EVALUATING THE IMPACTS OF CLIMATE CHANGE AND VARIABILITY ON GRAZING DAIRY PRODUCTION

By

Maria Melissa Rojas-Downing

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ABSTRACT

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The global demand for milk production is expected to double by 2050, mostly due to population growth and income rise in developing countries. Meanwhile, increases in milk production can accelerate negative impacts that contribute to land degradation, climate change, water shortages and pollution. Therefore, it is important to meet the increasing demand for milk production under sustainable practices. Meanwhile, milk production is also impacted by climate change and variability. The rise of carbon dioxide, temperature increases, and increasing precipitation variation are the main factors that will impact forage quality and growth. Therefore, among livestock systems, the grazing system is likely to be the most impacted by climate change and variability because of its dependency on forage quality and quantity. However, the level of impacts and measures to mitigate and adapt to these impacts are not very well known.

To address these knowledge gaps, we developed a study based on the following research objectives: 1) understand the global impacts of climate change on livestock production, the contribution of livestock production to climate change, and specific adaptation and mitigation strategies for the sector; 2) study the adoption measure (pasture diversification) to identify the most climate resilient pasture composition for a representative grazing dairy farm in Michigan; and 3) identify the most sustainable milk production for a representative grazing dairy farm in Michigan by considering economic, water, energy, and carbon footprints.

In order to address the first objective, a literature review was performed, which showed that livestock production will be limited by climate change and variability and competition for

water, land, and food security. Meanwhile, the livestock sector is a major contributor to greenhouse gas (GHG) emissions, driving further climate change. Consequently, the livestock sector will be a key player in the mitigation of GHG emissions and improving global food security. Therefore, in the transition to sustainable livestock production, there is a need for assessing the use of adaptation and mitigation measures tailored to the location and livestock production system.

To address objectives two and three, a representative farm was developed based on grazing dairy farm practices surveys and incorporated into the Integrated Farm System Model (IFSM). For the pasture compositions, four cool-season grass species with the two legumes were evaluated, which resulted in 48 pasture compositions.

For objective two, the effectiveness and resiliency of the pasture compositions to climate change impacts were evaluated based on economic and resource use criteria. Results showed that the increase in precipitation and temperature of the most intensive climate scenario would significantly improve farm net return per cow and whole farm profit. Perennial ryegrass with red clover was identified as the most resilient pasture composition to improve farm economics and resource use under climate change.

Under objective three, a multi-criterion decision making method was used to calculate a new footprint (food footprint) to assess sustainability of a grazing dairy farm. Using IFSM, carbon, water, energy, and economic impacts of the representative farm in 10 locations in Michigan were calculated. Using food footprint, the most sustainable milk production level was identified in each location. The results of this analysis are promising since it encourages a high level of milk production (8,618 kg/cow/year) while promoting the most sustainable approach for grazing farm management.

To my husband, who with all his love, support, sacrifice, encouragement and faith made the accomplishment of this thesis possible. With all my love this is for you.

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KEY TO ABBREVIATIONS

ANPP: Net Primary Productivity

ARS: Agricultural Research Service

BCC: Beijing Climate Center

BCSD: Bias-Correction Spatial Disaggregation

BOM: Bureau of Meteorology

CCCma: Canadian Centre for Climate Modelling and Analysis

CGIAR: Consultative Group for International Agricultural Research

CH_4: Methane

CMIP5: Coupled Model Intercomparison Project Phase 5

CNRM-CERFACS: Centre National de Recherches Meteorologiques - Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique

CO_2: Carbon Dioxide

CP: Crude Protein

CSIRO: Commonwealth Scientific and Industrial Research Organization

CSIRO-QCCCE: Commonwealth Scientific and Industrial Research - Queensland Climate Change Centre of Excellence

DM: Dry Matter

DNA: Deoxyribonucleic Acid

FAO: Food and Agriculture Organization of the United Nations

FCPM: Fat and Protein Corrected Milk

GCESS: College of Global Change and Earth System Science

GCM: General Circulation Model

GFDL: Geophysical Fluid Dynamics Laboratory

GHG: Greenhouse Gas

GIS: Geographic Information System

GLEAM: Global Livestock Environmental Assessment Model

GMFD: Global Meteorological Forcing Dataset

GRAZPLAN: Decision Support Software for Grazing Enterprises

GWP: Global Warming Potential

HUC: Hydrologic Unit Codes

IFSM: Integrated Farm System Model

INM: Institute for Numerical Mathematics

IPCC: Intergovernmental Panel on Climate Change

IPSL: Institute Pierre-Simon Laplace

LCA: Life Cycle Assessment

MATLAB: Matrix Laboratory

MCDM: Multi-Criterion Decision-Making

MPI-M: Max Planck Institute for Meteorology

MRI: Meteorological Research Institute

MSU: Michigan State University

N_2O: Nitrous Oxide

NASA: National Aeronautics and Space Administration

NCAR: National Center for Atmospheric Research

NCC: Norwegian Climate Centre

NCDC: National Climatic Data Center

NDF: Neutral Detergent Fiber

NEFA: Non-Esterified Fatty Acids

NEX-GDDP: Earth Exchange Global Daily Downscaled Projections

NFIFO: Net Farm Income from Operations

NOAA: National Oceanic and Atmospheric Administration

NSF-DOE-NCAR: National Science Foundation - Department of Energy - National Center for Atmospheric Research

RCP: Representative Concentration Pathways

SD: Standard deviation

SWAT: Soil and Water Assessment Tool

USDA: U.S. Department of Agriculture

VIKOR: Multi-Criteria Optimization and Compromise Solution

WXGEN: Stochastic Weather Generator Model

1 INTRODUCTION

In the last 40 years, livestock production and demand have rapidly expanded and are expected to continue, mainly due to population growth and improvement in the worldwide standard of living (FAO, 2008; FAO, 2014). Livestock is a major sector of the agricultural industry, accounting for 40% of the global value of agricultural outputs (FAO, 2017). In the United States, the annual economic contribution from the livestock sector is worth $346 billion (United Soybean Board, 2013). In addition, this sector contributes to the livelihoods of 70% of the world's lowest income rural population and employs close to 1.1 billion people (Hurst et al., 2005; FAO, 2014). Livestock products provide 17% of global kilocalorie consumption and 33% of global protein consumption making them an important agricultural commodity for global food security (Rosegrant et al., 2009). Therefore, the growth of the livestock sector provides opportunities for agricultural development, food security, and poverty reduction (FAO, 2017). However, it will be fundamental for the sector to meet the growing demand in a sustainable manner under stressors, such as climate change.

Climate change is a threat to livestock production because of the impacts on quality and quantity of feed crop and forage, water availability, animal and milk production, livestock diseases, animal reproduction, and biodiversity (Chapman et al., 2012; IFAD, 2010; Polley et al., 2013; Thornton et al., 2009; Henry et al., 2012; Nardone et al., 2010; Reynolds et al., 2010). Among livestock systems, grazing is likely to be the most impacted by climate change because of its dependency on feed quality and availability. Meanwhile, adaptation measures can increase the resilience of livestock production to climate change. Therefore, there is a need to identify successful adaptation measures that can be implemented to reduce the negative impacts of climate change. Among adaption measures, plant diversification is one that has high probability of selection by grazing farm producers since it only requires changing the seeding practices.

