THESIS

ENVIRONMENTAL ASSESSMENT OF NORTHERN COLORADO DAIRY SYSTEMS: WHOLE-FARM PREDICTIONS FOR PAST, FUTURE, AND BENEFICIAL MANAGEMENT PRACTICES

Submitted by

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ABSTRACT

ENVIRONMENTAL ASSESSMENT OF NORTHERN COLORADO DAIRY SYSTEMS: WHOLE-FARM PREDICTIONS FOR PAST, FUTURE, AND BENEFICIAL MANAGEMENT PRACTICES

The Northern Great Plains region is projected to experience rising average daily temperatures, greater precipitation variability, and increased overall weather variability over the next 75 years. These changes have potentially negative implications for Colorado dairy systems. The objective of this study was to (1) evaluate implications of climate change on resource use and environmental footprints of Colorado dairies through the 21st century using the Integrated Farms Systems Model (IFSM) and (2) identify and evaluate Beneficial Management Practices (BMPs) to assess the Colorado dairy industry's ability to remain sustainable and productive through 2100. The Integrated Farm System Model (IFSM) was used to estimate the carbon (CF), blue water (WF), reactive nitrogen (RnF), and energy (EF) footprints of three dairy operations: 1100-head conventional (1100C), 1100-head organic (1100OR), and 2000-head conventional (2000C). The IFSM is a whole-farm, process-based model that simulates major biophysical processes, environmental impacts, and economics of beef, dairy, and crop farms over many years of weather. Model inputs were obtained from the literature, publicly available USDA databases, and expert input. Each farm was simulated over three time periods: historic (1990-2015), mid-century (2040-2065), and late century (2075-2100). Eight general climate models (GCMs) and two representative concentration pathway scenarios (RCP 4.5 and

8.5) were used to evaluate potential climate impacts to resource use and environmental footprints of the farms. After baseline footprints were obtained, BMPs were modeled to assess the impacts on each farm's environmental footprints over each time. BMPs included 1) covered manure basin on all three farms 2) covered manure basin with flare on the 1100C farm 3) spring and fall cycle calving and milking on the 1100OR and 4) decrease in dietary crude protein from the NRC recommendation of 16% to 14% and supplementation with amino acids on the 2000C farm. The results of this study indicate that BMPs have the potential to reduce environmental footprints on dairy farms in Colorado under future climate changes. On average, manure management BMPs reduced RnF and CFs over time by 11and 5%, respectively. Reducing CP to 14% reduced ammonia emissions on the 2000C farm by up to 10% over time, however, it resulted in an increase to total CF and WF, likely from changes in upstream processes from the baseline. Spring cycle milking and calving on the 1100OR farm reduced the WF, EF, and RnF over time by 6, 3, and 5% on average, respectively. Fall cycle milking and calving increased these footprints compared to the baseline and other BMPs. Both seasonal milking BMPs increased CFs. A significant finding of the study was that WFs were predicted to decrease over time on the 1100OR and 2000C farms, both of which were producing homegrown feed. Colorado is predicted to have significant water scarcity issues in the later part of the century, and these results show that the decrease in water availability will limit the dairy industries abilities to meet its production needs. Predicted footprint values for baseline and BMP scenarios were compared to studies that evaluated regional and national dairy production using IFSM, as well as life cycle assessment (LCA) findings that averaged US dairy production from many farms. Overall, this study predicts that BMPs can be effective in reducing environmental footprints of Colorado dairy farms, which may reduce the environmental impacts of the state's dairy industry. However, farms should be wary of one size fits all solutions and need to assess their goals, productivity needs, and feasibility before implementing changes to management practices.

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Lastly, I must offer an indescribable thank you to my friends and family, near and far. You have all provided unwavering support through this process and I truly would not have stayed sane without each and every one of you.

DEDICATION

I dedicate this work to all my furry, four legged friends and to Mother Earth who which we are all derived from.

"The earth does not belong to man; man belongs to the earth. All things are connected like the blood that unites us all. Man did not weave the web of life; he is merely a strand in it. Whatever he does to the web, he does to himself."

-Chief Seattle of the Duwamish and Suquamish tribes

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

Ruminant livestock are critical to the future of global and US food security. Much of the World's existing land is not arable for human food production, but is substantial for well-managed grazing land (Gill et al., 2010). Ruminant animals can convert pasture and other plant materials into high quality sources of nutrients for human consumption (Rinehart, 2008). Colorado's climate and ecology are particularly suited for well-managed beef and dairy production systems. However, regional changes in climate and the environmental costs of production pose challenges to continuing to meet this need in a sustainable way (Reeves et al., 2017; Derner et al., 2018). As Colorado is the largest producer of milk in the Northern Great Plains region (USDA ERS, 2019), impaired dairy productivity has significant economic, nutritional, and food security implications. To remain productive, dairy production systems must be resilient to external shocks.

The use of modeling and life cycle assessment (LCA) tools are beneficial for evaluating the environmental impacts of the Colorado dairy industry while also identifying areas in which production systems may be vulnerable to changes in regional climate. Studies in recent years have utilized LCA and a process-based farm model called the Integrated Farm Systems Model (IFSM) to assess the sustainability of US dairy systems on national and regional scales (FAO, 2010; Veltman et al, 2018; 2021; Rotz et al., 2009; 2019; 2020; 2021). Furthermore, IFSM has been used to evaluate Beneficial Management Practices (BMPs) that may be implemented to mitigate the environmental impacts of dairy production systems and improve sustainability of production into the future (Veltman et al., 2018, 2021)

Sustaining the future of the Colorado dairy industry depends on a myriad of factors, from consumer habits, regulations, and labor to natural resources and mitigation strategies. All of these variables will impact the profitability of dairy enterprises and their environmental footprints (reviewed by von Keyserlingk et al., 2013). The following work builds on the previous studies of Rotz et al. (2021) and Veltman et al (2018) to assess the environmental impacts and long-term sustainability of dairy production systems in northeastern Colorado. Objectives of this study were to:

1. Evaluate implications of climate change on resource use and environmental footprints of Colorado dairies through the 21st century using the Integrated Farms Systems Model (IFSM).

2. Identify and evaluate Beneficial Management Practices (BMPs) to assess the Colorado dairy industry's ability to remain sustainable and productive through 2100.

CHAPTER 2: LITERATURE REVIEW

2.1 Defining Climate Change

Defining climate change can be a contentious topic (Werndl, 2016) and often remains unclear. Choosing good definitions of climate change is important in order for science and policy sectors to best develop and implement adequate mitigation and adaptation strategies that support societal needs. In order to define climate change, one must understand the difference between climate, weather, and how the two interact. NASA defines climate change as “a long-term change in the average weather patterns that have come to define Earth’s local, regional, and global climates”. Weather is any atmospheric condition that occurs locally over a short period of time (e.g., days) and dictates day-to-day activity. The term climate is used to describe regional or global averages for variables such as temperature and precipitation over a long-term period (e.g., years). A result of climate change is global warming. Although climate change and global warming have been used as interchangeable, they are not the same concept or atmospheric process. Unlike climate change, global warming is a result of long-term heating to the climate from human activities in combination with natural warming (Shaftel, 2020). Global warming is driven by an increase in greenhouse gases (GHG). Naturally, GHG help to absorb radiation and trap heat to maintain Earth’s temperature (EPA, 2022). However, GHG from human derived industries such as burning fossil fuels, agriculture, and transportation lead to higher concentrations of GHGs being absorbed in the atmosphere, which leads to expedited warming, and climate change (EPA, 2022). Greenhouse gases that are caused by human activities are known as anthropogenic emissions (IPCC, 2018).

While climate change, global warming, and GHG are natural phenomenon in Earth’s atmosphere, researchers are pushing the existing definitions and terminology to encompass dangerous climate change, or that which is beyond biological norms and has potential to drastically disrupt human livelihood (Dessai et al., 2004). Definitions for dangerous climate change consist of external and internal definitions. External definitions tend to be derived from risk analysis of climate change that is performed by experts and identifies physical or social characteristics of a system. Internal definitions address real human dangers that are related to climate change (insecurity or lack of safety) and are recognized as being real through experience or perception of individuals (Dessai et al., 2004). It is important for climate change studies to consider both external and internal variables of a system to minimize the uncertainty of results and apply quantitative measures to qualitative realities.

In addition to a solid definition of climate change, our approach to addressing climate change through research and governance is equally as important. Analyzing climate change can follow two trajectories: top-down and bottom-up. Top-down approaches aim to quantify physical measures and vulnerabilities (e.g., natural resource availability) of systems to climate change. Bottom-up approaches focus on societal vulnerability to current and future climate change. A bottom-up approach can focus on both individuals and larger groups (Eicken et al., 2021; Gallup, 2018; Timilsina et al., 2019). These difference approaches support analysis of climate changes contributions and impacts on society and the environment.

2.3 Current Climate Change Trends

2.3.1 Global and US Climate Change

In the past century, average temperature has increased at a rate of 0.14°F per decade, with the bulk of the increase occurring in the second half of the century (Oudejans, 2016). Globally, there has been a steady rise in land surface air temperatures since the pre-industrial period because of increasing GHG emissions, land use, and deforestation. This increase in temperature and emissions has contributed to atmospheric warming, melting of glacial caps, and increased wildfire activity (Polley et al., 2013). Temperatures are predicted to increase continuously through the remainder of the century and will depend on the culmination of anthropogenic emissions (historical, present, and future), variability in weather patterns, and unpredictable changes in human emissions and habits (EPA, 2022a).

Like global trends, the United States is experiencing shorter cold seasons, longer bouts of warm and hot temperatures, and increased precipitation (Adler et al., 2018; Adler et al., 2017; Hoegh-Guldberg et al., 2018; Huang et al., 2017; Menne et al., 2018). Historically, average temperatures have been rising in the US since the 19th century with the majority of increases occurring since 1970. Annual average precipitation across the US has also been increasing for certain regions (Northeast, Midwest, and Southern Great Plains) since the late 20th century. Other regions (Southeast and Southwest) have experienced a mixture of increasing and decreasing average precipitation. While the frequency of heavy precipitation events may increase, total rain events are generally predicted to become less frequent. As a result, the amount of consecutive dry days between heavy rainfall will increase, which would lead to longer dry seasons and potential for drought. (Wuebbles et al., 2014).

2.3.2 Climate Change in the Western United States

The western United States is experiencing a shift in vegetation types, soil quality, increased temperature, and altered precipitation patterns (Polley et al., 2013). Warmer temperatures and changes in precipitation will impact national forests, presence of pests, severity and length of the wildfire season, and have negative implications for human health (Joyce et al., 2018; Oudejans, 2016). Increases in summer temperatures and decreases in summer humidity suggest an increase in wildfire activity throughout the West, with the most affected region being the Northern Rockies. It is predicted that by 2070, the length of wildfire season will have increased by 2-3 weeks (Barnett et al., 2004). With CO_2 emissions on the rise, the western region of the United

States may also experience warmer and longer growing seasons, increased climactic variability, more extreme weather events (Reeves et al., 2017).

One critical climate change impact in the West is the increasing lack of water availability (Sun & Myers, 2008). Naturally prone to drought, communities in the west rely on basins to store water from the mountains and deliver it to downstream users (Qin et al. 2020). Using downscaled climate projections to estimate how climate change may impact water and resource availability in the western United States, Barnett et al. (2004) predicted temperature increases of 1–2°C by mid-century (2050). Warming to this extent would result in reduction of mountain snowpack that communities rely on to replenish and maintain water availability through rivers and basins (Qin et al., 2020). Specifically, in Colorado, the reservoir system will be unable to keep up with demands. Reservoir levels will be reduced by more than 30% and allocation to municipal and agriculture needs by as much as 17% by middle of the century (Barnett et al., 2004). Colorado is required to contribute a certain fraction of water to inter-basin transfers between California and Nebraska, but if the state cannot meet its own demand there will be limitations to the ability to fulfill these transfers. Not only does this impact regional productivity, but it will have severe implications for the state to support the industrial, agricultural, and municipal sectors.

Among the western states, those that rely on the lower Colorado River Basins were determined as experiencing the greatest effects on water availability. Authors of this study wrote, "Basically, we found the full allocated Colorado system to be at the brink of failure, wherein virtually any reduction in precipitation over the basin, either natural or anthropogenic, will lead to failure to meet mandated allocations" (Barnett et al., 2004). Effects of warming have already been observed through changes in earlier melting mountain snowpack and spring runoff in

Western states (Dettinger et al., 2004; Qin et al., 2020; Stewart et al., 2004). In 2015, ~600 million people were living in areas dependent on basins where 10–50% of annual stores come from snowmelt (Qin et al., 2020). The number of people relying on basins are more concentrated in the Western United States, making snowmelt runoff a vital source of water for food and animal production.

Qin et al. (2020) looked at the world's dependence on snowmelt runoff for irrigation in agriculture. Their study used the San Joaquin basin in California as an example of how the majority of runoff occurs during winter months when the demand for water is at its lowest (e.g., when water is not needed to irrigate crops). In spring, water demand for irrigation increases and is almost entirely met by the accumulated snowmelt runoff. By summer, irrigation rates are at their highest and water demand is met entirely by basin stores and transfers. The ability of these sources to provide water for irrigation is not sustainable in the long run because current basins that supply inter-basin transfers (i.e., Colorado to California) are losing storage capacity and the ability to meet their own water needs (Barnett et al., 2004).

Basins in the west were simulated under two scenarios: 2 °C and 4 °C warming. Under both simulations, average snowmelt decreased, and runoff shifted towards early spring, which decreased or eliminated snowmelt runoff available for summer irrigation. For some simulations, rainfall runoff (warm-season precipitation) increased in magnitude although timing of precipitation did not change. It is possible that the increased rainfall runoff could be used to compensate for declines in snowmelt runoff (Qin et al., 2020). A caveat of the study findings is that water demand was kept static under both warming scenarios. This is not necessarily realistic because water consumption has been projected to increase due to rising population, temperatures, and irrigation expansion. As a result, the predicted increase in demand for alternative water sources reported by the study are likely conservative compared to future reality. The findings of these two studies emphasize the absolute importance of shifts in water management and use in Colorado and surrounding western states. Without adaptation, many of our systems, specifically agricultural systems, will not be viable in the long term, which may lead to disastrous outcomes for the sustainability of patrons in the region.

While global and regional changes in climate and weather trends are of concern, impacts of nitrogen loss are of special concern in the western region of the United States. Of all the states in the West, California has the highest rates of ammonia emissions followed by Colorado (EPA, 2011). Nitrogen deposition rates range from 1-4 kg/ha/year in most of the western region, however, in some areas rates can be as high as 90 kg/ha/year (Fenn et al., 2003). These values include wet and dry deposition and are influenced by proximity to urban areas and agricultural development (Fenn et al., 2003; Wetherbee et al., 2019). By 2050, nitrogen deposition rates are expected to increase as much as 66% (United Nations, 2015). Increases in N will impact water and air quality of the West, increase presence of noxious weeds, deplete soil quality, create nutrient imbalances for plant species, and cause soil acidification (Clark et al., 2013) . The ramifications from the effects of climate change will impact the West's future for many industries, and will make it especially hard for continued productive success and sustainability of agricultural systems in the region.

2.2 Climate Modeling

Although effects of climate change will differ based on location, the frequency of warm spells, heat waves, and heavy rainfall are projected to increase worldwide through the end of the century (IPCC, 2007). These effects will impact availability of resources such as water and land, leading our ecosystems to develop specific climate vulnerabilities. To determine how the climate will continue to change, vulnerabilities that may develop, and proper adaptation, we rely on climate projections. Climate projections are generated using a combination of theoretical models, observations, and climate data from the past and present to represent future scenarios. Projection outputs represent temperature increases, rising sea levels, ice loss and glacial melt, frequency, and severity of changes in extreme weather events, and precipitation (Shaftel, 2020). In 1992, the IPCC created six scenarios to represent the trajectory of emissions from 1990-2100. By evaluating multiple scenarios, the panel was able to decrease uncertainty surrounding the role of anthropogenic emissions in climate change. Each model represents a different approach to simulating emissions and integrates either a top-down, bottom-up, or combined framework (IPCC, 2000).

In addition to the IPCC emissions scenarios, researchers also use general circulation models (GCM) to predict the impacts of climate change. General circulation models have been around since the late 1980's and provide weather files based on large-scale climate conditions (Leung et al., 2003). Multiple GCMs can be used in conjunction with one another for climate research to reduce uncertainty and provide more specific weather pattern data for impact assessments of climate change (Semenov & Stratonovitch, 2010). Further development of GCMs has included increased resolution to fill the gap between global and regional models. Now, GCMs provide both large-scale climate conditions to downscale while also generating regional climate information (Leung et al., 2003).

2.2.1 Downscaling Climate Projections to Regional Scales

Downscaling is when information that is available at large scales is used to make predications at local scales (Simonovic & Gaur, 2010). This technique is used to translate data from GCMs to, "be better utilized by regional and local stakeholders to address their specific needs," (Lanzante et al., 2020; Li et al., 2010; Pourmokhtarian et al., 2016; Wootten et al., 2021). General circulation models mathematically represent a variety of physical processes in a climate system (Trzaska & Schnarr, 2014), and are vital for climate change research and projections. However, it is difficult to understand changes at regional and local scales using global-scale data. Global-scale models can represent large-scale features that determine climate and climate change over a smaller area or region (e.g. the western United States), but these models cannot give the precision of detail needed to simulate accurate hydrologic responses on a finer scale. General circulation models are also unable to represent effects of mountainous terrain on local and regional climate variability. As a result of the pitfalls of GCMs being used to predict local climate change these simulations must be downscaled (Barnett et al., 2004). There are two methods for downscaling: dynamical downscaling (DD) and statistical downscaling (SD) (Lanzante et al., 2018). Dynamical downscaling allows for simulation of climate mechanisms, is continually advancing, and encourages collaborations between disciplines, while SD builds on the shared statistical expertise of researchers and allows for the assessment of specific climate results over a range of GCMs (Patz & Holloway, 2005). Statistical downscaling is more widely used for downscaling, as it requires fewer resources.

Downscaled datasets are created by combining a GCM with a representative concentration pathway (RCP). The RCPs are greenhouse gas concentration trajectories that were adopted by the International Panel for Climate Change (IPCC). Four pathways have been identified: 2.6, 4.5, 6.0, and 8.5, and are expressed on CO_2e basis. Each RCP describes a different climate future that is possible based on the volume of the GHG emitted in future years (Table 2.1). Pathways are labeled after the possible range of radiative forcing values through the year 2100 (Figure 2.2) (IPCC, 2014) and describe specific emissions trajectories (Wayne, 2013). Globally, the average temperature increase across all RCPs is 0.3-4.8 °C.

Table 2.1. Overview of IPCC Representative Concentration Pathways (RCPs). Trends are describing when emissions peak, taper off, or decline for each emissions scenario (Wayne, 2013).

RCP	General (Moss et al., 2010)	CO_2 equiv. (ppm) (Moss et al., 2010)	Projected temp. increase (°C) by 2065 (IPCC, 2014)	Projected temp. increase (°C) by 2100 (IPCC, 2014)
2.6	Peak and then decline	1370	0.4-1.6	0.3-1.7
4.5	Stabilization after mid-century	850	0.9-2.0	1.1-2.6
6.0	Stabilization after mid-century	650	0.8-1.8	1.4-3.1
8.5	Continued rising without stabilization or decline	490	1.4-2.6	2.6-4.8

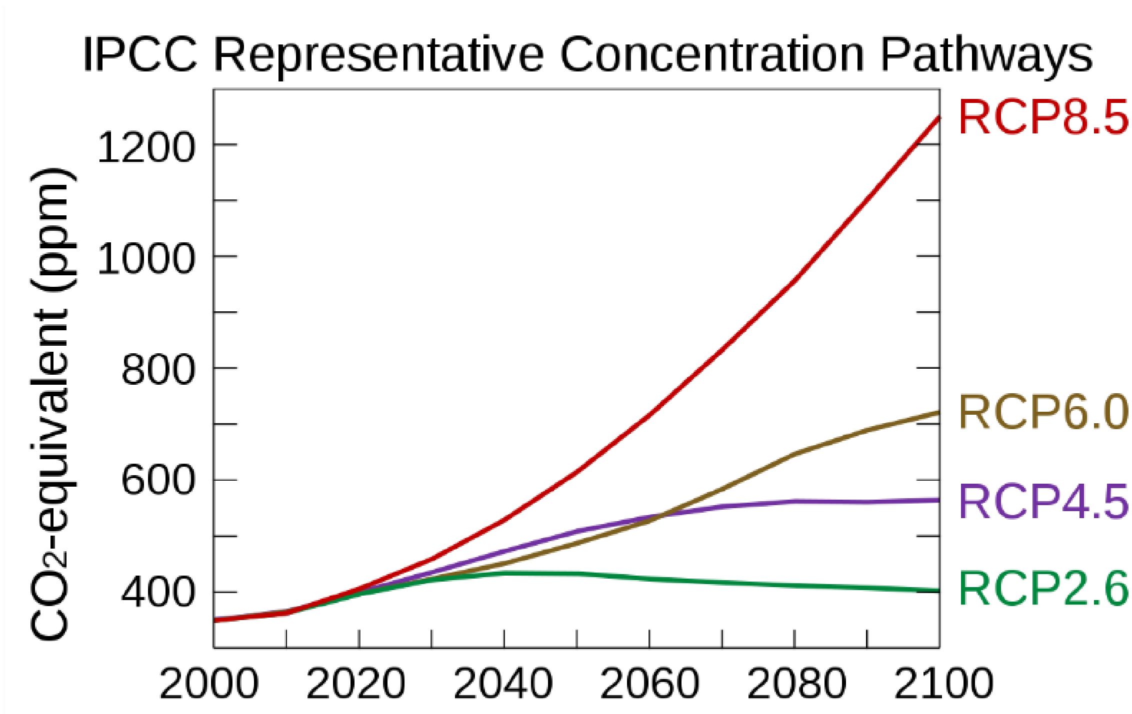


Figure 2.1. Radiative Forcing for each RCP through 2100 (IPCC, 2014).

While downscaling aids in bringing global projections down to a finer resolution for local contexts, there are some limitations to the methodology that researchers should consider. First, since downscaling relies on assumptions and approximations about local climate and weather conditions, uncertainty of data are inevitable. Data that are inputted to the GCMs can be obtained from a variety of sources and only reflect a resolution between 250 to 600 km, 10 to 20 vertical layers, and up to 30 layers in the oceans, which all impact the accuracy and specificity of the downscaled data (IPCC, 2022). Second, different statistical downscaling methods exist for different emissions scenarios and climate projections, so it is critical understand the nuances that exist, and which approach best suits a study's objective(s) (Lanzante et al., 2018). Downscaled climate data and climate change projections are the basis for evaluating the environmental impacts of different systems, and how specific industries may contribute or be vulnerable to climate change, and areas of resilience or adaptation for future production.

