.4	17.6	19.2
% Δ Facilities	66.7	67.7	66.7	66.8	66.9	71.8	67.0
% Δ Energy	-128.2	-132.1	-120.6	-112.6	-119.1	-113.7	-119.3
% Δ Labor	-0.3	2.7	-4.1	4.1	2.5	1.6	1.9
% Δ Seed, Fertilizer & Chemical	0.0	0.0	0.0	24.1	35.8	191.8	57.6
% Δ Net Purchased Feed & Bedding	0.0	14.3	0.5	-4.4	-18.1	-49.3	-25.2
% Δ Animal Purchase and Livestock Expense	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Milk Hauling and Marketing Fees	0.0	9.0	3.1	4.1	-0.3	0.3	0.1
% Δ Property Tax	0.0	1.0	0.0	0.0	0.0	0.0	0.0
% Δ Total Cost	1.2	8.6	1.0	2.8	3.4	-8.7	-4.2
% Δ Income from Milk Sales	0.0	9.0	3.1	4.1	-0.3	0.3	0.1
% Δ Income from Animal Sales	0.0	7.2	0.0	0.0	0.0	0.0	0.0
% Δ Return to Management	-1.4	9.2	5.1	5.0	-4.6	11.0	5.1
Change in lbs. CO2e							
% Δ Animal Emissions	0.0	7.3	-23.2	-4.1	-2.4	-1.9	-0.8
% Δ Manure Emissions	-6.9	2.4	-13.6	-15.3	-7.2	-8.7	-7.7
% Δ Direct and Indirect Land Emissions	2.6	14.2	-10.0	11.5	24.9	14.8	4.4
% Δ Anthropogenic	-1.5	6.9	-13.0	-4.4	5.7	-0.3	-7.2
% Δ Production of Resource Inputs (e.g., Feed)	-44.8	-37.9	-33.3	-40.0	-51.2	-55.0	-42.0
% Δ Total Emissions Allocated to Milk Production	-10.6	-2.6	-21.0	-12.3	-11.0	-12.8	-10.6
% Δ Total Emissions with Biogenic Reductions	-14.3	-6.6	-29.4	-16.4	-14.0	-17.5	-14.3
% Δ Carbon Footprint Without Biogenic CO2 (lb./lb. FPCM.)	-10.3	-10.3	-23.4	-15.9	-11.2	-13.1	-10.3
% Δ Carbon Footprint With Biogenic CO2 (lb./lb. FPCM.)	-13.3	-13.3	-30.1	-19.3	-13.3	-16.9	-13.3

Appendix P. Minnesota 5000 Farm Models in IFSM.

MN-5000 Farm	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6		Model 7	
Model Variables	Original Baseline		Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)		Feed Changes (Forage-to-Grain Ratio)		Pastureland Included (1 Acre /Lactating Cow)		Alfalfa Increased (1 Acre /Lactating Cow)		Corn Increased (1 Acre /Lactating Cow)		Soybean Increased (1 Acre /Lactating Cow)	
Land (acres)	7,043		7,043		7,043		12,043		12,043		12,043		12,043	
Electricity Purchase Price (¢/kWh)	11.22		11.22		11.22		11.22		11.22		11.22		11.22	
Lactating Herd Size (each)	5,000		5,000		5,000		5,000		5,000		5,000		5,000	
FPCM per Cow, (lbs./cow)	22,166		24,161		22,224		22,689		22,214		22,311		22,164	
FPCM Productions (lbs.)	110,830,000		120,805,000		111,120,000		113,445,000		111,070,000		111,555,000		110,820,000	
Financial Costs (\$)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Equipment	1,991,083	236,831	2,003,182	237,457	1,958,486	236,724	1,985,758	236,869	2,404,169	119,033	2,289,891	125,987	2,272,717	144,050
Facilities	2,008,883	14,677	2,012,017	16,364	2,010,482	17,491	2,010,942	17,469	2,023,156	14,730	2,038,915	10,116	2,016,028	11,988
Energy	899,864	33,346	944,357	33,886	870,690	32,588	880,658	33,227	995,787	43,257	1,098,307	92,787	970,188	39,170
Labor	2,053,694	5,651	2,067,647	6,106	2,047,835	5,584	2,177,946	5,777	2,079,972	6,362	2,113,601	11,923	2,112,656	6,387