Most of the grazing livestock systems are for beef and dairy production and the demand is expected to increase 44% and 55%, respectively, by 2030 (Havlík et al., 2014). In addition, the United States is the largest cow's milk producer in the world with 41% of its production concentrated in the Great Lakes region (USDA-NASS 2014c; FAO 2016a). Therefore, the ***goal*** of the first study was to identify the most resilient pasture composition for a representative grazing dairy farm in order to minimize the negative impacts of climate change. The study assesses the resiliency of the pasture compositions by evaluating the economic and resource use (feed production and consumption) of the farm. The specific objectives were:

- Identify the best pasture composition under current and future climate scenarios concerning farm economics and resource use
- Assess economic and resource use impacts of pasture compositions under future climate scenarios
- Evaluate the resiliency of pasture compositions to climate change

Meanwhile, livestock production is the largest user of resources in the world (FAO, 2017). Livestock feed production currently accounts for 80% of all agricultural land (FAO, 2017). In addition, this sector accounts for about 8% of global human water use (Nardone et al., 2010). The livestock sector is also responsible for several environmental issues such as land and habitat degradation, water and air pollution, and biodiversity destruction (Bellarby et al., 2013; Reynolds et al., 2010; Steinfeld et al., 2006; Thornton and Gerber, 2010). Moreover, the livestock sector is one of the largest contributors to anthropogenic GHG emissions (14.5% of global anthropogenic GHG emissions), which are the major cause of global climate change

(Gerber et al., 2013). Therefore, there is a need to identify mitigation measures that will improve the sustainability of livestock productions. The US Department of Agriculture (USDA) defines sustainable agriculture as a site-specific plant-animal production system that in the long-term will fulfill human feeding needs (e.g. milk), improve the environment (e.g. GHG emissions), use resources efficiently (e.g. water, energy), maintain financial management (e.g. farm economy), and enhance the life quality of both farmers and society (e.g. social wellbeing) (Gold, 2007). Different indicators, such as footprints, have been used to measure sustainability (Čuček et al., 2012). However, the majority of studies have used carbon footprint as the only measure of sustainability (Adom et al., 2012; de Léis et al., 2015; FAO, 2010b; Flysjö et al, 2011; Mc Geough et al., 2012; O'Brien et al., 2014). A comprehensive sustainability study should also consider other aspects, such as water and energy requirements and economic feasibility that may be impacted by the proposed management practices (OECD, 2004). Therefore, the ***goal*** of the second study was to identify the most sustainable milk production system for a representative grazing dairy farm under different climate conditions within the State of Michigan. The specific objectives were:

- Identify the most sustainable milk production system in different locations
- Identify the pasture composition for each targeted milk production in different locations
- Understand the spatial variability of sustainable milk productions and associated pasture compositions for different locations

2 LITERATURE REVIEW

2.1 Overview

Human population is expected to increase from 7.2 to 9.6 billion by 2050 (UN, 2013). This represents a population increase of 33%, but as the global standard of living increases, demand for agricultural products will increase by about 70% in the same period (FAO, 2009a). Meanwhile, total global cultivated land area has not changed since 1991 (O'Mara, 2012), reflecting increased productivity and intensification efforts.

Livestock products are an important agricultural commodity for global food security because they provide 17% of global kilocalorie consumption and 33% of global protein consumption (Rosegrant et al., 2009). The livestock sector contributes to the livelihoods of one billion of the poorest population in the world and employs close to 1.1 billion people (Hurst et al, 2005). There is a growing demand for livestock products, and its rapid growth in developing countries has been deemed the “livestock revolution” (Thornton, 2010; Wright et al., 2012). Worldwide milk production is expected to increase from 664 million tonnes (in 2006) to 1077 million tonnes (by 2050), and meat production will double from 258 to 455 million tonnes (Alexandratos and Bruinsma, 2012). Livestock production is likely to be adversely affected by climate change, competition for land and water, and food security at a time when it is most needed (Thornton, 2010).

Global climate change is primarily caused by GHG that result in warming of the atmosphere (IPCC, 2013). The livestock sector contributes 14.5% of global GHG emissions (Gerber et al., 2013), and thus may increase land degradation, air and water pollution, and declines in biodiversity (Bellarby et al., 2013; Reynolds et al., 2010; Steinfeld et al., 2006; Thorton and Gerber, 2010). At the same time, climate change will affect livestock production through competition for natural resources, quantity and quality of feeds, livestock diseases, heat stress and biodiversity loss. Therefore, the challenge is to maintain a balance between productivity, household food security, and environmental preservation (Wright et al., 2012).

There is growing interest in understanding the interaction of climate change and agricultural production and it is motivating a significant amount of research (Aydinalp and Cresser, 2008). There is still limited research regarding the impacts of climate change on livestock production (IPCC, 2014). This literature reviews the impacts of climate change on livestock production and food security, and the livestock sector's contribution to climate change.

2.2 Topical Review

2.2.1 Impact of Climate Change on Livestock

Despite uncertainties in climate variability, the IPCC Fifth Assessment Report identified the "likely range" of increase in global average surface temperature by 2100, which is between 0.3°C and 4.8°C (IPCC, 2013). The potential impacts on livestock include changes in production and quality of feed crop and forage (Chapman et al., 2012; IFAD, 2010; Polley et al., 2013; Thornton et al., 2009), water availability (Henry et al., 2012; Nardone et al., 2010; Thornton et al., 2009), animal growth and milk production (Henry et al., 2012; Nardone et al., 2010; Thornton et al., 2009), diseases (Nardone et al., 2010; Thornton et al., 2009), reproduction (Nardone et al., 2010), and biodiversity (Reynolds et al., 2010). These impacts are primarily due to an increase in temperature and atmospheric carbon dioxide (CO_2) concentration, precipitation variation, and a combination of these factors (Aydinalp and Cresser, 2008; Henry et al., 2012; IFAD, 2010; Nardone et al., 2010; Polley et al., 2013; Reynolds et al., 2010; Thornton et al., 2009). The impacts of climate change on livestock production factors are presented in Figure 1. Temperature affects most of the critical factors for livestock production, such as water availability, animal production, reproduction and health. Forage quantity and quality are affected by a combination of increases in temperature, CO_2 and precipitation variation. Livestock diseases are mainly affected by an increase in temperature and precipitation variation.