2.4 Environmental Impacts of Livestock Production Systems

Based on a review done by Knapp et al. (2014), agriculture and land use, meaning livestock and crop production plus the land required to maintain the industry, currently contribute 22% of global anthropogenic GHG emissions. On a national basis, agriculture is responsible for 11% of total GHG emissions (EPA, 2022b) More specifically, United States livestock systems are assumed to contribute 3% of total emissions (EPA, 2022). Of this, about half of the emissions are derived from animal and manure emissions (EPA, 2022). Global populations are predicted to increase through the mid-century, which will require an increase in food production while simultaneously reducing food waste (Fedoroff, 2015) and GHG emissions (EPA, 2022). Livestock production practices are viewed as being generally wasteful because of their high requirements for feed, water, and land, which adds to the public perception of livestock production being negative because of side effects that can be detrimental to the climate, biodiversity, and the environment (Leroy et al., 2022). Environmental impacts come from greenhouse gas emissions, changes in water and air quality, and increased presence of insect vectors and pathogens (Mbow et al., 2019).

2.4.1 Greenhouse Gas Emissions

Greenhouse Gas emissions include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Each gas has individual global warming potentials (GWP), which is the measure of energy 1 ton of gas will absorb over a given period of time (EPA, 2022b). Global warming potentials are most commonly calculated over 100 years (EPA, 2022b). Furthermore, GHG emissions can impact air and water quality, algal blooms, eutrophication, deterioration of ecosystems, and decline in overall soil health (Capper & Cady, 2020, p. 2020; Eshel et al., 2014; Gerber et al., 2013; Milani et al., 2011; Oudejans, 2016). Different regions and production systems will vary in emission intensities and quantities. Emissions from livestock are both direct and indirect. Direct emissions come from enteric fermentation from cattle and manure wastes, while indirect emissions come from animal feed production and post-harvest activities (Gerber et al., 2013).

Carbon dioxide (CO_2) is the main gas responsible for the increases in the greenhouse effect (EPA, 2022). It is consistently reported as the most significant GHG to mitigate because it makes up the greatest number of emissions from human activities, also known as anthropogenic emissions (EPA, 201). Sources of anthropogenic emissions include combustion of fossil fuels from the energy industry, agriculture, land-use change, and waste management. CO_2 has a lower GWP than any of the other main GHG, however, what makes it harmful is that it stays in the atmosphere for hundreds of years. This long residence time causes atmospheric concentrations and global warming conditions to increase, which have lasting effects for thousands of years (EPA, 2011). Specific to livestock, much of the CO2 emissions come from feed production, manure, and microbial fermentation in ruminant animals. Machinery use on farms and transportation of livestock also contributes to the amount of CO2 emissions from the livestock industry.

Methane is the second most potent greenhouse gas contributing to global warming (EPA, 2015). It is derived from atmospheric carbon and is part of the biogenic carbon cycle. Its GWP is 84-87 times more than CO_2 over a 20-year timeframe and 28-36 times more than CO_2 when considered over a 100-year time frame (EPA, 2015). CH_4 has an atmospheric residence time of 9-12 years (IPCC, 2017; EPA, 2015) before being converted back to CO_2 and contributing to global warming indirectly. In 1992 methane was predicted to cause 15-17% of global warming over the next 50 years (IPCC, 1992). Today, methane emissions account for 10% of greenhouse gases. Of that portion, roughly 40% comes from manure management and enteric fermentation (EPA, 2015). Globally, Brazil, China, India, the EU, and US have the largest livestock associated CH_4 outputs. CH_4 outputs from the livestock sector consist of manure CH_4 and enteric CH_4. Among the top five countries, the US is last in its total CH_4 production, however, they are second behind the EU for their CH_4 outputs derived from manure (EPA, 2011). This indicates that while the United States has worked well to increase efficiency and minimize total GHG outputs on farms, there is still room for improvement in our manure management practices.

Nitrous oxide is known as the most potent GHG and contributes to global warming and ozone depletion (EPA, 2015). N_2O results from denitrification of N. Denitrification occurs when nitrate and nitrite are reduced to a gaseous form via microbial processes. N_2O has a GWP that is 273 times more than CO_2 for a 100-year timescale (EPA, 2022b), which can have serious implications for semi-arid and arid western regions (Holly et al., 2018).

2.4.2 Water and Air Quality

The main contributing livestock industries to water and air quality are red meat, dairy, poultry, and egg producers (Eshel et al., 2014). Hribar & Schultz (2010) describes how excess manure, inadequate storage, or management can impact ground and surface water quality. Animal agriculture can contaminate groundwater via manure application, leaching, or through leaks and breaks in the manure storage systems (Hribar & Schultz, 2010). Contaminated groundwater stores can lead to contaminated surface water by lateral movement of water into the surface water stores (Spellman & Whiting, 2007). Different sources of N have been found in surface waters near concentrated animal feeding operations (CAFOs) with nitrates and ammonia being the most common and concentrated (Hribar &. Schultz, 2010). NH_3 will cause depletion of oxygen levels in water, which disrupts aquatic ecosystems and kills marine life, and if excess N and P enters surface water from CAFOs, nutrients will build up and result in eutrophication (Hribar & Schultz, 2010). Eutrophication makes waters inhabitable for aquatic life and is detrimental to ecological balance of marine ecosystems (Hribar & Schultz, 2010). NH_3 also pollutes groundwater through N runoff, because NH_3 that is present in groundwater stores can undergo denitrification and further contribute to emissions of N_2O in the atmosphere (EPA, 2010; A. Hristov et al., 2015).

CAFOs can also be responsible for reduced air quality in surrounding areas. The primary cause of decreased air quality is from gaseous emissions from animal manure. The type and rate of emissions depends on how much manure is being process, what state it is in (liquid, slurry, or solid) and how much it is treated or contained after excretion. Emissions are also cause by land application of fertilizers and the general processing of land. Emissions are highest immediately following manure application and then again later after substances or additives have been broken down in the soil. The most typical air pollutants from CAFOs are NH_3, hydrogen sulfide, CH_4 and fine particulate matter ($PM_{2.5}$). Each pollutant has individual impacts on human health and the environment, which can be hazardous (Hribar & Schultz, 2010).

A study by (Domingo et al., 2021) looked at ways to quantify air quality related deaths from $PM_{2.5}$ released by livestock production systems. Primary $PM_{2.5}$ was that directly emitted from the farm and animals. Secondary $PM_{2.5}$ was what was formed in the atmosphere by GHG. It was found that most air quality damages are driven by NH_3 emissions from fertilizer and livestock waste. Degraded air quality can create severe health hazards for humans. United States agriculture is responsible for 17,900 air-quality related deaths, 15,900 of which are directly related to food production. Of the 15,900, 80% can be attributed to animal production (Bauer et al., 2016; Goodkind et al., 2019; Lelieveld et al., 2015; Stanaway et al., 2018). It was concluded that changes in feed practices (e.g., reduce the amount of excess protein ingested to lower amounts of excreted nitrogen) or use of fertilizer amendments are great ways to reduce the negative contributions of animal production to air quality (Domingo et al., 2021).

2.4.3 Insect Vectors and Pathogens

Animal production systems and CAFOs are avid breeding grounds for insect vectors. Common and most abundant species consist of houseflies, stable flies, and mosquitos. While flies are mostly a nuisance to both humans and animals, mosquitos can carry zoonotic diseases that can infect humans and animals alike. Additionally, animal manure is a major source of pathogens. Pathogens are classified as parasites, bacteria and viruses that infect humans or animals and cause harm. Sources of transmission are through fecal-oral contact, inhalation, drinking water, and incidental consumption of contaminated water. The transfer of pathogens among animals is higher in confinement operations because there are more animals in a smaller space (Hribar, 2010). The increased present of insect vectors and pathogens will impact livestock industries, human communities, and ecosystems.

2.5 Environmental Impacts of U.S. Dairy Production Systems

As of 2019, the number of dairy cows in the US was estimated to be 9.35 million and total milk production was 99,056 Gg of milk (USDA-NASS, 2020). When it comes to climate change and environmental impacts, dairy production systems are seeing quite a bit of attention from consumers and policy makers. Dairy production has a wide variety of environmental concerns and contributions, both locally on soil, water, and air, and globally through GHGs and energy use (C. A. Rotz, Stout, et al., 2020). Globally, the dairy sector contributes 4% of the total anthropogenic GHG emissions (FAO, 2010) with the US dairy industry contributing to approximately 1.9% of the total GHG emissions (Thoma et al., 2013). Anthropogenic emissions are those associated with milk production, processing, transportation, and emissions from culled animals. Primarily, GHG emissions from the dairy sector consist of nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) (Rotz et al., 2009; Veltman et al., 2018). Most GHG emissions associated with milk production are emitted directly from cattle through enteric mechanisms and their manure (Martin et al., 2017).

Ammonia (NH_3) is another form of gaseous N, which has emissions that are also a growing concern for the dairy industry. It is not considered a GHG, but still has negative ramifications for the environment (TEAGASC & AFDA, 2020). Ammonia is a volatile gas that is released into the atmosphere, subsequently reducing the amount of available N in manure that may be transported to soil. In contrast, the ionized form of ammonia, ammonium (NH_4^+), makes up a large portion of N concentrations in manure. Ammonium results from decomposition of urea by the enzyme urease after urine is released on barn floors and pastures (Lupes et al., 2010). Manure that is harvested from barn floors will retain urine, thus resulting in urea conversion to NH_4^+ during storage and application. Impacts of NH_3 and NH_4^+ include changes in biodiversity, soil acidification, and altered susceptibility of plants to frost, drought, and pathogens (Guthrie et al., 2018).

Nitrates (NO_3) and nitrites (NO_2) are also important forms of N in agriculture, and like NH_3 are not a GHG but still have significant environmental impacts. Both occur naturally in soil, water, and air, and are required for a myriad of organisms and species to live and grow. They have been adapted by the industry to be used as a main source of fertilizer for crops, however, nitrates tend to be more common (Powlson & Addiscott, 2005) NO_3 contributes to N loss from manure via leaching and contributes about 10-30% of total loss (Rotz, 2004). NO_3 leaching has been found to contaminate ground water stores, which impact fish habitats (Levit, 2010) and other ecosystems that rely on groundwater. Furthermore, accumulations of NO_3 result in hot spots of NO_2 where groundwater feeds into surface water supplies (Loick et al., 2017).

In dairy systems, the main source of N_2O is manure, and accounts for 2-5% of on farm N loss (Rotz, 2004). Nitrogen lost in the form of NH_3 accounts for 30-40% of total farm losses (Rotz, 2004). It has been estimated that approximately 25% of N inputs on a dairy farm cannot be accounted for in manure or milk production within 24h of excretion from animals. Most of this loss was attributed to NH_3 volatilization (Hristov et al., 2011). Other research has also found substantial linkages of nitrogen losses from dairy operations that contaminate surface water (Harter et al., 2013; Vadas et al., 2015). Nitrogen emissions and losses from dairy production systems can have negative impacts on surrounding ecosystems, communities, and the environment.

The dairy industry is a large contributor to carbon emissions, specifically through concentrations of CH_4. Dairy makes up 50% or more of total annual methane emissions on a global scale (FAO, 2010). Enteric fermentation is the largest source of CH_4 from dairy farms

(Chianese et al., 2009b). Methane emissions occur when microbes in the rumen, known as methanogens, convert cellulose to CH_4 to be used as energy (Buan, 2018). Methanogens work to decrease the amount of hydrogen in the rumen by converting CO_2 to CH_4. The CH_4 gas is then emitted into the atmosphere through eructation or belching (C. A. Rotz et al., 2018). How much CH_4 is released because of enteric fermentation depends on breed and size of animals, digestibility, DM intake, and total carbohydrates present in a ration (Chianese et al., 2009a). On average, cattle produce anywhere between 250 and 500 L of CH_4 and are losing approximately 6% of ingested energy through eructated methane daily (Johnson & Johnson, 1995).

Methane emissions from the dairy sector vary regionally and by management practice. For example, pasture-based and extensive dairy operations have higher rates of CH_4 emissions per kg of milk. This is because of the low digestibility of grasses compared to intensive operations that feed higher amounts of grain and silage. Comparatively, intensive operations have higher emissions associated with manure storage. Manure storage makes up roughly 15-20% of CH_4 emissions on intensive dairies compared to less than 5% on extensive ones (FAO, 2010).

Manure is valuable for fertilizer, but the amount produced on dairy farms is becoming unmanageable and problematic. Many livestock operations no longer grow all their own feed so the excess manure cannot be applied to their land. Overapplication of manure results in soil that is saturated with macronutrients that are subsequently leached (Burkholder et al., 2007). Furthermore, manure contains a plethora of potential contaminants. Growth hormones, antibiotics, chemical additives, animal blood, silage leachate, copper sulfate from foot baths, N, and P can all leach out of manure into the soil and water stores causing contamination. The most pressing environmental and public health related issue to animal operations is manure, the amount produced, and the implications on the environment through GHG emissions and leaching (Hribar, 2010).

The dairy industry will inevitably be faced with the decision to adapt management innovations that enhance feed production and efficiency of cows. These adaptations will be necessary because of multiple food security (human and animal) and environmental issues associated with dairy and other agricultural production systems. Increasing populations are going to increase demand for dairy products. The industry will need to determine how to properly manage production to meet the needs of society while simultaneously combatting against temperature and moisture changes, soil quality concerns, competition for land, and the overarching need to reduce on farm footprints, namely carbon and water (Martin et al., 2017). One solution to combatting these challenges and creating more sustainable dairying is to increase the number of pasture-based systems in the United States. The downfall to this solution is that while populations of dairy herds have been growing to meet the increased demand of dairy products, conventional practices have also increased the need for imported feeds. Dairy farms are predominantly intensive and confined with large herd sizes and do not always have access to the land required to grow their own feed and recycle waste (USDA & NRCS, 2007; von Keyserlingk et al., 2013). Finding land that is both affordable, viable, and capable of supporting the dairy herds of the country will be the first hurdle to overcome if extensive dairying is to become the norm.

2.5.1 Life Cycle Assessments to Determine Environmental Impacts of the Dairy Industry

To properly quantify the environmental impacts of dairy production and to recommend reasonable mitigation strategies, recent science has aimed to evaluate the impacts of dairy production systems, how significant they are, and how to mitigate consequences. Research has shifted towards using life cycle assessments (LCAs) of operations to further evaluate environmental impacts of livestock. The purpose of an LCA is to provide insight to environmental footprints and economical parameters of a system from cradle to grave (Muralikrishna & Manickam, 2017). LCAs assist researchers in identifying the imbalances and parts of a system that can be improved through providing a whole farm analysis that addresses the nuances of different systems. Furthermore, LCAs address interaction of different components within a system that may not be identified when analyzing components individually (Rotz et al., 2010). In recent decades, LCAs have become increasingly popular for assessing the environmental impacts of dairy systems.

Globally, LCAs have determined that dairy production systems have total carbon footprints anywhere between 1 to 7.5 kg CO_2e/kg FPCM, with the average footprint around 2.5 kg of CO_2e/kg FPCM (FAO, 2010). This LCA done by the Food and Animal Organization (2010) was a follow up to their larger work, *Livestock's Long Shadow*. The analysis included all animals related to milked cows (replacement animals and surplus calves sold for meat), but excluded land use under constant management practices, capital goods such as farm equipment and buildings, on-farm milking and cooling, and retail stage activities such as refrigerating and disposal of milk products. Further results of this study found that the cradle to farm gate portion of the LCA of dairy production is responsible for 93% emissions associated with the dairy supply chain. It is recommended that LCAs continue to be used for future analysis of the environmental impacts of dairy production because they provide a holistic visual of the farm system, which can better influence decisions regarding management (FAO, 2010).

Several LCAs have been conducted to determine the environmental impacts of US dairy production systems. Thoma et al., (2013) conducted a cradle to grave LCA to help identify opportunities for producers, processors, and consumers to contribute to long-term sustainability of the dairy supply chain and industry. Results of this study were similar to the global findings of the FAO report (2010). The analysis looked at dairy supply chains nationwide and found that majority of emissions were being released from cradle-to-farm gate versus during retail and consumptions. For the dairy supply chain, the cumulative GHG emission is 2.05 kg of CO_2e/kg milk consumed. Of this, 72% of the emissions are released at the farm gate. Sources of these emissions include crop production (on farm and imported feeds) manure storage, processing, and application. While aspects of retail and consumption contribute to the environmental footprints of the dairy supply chain and are important to consider, these findings call attention to the opportunities available to dairy producers to improve management practices.

A LCA conducted by (Rotz, Stout, et al., 2020) looked at regional impacts of dairy farms in Pennsylvania. The researchers divided the Northeast state up into seven regions and simulated representative dairy farms for each region using the Integrated Farm Systems Model (IFSM). Through the modeled simulations, they found that environmental footprints varied widely from region to region with the state. Variation was the result of differing soil characteristics, climate, and farm management. Initially, it was hypothesized that environmental footprints from the different dairy farms would mirror estimates for the entire state, however, it was found that GHG emissions, energy use, and blue water use associated with dairy farms in each region were less than overall total estimates for the state. These findings highlight the opportunity to focus on other aspects of the dairy system, such as ammonia emissions (Rotz et al., 2020), where values may represent a higher contribution to total emissions.

A second study by (Rotz et al., 2021) took the methodology of the Pennsylvania analysis and used it to complete an environmental assessment of dairy farms throughout the United States. The study used the same framework and divided the US up into six regions: Northwest, Southwest, South Central, Midwest, Southeast, and Northeast. To complete an accurate assessment of the dairy industry, the system boundary was defined as: anything that enters or leaves the farm is relevant and must be considered. Results for each region were compared to total GHG estimates reported for the US. Like the LCA conducted for Pennsylvania dairy farms, results showed that environmental footprints varied from region to region. Each region has differing climates, soil characteristics, natural resource availability, and access to imported resources. It was concluded that steps can be taken in each region to minimize environmental impacts of dairy production, however, they must be specific to individual farms and determined on a place-to-place basis (Rotz et al., 2021).

Belflower et al., 2012 looked at the differences of environmental footprints between pasture based and confined dairy farms in Georgia. The study found that pasture-based systems had higher amounts of CH_4 emissions compared to confined systems because of fermentation of different feeds (grass vs. grain). When looking at N_2O at CO_2 emission on the two farms the confined system had higher emissions rates compared to the pasture-based system because of fuel combustion. Furthermore, the pasture-based system had lower net CO_2 emissions and a significantly higher potential for carbon sequestration. The carbon sequestration potential for the confined system was zero (Belflower et al., 2012). A study by Rotz et al. (2010) aimed to evaluate the total farm carbon footprint of dairy production systems using a partial LCA. In the study, six farms were evaluated: four from central Pennsylvania and two from southern California. Overall, larger farms that used confined housing systems versus pasture-based or small farms had lower total emissions, but distribution of emissions differed based on individual farm management practices.

Yan et al., 2013 used LCA to analyze how land use for milk produced on commercial farms impacted the carbon footprint of dairy operations. Input data for the LCA was gathered from eighteen commercial dairy farms in Ireland that all utilized different land management tactics for on farm feed growth and animal support. While there was large variation in management tactics the carbon footprints only differed by 13% for land use and 18% for milk production. The average CF for land use and milk production was 1.23 kg CO_2e and 1.22 $m^{\wedge 2}$/kg of FPCM. Results concluded that combining different land use management tactics were correlated to the farms CFs, amount of land used to meet the farms needs was not the causation of higher or lower CFs.

A recent cradle-to-farm-gate LCA done by Capper and Cady (2020) aimed to compare the environmental impacts of the US dairy cattle industry from 2007-2017. The researchers modeled herd demographics, metabolism, typical management practices, production data, and nutrient requirements of dairy cattle in the US to estimate LCA inputs that were representative of the entire nation during the 10-year time. As hypothesized, dairy farms in 2017 had reduced resources per one million metric t of FPCM compared to those in 2007. In 2017, cattle use, feedstuffs, land use, and water use were reduced approximately 25%, 20%, 20%, and 30%, respectively. GHG emissions were reduced by approximately 20% for both CH_4 and N_2O between 2007 and 2017. While the dairy industry has made great strides to improve contributions to climate change and environmental impacts while continuing to increase milk production, the results of this LCA found that total GHG emissions only decreased by 1% during the 2007-2017 decade. Authors applaud dairy producers for what progress has been made but call on continued demonstration of the commitment to improvement of industry (Capper & Cady, 2020).

Based on the literature, it is apparent that the use of LCAs is one of the most holistic ways to determine the environmental footprints of the United States dairy industry. Furthermore, LCAs have proven to be a beneficial way to address mitigation practices within the dairy industry through the ability of identifying individual needs of operations. Doing so allows researchers, producers, policy makers, and other stakeholders to prescribe place-based strategies at the farm level rather than enforcing uniform practices across a region, state, or country.

2.5.2 Implications of Climate Change for Dairy Production Systems

It is certain that agriculture is contributing to climate change, however, the effects of our changing climate on specific agriculture systems is becoming more apparent. Changes in temperature, precipitation, growing seasons, and natural resources have the potential to drastically impact capabilities of dairy systems to reach future demands. Cows may begin to experience heat stress from higher temperatures, which results in reduced productivity and lower rates of weight gain and conception (Ortiz-Colón et al., 2018). Shorter cold seasons also reduce the period necessary for vector bugs and parasites that impact dairy cattle to go dormant. As a result, they will not be killed off as quickly and are able to migrate further North to inoculate new populations and will negatively compound to impact cattle operations (Polley et al., 2013). Furthermore, cost of production is also likely to increase because of climate change. These increases will be most prevalent in costs of purchased feed and medical treatments but may also impact cost of reproduction and other agricultural resources in the supply chain (Godde et al., 2021).

Climate change has implications on feed production, and subsequently feed availability. While there are some regional benefits to a warmer climate such as longer growing seasons or better growing conditions for certain pasture species and crops (Hristov et al., 2018) potential ramifications include desertification, reduced crop yields, and increased prevalence of pathogens or diseases that are currently limited by cold weather (Godde et al., 2021). Wuebbles et al. (2014), found that rainfall events have become less frequent and more concentrated, which may cause a greater reliance on irrigated lands and drought resistant technologies. It is predicted that by 2030 the total area of irrigated crops in the United States will increase be ~16% (Qin et al., 2020). However, water available for irrigation in the future may be scarce (Wuebbles et al., 2014; Qin et al., 2020). This combined with projected decreases in precipitation and water availability will have drastic impacts on producers' abilities to support current demands for yield and quality (Martin et al., 2017).

Water use is not high on dairy farms, but the industry is heavily reliant on imported feeds that require high amounts of irrigation. Irrigation is a beneficial and effective way to combat changes from increased temperatures, precipitation, and lengthened dry spells occurring because of climate change. However, some states, such as Colorado, are seeing implications of climate change on water availability outside of rainfall (Barnett et al., 2004; Qin et al, 2020; Troy et al., 2015, Deines et al., 2020). Therefore, when growing feed, dairy systems and feed operations supplying the dairy industry should be cautious when using irrigation to mitigate changes to plant growth and yields (Troy et al., 2015).

(Deines et al., 2020) modeled future irrigation losses and resulting land changes in systems that rely on the Ogallala, or High Plains, aquifer in the West. By 2100, 24% of currently irrigated lands in the High Plains aquifer region may be unable to support irrigation demands, therefore making the land unable to support current irrigation crop needs of the dairy industry in Northeast Colorado. A portion of land may be transformed into dry land crop production, however, 13% of the 24% will have too low of soil quality and will only be viable for dry land pasture. If there are no changes to feed production in agricultural industries, the High Plains aquifer will lose 40% of water available for irrigation by 2100 (Haacker et al., 2016).