Seed, Fertilizer & Chemical	895,429	0	895,429	0	895,429	0	1,019,179	0	1,164,124	0	1,798,938	0	1,296,774	0
Land Rental	16	0	16	0	16	0	820,015	0	820,015	0	820,015	0	820,015	0
Net Purchased Feed & Bedding	3,003,828	395,289	3,850,899	365,681	3,231,233	396,725	2,661,565	413,840	2,166,265	350,141	344,503	926,386	345,953	466,112
Animal Purchase and Livestock Expense	2,072,760	0	2,072,760	0	2,072,760	0	2,072,760	0	2,072,760	0	2,072,760	0	2,072,760	0
Milk Hauling and Marketing Fees	1,200,467	8,528	1,308,521	9,198	1,203,617	8,191	1,228,776	7,990	1,203,042	6,055	1,208,296	5,532	1,200,326	8,529
Property Tax	239,069	0	239,069	0	239,069	0	239,069	0	239,069	0	239,069	0	239,069	0
Total Costs	14,365,093	-	15,393,897	-	14,529,617	-	15,096,668	-	15,168,359	-	14,024,295	-	13,346,486	-
Income from Milk Sales	28,776,896	204,417	31,367,116	220,491	28,852,422	196,353	29,455,514	191,527	28,838,620	145,141	28,964,574	132,599	28,773,530	204,460
Income from Animal Sales	1,756,456	0	1,883,419	1	1,756,456	0	1,756,456	0	1,756,456	0	1,756,456	0	1,756,456	0
Return to Management	16,168,255	452,887	17,856,640	431,054	16,079,256	448,810	16,115,302	491,330	15,426,720	339,362	16,696,735	960,173	17,183,500	496,365
Greenhouse Gas Emissions (lbs. of CO ₂ e)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Animal	56,345,832	310,038	60,543,564	267,332	47,793,176	235,174	56,686,060	273,145	56,551,940	235,716	56,897,444	235,526	56,352,532	320,038
Manure	22,181,274	1,553,683	24,132,862	1,750,106	20,900,954	1,404,027	16,820,432	1,053,184	22,120,320	1,482,208	22,007,682	1,332,821	22,200,716	1,534,212
Direct & Indirect Land	7,605,331	722,381	8,765,663	824,629	5,838,802	654,941	6,942,375	673,866	7,802,882	792,111	6,796,990	1,119,936	7,590,280	757,944
Net Biogenic CO ₂	-	224,255	-	235,239	-	189,167	-	227,721	-	165,336	-	151,685	-	213,355
Anthropogenic CO ₂	3,098,226	267,117	3,385,662	289,389	2,052,542	231,613	2,816,686	310,832	3,258,258	322,302	3,805,337	1,083,762	2,725,602	164,031
Production of Resource Inputs (e.g., Feed)	26,795,620	1,265,218	29,199,378	1,225,953	30,118,434	1,277,707	25,021,800	1,455,624	26,262,610	1,062,114	26,554,422	808,998	26,296,458	1,162,167
Not Allocated to Milk Production	-	340,492	-	376,513	-	340,035	-	278,618	-	312,663	-	394,500	-	354,868
Total Emissions Allocated to Milk Production	99,698,342	-	108,130,121	-	91,727,015	-	93,400,062	-	99,707,667	-	99,835,862	-	98,956,848	-
Total Emissions with Biogenic Reductions	69,430,238	-	75,109,799	-	61,392,141	-	63,098,432	-	69,384,127	-	69,389,136	-	68,705,560	-
Carbon Footprint without Biogenic CO ₂ (lb./lb. FPCM.)	0.9	0.02	0.9	0.02	0.83	0.02	0.82	0.02	0.9	0.02	0.89	0.02	0.89	0.02
Carbon Footprint with Biogenic CO ₂ (lb./lb. FPCM.)	0.66	0.02	0.66	0.02	0.59	0.02	0.59	0.02	0.66	0.02	0.66	0.02	0.66	0.02

Appendix Q. Changes from Original Base Model, Minnesota 5000 Farm in IFSM.