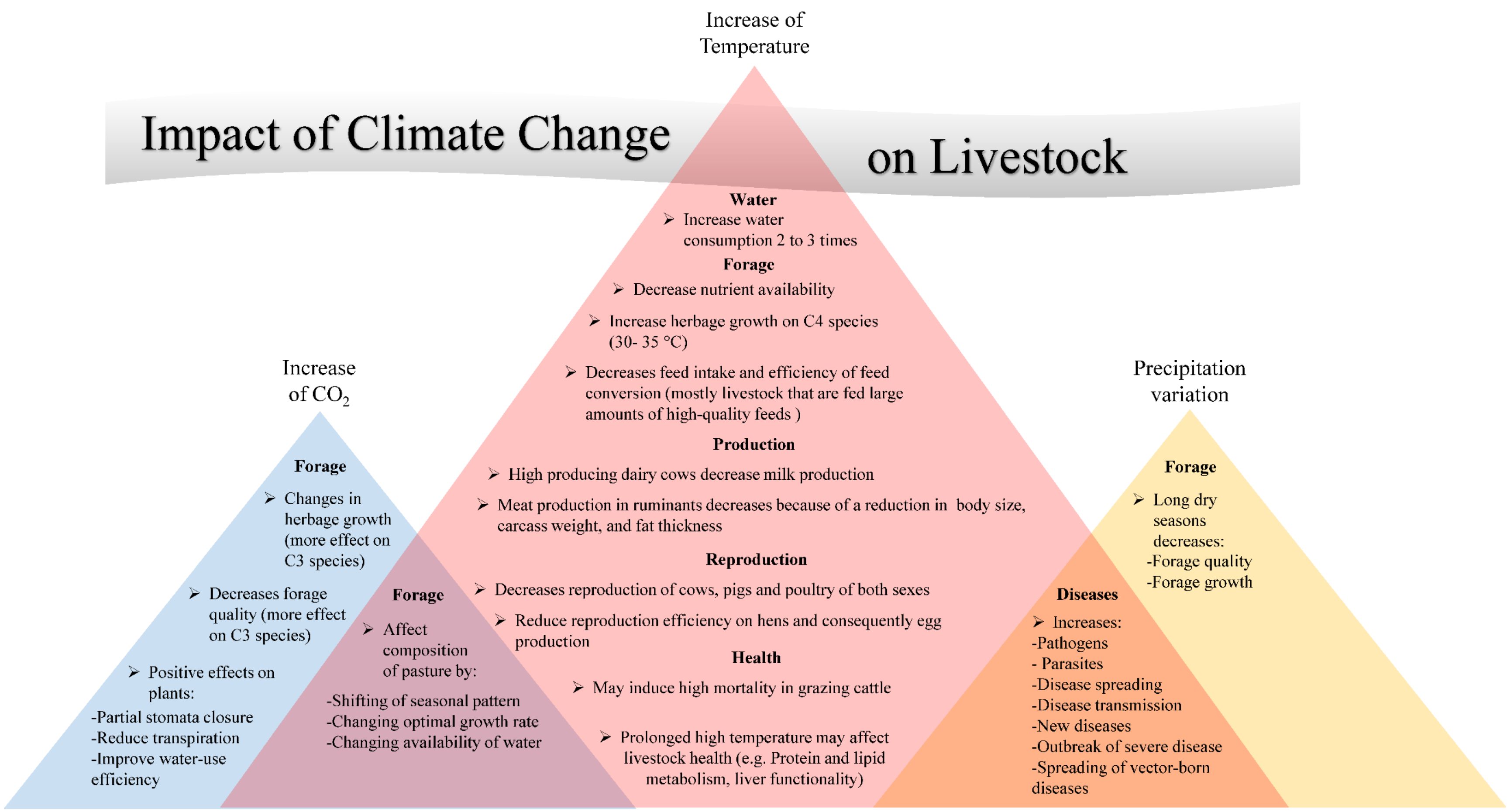

Figure 1. Impacts of Climate Change on Livestock

2.2.1.1 Quantity and quality of feeds

Quantity and quality of feed will be affected mainly due to an increase in atmospheric CO_2 levels and temperature (Chapman et al., 2012). The effects of climate change on quantity and quality of feeds are dependent on location, livestock system, and species (IFAD, 2010). Some of the impacts on feed crops and forage are:

- Increase of CO_2 concentration will result in herbage growth changes, with greater effect on C3 species and less on grain yields (Chapman et al., 2012; Hatfield and Prueger, 2011; Thornton et al., 2009, 2015). The effects of CO_2 will be positive due to inducing partial closure of stomata, reducing transpiration, and improving some plants' water-use efficiency (Rotter and van de Geijn, 1999; Wand et al., 1999).
- C4 species (which account for less than 1% of plants on Earth) are found in warm environments, and have higher water-use efficiency than C3 plants. Temperature increases to 30-35°C could increase herbage growth, with larger effects on C4 species. However, the effects may vary depending on the location, production system used, and plant species (Hatfield and Prueger, 2011; IFAD, 2010; Thornton et al., 2009; Thornton and Herrero, 2010).
- Changes in temperature and CO_2 levels will affect the composition of pastures by altering the species competition dynamics due to changes in optimal growth rates (IFAD, 2010; Thornton et al., 2008; Thornton et al., 2009, 2015). Plant competition is influenced by seasonal shifts in water availability (Polley et al., 2013). Primary productivity in pastures may be increased due to changes in species composition if temperature, precipitation, and concurrent nitrogen deposition increase (IPCC, 2007).

- Quality of feed crops and forage may be affected by increased temperatures and dry conditions due to variations in concentrations of water-soluble carbohydrates and nitrogen. Temperature increases may increase lignin and cell wall components in plants (Polley et al., 2013; Sanz-Saez et al., 2012), which reduce digestibility and degradation rates (IFAD, 2010; Polley et al., 2013), leading to a decrease in nutrient availability for livestock (Thornton et al., 2009). However, as CO_2 concentration rises forage quality will improve more in C3 plants than C4 plants. C3 plants also have greater crude protein content and digestibility than C4 plants (Polley et al., 2013; Thornton et al., 2009; Wand et al., 1999).

Impacts on forage quantity and quality depend on the region and length of growing season (Polley et al., 2013; Thornton et al., 2009). An increase of 2°C will produce negative impacts on pasture and livestock production in arid and semiarid regions and positive impacts in humid temperate regions. The length of growing season is also an important factor for forage quality and quantity because it determines the duration and periods of available forage. A decrease in forage quality can increase methane emissions per unit of gross energy consumed (Benchaar et al., 2001). Therefore, if forage quality declines, it may need to be offset by decreasing forage intake and replacing it with grain to prevent elevated methane emissions by livestock (Polley et al., 2013).

2.2.1.2 Water

Global agriculture uses 70% of fresh water resources, making it the world's largest consumer (Thornton et al., 2009). However, global water demand is moving towards increased competition due to water scarcity and depletion, where 64% of the world's population may live under water-stressful conditions by 2025 (Rosegrant et al., 2002).

Water availability issues will influence the livestock sector, which uses water for animal drinking, feed crops, and product processes (Thornton et al., 2009). The livestock sector accounts for about 8% of global human water use and an increase in temperature may increase animal water consumption by a factor of two to three (Nardone et al., 2010). To address this issue, there is a need to produce crops and raise animals in livestock systems that demand less water (Nardone et al., 2010) or in locations with water abundance.

As sea level rises, more saltwater will be introduced into coastal freshwater aquifers (Karl et al., 2009). Salination adds to chemical and biological contaminants and high concentrations of heavy metals already found in waterbodies worldwide and may influence livestock production (Nardone et al., 2010). Water salination could affect animal metabolism, fertility, and digestion. Chemical contaminants and heavy metals could impair cardiovascular, excretory, skeletal, nervous and respiratory systems, and impair hygienic quality of production (Nardone et al., 2010).

There is a lack of research related to implications of reduced water availability for land-based livestock systems due to climate change (Thornton et al., 2009). Therefore, it is important to consider water availability and appropriate mitigation strategies in the context of sustainable livestock production.

2.2.1.3 Livestock diseases

The effects of climate change on livestock diseases depend on the geographical region, land use type, disease characteristics, and animal susceptibility (Thornton et al., 2009). Animal health can be affected directly or indirectly by climate change, especially rising temperatures (Nardone et al., 2010). The direct effects are related to the increase of temperature, which increases the potential for morbidity and death. The indirect effects are related to the impacts of climate change on microbial communities (pathogens or parasites), spreading of vector-borne diseases, food-borne diseases, host resistance, and feed and water scarcity (Nardone et al., 2010; Thornton et al., 2009; Tubiello et al., 2008).