Certain species, such as C3 plants (pasture grasses, small grains, and soybeans), may benefit from rising temperatures and CO_2 levels because they demonstrate improved water efficiency which makes them less vulnerable to changes in precipitation (Morgan et al., 2003). However, other species, such as C4 plants, do not demonstrate this beneficial adaptation to changes in climate (Taub, 2010). Corn is a C4 plant, and a crop that the dairy industry is heavily reliant on as a source of silage and grain. Both C3 and C4 plants are vulnerable to increasing temperatures, which has the potential to speed up crop maturation, resulting in intensified lignification and reduced digestibility and nutritional values (Van Soest, 1982).

It will becoming increasingly difficult for cropping systems to remain sustainable with limited diversity (Martin et al., 2017). Monocultures or simple crop rotations will not be able to withstand unpredictable and varying weather. With water availability projected to further decrease, the water needs of water intensive plants will not be met, therefore reducing their availability as a feed source for dairy cows (Troy et al., 2015). However, it has been predicted that we will need to increase crop production to meet growing food needs, especially in areas where irrigation is required to sustain production (FAO, 2017; Hunter et al., 2017). Sanderson et al. (2005) suggests that grasslands will be an important technique for diversifying crop systems to make them more sustainable long-term. Grasslands are easier to manage overall and require less water and nutrient inputs (Stockin et al., 2006). Other practices for increasing the sustainability of cropping systems include use of perennial crops, cover cropping or intercropping, alternative forage or grain crops, composition of dairy cow diets, and genetic modification to make plants more resilient to the effects of climate change. Dairy cows can successfully produce current standards of milk (~80-90/lbs for a high producing animal) with alternative grain and forage species as well as on grasslands (Distel et al., 2020; Undersander et al., n.d.; USDA & NRCS, 2007). For the dairy industry to remain successful farmers will need to stop transitioning to alternative feeds sooner rather than later.

A study done by Reeves et al. (2017) evaluated projected impacts of climate change on Western U.S. Rangelands through 2100 in attempt to identify sources of vulnerability to cattle operations that rely on rangelands in the region. Four indicators of vulnerability were assessed in seven regions of the West: forage quantity, vegetation type trajectory, heat stress, and interannual forage variability. The seven regions included the Northern Great Plains, Southern Great Plans, Desert Southwest, Southwest, Eastern Prairies, Pacific Southwest, and Interior West. Results determined that forage quantity generally increased in Northern regions, vegetation shifted from woody plants to grassier vegetation types, the number of heat-stress days as early as 2020-2030, and a higher interannual variability for forage quantity. All seven regions displayed increased vulnerability through the 21st century, however the Southwest and Desert Southwest had that greatest increase (Reeves et al., 2017). The projected increase in vulnerabilities from this study have the potential to negatively impact dairy production systems in the Western U.S., and in the Northeast region of Colorado.

Current and future climate change poses challenges for the dairy industry to continue meeting society's needs in a sustainable and efficient way. The dairy industry is experiencing increased risk of developing climate vulnerabilities that further stress dairy systems and the environment. The future of dairy and cattle production depends on a myriad of social, economic, and management factors, however it is ultimately controlled by the environment (Reeves et al., 2017).

2.6 Beneficial Management Practices

One way that dairy producers have begun to combat climate change and build resilience within their systems is through the implementation of Beneficial Management Practices (BMPs). BMPs are specific techniques that help producers manage their land and animals to mitigate pollution of air, water, and contributions to climate change (*Best Management Practices*, 2020). Some BMPs are low tech and easy to implement while others require significant financial investments and changes to infrastructure (Sharvelle & Loetscher, 2011). To date, dairy farm BMPs have considered a myriad of inputs for mitigating the industries environmental impacts. They include, but are not limited to, manure management (handling and application), diet manipulation, waste management (e.g., anaerobic digestion), pasture-based systems, and overall nutrient management (Veltman et al., 2018; Veltman et al., 2021; Sharvelle & Loetscher, 2011; Hribar & Schultz, 2010; Waskom & Davis, 1999).

Two studies done by Veltman et al. focused on the potential for success of BMPs in the dairy industry. The first, done in 2018, looked at two farms (1500 and 150 head) in the Great Lakes Region of the United States. Each farm was simulated using the IFSM over 25 years of weather. Initially, baseline carbon footprints were determined for each farm before simulating 18 BMPs. BMPs were related to manure management, diet manipulation, and field interventions. After each BMP was simulated a whole farm-based mitigation strategy was determined using a combination of the best BMPs for each herd size. Lastly, a whole farm-based BMP simulation was run for both farms.

The results of this study showed that manure management BMPs can reduce C footprints by up to 20%, dietary manipulation BMPs by up to 12%, and field intervention BMPs by no more than 3%. However, field intervention BMPs were found to hold potential for decreasing reactive N losses and P losses by up to 19 and 47% respectively. The whole farm mitigation strategy was found to reduce C footprints by up to 41%, reactive N footprints by up to 41%, and P losses by up to 46%. Milk production and net return per cow was increased up to 11 and 27% respectively. Results from the IFSM were compared to results from other models (CNCPS, Manure-DNDC, and EPIC), all of which presented similar trends to the IFSM findings (Veltman et al., 2018). Use of a whole farm-based mitigation strategy appears to hold the most potential for reducing C footprints on dairy farms. This is because all the components that make up a dairy system are interconnected and using a whole farm approach considers the nutrient flows between each component.

A whole farm-based mitigation strategy may also be known as a total systems approach. A total systems approach to farm management focuses on each individual input and output of a farm (e.g., manure) but expands it to also focuses on the relationship between the two. Under a total systems approach considerations are evaluated for factors like human and animal health, odor control, nutrient management, feeding management, nutrient utilization, manure management, and exportation of goods. This methodology allows for maximum efficiency and production of a dairy operation. At any point if a system is not well managed there is potential loss to the efficiency and success of it (Grusenmeyer & Cramer, 1997). A total systems approach can give researchers, producers, and other stakeholders a realistic idea of the environmental impacts of dairy farms and how to best manage them for mitigation.

The second study done by Veltman et al. (2021), looked at the environmental impacts of three dairy farms: 150-cow in WI, 1500-cow in NY, and 50-cow in PA. Each farm was built using representative farming practices for each region. IFSM was used to predict the productivity and environmental impacts under current and future climate conditions without any change to management practices. After the baseline simulations were complete, farm-specific BMP packages were developed and included interventions to animal diet, housing, manure, and field management. The unique BMP package for each farm considered resource and economic feasibility. BMP simulations were run using IFSM and downscaled climate data through 2100. Results of this study showed that the environmental impact of all three dairies will continue to increase by mid-century without mitigation. If BMPs are adopted, GHG emissions and nutrient losses can be reduced under current climate conditions. Additionally, adoption of BMPs will stabilize environmental impacts from each dairy without affecting productivity (Veltman et al., 2021). Both studies provide a valuable basis for the implementation of BMPs in the dairy industry. In general, when deciding what BMPs may be most suitable for an operation, producers should first evaluate their short- and long-term goals, the feasibility of desired BMPs, the potential for whole farm mitigation, and most importantly economic means.

2.6.1 Manure Management

A significant source of GHGs and pollutants on dairy farms is manure. Manure is responsible for emitting NH_3, N_2O, CH_4, and CO_2. Manure from ruminant animals is an excellent source of nutrients required for plant growth. Animal manure is a natural alternative to synthetic fertilizers, and can be effective in providing crops with balanced sources of N and P. However, if accumulation of organic wastes goes unmanaged, there is an increased concern surrounding human, animal, and environmental health. Concerns include leaching of compounds into ground water, algae blooms, eutrophication, deterioration of ecosystems, and decline in overall soil health through excess nutrients, salts, and metals (EPA, 2011; Gerber et al., 2005; Ponisio et al., 2015; Steinfeld et al., 2006). Therefore, it is pertinent for dairy operations to have adequate means of manure management through determined beneficial management practices. The best way to directly manage manure is to decrease time (Philippe et al., 2007)and temperature (Monteny et al., 2006) of manure while it is being stored. The longer manure is stored the more time there is for anaerobic conditions to form, leading to increased CH_4 emissions. Additionally, if manure is stored outside in cold climates CH_4 emissions can be further reduced (Monteny et al., 2006; Philippe et al., 2007)

Housing on dairy operations is a contributor to GHG emissions from manure and different styles of manure collection within a housing system effects GHGs even further. Common collection systems include flush, gravity flow, and scrape. (Hristov et al., 2012) looked at how these common systems differ in their contributions to on farm GHG emissions. Results found that the barn floor ammonia and methane emissions were lowest for the flush system and highest for the gravity flow systems. There was no difference in CO_2 emissions and N_2O emissions were negligible in all systems. Based on these results, NH_3 and CH_4 emissions tend to be much higher on farms where manure remains in the housing system long-term compared to practices that remove manure frequently and more comprehensively. Furthermore, that housing contributes to a decent portion of on farm GHG emissions (Hristov et al., 2012). Switching to a manure collection system that emits less NH_3 and CH_4 should be considered as a potential BMP for dairy producers to adopt.

Storage covers have also been identified as an effective way to mitigate GHG emissions from manure stored in lagoons because they slow the release and reduce effects of wind and heat on emission rates (Lupis et al., 2012). Natural crusts, straw, wood chips, oil layers, wood, semipermeable, and sealed plastic covers are all being used in industry (Lupis et al., 2012; Montes et al., 2013). Depending on which cover is being used, there is potential to lower CH_4, NH_3, and N_2O emissions, however, it is unlikely that all three can be mitigated in unison. Each type of cover offers individual benefits, so producers should identify what their goals regarding mitigation are before selecting the cover system best for their operation.

Anaerobic digestors are quickly gaining popularity as a means of mitigation GHG emissions on dairy farms. Anaerobic digestion is the process in which bacteria are used to degrade organic materials in the absence of oxygen to produce CH_4, CO_2, and gas by-products (Montes et al., 2013). These gasses are harvested and used as a source of renewable energy for dairy farms and municipal grids (Roos et al., 2004; Sharvelle & Loetscher, 2011). Using CH_4 from anaerobic digestion can provide an alternative to fossil fuels, further reducing GHG emissions from other industries. It is imperative that anaerobic digestors have proper maintenance and operation. If they do not, they can cause CH_4 leaks and become a net contributor to GHG emissions (Montes et al., 2013). Another limitation that producers should consider when adopting an anaerobic digester is that they require specific inputs to work successfully. Any feed or waste that is put into the digest must be of low solids contents and have no inorganic material. The recommended amount is less than 15% solids by weight for optimal functioning. Many dairy farms have wastes with a high solid and inorganic material content, which would not make anaerobic digesters a suitable alternative for them. However, if they are willing to invest the time and money required to implement and maintain an anaerobic digester, they do hold immense promise for the future of sustainable dairy production (Sharvelle & Loetscher, 2011).

Land application is also considered when evaluating on farm manure management and its contributions to the farm's environmental impacts. While most dairies in the United States purchase and import their feed, there are still dairies throughout the country that own land to home grow feed (USDA-NASS, 2020). BMPs centered around manure application include incorporating manure as soon as possible after application, applying manure uniformly, avoiding over application of manure, timing application to match crop nutrient uptake patterns, avoid applying manure on frozen or saturated fields, and planting buffer areas around fields to prevent surface runoff and decrease potential for N_2O, CH_4, and CO_2 emissions(Waskom & Davis, 1999)

2.6.2 Diet Manipulation and Feed Alternatives

Diet can have significant impacts N excretion from dairy cows and N losses from dairy farms. Dietary protein has been determined as one of the most important variables that determines milk N efficiency, N lost from urine, and NH_3 emissions from dairy cow manure (Hristov & Giallongo, 2014). Urea is the main source of nitrogen in ruminant urine, and in high producing cows makes up ~60-80% or more of total urinary N (Vander Pol et al., 2008). When manure is stored, urea decomposes to NH_4^+, which is then emitted as NH_3. Lee et al., 2011 found that urinary N is the primary source of NH_4^+ in dairy cow manure, and subsequently makes up 88 to 97% of NH_3 emitted within the first 10 days of manure being stored.

Urinary N has been found to decrease as dietary CP and intake also decreases (Colmenero & Broderick, 2006). Reduced CP is likely the most effective way to decrease NH_3 emissions from stored manure. The current NRC recommendation for CP is 16-18% for lactating cows, an amount which decreases to the lower end of 16% when cows are dry (Moreira, 2020). Studies have found that lactating and dry animals can maintain production with values as low as 12% for low producing cows (Aschemann et al., 2012). For high producing cows, it has been determined that balanced diets with 14-16% CP will maintain milk production and composition while simultaneously lowering urinary N (Hristov & Giallongo, 2014).

However, producers should be wary that reducing the portion of CP in a dairy cow ration will alter the amount of fermentable carbohydrates, which in turn may increase CH_4 production in ruminant animals. One study found that reduced CP was successful in decreasing N_2O emissions on farm, however, the impacts on the overall carbon footprint of the farm was negligible because of increased CH_4 emissions. Changes in CP content of dairy cow rations may be beneficial if the goal of the farm is to focus on reducing sources of N pollution and GHGs. Furthermore, reducing dietary protein can also reduce feeding costs. A study done by Prestegaard-Wilson (2021) conducted a survey of US dairy cattle nutritionist to determine how many herds are utilizing a reduced CP diet. They surveyed 77 nutritionists who represent 1,065 herds across 28 states. Of the 77, 72% said they are currently formulating rations with a lower CP content then they have historically. While this sample size only represents about 6% of the total dairy cattle population in the United States, it is encouraging to see this BMP being adopted to mitigate environmental impacts of the dairy industry.

Another way to mitigate contributions to GHG emissions on dairy operations is through feed quality. It has been found that improving forage quality and efficiency of nutrient use can decrease the amount of CH_4 emitted from ruminant animals. Forage quality influences feed digestibility. Intake of poor quality, less digestible forages is not effective in reducing CH_4 emissions, regardless of DMI (Johnson & Johnson, 1995)Alternatively, if animals are fed high quality, more digestible forages, increased DMI can reduce the amount of CH_4 produced per unit of feed consumed, and per unit of product produced because it dilutes maintenance energy (Hammond et al., 2009). Generally, other research has found that reductions of CH_4 emissions on farm are associated with feeds that provide greater nutrient quality and digestibility (Hristov et al., 2013). Additionally, certain feeds will enhance the amount of propionate being produced in the rumen while decreasing acetate production. Decreased acetate will result in lower amounts of H_2 to be converted to CH_4 (Knapp et al., 2014).

Hristov et al. (2015) looked at the use of dietary inhibitors to decrease the amount of enteric methane emitted from dairy cows. In this study, 3-nitrooxypropanol (3NOP) was observed in vivo in sheep, beef, and dairy cattle. Specifically, 48 Holstein cows were used in a

14-week trial (2 wk covariate period and 12 wk data collection period), and feed intake, milk production, and fiber digestibility were not affected. The results of this study showed the using 3NOP increased milk protein and lactose yields and decreased rumen methane emissions. Methane emissions from the treated cows were about 30% less than control cows. Additionally, the body weight of treatment cows was about 80% great than control cows. This study shows that using a 3NOP to inhibit methane emissions can be successful without negative impacts to body weight, feed intake, milk production, or milk composition.

Overall, BMPs that are focused on diet and feed management, or alternatives can effectively mitigate emissions on dairy farms. The BMPs described in this section can reduce N losses by targeting NH_4^+ concentrations in urine and manure outputs of ruminant animals. Furthermore, it is possible that nutrition and feeding BMPs can reduce CH_4 emissions anywhere between 2.5 to 15% per unit of FPCM (Knapp et al., 2014).

2.6.3 Animal Management

When it comes to animal management the most successful BMP has been increased animal efficiency. Since the mid-20th century, the US dairy industry has made strides to being less environmentally impactful through increased efficiency and production (US Sustainability Alliance, n.d.). To further prove this point, a study done by Capper et al., (2009) found that reducing herd size on dairy farms was the "single most influential strategy that significantly reduces C footprints of the United States dairy industry." Another study used a partial LCA to model the US dairy industry and found that improved feed efficiency and milk production resulted in decreased on from GHG emissions and overall land use of the dairy herd (Bell et al., 2011). Improved efficiency is beneficial for reducing the mathematical value of footprints from the dairy sector; however, producers should be cautious to rely entirely on this mitigation tool as the sole way to lessen their environmental impacts. Dairy cows will continue to emit GHGs through enteric fermentation, manure, and dietary needs regardless of efficiency. Therefore, if a producer chooses to focus on increased efficiency, they should do so by also having other BMPs in place that align with the goals of mitigating what emissions they are producing.

2.6.4 Grazing Practices

Grazing practices and pasture-based systems are commonly used worldwide for beef production and are becoming more popular in the dairy industry (Moscovici Joubran et al., 2021). Grass-fed dairy cows have the potential to contribute the same environmental benefits as grass-fed beef cattle (Provenza et al., 2019). Pasture-based systems keep land in permanent vegetation instead of relying on annual crops to be harvested and imported to confined animals (USDA & NRCS, 2007). Furthermore, transitioning monoculture and annual cropping systems back to perennial pastures may reduce soil erosion, pesticide, and synthetic fertilizer use while simultaneously supporting an increase in ecological biodiversity, soil fertility, and carbon sequestration (Culman et al., 2010).

In a study by (Soder & Rotz, 2001), a whole farm analysis was conducted to evaluate the potential long-term environmental impact and economic benefit of varying the level of concentrate supplementation on seasonal grazing dairies. A representative grazing dairy farm was simulated with various production strategies over 25 years of historic Pennsylvania weather using the Dairy Forage System Model (DAFOSYM). The outputs of the grazing farm were compared to a confined farm with the same herd size that fed an alfalfa and corn-based diet. Overall, it was found that grazing dairies tend to have fewer negative ramifications for the environment, however lower amounts of milk were produced in comparison to the confined dairy. To combat this, the findings recommend supplementing grazing dairies with concentrates to increase milk production and profitability while continuing to minimize environmental impacts. The use of concentrates on grazing dairies has the biggest impact on decreasing on farm nitrogen losses. It was also concluded that grazing dairies tend to be low cost because they require less labor, management, and inputs, although depending on the operation's goals and demands, this system framework may be most suitable for smaller herd sizes.

Rotz et al. (2009), found that adopting grazing practices can reduce the environmental impacts of dairy systems. In their study, they simulated four management scenarios on a 250-acre dairy farm that was representative of real dairy operations in Pennsylvania. The four scenarios included a confinement fed herd that produced 22,000 lbs of milk/cow/year, a confinement fed herd producing 18,500 lbs of milk/cow/year, a confinement fed herd with summer grazing producing 18,500 lbs of milk/cow/year, and a seasonal herd that was maintained outdoors and produced 13,000 lbs of milk/cow/year. Beyond the four herd management strategies two land use scenarios were also included. Each farm was simulated with conversion of 75 acres converted to perennial pasture and then full conversion to perennial pasture. Both conversion strategies reduced soil erosion, sediment bound, and soluble P loss. Implementing grazing practices reduced ammonia volatilization up to 30%, however, nitrate leaching increased up to 65%. GHG emissions were reduced up to 14% on grazing dairies and the total C footprint by up to 20%. When C sequestration was included, it further reduced the C footprint of all grassland dairy farm up to 80%. Based on these results, it is apparent that grass-based dairies provide environmental benefits and should encourage greater adoption of rotational grazing in regions where feasible.

Müller-Lindenlauf et al. (2010) looked at organic dairy farms in Germany to determine their environmental impacts. Farms in this study were classified by percentage of pastureland on the farm and feeding intensities. Operations that practiced more intensive feeding had less of an effect on climate change and land demand, however, the lower-input pasture-based farms showed increased benefits for animal welfare, milk quality, and ammonia losses. The researchers of this study concluded that overall, the intensive dairy operations had less of an environmental impact compared to the extensive dairy operations. While this is a valuable consideration for producers trying to determine which type of system fits their operation, one should caution to make decisions based off results showing efficiency and nothing else.

Rotz et al. (2020) considered this caveat and conducted a study with the objective to quantify the important environmental contributions of grass-based dairy farms to the in Pennsylvania, US. Considerations of the dairy farms included nutrient loss (N and P) and LCAs of water, energy, reactive nitrogen, and GHG footprints. Dairy operations were simulated used the Integrated Farm Systems Model (IFSM). After the initial assessment of grass-based dairies they compared results to those of other dairy production systems that are common in the state. In general, the grass-based dairies had lower nutrient losses and environmental footprints on a land-use basis than the confined dairies, but when considered on an intensity basis (i.e., output/kg FPCM) the grass-based dairies had higher nutrient losses and environmental footprints because of lower milk production. Grass-based operations also tended to have lower on farm energy and water use for both intensity and farmland basis. This is because grass-based systems don't have as much reliance on purchased feeds. Economically, it was found that grass-based systems tend to have lower input costs and higher profitability even when producing less milk than confined operations.

Grass-fed and grazing based dairy operations offer a myriad of environmental and economic benefits, however, producers should be aware of the resources available to them and the goals of their operation when considering adoption of extensive management practices. Herd size, natural resource availability, and demand will all influence the success of a grazing centric dairy farm. Positive environmental attributes from grazing dairies include increased soil health, carbon sequestration, biodiversity, and perennial stands. Furthermore, there is a decrease in labor needs, farm inputs, and reliance on synthetic fertilizers or pesticides. However, implementing grass-based feeding strategies are not without pitfalls. If a dairy producer chooses to transition to a grazing-based operation they should be sure to educate themselves on the different types of grazing practices (e.g., continuous, mob, management intensive grazing, and rotational). One practice might suit their farm well and another could be detrimental for their success if not carried out correctly. Furthermore, each grazing technique has different impacts on plant foliation, which producers will need to understand to properly operate a grazing dairy operation.

2.6.5 Beneficial Management Practices in Colorado

While BMPs have made progress towards mitigating environmental impacts of dairy systems, there is still much to learn about the relationships and tradeoffs that result from combining these practices in the state of Colorado. Researchers have started to solidify which BMPs suit Colorado dairy production. Some of the more promising have shown to be related to diet and manure management. More specifically, BMPs associated with lowered N emissions are among the most suitable for the state because of the high concentrations of nitrogen species such as NH3 (Holly et al., 2018). However, there is a need for a whole farm analysis through modeling to determine the feasibility of BMPs to best address concerns about climate change and disruption to future production capabilities.

When determining what BMPs are most suitable for the region and its operations, stakeholders should be wary of potentials for “pollutant swapping”. Pollutant swapping is when mitigation technique is introduced to a system in hopes of reducing one pollutant but results in increases a different pollutant (Quinton & Stevens, 2010). For example, CH_4 and N_2O have antagonistic processes. Methane is produced in anaerobic conditions while nitrous oxide in aerobic conditions. BMPs that utilize aeration of manure to lower CH4 emissions will likely increase N2O emissions (Montes et al., 2013).