MN-5000 Farm	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Changes in Model Variables Results	Original Baseline	Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)	Feed Changes (Forage-to-Grain Ratio)	Pastureland Included (1 Acre /Lactating Cow)	Alfalfa Increased (1 Acre /Lactating Cow)	Corn Increased (1 Acre /Lactating Cow)	Soybean Increased (1 Acre /Lactating Cow)
% Δ Land (acres)	-	577.9	577.9	1059.1	1059.1	1059.1	1059.1
% Δ FPCM Milk Productions (lbs.)	-	9.0	0.3	2.4	0.2	0.7	0.0
Change in Costs (\$)							
% Δ Equipment	-	0.6	-1.6	-0.3	20.7	15.0	14.1
% Δ Facilities	-	0.2	0.1	0.1	0.7	1.5	0.4
% Δ Energy	-	4.9	-3.2	-2.1	10.7	22.1	7.8
% Δ Labor	-	0.7	-0.3	6.1	1.3	2.9	2.9
% Δ Seed, Fertilizer & Chemical	-	0.0	0.0	13.8	30.0	100.9	44.8
% Δ Net Purchased Feed & Bedding	-	28.2	7.6	-11.4	-27.9	-88.5	-88.5
% Δ Animal Purchase and Livestock Expense	-	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Milk Hauling and Marketing Fees	-	9.0	0.3	2.4	0.2	0.7	0.0
% Δ Property Tax	-	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Total Cost	-	7.2	1.1	5.1	5.6	-2.4	-7.1
% Δ Income from Milk Sales	-	9.0	0.3	2.4	0.2	0.7	0.0
% Δ Income from Animal Sales	-	7.2	0.0	0.0	0.0	0.0	0.0
% Δ Return to Management	-	10.4	-0.6	-0.3	-4.6	3.3	6.3
Change in lbs. CO2e							
% Δ Animal Emissions	-	7.4	-15.2	0.6	0.4	1.0	0.0
% Δ Manure Emissions	-	8.8	-5.8	-24.2	-0.3	-0.8	0.1
% Δ Direct and Indirect Land Emissions	-	15.3	-23.2	-8.7	2.6	-10.6	-0.2
% Δ Anthropogenic	-	9.3	-33.8	-9.1	5.2	22.8	-12.0
% Δ Production of Resource Inputs (e.g., Feed)	-	9.0	12.4	-6.6	-2.0	-0.9	-1.9
% Δ Total Emissions Allocated to Milk Production	-	8.5	-8.0	-6.3	0.0	0.1	-0.7
% Δ Total Emissions with Biogenic Reductions	-	8.5	-8.0	-6.3	0.0	0.1	-0.7
% Δ Carbon Footprint Without Biogenic CO2 (lb./lb. FPCM.)	-	0.0	-7.8	-8.9	0.0	-1.1	-1.1
% Δ Carbon Footprint With Biogenic CO2 (lb./lb. FPCM.)	-	0.0	-10.6	-10.6	0.0	0.0	0.0

Appendix R. Minnesota 5000 Farm Models in IFSM with AD System

MN-5000 Farm, with AD System	AD Model 1		AD Model 2		AD Model 3		AD Model 4		AD Model 5		AD Model 6		AD Model 7	
Model Variables	AD System Baseline		Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)		Feed Changes (Forage-to-Grain Ratio)		Pastureland Included (1 Acre /Lactating Cow)		Alfalfa Increased (1 Acre /Lactating Cow)		Corn Increased (1 Acre /Lactating Cow)		Soybean Increased (1 Acre /Lactating Cow)	
Land (acres)	7,043		7,043		7,043		12,043		12,043		12,043		12,043	
Electricity Purchase Price (¢/kWh)	11.22		11.22		11.22		11.22		11.22		11.22		11.22	
Lactating Herd Size (each)	5,000		5,000		5,000		5,000		5,000		5,000		5,000	
FPCM per Cow, (lbs./cow)	22,173		24,163		22,229		22,720		22,214		22,310		22,171	
FPCM Productions (lbs.)	110,865,000		120,815,000		111,145,000		113,600,000		111,070,000		111,550,000		110,855,000	
Financial Costs (\$)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Equipment	1,973,920	236,905	1,991,228	237,497	1,947,540	236,758	1,973,920	236,905	2,393,323	119,068	2,277,902	125,833	2,261,574	144,104
Facilities	2,763,634	17,996	2,766,468	16,676	2,764,654	17,883	2,763,634	17,996	2,777,657	14,928	2,794,559	9,908	2,770,390	12,365