Temperature increases could accelerate the growth of pathogens and/or parasites that live part of their life cycle outside of their host, which negatively affects livestock (Harvell et al., 2002; Karl et al., 2009; Patz et al., 2000). Climate change may induce shifts in disease spreading, outbreaks of severe disease, or even introduce new diseases, which may affect livestock that are not usually exposed to these type of diseases (Thornton et al., 2009). Evaluating disease dynamics and livestock adaptation will be important to maintain their resilience. Global warming and changes in precipitation affect the quantity and spread of vector-borne pests such as flies, ticks, and mosquitoes (Thornton et al., 2009). In addition, disease transmission between hosts will be more likely to happen in warmer conditions (Thornton et al., 2009). For example, White et al. (2003) simulated the impacts of climate change on Australian livestock, finding that livestock lost about 18% of their weight due to increased tick infestations. Wittmann et al. (2001) also used a model to simulate the response of *Culicoides imicola* in Iberia, which is the main vector of the bluetongue virus that affects mainly sheep and sometimes cattle, goat, and deer. They reported that the vector would spread extensively with a 2°C increase in global mean temperature. However, these predicted spreads may be prevented by disease surveillance and technologies, such as DNA fingerprinting, genome sequencing, tests for understanding resistance, antiviral medications, cross-breeding, and more (Perry and Sones, 2009; Thornton, 2010). Because of the dependence of diseases on animal exposure and multiple interactions of factors, there are no methods to confirm actual disease risk (Randolph, 2008).

2.2.1.4 Heat stress

All animals have a thermal comfort zone, which is a range of ambient environmental temperatures that are beneficial to physiological functions (FAO, 1986). During the day, livestock keep a body temperature within a range of ±0.5°C (Henry et al., 2012). When temperature increases more than the upper critical temperature of the range (varies by species type), the animals begin to suffer heat stress (FAO, 1986). Animals have developed a phenotypic response to a single source of stress such as heat called acclimation (Fregley, 1996). Acclimation results in reduced feed intake, increased water intake, and altered physiological functions such as reproductive and productive efficiency and a change in respiration rate (Lacetera et al., 2003; Nardone et al., 2010).

Heat stress on livestock is dependent on temperature, humidity, species, genetic potential, life stage, and nutritional status. Livestock in higher latitudes will be more affected by the increase of temperatures than livestock located in lower latitudes, because livestock in lower latitudes are usually better adapted to high temperatures and droughts (Thornton et al., 2009). Confined livestock production systems that have more control over climate exposure will be less affected by climate change (Rotter and van de Geijn, 1999).

Heat stress decreases forage intake, milk production, the efficiency of feed conversion, and performance (Haun, 1997; McDowell, 1968; Wyman et al., 1962). Warm and humid conditions cause heat stress, which affects behavior and metabolic variations on livestock or even mortality. Heat stress impacts on livestock can be categorized into feed nutrient utilization, feed intake, animal production, reproduction, health, and mortality. The following presents these in more detail:

Feed nutrient utilization and feed intake: Livestock have several nutrient requirements including energy, protein, minerals, and vitamins, which are dependent on the region and type of animal (Thornton et al., 2010). Failure to meet the dietary needs of cattle during heat stress affects metabolic and digestive functions (Mader et al., 2003). Sodium and potassium deficiencies under heat stress may induce metabolic alkalosis in dairy cattle, increasing respiration rates (Chase, 2012).

Most of the research concerning feed intake in livestock animals has been focused on cattle. Thermal livestock stress decreases feed intake (Mader and Davis, 2004; Thornton et al. 2009; Wyman et al., 1962) and efficiency of feed conversion (McDowell, 1968), especially for livestock that are fed large amounts of high quality feeds (Haun, 1997). In the case of cattle, feed intake reduction leads to a negative energy balance and reduced weight gain (Lacetera et al., 1996; Lacetera et al., 2003). Reduction of water intake may also decrease sweating and feed intake (Henry et al., 2012).

Animal production: One of the major causes of decreased production in the dairy and beef industry is heat stress (Nardone et al., 2010) and significant economic losses have been related to this. The United States livestock industry has an annual economic loss between 1.69 and 2.36 billion US dollars due to heat stress, of which 50% occurs in the dairy industry (St-Pierre et al., 2003). High-producing dairy cows generate more metabolic heat than low-producing dairy cows. Therefore, high-producing dairy cows are more sensitive to heat stress. Consequently, when metabolic heat production increases in conjunction with heat stress milk production declines (Berman, 2005; Kadzere et al., 2002). Heat stress also affects ewe, goat, and buffalo milk production (Finocchiaro et al., 2005; Nardone et al., 2010; Olsson and Dahlborn, 1989). However, less attention has been given to these animals because of their adaptability to warm conditions and lower demand for their milk (Nardone et al., 2010).

In the case of meat production, beef cattle with high weights, thick coats, and darker colors are more vulnerable to warming (Nardone et al., 2010). Global warming may reduce body size, carcass weight, and fat thickness in ruminants (Mitloehner et al., 2001; Nardone, 2000). The same is true in pig production, where larger pigs will have more reduction in growth, carcass weight, and feed intake (Nardone et al., 2010). Piglets' survival may be reduced because of a reduction of sows feed intake during suckling periods with temperatures greater than 25°C, which reduces the milk yield of the sow (Lucas et al., 2000).

The poultry industry may also be compromised by low production at temperatures higher than 30°C (Esminger et al., 1990). Heat stress on birds will reduce body weight gain, feed intake and carcass weight, and protein and muscle calorie content (Tankson et al., 2001). Heat stress on hens will reduce reproduction efficiency and consequently egg production because of reduced feed intake and interruption of ovulation (Nardone et al., 2010; Novero et al., 1991). Egg quality, such as egg weight and shell weight and thickness may also be negatively affected under hotter conditions (Mashaly et al., 2004).

Reproduction: Reproduction efficiency of both livestock sexes may be affected by heat stress. In cows and pigs, it affects oocyte growth and quality (Barati et al., 2008; Ronchi et al., 2001), impairment of embryo development, and pregnancy rate (Hansen, 2007; Nardone et al., 2010; Wolfenson et al., 2000). Cow fertility may be compromised by increased energy deficits and heat stress (De Rensis and Scaramuzzi, 2003; King et al., 2006). Heat stress has also been associated with lower sperm concentration and quality in bulls, pigs, and poultry (Karaca et al., 2002; Kunavongkrita et al., 2005; Mathevon et al., 1998).

Health: Nardone et al. (2010) presented several livestock health problems related to climate change. Prolonged high temperature may affect metabolic rate (Webster, 1991), endocrine status (Johnson, 1980), oxidative status (Bernabucci et al., 2002), glucose, protein and lipid metabolism, liver functionality (reduced cholesterol and albumin) (Bernabucci et al., 2006; Ronchi et al., 1999), non-esterified fatty acids (NEFA) (Ronchi et al., 1999), saliva production, and salivary HCO_3^- content. In addition, greater energy deficits affect cow fitness and longevity (King et al., 2006).

Mortality: Warm and humid conditions that cause heat stress can affect livestock mortality. Howden et al. (2008) reported that increases in temperature between 1 and 5°C might induce high mortality in grazing cattle. As a mitigation measure, they recommend sprinklers, shade, or similar management practices to cool the animals. Sirohi and Michaelowa (2007) linked livestock mortality to several heat waves between 1994 and 2006 in the United States and northern Europe.