2.7 Characteristics of Colorado Dairy Systems

2.7.1 Overview

The world is slated to reach a global population of 10.4 billion by 2067 (Britt et al., 2018), which makes it imperative for dairy production to adapt to changing practices and resource availability. Suitable locations for dairy cattle and farming will change. Approximately 42% of US dairy production currently exists in states that are projected to have severe water shortages by 2067. Additionally, temperature increases in tropical and temperate zones will results in migration of growing seasons and dairy farming to the Northern Hemisphere. Areas that are expected to have adequate water and other resources to support consistent dairy production by 2067 are the Upper Midwest, Great Lakes Region, and Central Canada (Roy et al., 2012). However, dairy farming remains a prominent portion of Colorado's economy and agricultural sectors. Colorado is ranked 13th for milk production and 14th for number of dairy cows in the United States, making the state a relevant contributor to the overall production of dairy goods in the country (USDA-NASS, 2021). The state has nearly doubled its milk production in the past two decades, producing over 5 million pounds in 2021 (USDA-NASS, 2021). As of January 2021, the total cow inventory of Colorado was 201,000 head, an increase of 5.97% from 2020 totals.

In total, Colorado has 583 farms with milk cow inventory (USDA-NASS 2018; 2020). Colorado farms that are actively milking cows have a total of 315,511 animals, with 180,717 being calved cows and heifers and 169,423 being milk cows (USDA-NASS 2018; 2020). Eighty-eight percent of dairy herds in Colorado milk Holstein cows, with a few herds milking Jerseys and other breeds (USDA-ERS, 2017). The average farm has a herd size of about 1200 head.

Farms with 500 head or more manage a total of around 1,756 head on average (USDA-ERS, 2017). The USDA census classifies farms by the following herd sizes: less than 500, greater than or equal to 500, greater than or equal to 1000, and greater than or equal to 5000 head (2017). Majority of dairy farms in Colorado are greater than or equal to 1000 head (44.34%), followed by greater than or equal to 5000 (42.79%), greater than or equal to 500 (7.72%), and less than 500 (5.02%) (Table 2.2) (USDA-ERS, 2017). Dairy farms are concentrated to mainly Larimer and Weld counties, making Northeast Colorado the hub for production in the state (USDA-ERS, 2017).

Table 2.2. Summary of number of farms and cows by herd size for Colorado dairy operations (USDA-NASS, 2017).

	Totals	<500	≥500	≥1000	≥5000
No. Farms	583	517	19	37	10
No. Cows	169,423	8,510	13,079	75,123	72,509

2.7.2 Feeds & Feeding

The typical dairy cow ration consists of different sources of forages and grains to meet animal nutrient needs. In Colorado, these feed sources are both homegrown and purchased. Annually, the average Colorado dairy cow requires 6,464 kg of DM. Of that, 52% comes from forage, 13.5% from grain, and 11.4% are from protein (USDA-ERS, 2017). Common sources of forage crops include alfalfa hay, other hay types (*e.g.*, grass hay), corn silage, sorghum silage, and pasture. Grain crops include corn, small grains, and sorghum. The main source of protein for dairy cows in Colorado is soybeans (USDA-ERS, 2017).

2.7.3 Housing

The USDA-ERS (2017) found that the main types of housing for dairy cows in Colorado are dry lots, free stalls, bedded packs, and tie stalls (33%, 24% 23%, and 4%, respectively). Heifers are bedded on dry lots, bedded packs, loafs, and free stall facilities (44%, 15%, and 4%, respectively). Calves are housed either in calf hutches or calving barns (25% and 12.5%, respectively) (USDA-ERS, 2017).

2.7.4 Milking

In Colorado, four main facility styles are used for milking parlors: herringbone, parallel, carousel, and swing. Of the four, herringbone parlors are the most common (54%). Parallel parlors represent 36% of milking facilities, followed by swing and carousel parlors (7% and 3%, respectively) (USDA-ERS, 2017).

2.7.5 Manure Management

Manure management in Colorado includes storage, collection, land application, and export/sale of manure. When stored, manure is either dry solids or liquid. Storage types include slabs, barns, ponds, lagoons, open pits, and earth basins. Collection methods for liquid matter are manual or scraped, and solids are collected from dry lots. Land application depends on the farms crop systems management. Generally, manure is either incorporated as solids, applied as a liquid through irrigation, or applied as a slurry through broadcast methods or incorporation. Excess manure is often sold from the farm (USDA-ERS, 2017).

2.7.6 Environmental Footprints of Colorado Dairy Systems

In Rotz et al. (2021) environmental assessment of dairy farms by region, environmental footprints were determined for the South-central region of that country, in which Weld, CO was used to represent Northern Colorado. Total GHG emissions, fossil energy footprints, blue water footprints, reactive nitrogen footprints, and ammonia emissions were averaged for the entire region. The weighted mean, or the mean footprint weighted by FPCM milk produced in each region, was determined to be 1.03 kg CO_2e/kg FPCM, 2.54 MJ/kg FPCM, 143 L/kg FPCM, 11.2 g N/kg FPCM, and 8.15 g N/kg FPCM, respectively. These results resemble other regions of the country. The following study adapts the methodology of Rotz et al. (2021) and Veltman et al. (2021) to determine the environmental footprints specific to Northern Colorado, the ways in which the Colorado dairy production may be vulnerable to climate change, and what BMPs would be beneficial in combating these vulnerabilities, therefore contributing to the future sustainability of the dairy industry in Northern Colorado.

CHAPTER 3: MATERIALS AND METHODS

Three representative Colorado dairy farms were simulated using the Integrated Farm Systems Model (IFSM) (USDA, 2018) to assess the implications of climate change on the environmental footprints of Colorado's dairy systems through 2100. To develop representative systems, data were obtained from the USDA Agricultural Resource Management Survey (ARMS), Economic Research Service (ERS) and National Agriculture Statistics Service (NASS). Each USDA database provides access to information about land use, feed production, herd management, farm facilities, manure management, and economics. These data allow for region-specific environmental and economic assessments. Inputs were further refined through visits to local dairy farms in Larimer and Weld Counties, and conversations with Colorado State University personnel.

3.1 Modeling Procedure

3.1.1 Integrated Farm Systems Model

The IFSM (Figure 3.1) is a process-based model that simulates major biophysical processes, environmental impacts, and economics of beef, dairy, and crop farms over many years of weather (Rotz et al., 2018). This project used IFSM version 4.6, downloaded on July 16, 2021. Activities including feed production, feed intake, animal production, and nutrient cycling within the production cycle are all simulated over 25 years of weather (Rotz et al., 2018). Crop production is predicted daily to best represent feed yield, quality, and losses (Rotz et al., 2020). If a farm cannot meet the herd's needs with home grown feeds, they are supplemented with purchased feeds. Herd inputs to the model include characteristics related to animal growth replacement heifers, dry cows, and lactating cows.

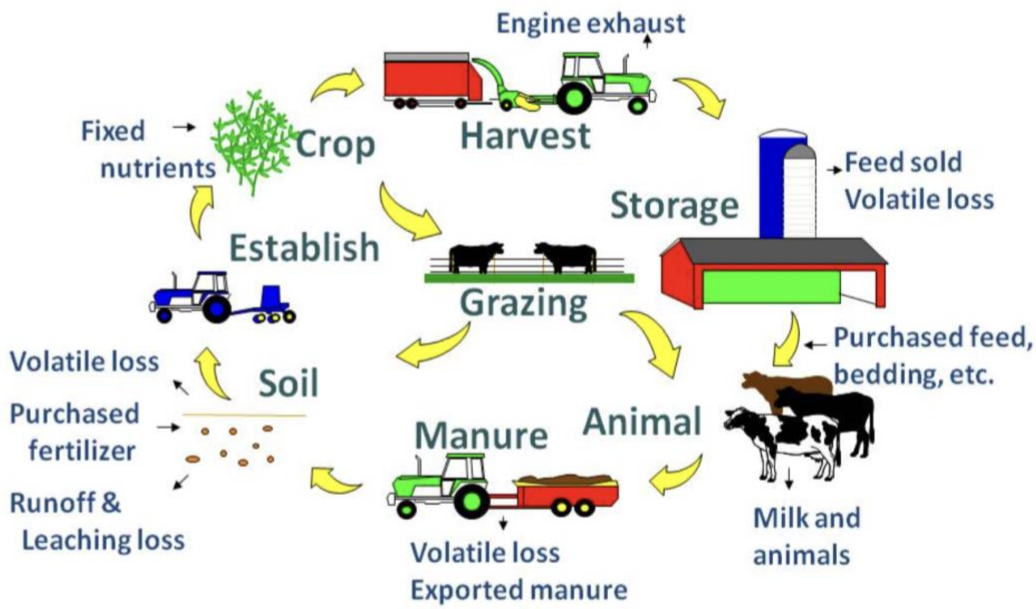


Figure 3.1. The Integrated Farm Systems Whole Farm Process-Based Model (Rotz et al., 2018).

Simulations use three different parameter files: farm, weather, and machinery. Farm files include farm inputs and characteristics including information about soil properties, crop and animal management practices, and fertilizer use. Weather files include daily precipitation, temperature, solar radiation, wind speed, and atmospheric carbon dioxide concentration data. Machinery parameter files include technical inputs for the types of machinery required by the farm being modeled (Rotz et al., 2020). The IFSM outputs include total annual milk production, forage and feed yield and quality, manure production and nutrient composition, environmental footprints, mass nutrient balances, and weather summaries. Summaries of the outputs from annual simulations are given as numerical totals, means, standard deviations, and coefficients of variation.

Within IFSM, a cradle-to-farm gate LCA is conducted to calculate annual reactive nitrogen, blue water (non-precipitation), energy, and carbon (net GHG) footprints (Rotz et al., 2018). Each environmental footprint is expressed as total inputs per unit of fat and protein-corrected milk (FPCM) produced. The footprints that are estimated by IFSM are used to evaluate relative differences in management changes. The reactive nitrogen footprint is representative of the total amount of reactive nitrogen released to the environment per unit of product produced. Both primary emissions from the farm and secondary emissions from upstream processes and manufacturing are considered. On farm, primary sources are NH_3 volatilization, N_2O, and (NO_x) emissions that result from de/nitrification and leaching or runoff of NO_3^-. Secondary sources come from fuel and electricity production and purchased fertilizers, feed, and animals. Ammonia emissions occur when manure is exposed to air (e.g., field applied manure, manure from grazing animals, or barn floors). Reactive nitrogen lost in this form is calculated by taking total NH_3 emissions of the farm divided by the molecular weight of NH3/N. Combustion of fuels is calculated using the GREET model (Wang, 2012). For every liter of fuel used 7.64g of reactive nitrogen are released. Denitrification is calculated as the total lost N_2O divided by the molecular weight of N_2O/N. Simulations predict volatilization hourly, and nitrification, denitrification, leaching, and runoff daily for the 25 years of weather. These losses are all influenced by temperature, wind speed, precipitation, soil conditions, and management practices (Rotz et al., 2018; Rotz et al. 2019; Rotz et al., 2020)

The IFSM provides a general estimate of water use across dairy systems and does not account for variance in water use between systems. Water use for individual operations is dictated by the climate and precipitation values of an area, production goals, and type of production system. When calculating the water footprint, the model considers the amount required for crop and feed production (irrigation), drinking water for the herd, feed intake, milk production, cleaning, and animal cooling as primary inputs. Secondary water use is considered for purchased feed, animals, and seeds. Simulations calculate both green and blue water footprints. The green water footprint includes water that is attributed to precipitation and evapotranspiration. The blue water footprint excludes these aspects of the water cycle and only accounts for water that is sourced from surface or groundwater stores (Rotz et al., 2018).

Energy use is calculated by totaling energy required to produce a respective unit of feed, milk, or beef. Fuel to power equipment for feed production, feeding, and manure handling make up a significant portion of energy use on farms. Assumed values of 35.8 MJ/liter of fuel and 3.6 MJ/kWh of electricity are used to convert fuel and electrical values to energy. Primary sources of electricity include milking and housing of animals, farm operations, and general truck use (Rotz et al., 2020). The variation in electricity uses for different types of production systems is accounted for in each simulation. Secondary energy is also considered and is any fuel or electricity that is used to produce farm inputs. Farm inputs are fuel, electricity, machinery, fertilizer, pesticides, seed, and plastic. Another secondary energy source of importance is heifers or cows that are not born and raised on farm. The energy used to purchase and import these animals to the farm is determined by multiplying the body weight of each animal by the energy use factor of 30 MJ/kg. This value is an average energy use factor that was determined by simulating multiple raising systems in IFSM (Rotz et al., 2018).

Carbon footprints are defined as the net production of all greenhouse gases (GHG) associated with and emitted by a production system divided by the total product produced (Rotz et al., 2019). The total amount of methane (CH_4), nitrous oxide and carbon dioxide (CO_2) emitted are expressed in CO_2 equivalent units (CO_2e). CO_2e are calculated by taking 100-year global warming potentials (GWP) of CH_4 and N_2O (IPCC, 2014). Emissions are produced by primary and secondary sources. Primary emissions come directly from the farm during the production process and secondary emissions occur during manufacturing or production of resources used in a production system. Enteric fermentation, microbial decomposition of manure, and animal respiration are the driving source of CH4 and CO2 emissions from the farm (Rotz et al., 2020). A net annual number of emissions is calculated by dividing primary and secondary emissions by annual production to produce a carbon footprint in CO_2e per unit of feed or milk produced.

Emissions associated with upstream processes are also considered in the LCA. These include estimates for purchased feed, replacement heifers, and processes not allocated to milk. An allocation method suggested by the International Dairy Federation (IDF, 2015) is incorporated into the model to account for animals leaving the farm for beef production. The IDF allocation is calculated by taking the BW of calves and cull cows exported relative to the milk weight sold (Rotz et al., 2020). To date, studies have used life cycle assessments to evaluate dairy systems for general regions of the United States (Belflower et al., 2012; Capper & Cady, 2020; FAO, 2010; C. A. Rotz et al., 2010; Thoma et al., 2013), but no studies have reported results of assessments specific to Colorado, specifically, the Northeastern region of the state.

3.2 Down Scaled Climate Change Data

For each herd size, a total of 48 simulations were run using weather input data generated by eight general circulation models (GCMs) (Table 3.1) for two projected emissions scenarios: RCP 4.5 and RCP 8.5 (IPCC, 2014). General circulation models are also referred to as global climate models, with the terms being used interchangeably. The International Panel on Climate Change (IPCC) describes GCMs as numerical models that represent physical processes in the atmosphere, ocean, cryosphere, and land surface (2017). Currently, they are the most advanced tool available to simulate responses of global climate change to greenhouse gas concentrations. GCMs provide climate change estimates by modeling atmospheric chemistry and other critical aspects of climate systems a specific region to estimate changes in global temperature, precipitation, solar radiation, and other variables related to climate change. Weather data from Sterling, CO was obtained from the USDA ARS (2020) for downscaling.

Table 3.1. Description of the eight general circulation models used to create weather data input files for IFSM; adapted from USDA ARS Integrated Farm System Model (USDA ARS, 2019).

General Circulation Model	**Abbreviation**
Community Climate System Model 4	CCSM4
Centre National de Recherches Meteorologiques Circulation Model 5	CNRM-CM5
Commonwealth Scientific and Industrial Research Organization Mark 3	CISRO-Mk3
Hadley Centre Global Environment Model 2 CC	HadGEM2-CC
Institute for Numerical Mathematics Climate Model 4	Inmcm4
Institut Pierre Simon Laplace Coupled Model 5A LR	IPSL-CM5A
Model for Interdisciplinary Research on Climate 5	MIROC5
Max-Planck Institute Earth System Model LR	MPI-ESM-LR

3.2.1 Community Climate System Model 4 (CCSM4)

CCSM4 is a coupled climate model that simulates the Earth's climate systems. It is made up of four separate sub-models that represent the atmosphere, ocean, land surface, sea-ice and one central coupler component. The CCSM4 is a subset model of the Community Earth Systems Model (CESM1) (UCAR, 2016).

3.2.2 Centre National de Recherches Meteorologiques Circulation Model 5 (CNRM-CM5)

CNRM-CM5 uses an atmospheric model ARPEGE-Climat5.2, the ocean model NEMO3.2, the land surface scheme ISBDA, and the sea-ice models GELATO5 and OASIS3. The model is meant to give realistic representations of recent climate and to reduce the number of drifts in preindustrial integration (Voldoire et al., 2013).

3.2.3 Commonwealth Scientific and Industrial Research Organization Mark 3 (CSIRO-mk3)

The CSIRO-mk3 model represents the four major components of a climate system: the atmosphere, land surface, oceans, and sea-ice. Its goal is to provide researchers with a coupled atmosphere-ocean system representation of current climate relative to prior models. Creators of the model state that it can be used to, "investigate the dynamical and physical processes controlling the climate system, for multi-seasonal predictions, and for investigations of natural climactic variability and climate change," (Gordon et al., 2010)

3.2.4 Hadley Centre Global Environment Model 2 CC (HadGEM2-CC)

HadGEM2 is a family of climate models that includes a coupled atmosphere-ocean configuration and a coupled Earth-System configuration. The atmosphere-ocean configuration is represented either with or without a vertical extension in the atmosphere. The Earth-System configuration includes dynamic vegetation, ocean biology, and atmospheric chemistry (MET Office, 2020).

3.2.5 Institute for Numerical Mathematics Climate Model 4 (INMCM4.0)

INMCM4.0 is a model that uses different parameterizations of many physical processes in the United States and Canada. It is a coupled atmosphere-ocean general circulation model. The previous version of the model was INMCM3.0 with the differences being improved special resolution and changes in the model formulation (Volodin et al., 2010).

3.2.6 Institut Pierre Simon Laplace Coupled Model 5A LR

IPSL-CM5A LR is a coupled model that includes the atmosphere, land, ocean, sea ice, and carbon cycle. The model components are LMDZ (atmospheric), NEMO (ocean model and sea ice), and ORCHIDEE (land). Model outputs represent monthly and daily outputs for atmospheric content (e.g., carbon, nitrogen, oxygen, and other gases), and monthly and/or yearly outputs for all other components (Sepulchre et al., 2020)

3.2.7 Model for Interdisciplinary Research on Climate 5 (MIROC5)

MIROC is a coupled general circulation model (CGCM) that combines the atmosphere and ocean GCMs with land and sea ice models to create a global climate model (Watanabe et al., 2010) and was developed by replacing schemes from the previously existing model MIROC3.2. The previous model was coupled with the atmosphere model CCSR-NIES-Frontier Research

Center for Global Change (FRCGC) AGCM and the CCSR Ocean Component model to create the current version.

3.2.8 Max-Planck Institute Earth System Model LR (MPI-ESM-LR)

MPI-ESM-LR combines the atmosphere, ocean, and land surface. This coupling is done through modeling the exchange of energy, momentum, water, and carbon dioxide. For the atmospheric model ECHAM6 is used with MPIOM for the ocean, JSBACH for terrestrial biosphere, and HAMOCC for the ocean's biogeochemistry (Max-Planck-Gesellschaft, 2022).

3.3 Representative Dairy Production Systems

3.3.1 Herd Characteristics

The focus of this assessment was on the environmental impacts of Colorado dairy systems. Colorado dairy farms range in size from small (50-99 cows) to large (≥500) with an average herd size of approximately 1200 cows (USDA ERS; ARMS, 2017). This study modeled three herd sizes: 2000- head conventional farm (2000C), 1100-head conventional farm (1100C), and 1100-head organic farm (1100OR). The systems that were simulated were combinations of herd sizes and traditional management practices that are representative of the typical Colorado dairy farm. Annual milk production was assumed using state averages for each herd size. Target annual milk production was set at 12,300 liters/cow/year for the 2000C and 1100C. Target annual milk production for the 1100OR milk production was set at 9,802 liters/cow/year. Milk production, animal management, and soil characteristics were held constant for all simulations. Each farm was simulated over three time periods: historic (1990-2015), mid-century (2040-2065), and late century (2075-2100).

3.3.2 Animal and Cropland Management

Input data for representative dairy operations included general herd demographics, target annual milk production, breed, heifer, and calf body weights, and cow cull rate (**Table 3.2**). Housing practices included confined, semi-confined, or grazing. For this study, confined operations are those where animals are managed in barns, however, heifers may be managed on pasture during the grazing months. Confined operations included the 1100C and 2000C farm. The 1100OR was the only grazing farm simulated, and during off season animals were housed in semi-confined barns. Lactating cows in semi-confined systems were managed in barns year-round with access to pastures for grazing in the summer months (Holly et al., 2019). Feed for animals was either purchased, or a mixture of purchased and home-grown feeds. The IFSM simulates on farm crop production before it simulates purchased feeds. For grazing systems, IFSM models pasture as the first crop simulated before other feeds that are grown on the farm (Rotz et al., 2018). The 1100OR and 2000C both grew 600 ha of feed and supplemented the herd with purchased feed. The 1100C farm purchased all its feed and had no crop production on farm. Barns were a mixture of bedded pack, free-stall, or dry lot for wet and dry cows. Heifers and calves were housed in a bedded pack, free stall, dry lot, calf barn or calf hutch. All farms purchased bedding for housing, which consisted of hay and sand with manure from the animals mixed in. Lastly, the milking facility for all three farms was a herringbone parlor.

Crop areas and plant species were summarized for all herd sizes **(Table 3.2).** The 2000-head conventional farm utilized a mixture of homegrown and purchased feeds. The 1100-head conventional farm relied solely on purchased feeds. Lastly, the 1100 organic farm had some homegrown and purchased feeds that supplemented the pasture. Primary feeds grown on the 1100-head organic and 2000-head conventional included high moisture corn, alfalfa hay, corn silage, and other hay or silage feeds. Feeds purchased by each farm included alfalfa hay, corn silage, low moisture corn, barley, complete feed mix, distillers dried grains, protein by-products, cotton seed, calf starter, and other hay, silage, and grain feeds.

Data reported for manure management include storage capacity, handling, distribution, and nutrient management practices for all herd sizes on percent of farm basis (**Table 3.2**). Manure was kept in both dry and liquid capacities with the average storage period being about one month. Manure was used as a source of nitrogen and phosphorous on all farms. Land applications include incorporated solids, liquid, broadcasted and incorporated slurry. Excess solid manure is exported, and land areas fertilized with manure were supplemented with commercial fertilizers. Commercial fertilizers included K_2O and N on the 2000-head dairy.

Table 3.2 Characteristics of representative Colorado dairy production systems for baseline simulations. If the value of a box is 0, that input is not included on the farm.