Energy	-41,279	42,528	-260,591	51,562	-166,440	44,407	-41,279	42,528	-104,171	53,570	163	100,512	-134,548	50,526
Labor	2,165,066	6,005	2,050,937	6,243	2,033,796	5,724	2,165,066	6,005	2,065,048	6,510	2,097,893	12,137	2,097,520	6,524
Seed, Fertilizer & Chemical	1,019,179	0	895,429	0	895,429	0	1,019,179	0	1,164,124	0	1,798,938	0	1,296,774	0
Land Rental	820,015	0	16	0	16	0	820,015	0	820,015	0	820,015	0	820,015	0
Net Purchased Feed & Bedding	2,711,153	431,001	3,875,972	381,762	3,266,043	412,374	2,711,153	431,001	2,187,999	364,057	421,139	942,236	379,640	481,499
Animal Purchase and Livestock Expense	2,072,760	0	2,072,760	0	2,072,760	0	2,072,760	0	2,072,760	0	2,072,760	0	2,072,760	0
Milk Hauling and Marketing Fees	1,230,478	7,424	1,308,586	9,110	1,203,878	8,184	1,230,478	7,424	1,203,081	5,961	1,208,256	5,541	1,200,745	8,388
Property Tax	239,069	0	239,069	0	239,069	0	239,069	0	239,069	0	239,069	0	239,069	0
Total Costs	14,953,995	-	14,939,874	-	14,256,745	-	14,953,995	-	14,818,905	-	13,730,694	-	13,003,939	-
Income from Milk Sales	29,496,302	177,961	31,368,668	218,377	28,858,664	196,185	29,496,302	177,961	28,839,568	142,890	28,963,618	132,826	28,783,564	201,084
Income from Animal Sales	1,756,456	0	1,883,419	1	1,756,456	0	1,756,456	0	1,756,456	0	1,756,456	0	1,756,456	0
Return to Management	16,298,758	503,046	18,312,212	434,636	16,358,377	455,312	16,298,758	503,046	15,777,119	344,877	16,989,378	963,356	17,536,080	502,320
Greenhouse Gas Emissions (lbs. of CO ₂ e)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Animal	56,724,412	263,754	60,550,308	266,881	47,813,372	237,026	56,724,412	263,754	56,564,136	244,061	56,916,868	228,906	56,380,832	338,421
Manure	6,837,832	314,632	9,297,512	530,421	8,169,091	420,680	6,837,832	314,632	8,604,248	443,477	8,543,332	400,863	8,612,455	464,013
Direct & Indirect Land	6,827,774	617,282	8,861,635	808,343	5,952,346	642,346	6,827,774	617,282	7,904,211	777,373	6,989,230	1,134,554	7,695,158	744,055
Net Biogenic CO ₂	30,301,598	224,483	33,020,322	235,239	30,340,526	197,855	30,301,598	224,483	30,323,540	165,336	30,446,726	151,685	30,268,048	217,191
Anthropogenic CO ₂	2,729,931	305,808	3,333,988	289,759	2,015,435	234,712	2,729,931	305,808	3,214,046	325,351	3,772,600	1,070,334	2,685,372	167,351
Production of Resource Inputs (e.g., Feed)	16,371,236	1,749,296	15,889,965	1,395,049	22,505,048	1,618,381	16,371,236	1,749,296	15,507,014	1,316,562	17,800,136	564,392	16,487,154	1,432,347
Not Allocated to Milk Production	12,285,681	267,376	13,905,676	238,108	12,131,350	261,825	12,285,681	267,376	12,888,737	233,537	13,144,877	291,974	12,923,209	267,055
Total Emissions Allocated to Milk Production	77,205,504	-	84,027,732	-	74,323,942	-	77,205,504	-	78,904,918	-	80,877,289	-	78,937,762	-
Total Emissions with Biogenic Reductions	46,903,906	-	51,007,410	-	43,983,416	-	46,903,906	-	48,581,378	-	50,430,563	-	48,669,714	-
Carbon Footprint without Biogenic CO ₂ (lb./lb. FPCM.)	0.68	0.01	0.7	0.01	0.67	0.01	0.68	0.01	0.71	0.01	0.73	0.02	0.71	0.01
Carbon Footprint with Biogenic CO ₂ (lb./lb. FPCM.)	0.45	0.01	0.46	0.01	0.43	0.01	0.45	0.01	0.48	0.01	0.49	0.02	0.48	0.01

Appendix S. Changes from Original Base Model, Minnesota 5000 Farm in IFSM with AD System.