More information is needed concerning the nature and extent of how heat stress affects feed nutrient utilization and feed intake, animal production, reproduction, and health. With greater knowledge related to nutritional and metabolism processes of livestock, management practices could be adapted to increase animal performance.

2.2.1.5 Biodiversity

Biodiversity refers to a variety of genes, organisms, and ecosystems found within a specific environment (Swingland, 2001) and contributes to human well-being (MEA, 2005). Populations that are decreasing in genetic biodiversity are at risk, and one of the direct drivers of this biodiversity loss is climate change (UNEP, 2012). Climate change may eliminate 15% to 37% of all species in the world (Thomas et al., 2004). Temperature increases have affected species reproduction, migration, mortality, and distribution (Steinfeld et al., 2006). The Intergovernmental Panel on Climate Change Fifth Assessment Report states that an increase of 2 to 3°C above pre-industrial levels may result in 20 to 30% of biodiversity loss of plants and animals (IPCC, 2014). By 2000, 16% of livestock breeds (ass, water buffalo, cattle, goat, pig, sheep, and horse) were lost (Thornton et al., 2009). In addition, the FAO (2007) has stated that from 7,616 livestock breeds reported, 20% were at risk, and almost one breed per month was being extinguished. Cattle had the highest amount of extinct breeds (N=209) of all species evaluated. The livestock species that had the highest percentages of risk of breed elimination were chicken (33% of breeds), pigs (18% of breeds), and cattle (16% of breeds). However, the breeds at risk depends on the region. Developing regions had between 7% and 10% of mammalian species at risk (not restricted to livestock), but between 60% and 70% of mammalian species are classified as of unknown risk. Conversely, in developed regions, where the livestock industry is very specialized and based on a small number of breeds, the mammalian species at risk were between 20% and 28% (FAO, 2007). Thornton et al. (2009) states that this biodiversity loss is mainly because of the practices used in livestock production that emphasize yield and economic returns and marginalization of traditional production systems where other considerations are also important (such as ability to withstand extremes).

Livestock and plants will be highly affected by climate change and biodiversity loss. These breeds and species cannot be replaced naturally; therefore, future work that studies the inherent genetic capabilities of different breeds and identifies those that can better adapt to climate conditions is vital.

2.2.1.6 Food security

About 842 million people (one in eight people worldwide) went hungry between 2011 and 2013, not receiving enough food to maintain an active and healthy life (FAO et al., 2013). Livestock contributes greatly to food security because: (1) they are suppliers of global calories, proteins, and essential micronutrients, (2) they are produced in areas that have difficulty growing crops, (3) most of the feed for livestock is not appropriate for human consumption, and (4) they provide manure for crop production (FAO, 2011). However, there are also concerns that livestock production is detrimental to food security. First, the use of grains as feed in livestock production is a worldwide concern because they are produced for animal feed and not for human consumption. For example, in 2002, one-third of the global cereal harvest was used as livestock feed (Steinfeld et al., 2006). The bulk of the livestock feed comes from grasses and legume forage that grows on land not suitable to agriculture (O'Mara, 2012), and in many countries livestock do not receive cereal supplements. In such areas, livestock are a positive contributor to food security. The debate occurs in areas where cattle are pastured in areas perfectly suitable for agriculture, or where they are fed substantial cereal supplements. Second, climate change, mostly via an increase in temperature, may decrease intake of digestible nutrients. Therefore, livestock production may decrease through declining forage quality and quantity and/or by reducing animal feed intake. These two factors affect livestock production because animals will use the available nutrients to first maintain their physiological needs, then for growth or milk production, and finally for reproduction (Hatfield et al, 2008). Third, climate change also affects nutritional content of livestock products because of potential increases in pathogens and diseases in their food and effects on the animals themselves (Harvell et al., 2002; Karl et al., 2009; Patz et al., 2000). As new pathogens and diseases emerge and spread, pesticide and veterinary medicine use will change, consequently changing the principal transfer process of environmental contaminants to food (Lake et al., 2012; van der Spiegel et al., 2012).

Sustainable livestock production needs more research, extension, and demonstration. Livestock are an important contributor to food security, but it is important to maintain an efficient conversion of natural resources to human food to sustain a neutral food balance (FAO, 2011). This can be accomplished through efficient production of protein from livestock (FAO, 2013). However, climate change will influence this conversion by affecting the nutritional content of livestock products (Harvell et al., 2002; Karl et al., 2009; Patz et al., 2000) and reducing livestock production (Hatfield et al, 2008). Currently, the livestock sector's best approach to contribute to food security is by addressing the primacy of food balance (FAO, 2013; FAO, 2011).

2.2.2 Impact of Livestock on Climate Change

Livestock contribute 14.5% of the total annual anthropogenic GHG emissions globally (Gerber et al., 2013). Livestock influence climate through land use change, feed production, animal production, manure, and processing and transport (Figure 2). Feed production and manure emit CO_2, nitrous oxide (N_2O), and methane (CH_4), which consequently affects climate change. Animal production increases CH_4 emissions. Processing and transport of animal products and land use change contributes to the increase of CO_2 emissions (Figure 2).

The livestock sector is often associated with negative environmental impacts such as land degradation, air and water pollution, and biodiversity destruction (Bellarby et al., 2013; Reynolds et al., 2010; Steinfeld et al., 2006; Thorton and Gerber, 2010). Increases in livestock production are expected to originate from a declining natural resource base, which will cause further environmental damage without proper natural resources management (Thornton and Herrero, 2010).