Input	Herd size		
	2000 Conventional	1100 Organic	1100 Conventional
Animal Breed	Holstein	Holstein	Holstein
Milk cows	2000	1100	1100
Young stock over 1 year	700	335	335
Young stock under 1 year	700	335	335
First lactation animals	35%	30%	30%
Target milk production (L/cow/yr)	12,300	9,802	12,300
Milking	year round	year round	year round
	Cow diet		
Feed source	grown & imported	grown & imported	imported
Total mixed ration (TMR)	yes	yes	yes
CP% (lactacting cows)	17%	17%	17%
P% of NRC requirements	100%	100%	100%
	Housing		
Cows	Free stall & dry lot	Free stall & dry lot	Free stall & dry lot
Heifers	Free stall & dry lot	hutches & dry lot	Free stall & dry lot
Calves	hutches	hutches	hutches
	Manure management		
Collection	scraper w/ slurry pump	scraper w/ bucket loading	scraper w/ bucket loading
Solid Storage	stack or compost (6 months)	stack or compost (6 months)	stack or compost (6 months)
Liquid Storage	top-loaded lined earthen basin	top-loaded lined earthen basin	top-loaded lined earthen basin
Application	broadcast	broadcast	none
Hualing distance (km)	1.61	1.61	1.61
Imported	0%	0%	0%
Exported	50%	0%	100%
	Crop and soil inputs		
Soil	medium sandy loam	medium loamy sand	medium loamy sand
Sand %	60	80.7	80.7
Silt %	25	11.9	11.9
Clay %	15	7.4	7.4
Bulk density (g/cm3)	1.5	1.51	1.51
Available water supply (mm)	190	112	112
Total crop area (ha)	600	600	0
Alfalfa (ha)	300	0	0
Corn silage (ha)	300	100	0
Oats (ha)	0	100	0
Grass crop (ha)	0	400	0
	Field management		
Tillage practice	tandem disk	tandem disk	NA
Corn silage			
Max annual irrigation (cm)	35	50	NA
Fertilizer N (kg N/ha)	50	0	NA
Fertilizer K2O (kg K2O/ha)	100	0	NA
Manure N (kg N/ha)	100% of that available	40% of that available	NA
Alfalfa			
Max annual irrigation (cm)	35	0	NA
Fertilizer N (kg N/ha)	0	0	NA
Fertilizer K2O (kg K2O/ha)	100	0	NA
Manure N (kg N/ha)	0	0	NA
Oats			
Max annual irrigation (cm)	NA	20	NA
Fertilizer N (kg N/ha)	NA	0	NA
Fertilizer K2O (kg K2O/ha)	NA	0	NA
Manure N (kg N/ha)	NA	10% of that available	NA
Grass crop			
Max annual irrigation (cm)	NA	50	NA
Fertilizer N (kg N/ha)	NA	0	NA
Fertilizer K2O (kg K2O/ha)	NA	0	NA
Manure N (kg N/ha)	NA	50% of that available	NA

3.3.2 Beneficial Management Practices

Three areas of management were identified across each farm as being suitable for implementation of Beneficial Management Practices (BMPs): manure management, diet manipulation, and milking strategy. For each area of management, appropriate BMPs were chosen and simulated on the respective farm where the BMP was most realistic for adoption. Table 3.3 provides an overview of each intervention and its associated BMPs, which farm it was applied to, and the expected effect (Veltman 2018). Individual BMPs were chosen based off the economic feasibility of the Colorado dairy industry. The BMPs included a covered lagoon, a covered lagoon with flare, reduced CP, and seasonal milking.

Table 3.3 Overview of Beneficial Management Practices (BMPs) for each farm size. Adapted from Veltman et al. (2018).

IFSM input	BMP	Farm applied	Expected effect
Manure management (Cov. Lag.)	Covered lagoon with broadcast application: permeable cover used on lagoon storage with application occurring as needed.	1100 conventional 2000 conventional 1100 organic	Reduced N_2O during storage (Montes et al., 2013)
Manure management (Cov. Lag. + F)	Covered lagoon with flare: permeable cover used on lagoon storage with biogas burned off using flare as needed.	1100 conventional	Reduced CH_4 during storage (Montes et al., 2013)
Feed management (Red. CP)	Diet manipulation: Protein content reduced 16% to 14% using soybean meal, 48% and supplemented with rumen protected AAs.	2000 conventional	Reduced urinary N and NH_3 emissions (Montes et al., 2013)
Milking (Spring)	Spring cycle calving: cows calve in March and are dry during January and February	1100 organic	Reduced C footprint (O'Brien et al., 2012)
Milking (Fall)	Fall cycle calving: Cows calve in October and are dry August and September.	1100 organic	Reduced C footprint (O'Brien et al., 2012)

A covered lagoon for manure storage was simulated in two different BMP scenarios. The first changed the manure storage method to a completely covered lagoon for liquid manure with solids separated out and stored in stack or compost piles. The second covered lagoon BMP also separated liquid and solids into a covered lagoon and stack or compost piles, but additionally included the use of flare to burn off biogas. For both BMPs, manure stored in the lagoon was part of primary manure handling and was removed from the barn using a slurry pump. Solid separation was part of secondary manure handling and was done using a scraper with bucket loading. The covered lagoon was applied to all three farms while the covered lagoon + flare was only applied to the 1100C farm. Target milk production, animal management, herd size, and feed production remained constant and unchanged from the baseline simulations.

Reducing CP intake is the most effective way to mitigate ammonia emissions from stored manure (Hristov et al., 2011). Less CP in the diet as a BMP is practical and affordable for dairy operations in Northern Colorado, and was simulated on the 2000C farm by reducing CP from 17 to 14%. This was done by decreasing the fraction of soybean meal in the ration, as recommended by previous research (Montes et al., 2013). To maintain milk production, cows were given a rumen protected amino acid supplement to meet metabolizable protein requirements. The IFSM uses CNCPS v.4 as the animal model to predict feed requirements and utilization, animal performance, and nutrient excretion (Rotz et al., 2018). Target milk production, animal management, herd size, and feed production remained constant and unchanged from the baseline simulations.

Seasonal milking was only simulated on the 1100 OR farm, and had scenarios for both spring and fall calving and milking cycles. The spring cycle had cows calving in March and drying off in January and February, while the fall cycle had cows calving in October and dry in

August and September. Both were simulated to determine if one cycle performs better over the other in Northern Colorado. Target milk production, animal management, herd size, and feed production remained constant and unchanged from the baseline simulations.

3.5 Regional Analysis

Initially, farm inputs were calibrated using 25 years of weather for Akron, CO. The difference in distance between Akron and Sterling, CO is 35 miles North or South. The purpose of this was to increase validity of baseline footprints from the historic time. While certain aspects such as weather, milk production, herd size, and feed footprints are legitimate information retrieved from databases, not all management practices simulated in this study are 100% representative of past production. Additionally, using calibration simulations helped work through model errors for each farm size. After all inputs were verified, baseline and BMP simulations were run for the historic, mid, and late time periods. The baseline footprints for the historic period used historically forced data, or data that predicts what the radiative forcing values may have been from 1990-2015. Radiative forcing is the change in net average radiation at the tropopause of atmosphere as a result of a change to an external drive of climate change (Enting, 2018), which in boundaries of this study are GHGs. Historic footprints were averaged for each GCM and compared to the mid and late period projected averages.

Baseline simulations predicted directional changes for the four footprints without any changes to current management practices. BMP simulations predicted how changes in management impacted the four footprints, and if they can make Colorado dairies more sustainable and resilient. Overall trends and individual process contributions (Table 3.4) were assessed for each of the four footprints. To provide perspective for the values determined, average annual environmental footprint values, trends, nutrient losses, and farm vulnerabilities were compared to Rotz et al. (2021) environmental assessment of dairy farms in the United States (see section 2.7.6). The results of the Northern Colorado assessment done in this study were compared to the results for the South-Central region of the United States and national averages. To verify carbon footprints for feed production on Northern Colorado dairies results were compared to regional carbon footprints for feed found by (Adom et al., 2012). Additionally, percent changes to footprints over time were evaluated for baseline and BMP scenarios. Three percent changes were calculated for each farm size and simulation scenario: historic-mid, mid-late, and historic-late.

Table 3.4 Individual process contributions considered for carbon, reactive nitrogen, blue water, and energy footprints on a representative dairy farm.

IFSM Calculated Footprint	Process Contributions
Carbon	- Anthropogenic CO_2 emissions - Direct & indirect land emissions - Manure emissions - Animal emissions - Upstream processes
Reactive nitrogen	- Fuel combustion - De/nitrification - Nitrate leaching & runoff - Ammonia emissions - Upstream processes
Blue water	- Irrigation - Cleaning - Animal cooling & dust control - Drinking - Upstream processes
Energy	- Feed production - Ventilation & lighting - Milking & milk cooling - Manure handling - Feeding - Upstream processes

CHAPTER 4: RESULTS

The results for environmental performance are presented by farm size for baseline and BMP scenarios, with all footprints standardized to fat and protein-corrected milk, assuming 4.0% fat and 3.3% protein (Rotz et al., 2018). Differences in environmental footprints between farms are reported on a percent change basis in Appendices A-C. Calibration simulations were used to ensure the model was running correctly, and to provide reference to the historically forced baseline values presented below. The initial footprints from the calibration simulations were similar to the historic baseline values predicted by IFSM using downscaled climate data. Environmental footprints from the downscaled climate data in this study were comparable to those reported for the South-Central region of the United States by Rotz et al. (2021). In that study the weighted averages for CF, RnF, and EF were predicted as 1.03 kg CO2e/kg FPCM, 11.2 g N/kg FPCM, and 2.54 MJ/kg FPCM, respectively. Rotz et al. (2021) predicted a WF of 143 L H_2O/kg FPCM, which was close in value to the 2000C baseline and covered lagoon scenario results presented here. The 2000C reduced CP scenario, and all scenarios for both 1100 farms did not fall within close range to the WF predicted in the Rotz et al. (2021) study. Additionally, the predicted CFs presented here are smaller than farm-gate CFs of 1.23 kg CO_2e/kg FPCM reported by Thoma et al. (2013) for the average US dairy farm.

4.1 2000-Head Conventional Farm

Although negligible, WFs increased through the end of the century (Figure 4.1). Water footprints for the mid-century period under RCP 4.5 were 160.6, 161.3, and 227.3 L H_2O/kg FPCM for baseline, covered lagoon, and reduced CP, respectively. For the late-century period under RCP 4.5, WFs were 159.0, 159.6, and 229.6 L H_2O/kg FPCM for baseline, covered lagoon, and reduced CP, respectively. Under RCP 8.5, mid-century WFs were predicted to be

160.4, 161.3, and 229.9 L H_2O/kg FPCM for baseline, covered lagoon, and reduced CP, respectively. The late-century period WF predictions were 165.5, 166.9, 244.3 L H2O/kg FPCM, respectively.

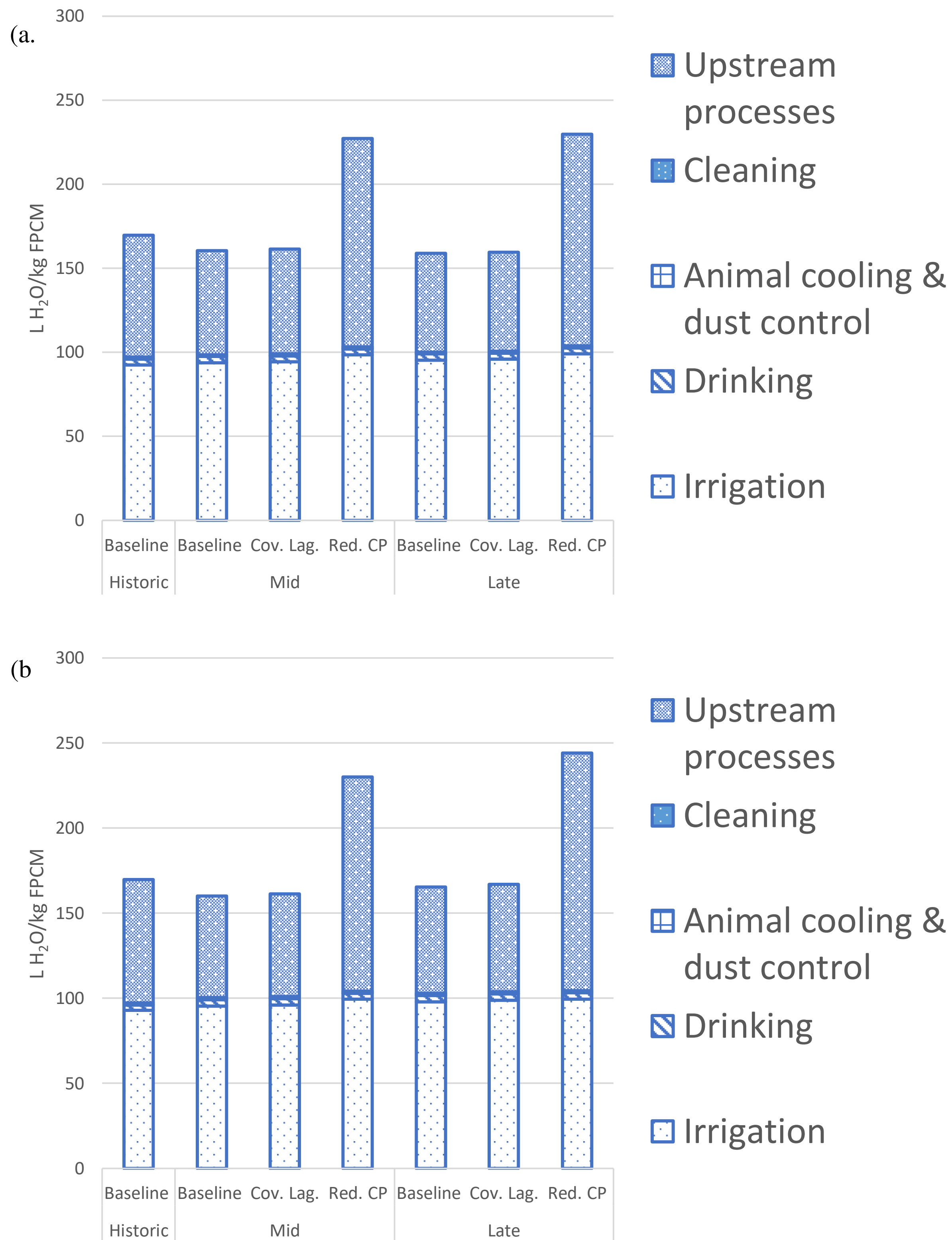
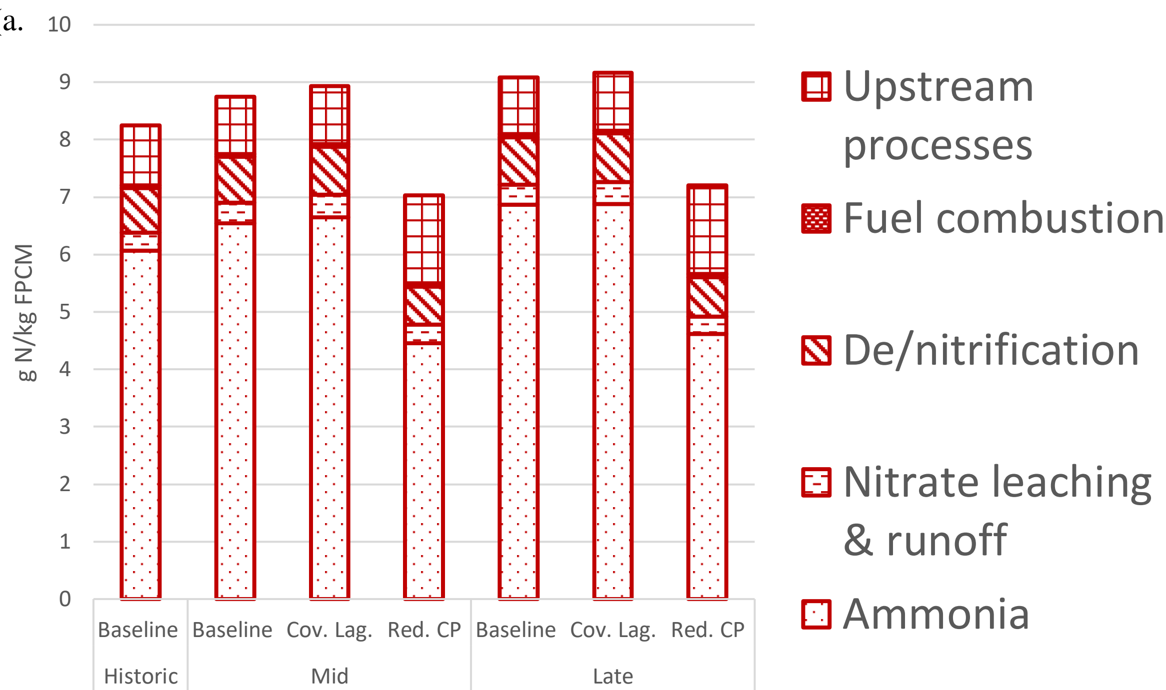


Figure 4.1: Blue water use footprints for a representative 2000C dairy farm in Northeast Colorado for historic (1990-2015), mid- (2040-2065), and late century (2075-2100) baseline and BMP scenarios across emissions scenarios (a) RCP 4.5 and (b) RCP 8.5.

Reactive nitrogen losses increased for all three scenarios over time (Figure 4.2). For the mid-century period under RCP 4.5, RnFs were 8.8, 8.9, 7.03 g N/kg FPCM, for baseline, covered lagoon, and reduced CP, respectively. Reactive nitrogen footprints for the late-century period under RCP 4.5 were 9.1, 9.2, and 7.2 g N/kg FPCM for baseline, covered lagoon, and reduced CP, respectively. Under RCP 8.5, mid-century RnFs were predicted to be 8.9, 9.13, and 7.2 g N/kg FPCM for baseline, covered lagoon, and reduced CP, respectively. The RCP 8.5 late-century period had footprints of 9.8, 10.0, and 7.79 g N/kg FPCM for baseline, covered lagoon, and reduced CP, respectively. For RCP 4.5, the majority of the increase to the RnF occurred by 2065 whereas RCP 8.5 consistently increased through the end of the century (Appendix A).

(a.



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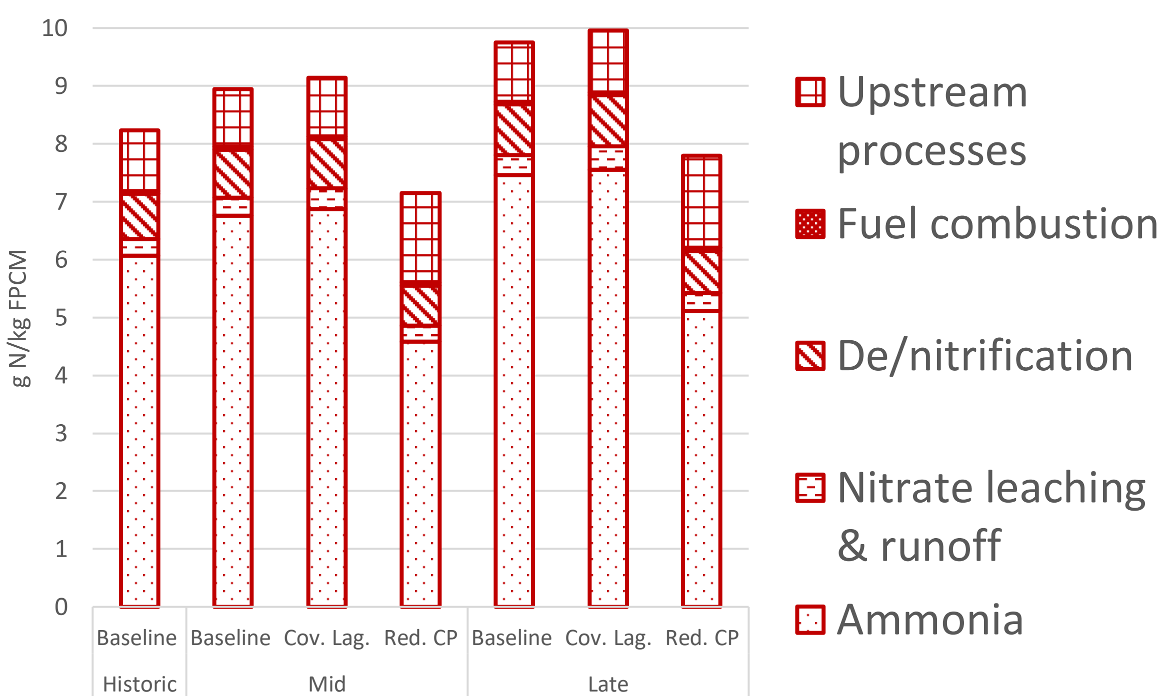


Figure 4.2: Reactive nitrogen loss footprints for a representative 2000C dairy farm in Northeast Colorado for historic (1990-2015), mid- (2040-2065), and late century (2075-2100) baseline and BMP scenarios across emissions scenarios (a) RCP 4.5 and (b) RCP 8.5.

Most of the EF was comprised of upstream processes (primarily purchased feed production) (Figure 4.3). For the mid-century period, EFs under RCP 4.5 were 2.4, 2.4, and 2.3 MJ/kg FPCM for baseline, covered lagoon, and reduced CP, respectively. Energy footprints for the late-century period under RCP 4.5 were 2.4, 2.4, and 2.3 MJ/kg FPCM for baseline, covered lagoon, and reduced CP, respectively. Under RCP 8.5, mid-century EFs were predicted to be 2.4, 2.4, and 2.3 MJ/kg FPCM for baseline, covered lagoon, and reduced CP, respectively. The RCP 8.5 late-century period predicted EFs of 2.5, 2.5, and 2.4MJ/kg FPCM as for the baseline, covered lagoon, and reduced CP scenarios, respectively. Under both RCPs, there was no noticeable differences in EFs between time periods or scenarios. Energy footprints were predicted to increase through the end of the century, but changes across scenarios and time periods were neg.

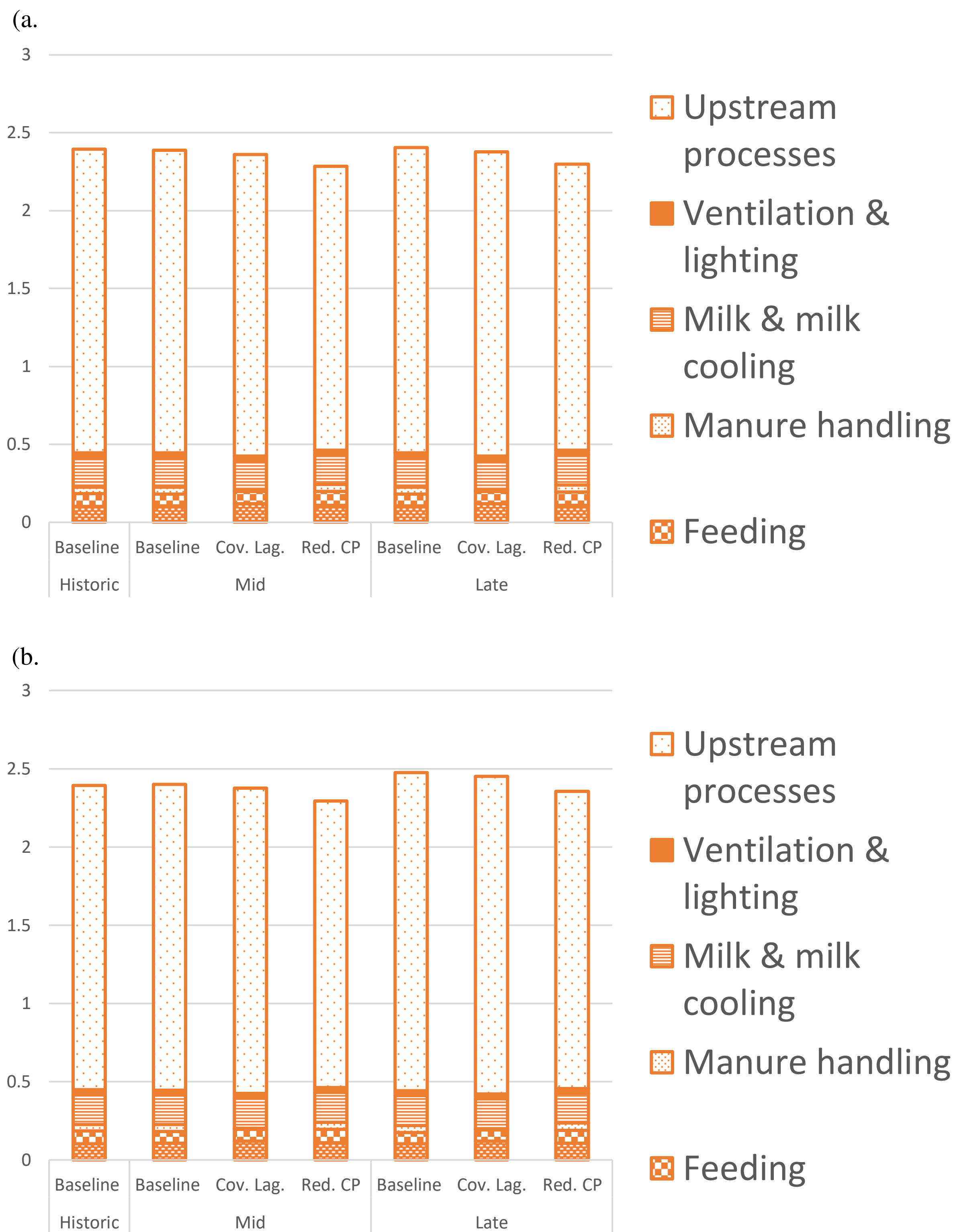


Figure 4.3: Fossil energy use footprints for a representative 2000C dairy farm in Northeast Colorado for historic (1990-2015), mid- (2040-2065), and late century (2075-2100) baseline and BMP scenarios across emissions scenarios (a) RCP 4.5 and (b) RCP 8.5.