MN-5000 Farm, with AD System	AD Model 1	AD Model 2	AD Model 3	AD Model 4	AD Model 5	AD Model 6	AD Model 7
Changes in Model Variables Results	AD System Baseline	Large Holsteins with Increased Milk Production (27,000 lbs./cow/year)	Feed Changes (Forage-to-Grain Ratio)	Pastureland Included (1 Acre /Lactating Cow)	Alfalfa Increased (1 Acre /Lactating Cow)	Corn Increased (1 Acre /Lactating Cow)	Soybean Increased (1 Acre /Lactating Cow)
% Δ Land (acres)	-	577.9	577.9	1059.1	1059.1	1059.1	1059.1
% Δ FPCM Milk Productions (lbs.)	0.0	9.0	0.3	2.5	0.2	0.6	0.0
Change in Costs (\$)							
% Δ Equipment	-0.9	0.0	-2.2	-0.9	20.2	14.4	13.6
% Δ Facilities	37.6	37.7	37.6	37.6	38.3	39.1	37.9
% Δ Energy	-104.6	-129.0	-118.5	-104.6	-111.6	-100.0	-115.0
% Δ Labor	5.4	-0.1	-1.0	5.4	0.6	2.2	2.1
% Δ Seed, Fertilizer & Chemical	13.8	0.0	0.0	13.8	30.0	100.9	44.8
% Δ Net Purchased Feed & Bedding	-9.7	29.0	8.7	-9.7	-27.2	-86.0	-87.4
% Δ Animal Purchase and Livestock Expense	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Milk Hauling and Marketing Fees	2.5	9.0	0.3	2.5	0.2	0.6	0.0
% Δ Property Tax	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Δ Total Cost	4.1	4.0	-0.8	4.1	3.2	-4.4	-9.5
% Δ Income from Milk Sales	4.1	4.0	-0.8	4.1	3.2	-4.4	-9.5
% Δ Income from Animal Sales	2.5	9.0	0.3	2.5	0.2	0.6	0.0
% Δ Return to Management	0.8	13.3	1.2	0.8	-2.4	5.1	8.5
Change in lbs. CO ₂ e							
% Δ Animal Emissions	0.7	7.5	-15.1	0.7	0.4	1.0	0.1
% Δ Manure Emissions	-69.2	-58.1	-63.2	-69.2	-61.2	-61.5	-61.2
% Δ Direct and Indirect Land Emissions	-10.2	16.5	-21.7	-10.2	3.9	-8.1	1.2
% Δ Anthropogenic	-11.9	7.6	-34.9	-11.9	3.7	21.8	-13.3
% Δ Production of Resource Inputs (e.g., Feed)	-38.9	-40.7	-16.0	-38.9	-42.1	-33.6	-38.5
% Δ Total Emissions Allocated to Milk Production	-22.6	-15.7	-25.5	-22.6	-20.9	-18.9	-20.8
% Δ Total Emissions with Biogenic Reductions	-22.6	-15.7	-25.5	-22.6	-20.9	-18.9	-20.8
% Δ Carbon Footprint Without Biogenic CO ₂ (lb./lb. FPCM.)	-24.4	-22.2	-25.6	-24.4	-21.1	-18.9	-21.1
% Δ Carbon Footprint With Biogenic CO ₂ (lb./lb. FPCM.)	-31.8	-30.3	-34.8	-31.8	-27.3	-25.8	-27.3