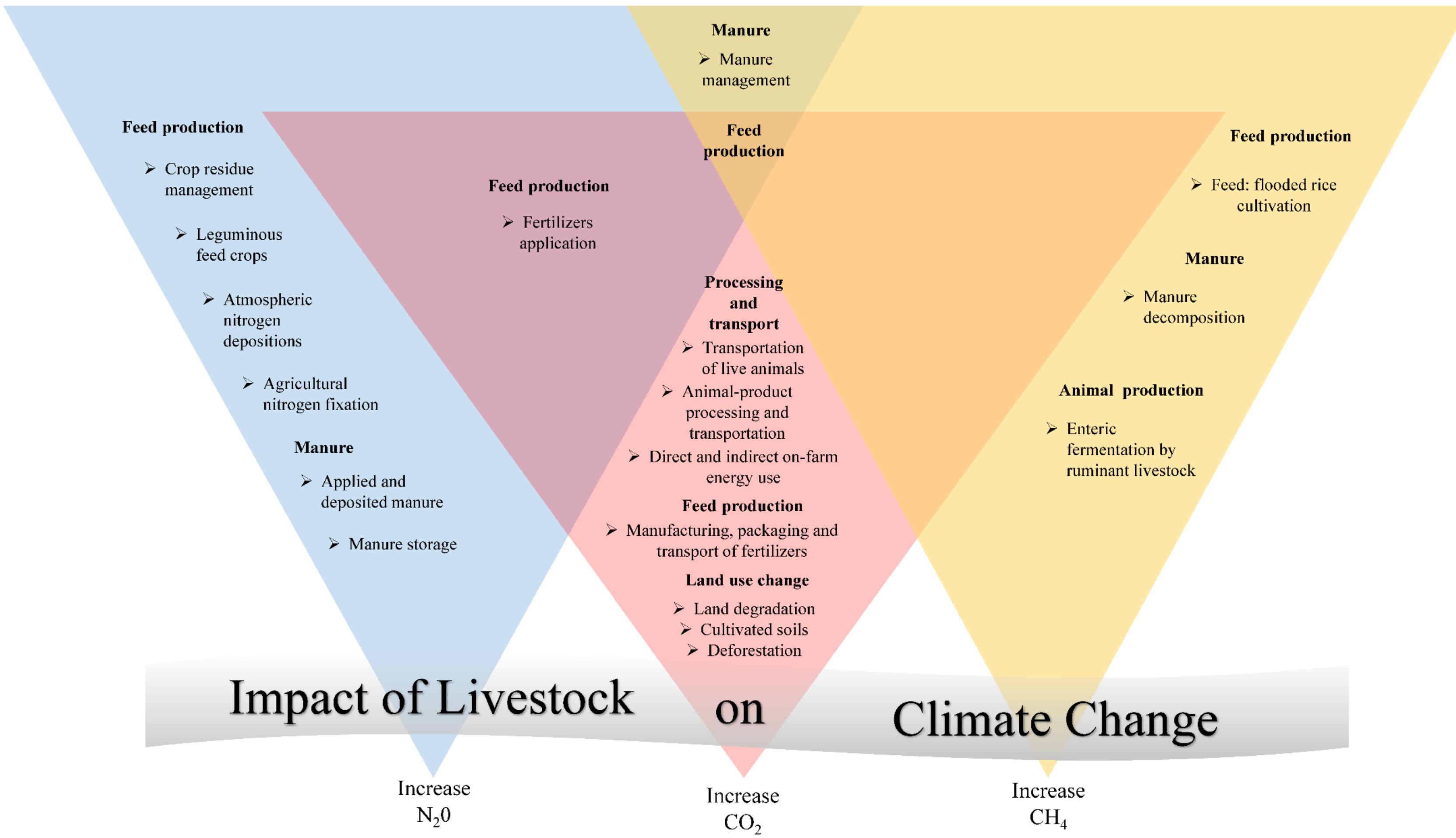

Figure 2. Impact of livestock on Climate Change

2.2.2.1 GHG emissions

The primary livestock GHG emissions are CO_2, CH_4, and N_2O. CH_4 contributes the most to anthropogenic GHG emissions (44%), followed by N_2O (29%) and CO_2 (27%) (Gerber et al., 2013). Globally livestock contribute 44% of anthropogenic CH_4, 53% of anthropogenic N_2O and 5% of anthropogenic CO_2 emissions (Figure 3). Higher concentrations of these gases, can be explained by lower efficiency and productivity of livestock system due to excess loss of nutrients, energy, and organic matter (Gerber et al., 2013).

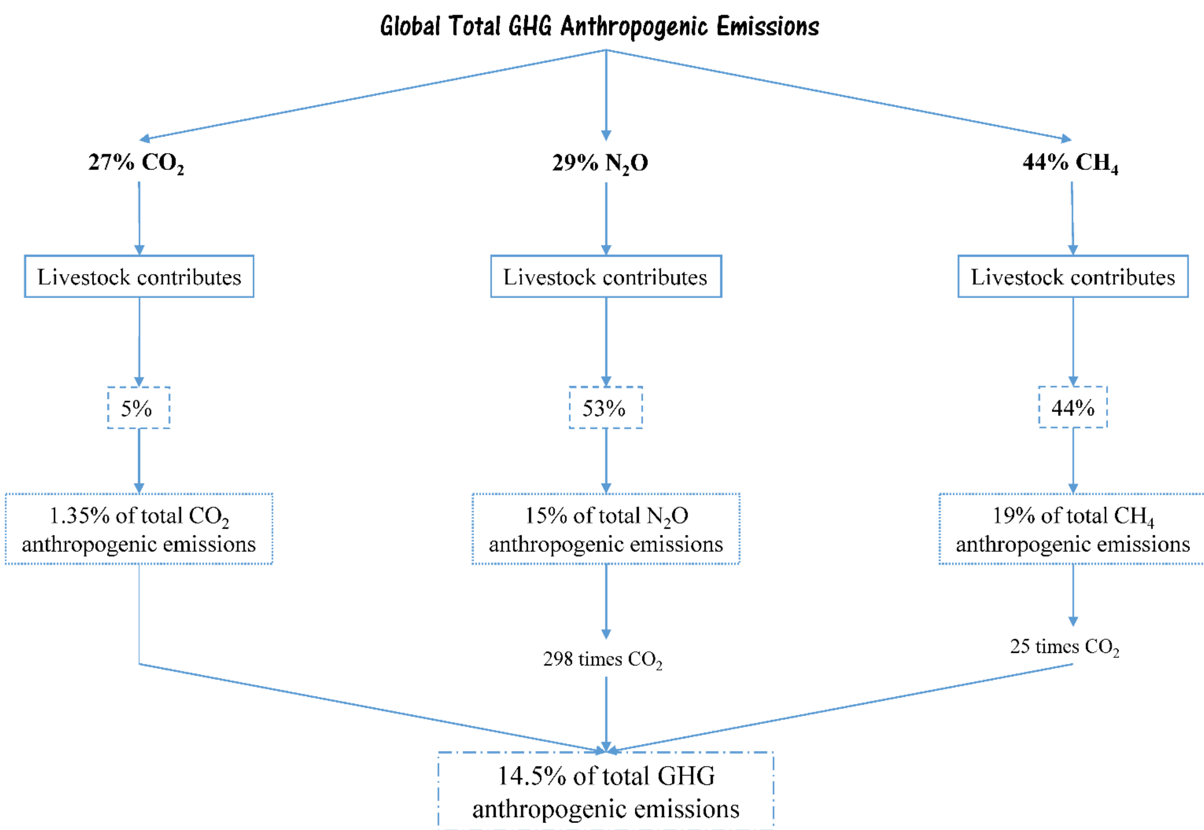

Figure 3. Contribution of livestock to the total GHG anthropogenic emissions

The global warming potential (GWP) of CH_4 and N_2O over a 100-year time horizon differs between the IPCC (2006), IPCC (2013), and the United Nations Framework Convention on Climate Change (UNFCC, 2014). Current assessments have estimated higher GWP than what was previously thought. IPCC (2006) is most commonly used in the literature for estimating livestock GHG emissions, and reported that the warming potential of CH_4 is 25 CO_2-eq, while N_2O is 298 CO_2-eq. However, the latest IPCC (2013) reported a warming potential for CH_4 of 34 CO_2-eq, while N_2O is 310 CO_2-eq. The UNFCCC (2014) stated that CH_4 emissions have a warming potential of 21 CO_2-eq, and N_2O is 310 CO_2-eq over a 100-year time horizon.

The world's transportation sector emits around 5656 Tg CO_2-eq yr^{-1} and the livestock sector emits 7100 Tg CO_2-eq yr^{-1} (DSI MSU, 2013; Gerber et al., 2013). Emissions from livestock production contribute more GHG to the atmosphere than the entire global transportation sector. The livestock sector contributes directly and indirectly to GHG emissions, including through animal physiology, animal housing, manure storage, manure treatments, land application, and chemical fertilizers (Casey et al., 2006; Monteny et al., 2001). Direct emissions from animal sources include enteric fermentation, respiration, and excretions (Jungbluth et al., 2001). Indirect emissions refer to emissions derived from feed crops, manure application, farm operations, livestock products processing, transportation, and land use allocation for livestock production (e.g. deforestation, desertification, carbon released from cultivated soils) (IPCC, 1997; Mosier et al., 1998). In the livestock sector, indirect emissions play a greater role in the release of carbon to the atmosphere than direct emissions (Steinfeld et al., 2006).