Cumulative GHG emissions were similar among baseline and BMP scenarios with the covered lagoon predicting a slightly lower CF over time (Figure 4.4). Carbon footprints for the mid-century period under RCP 4.5 were 0.9, 0.9, and 0.8 kg CO_2e/kg FPCM for baseline, covered lagoon, and reduced CP, respectively. For the late-century period, RCP 4.5 CFs were 1.0, 0.9, and 0.8 kg CO_2e/kg FPCM for baseline, covered lagoon, and reduced CP, respectively. Under RCP 8.5, mid-century CFs were predicted to be 1.0, 0.9, and 0.8 kg CO_2e/kg FPCM for baseline, covered lagoon, and reduced CP, respectively. The RCP 8.5 late-century period predicted 1.0, 0.9, and 0.9 kg CO_2e/kg FPCM as the CFs for baseline, covered lagoon, and reduced CP, respectively.

(a.

(b.

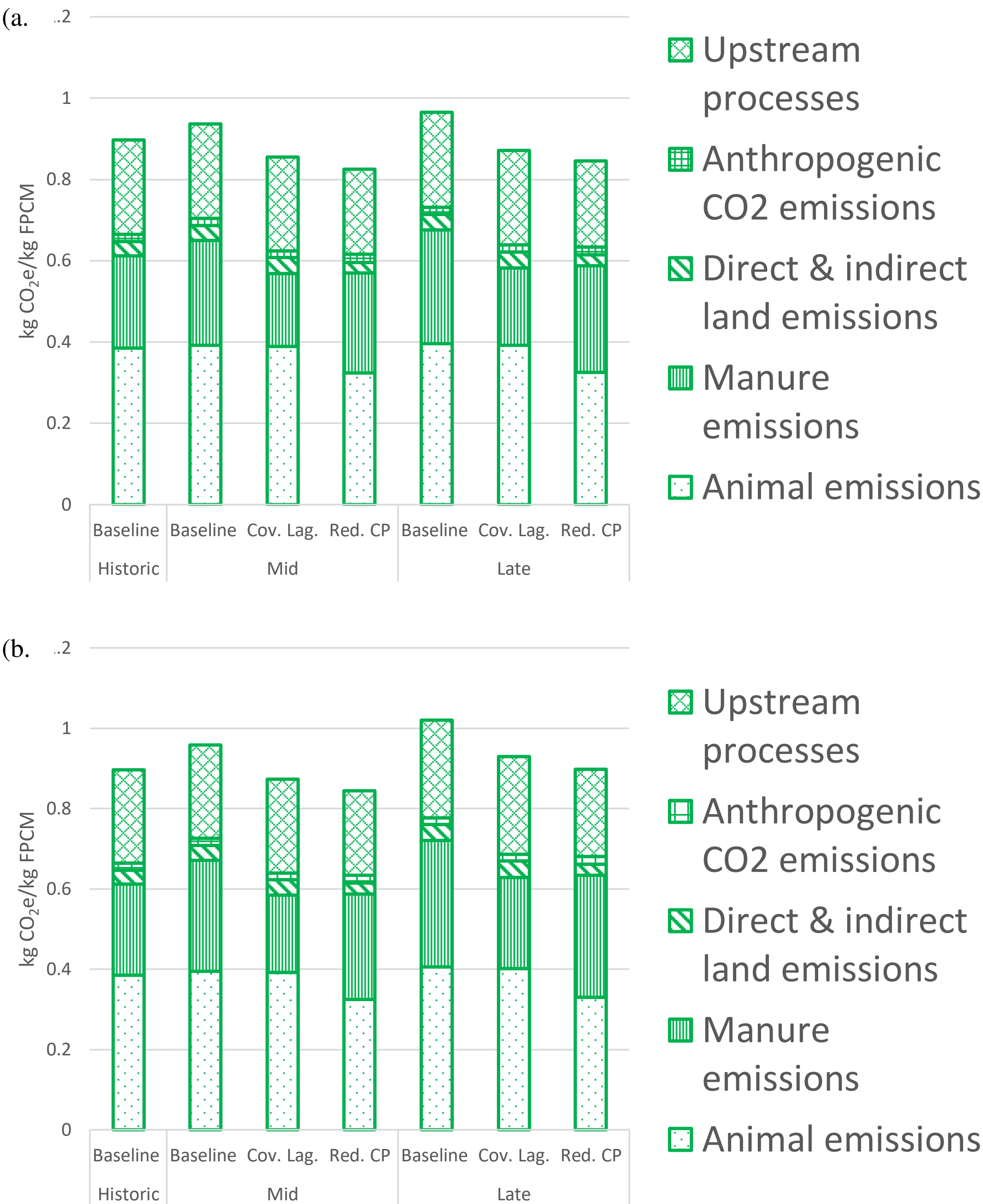


Figure 4.4: Carbon footprints for a representative 2000C dairy farm in Northeast Colorado for historic (1990-2015), mid- (2040-2065), and late century (2075-2100) baseline and BMP scenarios across emissions scenarios (a) RCP 4.5 and (b) RCP 8.5.

4.2 1100-Head Conventional Farm

For the 1100C farm, BMPs were designed to mitigate environmental impacts from manure production, handling, and storage. For WFs on the 1100C farm, there was no significant change in total footprint over time or between baseline and BMP scenarios (Figure 4.5). Water footprints for the mid-century period under RCP 4.5 were 452.3, 452.1, and 452.1 L H_2O/kg FPCM for baseline, covered lagoon, and covered lagoon + flare, respectively. For the late-century period, WFs under RCP 4.5 were 452.6, 452.4, and 452.4 L H_2O/kg FPCM for baseline, covered lagoon, and covered lagoon + flare, respectively. Under RCP 8.5, mid-century WFs were predicted to be 452.8, 452.5, and 452.5 L H_2O/kg FPCM for baseline, covered lagoon, and covered lagoon + flare, respectively. The RCP 8.5 late-century period simulated WFs to be 454.7, 454.4, and 454.4 L H2O/kg FPCM, respectively.

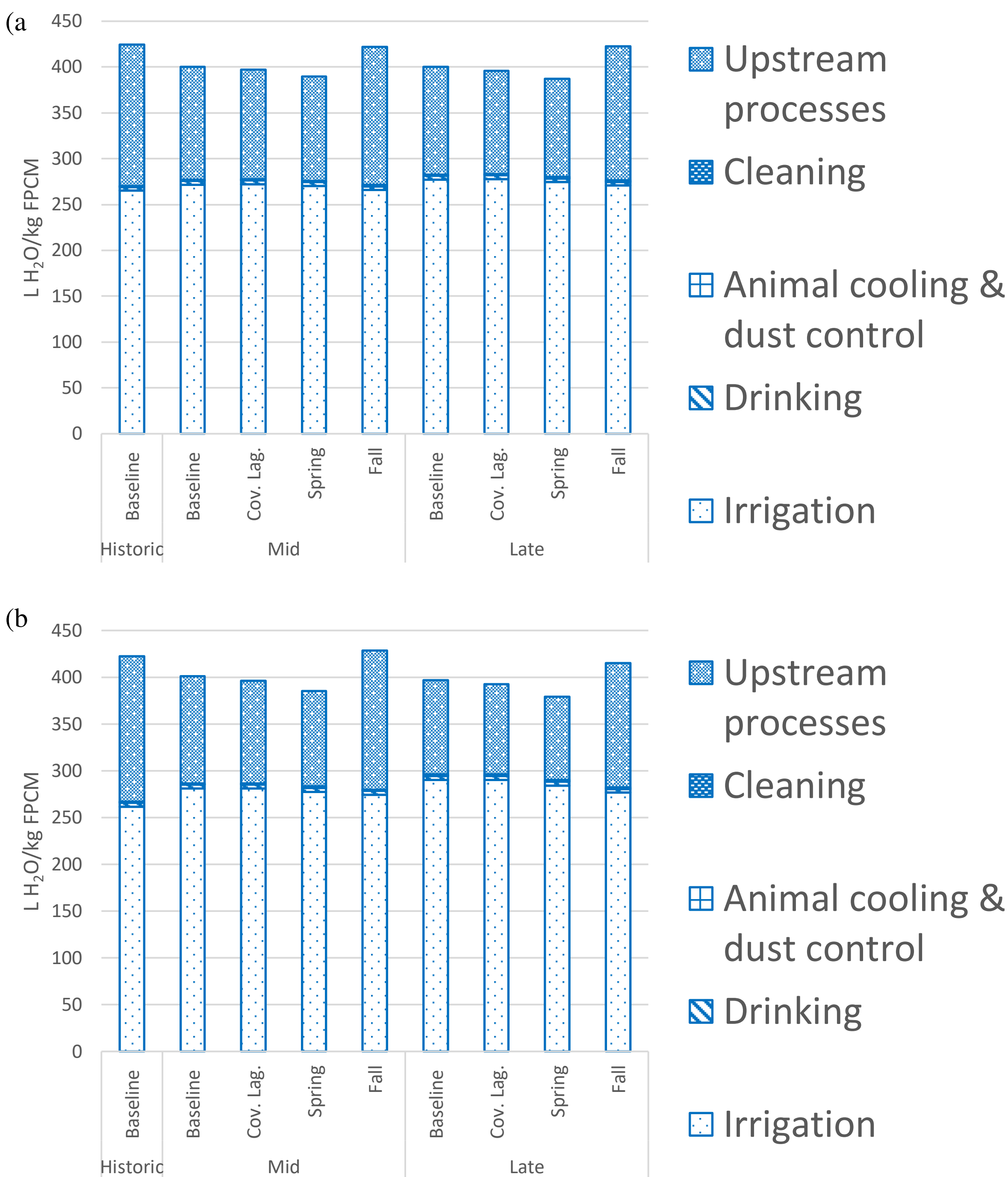
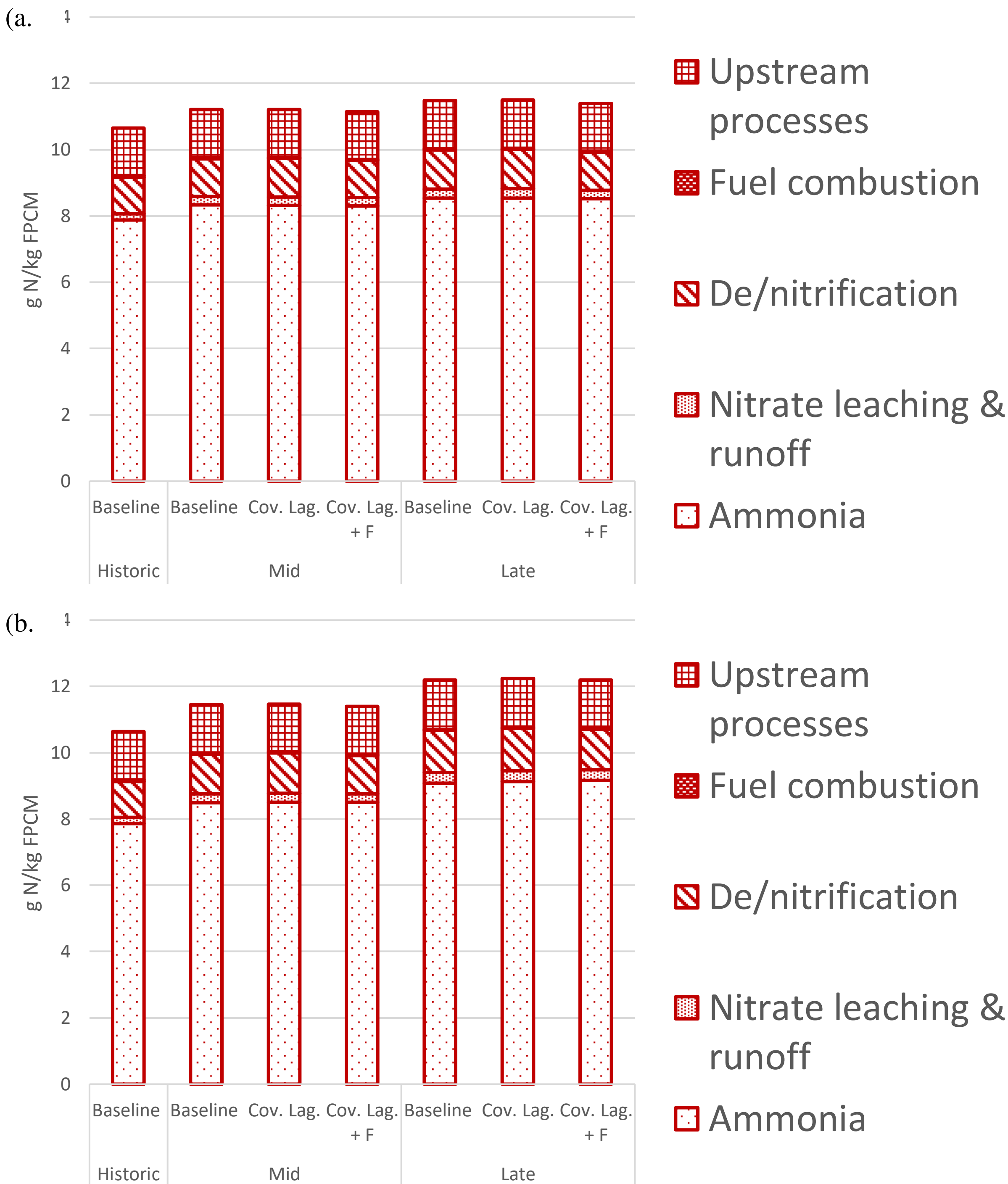


Figure 4.5: Blue water use footprints for a representative 1100C dairy farm in Northeast Colorado for historic (1990-2015), mid- (2040-2065), and late century (2075-2100) baseline and BMP scenarios across emissions scenarios (a) RCP 4.5 and (b) RCP 8.5.

The general trend for RnFs on the 1100C farm was to increase over time for baseline and BMP scenarios (Figure 4.6). For the mid-century period, RnFs under RCP 4.5 were 11.2 g N/kg FPCM for both baseline and BMP scenarios. The late-century period under RCP 4.5 simulated RnFs as 11.5, 11.5, and 11.4 g N/kg FPCM for baseline, covered lagoon, and covered lagoon + flare, respectively. Under RCP 8.5, mid-century WFs were predicted to be 11.5, 11.5, and 11.4 g N/kg FPCM for baseline, covered lagoon, and covered lagoon + flare, respectively. The RnF for the baseline and both BMP scenarios under RCP 8.5 for the late-century period were12.2 g N/kg FPCM.



Figures 4.6: Reactive nitrogen loss footprints for a representative 1100C dairy farm in Northeast Colorado for historic (1990-2015), mid- (2040-2065), and late century (2075-2100) baseline and BMP scenarios across emissions scenarios (a) RCP 4.5 and (b) RCP 8.5.

The EFs for the 1100C farm followed a similar trend of increasing overtime, however, both BMPs were effective in lowering the EF over time from baseline predictions (Figure 4.7). Energy footprints for the mid-century period under RCP 4.5 were 3.0, 3.0, and 2.9 MJ/kg FPCM for baseline, covered lagoon, and covered lagoon + flare, respectively. For the late-century period, EFs under RCP 4.5 were 3.0, 3.0, and 2.9 MJ/kg FPCM for baseline, covered lagoon, and covered lagoon + flare, respectively. Under RCP 8.5, mid-century EFs were predicted to be 3.0, 3.0, and 2.9 MJ/kg FPCM for baseline, covered lagoon, and covered lagoon + flare, respectively. The 8.5 late century simulated EFs to be 3.057, 3.02, and 2.941MJ/kg FPCM, respectively. The largest contributors to the EF for both RCPs were the upstream processes (primarily feed production), and there was not much variability between scenarios.

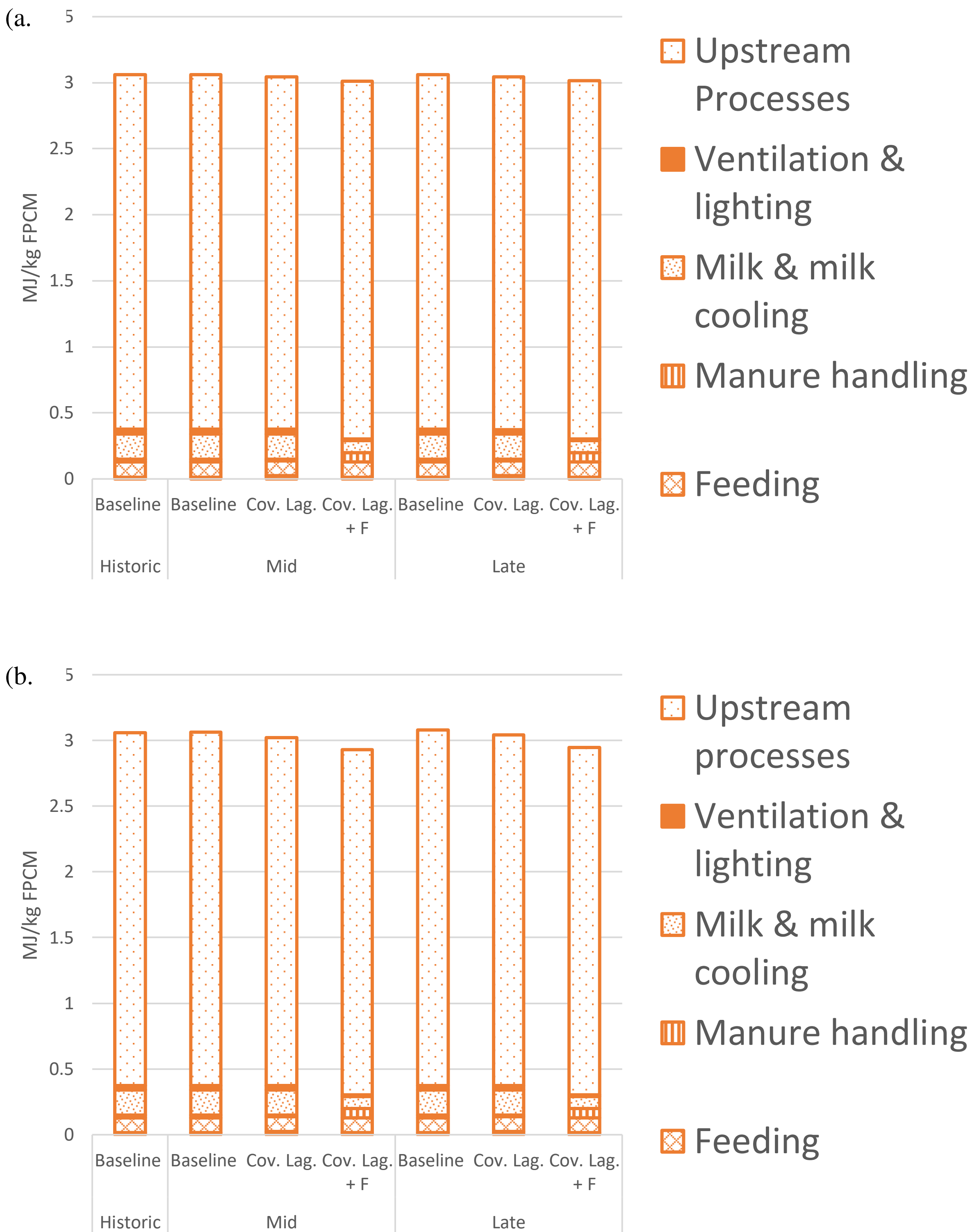
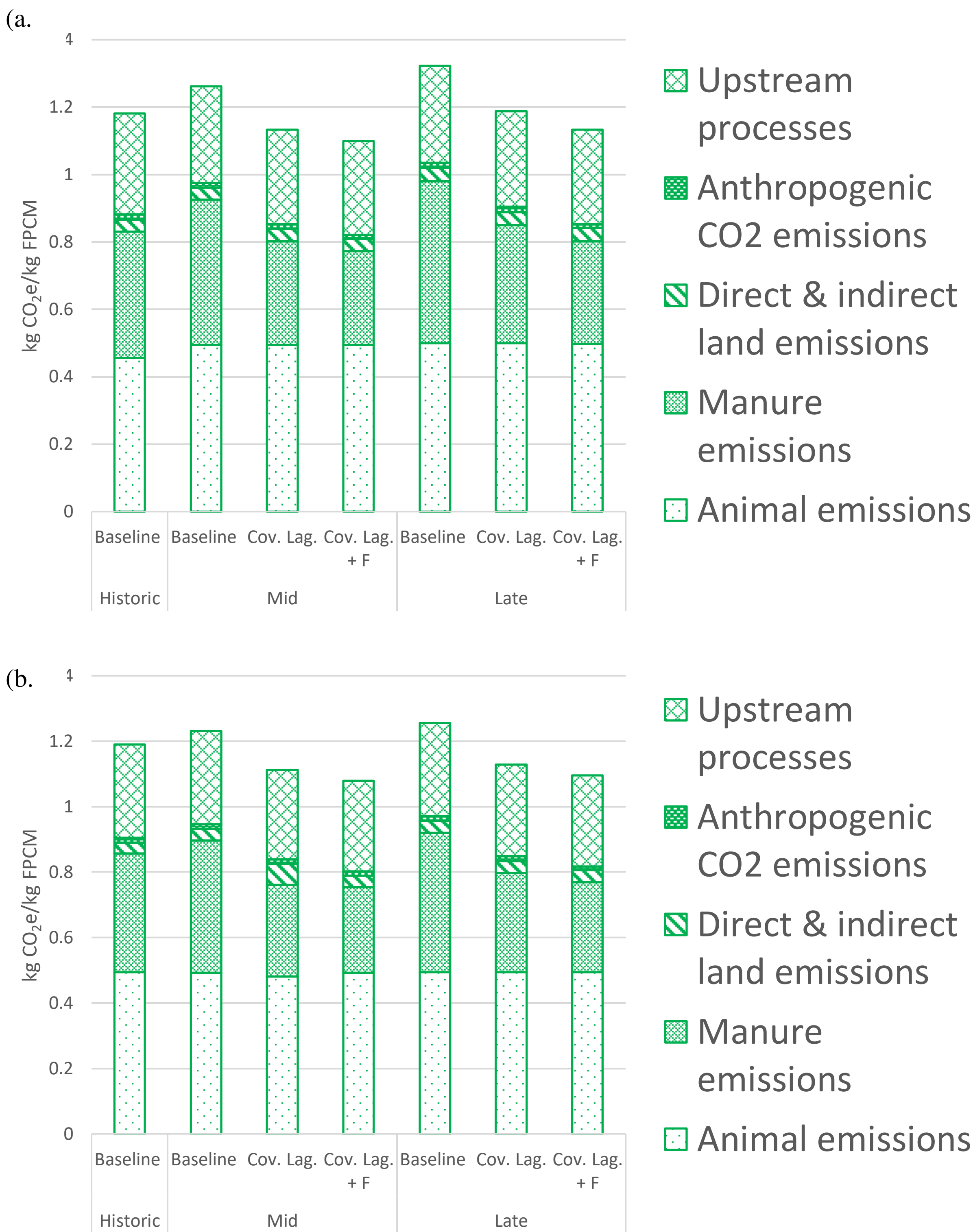


Figure 4.7: Fossil energy use footprints for a representative 1100C dairy farm in Northeast Colorado for historic (1990-2015), mid- (2040-2065), and late century (2075-2100) baseline and BMP scenarios across emissions scenarios (a) RCP 4.5 and (b) RCP 8.5.