The livestock sector's contribution of 14.5% of total anthropogenic GHG emissions was evaluated by Gerber et al. (2013) using a global livestock environmental assessment model (GLEAM). GLEAM performs an analysis of the emissions of global livestock production along supply chains. The main elements of the livestock supply chains that are analyzed by GLEAM are: herd, feed, manure, animals' energy requirement, feed intake, production, and emissions, allocation of the total emissions at the farmgate (physical farm boundaries) to co-products and services (emission per kg of product), and post-farmgate emissions (transport and processing). GLEAM also considers land use change as the conversion of forest to pasture or arable land for crops.

The contributors of the 14.5% of livestock GHG emissions are presented in Figure 4. Enteric fermentation is the largest contributor of the sector's emissions with 39.1%, followed by manure management, application, and direct deposit with 25.9%, feed production with 21.1%, land use change with 9.2%, post-farmgate with 2.9%, and direct and indirect energy with 1.8% (Gerber et al., 2013). However, contribution to GHG emissions varies depending on the type of farming system and region. For example, intensification of any of the three major livestock production systems and expansion of industrialized (or landless) systems will increase CO_2 emissions due to greater fossil fuel use and less solar energy utilized by photosynthesis (Steinfeld et al., 2006). Gerber et al., (2013) also estimated livestock GHG emissions by region, finding that, Asia produce the highest, followed by Latin America and the Caribbean, Europe, North America, Africa, and Oceania.

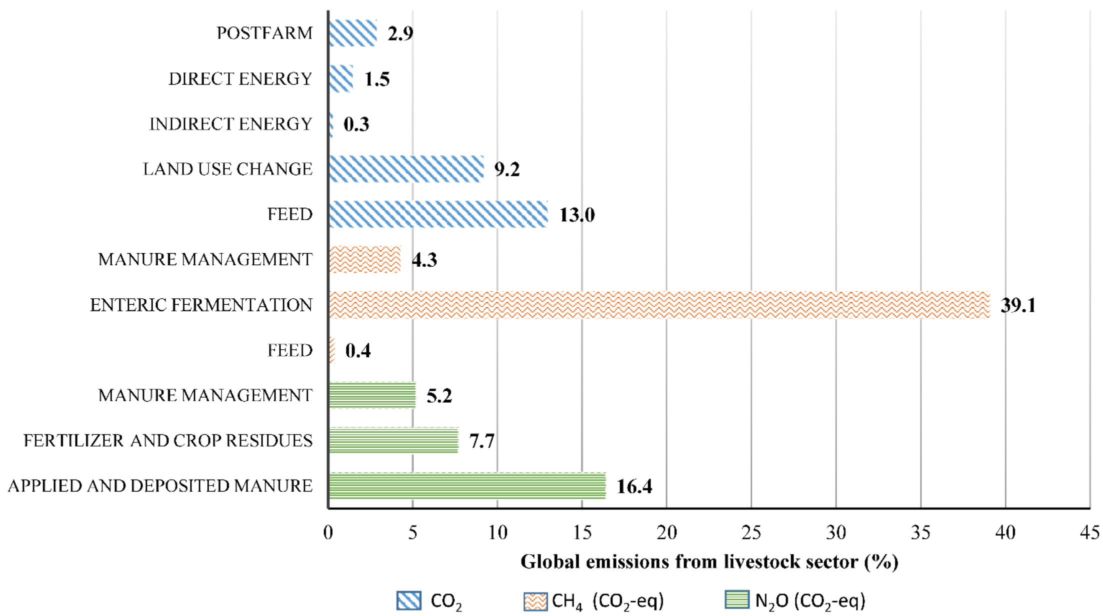

Figure 4. Global GHG emissions from the livestock sector (modified from Gerber et al., 2013)

2.2.2.2 Land use

Forests and natural habitats have been steadily converted to pasture and cropland since the 1850s (Goldewijk and Battjes, 1997). Agriculture lands cover about 38.5% of global total land area, which consists of 28.4% arable land and 68.4% permanent meadows and pasture (DSI MSU, 2015). Pasturelands have expanded by a factor of six since 1800, now covering 35 million km^2 (White et al., 2000). Agricultural land use change is related to two concepts: profit per unit of land and opportunity cost (Steinfield et al., 2006a). Profit per unit of land refers to the willingness of farmers to manage a specific land use. Profit will vary depending on several factors, such as the land's biophysical characteristics and price, access to markets, inputs, and services. The opportunity cost concept compares the social and economic cost of different ways to use the same land area. Opportunity costs include private production costs and ecosystem service costs. Therefore, when non-marketable ecosystem services have no associated cost, land use decisions are based on private profit per unit of land (Steinfeld et al., 2006).

The increasing demand for livestock products has significantly changed the natural landscape. Land degradation is the deterioration of physical, chemical, and biological properties of soil. Land degradation has been recognized as one of the drivers of land conversion from forest to croplands and pastures because producers exhaust their soil resources and thus search for more suitable land (Steinfeld et al., 2006). However, Asner et al., (2004) stated that due to climate and soil characteristics, the expansion of pasture into marginal areas is limited; therefore, they could only expand into areas with agro-ecological potential.

Land use change affects the natural carbon cycle, which consequently releases high amounts of carbon into the atmosphere, increasing GHG emissions. Natural habitats, mainly forests, sequester more carbon in soil and vegetation than croplands and pasturelands. Soil and terrestrial vegetation sequester up to 40% of global anthropogenic CO_2 emissions (The Royal Society, 2001). Furthermore, pasturelands contain more carbon than croplands. Croplands sequester 6% of global carbon, while tropical savannas and temperate pasturelands together sequester 27% (IPCC, 2000). However, soils sequester the most carbon in the terrestrial carbon cycle, and double that of vegetation (Steinfeld et al., 2006). Sundquist (1993) estimated that 1,100 to 1,600 billion tonnes of carbon is stored in soils. However, soil carbon can be lost through burning, volatilization, erosion, land use change, and agricultural management practices (Bolin et al., 1982). Therefore, when a forest is converted to cropland and pasture by logging or burning, high amounts of carbon are released into the atmosphere (Steinfeld et al., 2006).

Latin America has converted the most land from forest to pasture and croplands, and livestock ranching is one of the drivers of this change (Wassenaar et al., 2007). In the past 40 years, forested areas in Central America decreased by almost 40%, coinciding with an increase of pasturelands and cattle herds. In addition, crops used to feed livestock also affect land use change. In 2004-2005 alone, soybean expansion replaced 1.2 million hectares of rainforest (LEAD, 2014).

Deforestation, cultivated soils, and land degradation due to livestock production are the main source of CO_2 emissions. From total livestock GHG emissions, 9.2% is attributed to land use change, where 6% is due to pasture expansion and 3.2% is due to feed crop expansion (Gerber et al., 2013). However, land use change produces other emissions in addition to CO_2. Land conversion from forest to pastureland may also reduce CH_4 oxidation by soil microorganisms, resulting in pasturelands acting as net sources of CH_4 when soil compaction from cattle hooves limits gas diffusion (Mosier et al., 2004).