Both the covered lagoon and covered lagoon + flare were effective in reducing the CF for the 1100C farm, however, the covered lagoon + flare BMP was most effective for reducing whole-farm GHG emissions (Figure 4.8). Carbon footprints for the mid-century period under RCP 4.5 were 1.2, 1.1, and 1.1 kg CO_2e/kg FPCM for baseline, covered lagoon, and covered lagoon + flare, respectively. For the late-century period, CFs under RCP 4.5 were 1.3, 1.1, and 1.1 kg CO_2e/kg FPCM for baseline, covered lagoon, and covered lagoon + flare, respectively. Under RCP 8.5, mid-century CFs were estimated to be 1.3, 1.1, and 1.1 kg CO_2e/kg FPCM for baseline, covered lagoon, and covered lagoon + flare, respectively. The 8.5 late-century period had CF values of 1.3, 1.2, and 1.1 kg CO_2e/kg FPCM, for baseline, covered lagoon, and covered lagoon + flare, respectively.

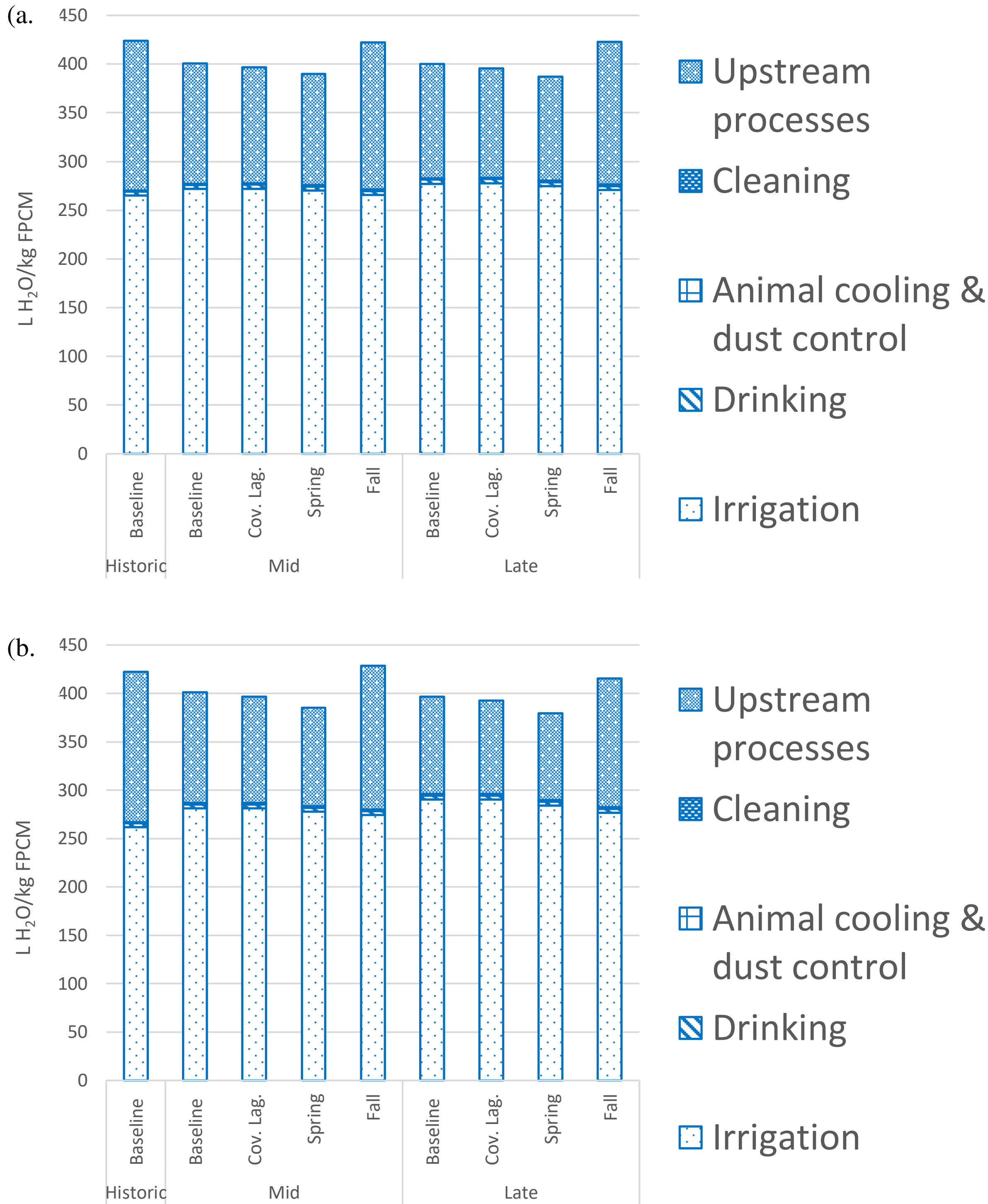


Figures 4.8: Carbon footprints for a representative 1100C dairy farm in Northeast Colorado for historic (1990-2015), mid- (2040-2065), and late century (2075-2100) baseline and BMP scenarios across emissions scenarios (a) RCP 4.5 and (b) RCP 8.5.

4.3 1100-Head Organic

For the 1100OR farm, the covered lagoon was the most successful in lowering all footprints from the baseline scenarios for all time periods. Spring milking also decreased footprint values compared to baseline values, however, fall milking increased footprints from baseline values. Results are visually presented in Figures 4.9-4.12 with each figure showing the general trend of footprints over time, changes to process contributions, and differences between RCPs 4.5 and 8.5.

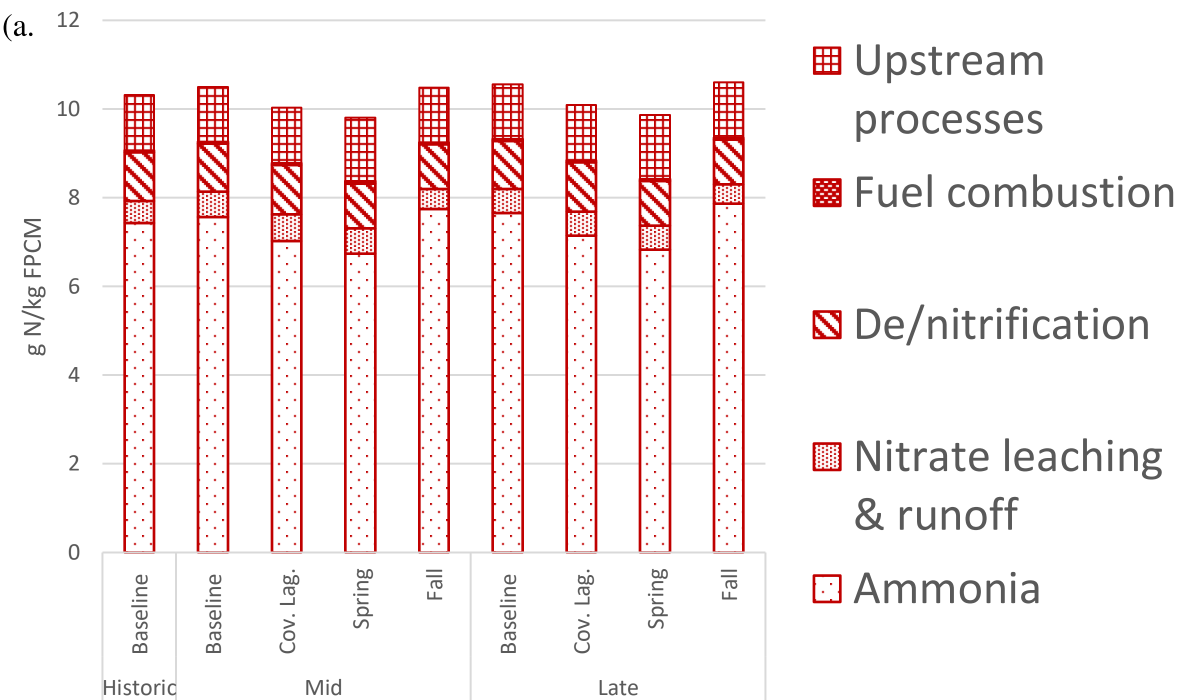
The directional change in WF for the 1100OR farm varied by time period and scenario (Figure 4.9). Water footprints for the mid-century period under RCP 4.5 were 400.5, 396.8, 390, and 422 L H_2O/kg FPCM for baseline, covered lagoon, spring milking, and fall milking, respectively. For the late-century period, WFs under RCP 4.5 were 400.4, 395.9, 386.9, and 422.9 L H_2O/kg FPCM for baseline, covered lagoon, spring milking, and fall milking, respectively. Under RCP 8.5, mid-century WFs were 401.3, 396.5, 385.1, and 428.4 L H_2O/kg FPCM for baseline, covered lagoon, spring milking, and fall milking, respectively. The 8.5 late-century period simulated 396.6, 392.5, 379.4, and 415.3 L H_2O/kg FPCM as the WFs for baseline, covered lagoon, spring milking, and fall milking, respectively. There was no noticeable difference in WF between baseline and covered lagoon scenarios , and no significant change in WF across all RCPs and scenarios over time.



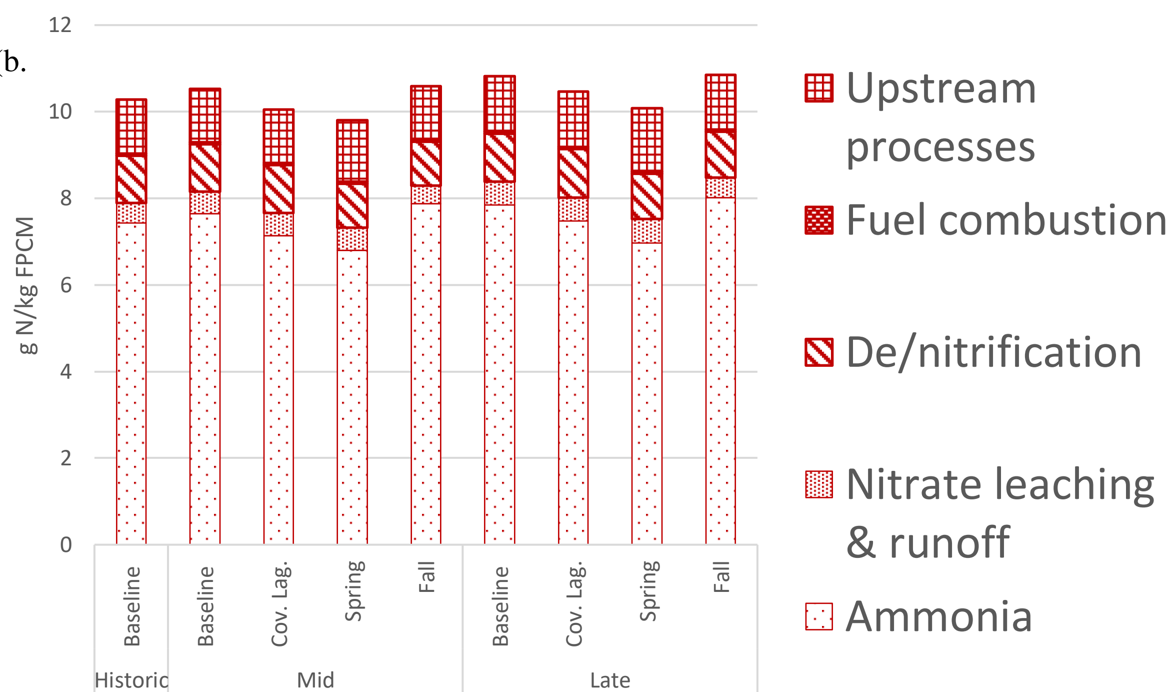
Figures 4.9: Blue water use footprints for a representative 1100OR dairy farm in Northeast Colorado for historic (1990-2015), mid- (2040-2065), and late century (2075-2100) baseline and BMP scenarios across emissions scenarios (a) RCP 4.5 and (b) RCP 8.5.

Both covered lagoon and spring milking were effective in reducing the RnF footprints from the 1100OR farm over time (Figure 4.10). The general trend for RnFs for all scenarios was an increase over time, and most of the increase occurred by 2065. For the mid-century period, RnFs under RCP 4.5 were 10.5, 10.0, 9.8, and 10.5 g N/kg FPCM, for baseline, covered lagoon, spring milking, and fall milking, respectively. Reactive nitrogen footprints for the late-century period under RCP 4.5 were 10.6, 10.01, 9.9, and 10.6 g N/kg FPCM for baseline, covered lagoon, spring milking, and fall milking, respectively. Under RCP 8.5, mid-century RnFs were 10.5, 10.1, 9.8, and 10.6 g N/kg FPCM for baseline, covered lagoon, spring milking, and fall milking, respectively. The 8.5 late-century period RnFs were 10.8, 10.471, 10.1, and 10.8 g N/kg FPCM as the RnFs for baseline, covered lagoon, spring milking, and fall milking, respectively. Fall milking was not much different from the baseline RnF, and during the mid-century period it was greater.

(a.

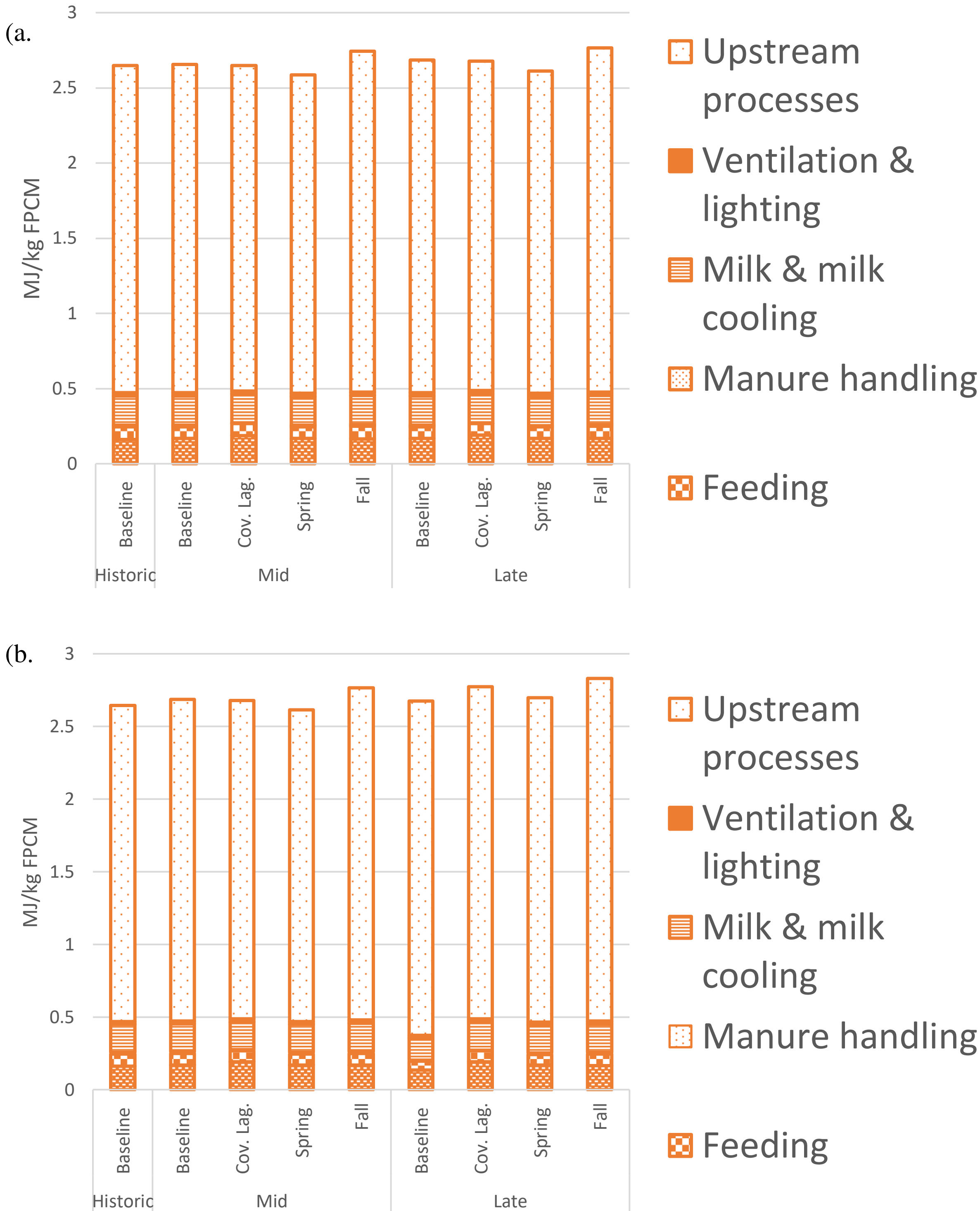


(b.



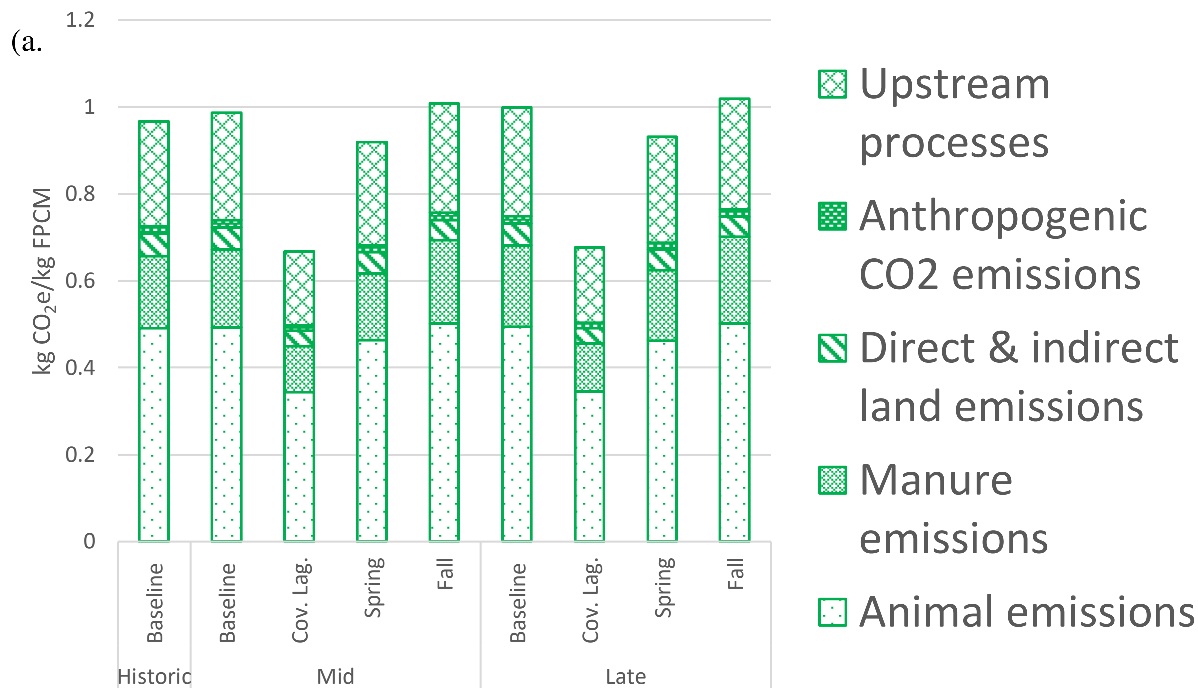
Figures 4.10: Reactive nitrogen loss footprints for a representative 1100OR dairy farm in Northeast Colorado for historic (1990-2015), mid- (2040-2065), and late century (2075-2100) baseline and BMP scenarios across emissions scenarios (a) RCP 4.5 and (b) RCP 8.5.

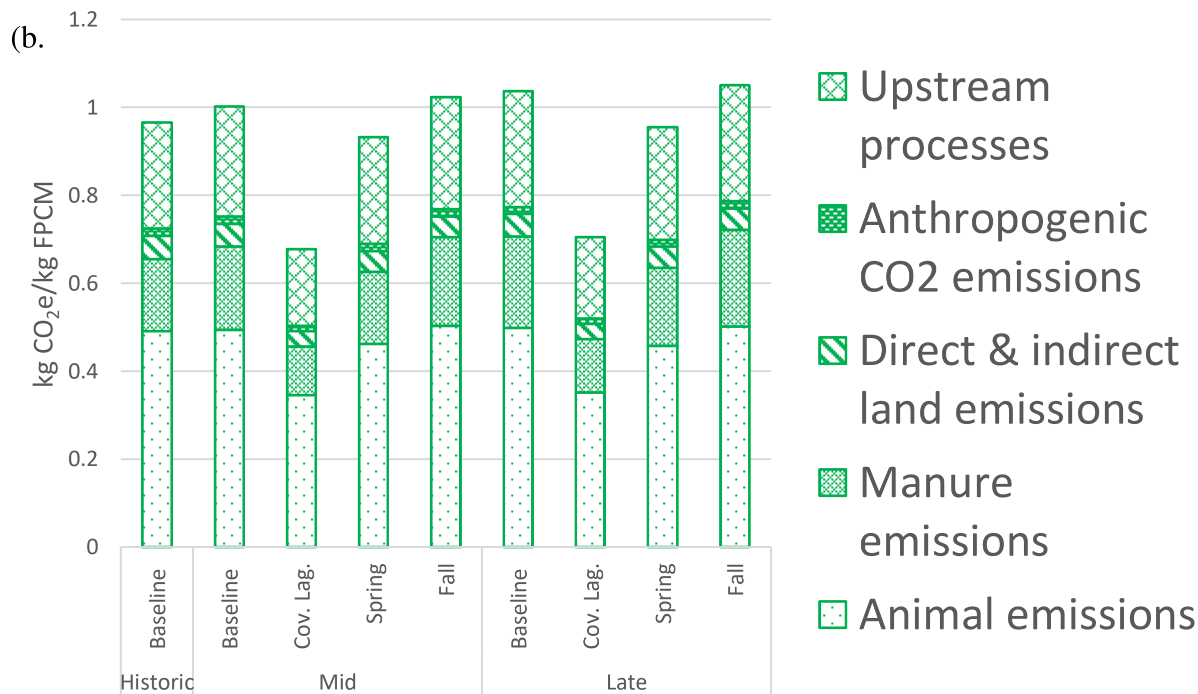
The general trend for EFs for all four scenarios was that energy use increased over time (Figure 4.11). For the mid-century period, EFs under RCP 4.5 were 2.7, 2.65, 2.6, and 2.7 MJ/kg FPCM for baseline, covered lagoon, spring milking, and fall milking, respectively. Energy footprints for the late-century period under RCP 4.5 were 2.7, 2.7, 2.6, and 2.8 MJ/kg FPCM for baseline, covered lagoon, spring milking, and fall milking, respectively. Under RCP 8.5, mid-century EFs were 2.7, 2.7, 2.6, and 2.8 MJ/kg FPCM for baseline, covered lagoon, spring milking, and fall milking, respectively. The EFs for the 8.5 late-century period were 2.8, 2.8, 2.7, and 2.8 MJ/kg FPCM for covered lagoon, spring milking, and fall milking, respectively.



Figures 4.11: Fossil energy use footprints for a representative 1100OR dairy farm in Northeast Colorado for historic (1990-2015), mid- (2040-2065), and late century (2075-2100) baseline and BMP scenarios across emissions scenarios (a) RCP 4.5 and (b) RCP 8.5.

For the 1100OR farm, covered lagoon and spring milking were successful in lowering the total GHG intensities (Figure 4.12). All four scenarios predicted an increase in the CF overtime. For the mid-century period, CFs under RCP 4.5 were 0.9, 0.7, 0.9, and 1 kg CO_2e/kg FPCM for baseline, covered lagoon, spring milking, and fall milking, respectively. Carbon footprints for the late-century period under RCP 4.5 were 1, 0.7, 0.9, and 1 CO_2e/kg FPCM for baseline, covered lagoon, spring milking, and fall milking, respectively. Under RCP 8.5, mid-century CFs were 1, 0.8, 0.9, and 1 CO_2e/kg FPCM for baseline, covered lagoon, spring milking, and fall milking, respectively. The 8.5 late-century period CFs were 1, 0.7, 0.9, and 1CO_2e/kg FPCM for covered lagoon, spring milking, and fall milking, respectively.





Figures 4.12: Carbon footprints for a representative 1100OR dairy farm in Northeast Colorado for historic (1990-2015), mid- (2040-2065), and late century (2075-2100) baseline and BMP scenarios across emissions scenarios (a) RCP 4.5 and (b) RCP 8.5.

CHAPTER 5: DISCUSSION

The results of the BMPs simulated in this study suggest that there is potential for mitigating future environmental impacts of northern Colorado dairy operations while maintaining current production levels. Generally, every footprint increased through 2100, irrespective of farm size, climate model, or RCP. Though all footprints increased through the end of the century, while implementation of some BMPs mitigated the rate and size of the change. Use of BMPs also changed the contribution of each process to the overall footprint, which in some cases mitigated the cumulative emissions and total resource use, even if the footprint increased overall. When considering percent change over time, differences from the baseline or historic environmental footprint values need to surpass 10% to be considered significant or indicative of vulnerability (Reeves et al., 2017). In this discussion, percent changes are discussed when they provide meaningful context to changes in footprints or are indicative of potential vulnerabilities.

The footprints for both baseline and BMP scenarios in this study are comparable to the range of footprints predicted for dairies in the South-Central region of the United States (Rotz et al., 2021); carbon footprints ranged from 0.82 to 1.27 kg CO_2e/kg FPCM, reactive nitrogen from 6.45 to 15.6 g N/kg FPCM, blue water from 28 to 327 kg H_2O/kg FPCM, and energy use from 2.08 to 2.91 MJ/kg FPCM.

5.1 Baseline Simulations

On the 2000C farm, the most meaningful changes to footprints over time were for the RnF and CF under both RCPs. Under RCP 4.5 the RnF was predicted to increase by 10% and the CF was predicted to increase by 8%. Both footprints exceeded a 10% increase under RCP 8.5, with the RnF increasing by 14% and the CF by 19% by 2100. The largest contributor to the RnF was ammonia emissions, which are of considerable concern in Colorado because of the arid climate, lack of moisture, and ability for ammonia to easily volatilize (Killpack & Buchholz, 2022). There were negligible increases in the 2000C farm WF and EF through the end of the century. However, blue water allocated to irrigation, drinking, and animal cooling showed slight increases (<5%) from the historic use to the end of century time period. This is likely a result of the increasing temperatures and decreasing and reduction in precipitation in Colorado present in the weather files generated by climate models (data not shown). These changes would lead to an increase in the plant and animal water demand to continue meeting current production standards (Elliott et al., 2014; Walz, 2015).

The 1100C farm presented similar trends for the baseline simulations. The RnF and CF showed the greatest change over time with the WF and EF changing, both were only a 1% reduction under both RCPs through 2100. As before, ammonia emissions from ammonification were the greatest contributors to the RnF, and manure, animal, and upstream processes emissions were the greatest process contributor to the CF. Blue water use on the 1100C farm was almost entirely attributed to upstream processes as the farm was not producing home grown feed. As a result, the WF stayed nearly constant through the end of the century. Cows on this farm also required more water for drinking and cooling purposes over time, but the increase was <5%.

Lastly, the 1100OR farm showed meaningful changes for the CF, because the footprint increased by more than 10% through the end of the century. Under RCP 4.5, the CF increased by 11%, and under RCP 8.5 it increased by 16%. On the 1100OR, animal emissions were the greatest process contributor to the CF, mainly due to greater CH_4 emissions. Additionally, the on-farm irrigation needs were greater for the 1100OR farm due to the use of irrigated pasture during the grazing season. In general, the WF and EF either stayed consistent or slightly increased under both RCPs through the end of the century. Similar to the conventional farms, the water requirements for irrigation, animal drinking, and animal cooling increased slightly.

5.2 Manure Management Simulations

Manure management BMPs were simulated for all three of the representative dairy farms used in this study. Across all farms, BMPs focused on improved manure storage showed promise for both smaller environmental footprints and decreased percent change over time compared to the baseline production practices. In general, the covered lagoon and covered lagoon + flare BMPs simulated in this study reduced both carbon and nitrogen emissions. On the 2000C farm, implementing a covered lagoon was successful in mitigating cumulative GHG emissions under both RCPs, specifically by reducing the contribution of manure N_2O emissions to the CF. Furthermore, under RCP 4.5, the covered lagoon successfully reduced the percent change of the CF over time, resulting in a 2% decrease to the footprint from the historic baseline CF. Under RCP 8.5, the percent change was 3% over time. However, the covered lagoon BMP was not successful in reducing the RnF over time, and was predicted to have a greater percent change through 2100 compared to the baseline scenario. Under RCP 4.5 the RnF footprint was predicted to have a similar trend to the baseline footprint, and increased by 11% over time. Under RCP 8.5, the RnF footprint was predicted to increase by 20% from the historic to late century time period, which may result in more environmental impacts than if manure management practices from the baseline scenario were maintained. Regardless of whether the covered lagoon BMP was successful in mitigating footprints in comparison to the baseline, both scenarios predict an increase to potential environmental impacts from manure management on the 2000C farm.

The 1100C farm was modeled with both a covered lagoon and a covered lagoon + flare manure management BMPs. Similar to the 2000C farm, the most notable changes were to the

RnF and CF for both RCPs. Under RCP 4.5, the RnF increased by 8% overtime, and under RCP 8.5 the RnF increased by 15% for both BMPs. Although the BMPs were successful in providing some reduction to reactive nitrogen losses on the 1100C farm, they predicted similar to, or greater percent change over time when compared to the baseline footprints. In an earlier modeling study of midwestern dairies, a sealed lagoon with flare on a 1500-head was not effective in reducing reactive nitrogen losses compared to their baseline scenario, which had a RnF of 11.8 g N/kg FPCM (Veltman et al., 2018). Both the covered lagoon and covered lagoon + flare BMPs reduced the CF on the 1100C farm over time compared to the baseline, most noticeably through manure emissions because of the form of manure storage (covered lagoon or covered lagoon + flare vs. top lined earthen basin and stacked). Under RCP 4.5 the CF was predicted to increase by 3% and under RCP 8.5 by 7%. Although negligible, use of both manure management BMPs also showed potential to reduce energy footprints on the 1100C farm under both RCPs by reducing energy required on farm for milking and milk cooling. The manure management BMPs showed the most promise in reducing cumulative GHG emissions from the 1100C farm, and potential to mitigate increases in environmental impacts.

The covered lagoon was similarly effective for the 1100OR farm, however, it performed better in reducing both the RnF and CF. For both footprints, the covered lagoon not only reduced the total value of the footprint from the baseline, but also reduced significant process contributions and the percent change over time. The CF was most impacted through reductions in both manure and animal emissions. Compared to the baseline, the total CF was reduced by approximately 32%, animal emissions by approximately 30%, and manure emissions by up to 40% depending on the RCP. The percent change over time for the CF was 3% under RCP 4.5 and 7% under RCP 8.5. The RnF did not show as dramatic of reductions when the covered lagoon BMP was implemented, but it was still successful in predicting reduced reactive nitrogen losses compared to the baseline scenario, most noticeably through lowered ammonia emissions. Through the end of the century, the RnF changed by 3% under RCP 4.5 and 8% under RCP 8.5. For the CF, use of a covered lagoon may be successful in reducing total footprint and percent change of footprint over time, however for the RnF the percent change over time may increase even if the total footprint is reduced.

Although both conventional and organic production systems require adequate manure management, the amount of manure being handled between the differing management systems may explain why the 1100OR farm had such success in reducing certain parameters of environmental footprints and impacts. The 1100OR farm likely had less manure to handle from the barn than the conventional farms because animals were kept on pasture for part of the year, while cows on the 2000C and1100C farms were managed in confinement year-round. Manure on the organic farm was only collected and stored when cows were kept in the barn, while during the pasture growing season it was left as fertilizer. This difference in manure and animal management may contribute to the 1100OR farm having lower GHG emissions from manure than the conventional farms.

5.3 Feed Management Simulations

Overall, reducing CP in lactating dairy cows was successful in achieving a smaller RnF, and was the most effective in reducing reactive nitrogen losses across BMPs. Compared to the baseline and manure management BMP, RnFs were smallest for the reduced CP simulations across time periods and under Both RCPs. This result was roughly 9% less than the reduced RnF following reduced dietary CP estimated for dairies in the Midwest (Veltman et al.). The RnF associated with reduced CP content in the Veltman et al. (2018) study was 10.1 g N/kg FPCM, which roughly 9% greater than the RnFs predicted in this study. In addition to successfully reducing the RnFs on the 2000C farm, reducing the CP in the diet predicted fewer animal emissions contributing to cumulative GHG emissions from the 2000C farm, which resulted in a smaller CF over time compared to the baseline. One unexpected impact of reducing the CP content of the diet was an increase in blue water use. Specifically, the water designated to upstream processes almost doubled in comparison to the production of resource inputs for the baseline and covered lagoon scenarios. The reduced CP scenario represented a change in ration formulation through the use of soybean meal and AA supplements, all of which were imported feed instead of homegrown. Such larger upstream requirements may be accounted for by the soybean meal and AA supplement having greater water footprints than feeds used in the baseline scenarios. Although reducing CP in the diet may be successful in mitigating nitrogen and carbon concerns on a dairy farm, producers should be wary of the impacts it may have on other footprints and environmental contributions.

5.4 Seasonal Milking and Calving Simulations

Seasonal milking and calving simulations were implemented on the 1100OR farm, and in some cases were successful in reducing environmental footprints and impacts from the farm. On the organic farm, there was more variability in footprint values between baseline and BMP scenarios compared to either conventional farm. For RnFs, the spring cycle reduced total reactive nitrogen losses and ammonia emissions over time compared to the baseline scenario, but the fall cycle increased them. Similar to the conventional farms, ammonia emissions were the process contribution driving the change in RnFs, between both spring and fall cycles, but also compared to the baseline. The fall cycle had greater ammonia emissions, which may be explained by the cows being confined and more manure being stored during peak production. Although ammonia is more volatile when temperatures are warmer, the manure during the fall cycle was not available during the growing season to align with plant growing cycles. The manure had more opportunity to volatilize and emit ammonia in storage over the winter season before being applied to fields as fertilizer, whereas the spring cycle either used manure as it was available for fertilizer, or left it on pasture when the animals were grazing. Furthermore, if the manure was applied to fields during the winter season, the soil would not be able to absorb the nutrients, which would increase the ammonia emissions as the manure N undergoes volatilization (Bauder et al., n.d.).

Both spring and fall cycles predicted a larger CF by the late time period than the baseline, however, both cycles reduced the percent change to <10% over time. Increases to the CF were a result of increased animal emissions. Opposite the other footprints, WFs on the 1100OR were predicted to decrease over time in some instances. The largest decrease was for spring milking, with RCP 4.5 decreasing by about 7% and RCP 8.5 by almost 9% (Appendix C). However, both seasonal milking BMPs had higher WFs than baseline and covered lagoon scenarios. The decrease in WF may be a result of water available in the West for irrigation and crop use, along with predicted decreases in precipitation throughout the region (Barnett et al., 2004).

Seasonal milking and calving are potentially beneficial practices for grazing-based dairies because they place all cows on a uniform lactation cycle, which allows producers to better match forage demands with forage availability and quality (Rotz et al., 2018). Seasonal dairying results in overall reduced farm costs, specifically because of lower grain costs, less use of equipment, and less of a need for labor year-round. Furthermore, individual cows tend to produce higher profits because of the lower input costs (Rotz et al., 2018). A limitation to seasonal milking and calving cycles is that the farm must have access to adequate land to maintain animals on pasture.

5.5 Limitations

The greatest limitation to implementing the findings of this study is the lack of infrastructure. Both the covered lagoon and covered lagoon + flare BMPs require land, resources, financial flexibility, and labor to be viable options for dairy producers, which may not be available on farms in Colorado. This is not necessarily a negative impact, but it does mean that clear targets with consideration for potential tradeoffs should be identified.

5.6 Recommendations and future work

Future work should build on this study by building whole-farm BMP packages where feasible (e.g., reducing dietary CP in combination with using a covered lagoon). This way, tradeoffs and interactions between emissions and footprints can be better accounted for and would provide additional insight to industry stakeholders about how to minimize environmental impacts moving forward. Specifically for manure BMPs, it would be beneficial to couple manure injection as a method of manure application to fields with covered lagoon storage. Future modeling studies should also continue to explore dietary manipulation on Colorado dairy farms. This could include simulating other forms of protein supplementation for reduced CP diets, and alternative feeds such as sorghum instead of corn.

CHAPTER 6: CONCLUSION

The IPCC Sixth Assessment Report shows that the global temperatures will reach or exceed °C within two decades (2021). As a result, Colorado and the broader west will likely experience negative ramifications to the environment, ecosystems, and agriculture production. Specifically, dairy production has significant environmental impacts that may challenge future production and the ability for the industry to meet production needs. The use of Beneficial Management Practices (BMPs) can mitigate GHG emissions and nutrient losses from the state's dairy systems that have negative ramifications for the environment. We used a process-based model (IFSM) to predict carbon, reactive nitrogen, blue water, and energy footprints under baseline and BMP scenarios for two representative concentration pathways (RCPs) and three time periods (historic, mid, and late century). The BMPs included reduced dietary protein, covered lagoon, covered lagoon with flare, and seasonal milking. BMPs were assigned based on feasibility of implementation and simulated on three representative farms (1100-head conventional, 2000-head conventional, and 1100-head organic). Implementation of a reduced protein BMP on the 2000C was successful in decreasing the RnF and CF. The covered lagoon BMPs (with and without flare) were both effective in reducing CFs across farms. The covered lagoon with flare was only applied to the 1100C farm, but it is likely that it would have the same impact on the 2000C and 1100OR farms. Lastly, seasonal milking was simulated for fall and spring cycles on the 1100OR farm. The spring cycle performed better, but did not necessarily reduce footprints from the baseline predictions through 2100. Next steps for this research will focus on assessing footprints on a whole-farm basis by simulating BMP packages instead of individual BMPs.

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APPENDIX

APPENDIX A.

PERCENT CHANGES OVER TIME FOR BLUE WATER, REACTIVE NITROGEN, ENERGY, AND CARBON FOOTPRINTS OVER TIME (1990-2100) ON A 2000-HEAD CONVENTIONAL DAIRY FARM.

BW	Baseline		Covered lagoon		REDUCED CP	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Historic-mid	-5.389	-5.355	-4.977	-4.839	45.936	48.016
Mid-late	-0.988	3.203	-1.046	3.488	0.333	0.708
Historic-late	-6.325	-2.324	-5.971	-1.519	46.422	49.063

RNF	Baseline		Covered lagoon		REDUCED CP	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Historic-mid	6.091	8.718	8.319	11.103	8.545	9.356
Mid-late	3.842	9.038	2.616	8.886	1.228	4
Historic-late	10.167	18.545	11.152	20.975	9.879	13.730

EF	Baseline		Covered lagoon		REDUCED CP	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Historic-mid	-0.261	0.313	-1.410	-0.731	9.392	9.770
Mid-late	0.785	3.177	0.689	3.211	0.341	0
Historic-late	0.522	3.501	-0.731	2.456	9.765	9.770

CF	Baseline		Covered lagoon		REDUCED CP	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Historic-mid	4.3178	4.318	-4.735	-2.650	12.674	14.923
Mid-late	3.071	6.389	1.900	6.447	1.360	1.820
Historic-late	7.521	13.807	-2.925	3.626	14.206	17.015

APPENDIX B.

PERCENT CHANGES OVER TIME FOR BLUE WATER, REACTIVE NITROGEN, ENERGY, AND CARBON FOOTPRINTS OVER TIME (1990-2100) ON A 1100-HEAD CONVENTIONAL DAIRY FARM.

BW	Baseline		Covered lagoon		Covered lagoon + flare	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Historic-mid	1.25676E-14	0.11055526	-0.002765	0.10230886	-0.002765	0.10230886
Mid-late	0.069091311	0.42240689	0.07189073	0.41986631	0.07189073	0.41986631
Historic-late	0.525093964	0.52509396	0.06912379	0.52260473	0.06912379	0.52260473

RNF	Baseline		Covered lagoon		Covered lagoon + flare	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Historic-mid	5.242171924	7.74929445	5.44129745	7.977409107	5.81257414	8.24325929
Mid-late	2.351236907	6.395285387	2.485510477	6.745123679	2.25336323	7.08877428
Historic-late	7.716664712	14.64016933	8.062051945	15.2606189	8.19691578	15.9163796

EF	Baseline		Covered lagoon		Covered lagoon + flare	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Historic-mid	0	0.20618557	-0.0833333	0.04166667	0	0.08561644
Mid-late	0.082474227	0.65843621	0.04170142	0.62473969	0.08561644	0.64157399
Historic-late	0.082474227	0.86597938	-0.0416667	0.66666667	0.08561644	0.72773973

CF	Baseline		Covered lagoon		Covered lagoon + flare	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Historic-mid	3.466386555	6.772486772	2.652825836	4.61361015	1.76886792	4.02366864
Mid-late	2.030456853	4.85629336	1.460674157	4.740904079	1.50637312	3.185438
Historic-late	5.567226891	11.95767196	4.152249135	9.573241061	3.30188679	7.33727811

APPENDIX C.

PERCENT CHANGES OVER TIME FOR BLUE WATER, REACTIVE NITROGEN, ENERGY, AND CARBON FOOTPRINTS OVER TIME (1990-2100) ON A 1100-HEAD ORGANIC DAIRY FARM.

BW	Baseline		Covered lagoon		Spring milking		Fall milking	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Historic -mid	-5.584	-4.942	-5.823	-5.533	-6.621	-7.470	-2.255	-0.349
Mid-late	-0.037	-1.171	-0.266	-1.018	-0.782	-0.074	0.210	-3.061
Historic -late	-5.619	-6.055	-6.072	-6.495	-7.351	-8.831	-2.050	-3.399

RNF	Baseline		Covered lagoon		Spring milking		Fall milking	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Historic -mid	1.695	2.284	2.426	3.035	1.581	1.949	2.694	4.0408
Mid-late	0.643	2.839	0.623	4.126	0.663	2.842	1.0972	2.514
Historic -late	2.350	4.845	3.064	7.287	2.255	4.847	3.821	6.657

EF	Baseline		Covered lagoon		Spring milking		Fall milking	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Historic -mid	0.236	1.560	0.331	1.659	0.731	2	-0.363	0.591
Mid-late	1.082	3.166	1.085	3.451	1.064	3.252	0.729	2.306
Historic -late	1.321	4.805	1.420	5.168	1.802	5.317	0.363	2.908

CF	Baseline		Covered lagoon		Spring milking		Fall milking	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Historic -mid	4.317	6.973	1.521	3.435	1.377	3.039	1.511	3.023
Mid-late	6.676	8.083	1.498	4.059	1.223	2.413	1.117	2.812
Historic -late	11.281	15.620	3.042	7.634	2.617	5.525	2.645	5.919

APPENDIX D.

AVERAGE TEMPERATURE, PRECIPITATION, ANNUAL SNOW, AND ANNUAL SOLARD RADITION FOR 25 YEARS OF WEATHER IN AKRON, CO.

	Temperature (°C)	Precipitation (mm)	Annual snow (mm)	Solar radiation (mJ/m2)
Winter	-1.7	16.8		
Spring	9.1	107.9		
Summer	21.6	184.1		
Fall	9.8	71.5		
Annual	9.7	380.3	12.8	15.8

APPENDIX E.

AVERAGE TEMPERATURE, PRECIPITATION, ANNUAL SNOW, AND SOLAR RADIATION FOR HISTORIC, MID, AND LATE CENTURY TIME PERIODS IN STERLING, CO.

HISTORIC	Temperature (°C)	Precipitation (mm)	Annual snow (mm)	Solar radiation (mJ/m2)
Winter	-1.92	25.50		
Spring	9.87	124.00		
Summer	23.15	158.90		
Fall	10.70	68.56		
Annual	10.41	376.93	11.50	16.91

MID	Temperature (°C)	Precipitation (mm)	Annual snow (mm)	Solar radiation (mJ/m2)
Winter	0.81	32.5		
Spring	12.08	144.65		
Summer	25.98	159.09		
Fall	13.04	71.31		
Annual	12.94	407.55	9.13	17.01

LATE	Temperature (°C)	Precipitation (mm)	Annual snow (mm)	Solar radiation (mJ/m2)
Winter	2.90	38.44		
Spring	13.87	155.10		
Summer	28.53	143.43		
Fall	15.14	72.60		
Annual	15.07	409.58	7.53	17.00