Regarding the other two contributors of livestock-land use GHG emissions, Steinfeld et al. (2006) estimated that livestock-related cultivated soils produce around 28 million tonnes of CO_2 per year and livestock-induced desertification of pastures produce 100 million tonnes of CO_2 per year. Reducing pasturelands as a mitigation strategy does not suggest an increase in soil carbon stocks because the relationship between pasturelands and soil carbon sequestration is complex due to their dependence on the environment, society, and economy (IFAD, 2010). Studies suggest that pasturelands can either increase or decrease GHG emissions depending on the grazing management and history, climate and ecosystem (IFAD, 2010; Henderson et al., 2015). Therefore, grazing management that can increase carbon sequestration are: i) not exceeding pastureland carrying capacity by having an effective stocking rate, ii) rotational grazing, and iii) excluding degraded pasturelands from livestock grazing (IFAD, 2010; Tennigkeit and Wilkes, 2008).

2.2.2.3 Feed production

The use of manure and synthetic fertilizers for forage and feed crop production, processing of feed, and transport of feed are the most important contributors of GHG emissions related to the livestock sector (IFAD, 2010; Thornton and Herrero, 2010). These make up 45% of global livestock anthropogenic GHG emissions, consisting primarily as CO_2, N_2O and NH_4 (Gerber et al., 2013).

The livestock sector contributes significantly to GHG emissions through the production of nitrogenous fertilizers used to produce crops for animal feed (Steinfeld et al., 2006). Oil, coal, and natural gas are used in fertilizer manufacture. By considering the amount of fertilizer use, packaging, transport, and application in the livestock sector, the manufacturing process of fertilizers contributes more than 40 million tonnes of CO_2 annually (Steinfeld et al., 2006). Forty percent of all the nitrogen up-take by crops comes from synthetic fertilizers (Smil, 2001). Ammonia volatilization loss from synthetic nitrogen fertilizer is an indirect contributor to GHG emissions. Between 4 to 5 million tonnes of mineral fertilizer is used for livestock feed production. The average loss due to ammonia volatilization from mineral fertilizer is about 14%. Therefore, it was estimated that the livestock sector contributes 3.1 million tonnes of global ammonia volatilization from mineral fertilizers per year (Steinfeld et al., 2006).

N_2O is another contributor to GHG emissions. Fertilizer use, agricultural nitrogen fixation, and atmospheric nitrogen deposition generally increase N_2O emissions (Bouwman, 1996). By following the same assumptions as ammonia, with a 1% average of N_2O-N (tonnes of nitrogen in nitrous oxide form) loss rate from mineral fertilizer, the livestock sector contributes 0.2 million tonnes N_2O-N of global N_2O emission from mineral fertilizer per year (Steinfeld et al., 2006). In addition, leguminous feed crops for livestock account for additional N_2O emissions. Steinfeld et al. (2006) estimated their contribution by considering the global area of soybeans used for livestock feed and doubling it to include alfalfa and clover, because there are no estimates of worldwide alfalfa and clover production. Therefore, the contribution of leguminous feed crops is more than 0.5 million tonnes per year of N_2O-N emissions. By adding both contributors (mineral fertilizer and leguminous feed crops), the total N_2O-N emissions are 0.7 million tonnes per year (Steinfeld et al., 2006). As growth in fertilizer and manure use continues, a 35-60% increase of N_2O emissions (0.9 to 1.1 million tonnes per year of total N_2O-N emissions) is expected by 2030 (Bruinsma, 2003).

On-farm fossil fuel use in livestock production produces 50% more CO_2 emissions than manufacturing N fertilizers for feed. The livestock sector includes direct and indirect (e.g. electricity) on-farm fossil fuel use, which is used for machinery operations, irrigation, heating, cooling, ventilation, production of herbicides and pesticides, and more. More than half of fossil-fuel use is attributed to feed production. By assuming CO_2 emissions from on-farm fossil fuel use are double that of manufacturing N fertilizers, and adding emissions related to livestock rearing, on-farm fossil fuels account for 90 million tonnes of CO_2 per year (Steinfeld et al., 2006).

2.2.2.4 Animal production

In general, livestock respiration is not counted as a net source of CO_2 emissions because they are part of the global biological system cycle. The vegetation consumed by the animal originates from the conversion of atmospheric CO_2 to organic compounds or biomass. Therefore, under the Kyoto Protocol it is assumed that the consumed amounts of CO_2 in vegetative form are equivalent to those emitted by the livestock. Conversely, the animal is a carbon sink because a fraction of the carbon consumed is absorbed in the live tissue of the animal (UNFCCC, 1998) and products such as milk.

Livestock contributes 44% of the world's anthropogenic CH_4 emissions through their normal digestive processes (enteric fermentation) and manure management (Gerber et al., 2013). Enteric fermentation and manure account for 80% of 52 agricultural emission sources (Steinfeld et al., 2006). During the animals' digestive process, enteric fermentation converts the feed consumed into digestible feed. Enteric fermentation releases a CH_4 by-product through exhalation (Beauchemin et al., 2009). Therefore, this by-product is considered an energy loss (Gerber et al., 2013). Feed composition and feed intake can vary enteric fermentation and hence methane emissions. Increasing the concentrate (high energy feeds containing cereal grains and oil meals) proportion in the animal diet can reduce methane emissions from the animal (Dourmad et al., 2008; Yan et al., 2000).

Methane emissions vary depending on production systems and regional characteristics (e.g. climate and landscape) (Gerber et al., 2013). The enteric fermentation produced by ruminant livestock (e.g. cattle, sheep, and goat) emits globally between 87 and 94 Tg of methane annually (IPCC, 2013). Mixed crop-livestock systems account for 64% of global enteric fermentation methane emissions; grazing systems account for 35%, and industrial 1% (Steinfeld et al., 2006). The high percentage from mixed crop-livestock systems reflects that two-thirds of total livestock animals are present in those systems (Steinfeld et al., 2006). The countries that contribute the most methane emissions related to livestock production are India, China, Brazil, and the United States (IPCC, 2013; Olivier and Janssens-Maenhout, 2012). India, with the largest livestock population in the world, emitted 11.8 Tg of CH_4 in 2003, from which 91% derives from enteric fermentation and 9% from manure management (Chhabra et al., 2013).

In Africa, methane emissions are expected to increase due to increases in livestock populations. Herrero et al. (2008) estimated that African cattle, goats, and sheep, which produced about 7.8 million tonnes of methane in 2000, are likely to increase to 11.1 million tonnes by 2030. If this linear relationship between methane emissions and livestock population continues, global methane emissions from livestock production may increase 60% by 2030 (Bruinsma, 2003). However, changing feeding practices and manure management could moderate methane emissions (Thornton and Herrero, 2010).

2.2.2.4.1 Emissions by Species and Commodities

Animals that contribute the most to livestock GHG emissions are beef and dairy cattle, accounting for 65% of the total livestock GHG emissions (Gerber et al., 2013). Pigs, poultry, buffaloes, and small ruminants contribute about 7 to 10%. If GHG emissions are estimated based on commodities, beef cattle contribute the most with 41% of the sector’s emission, followed by dairy cattle (20%), swine (9%), buffalo (8%), poultry (8%), and small ruminant (6%) (Gerber et al., 2013).

Enteric fermentation is the largest source of GHG emissions from cattle, buffalo, and small ruminants, comprising between 43% and 63% of the livestock sector emissions (Figure 5). However, for pigs and chickens the largest source of emissions is due to feed production (between 25% and 27%), which includes fertilizer production, machinery use, and feed transportation. Enteric fermentation from pigs is much lower than in ruminants because their digestive process does not produce as much methane as a by-product (Gerber et al., 2013).

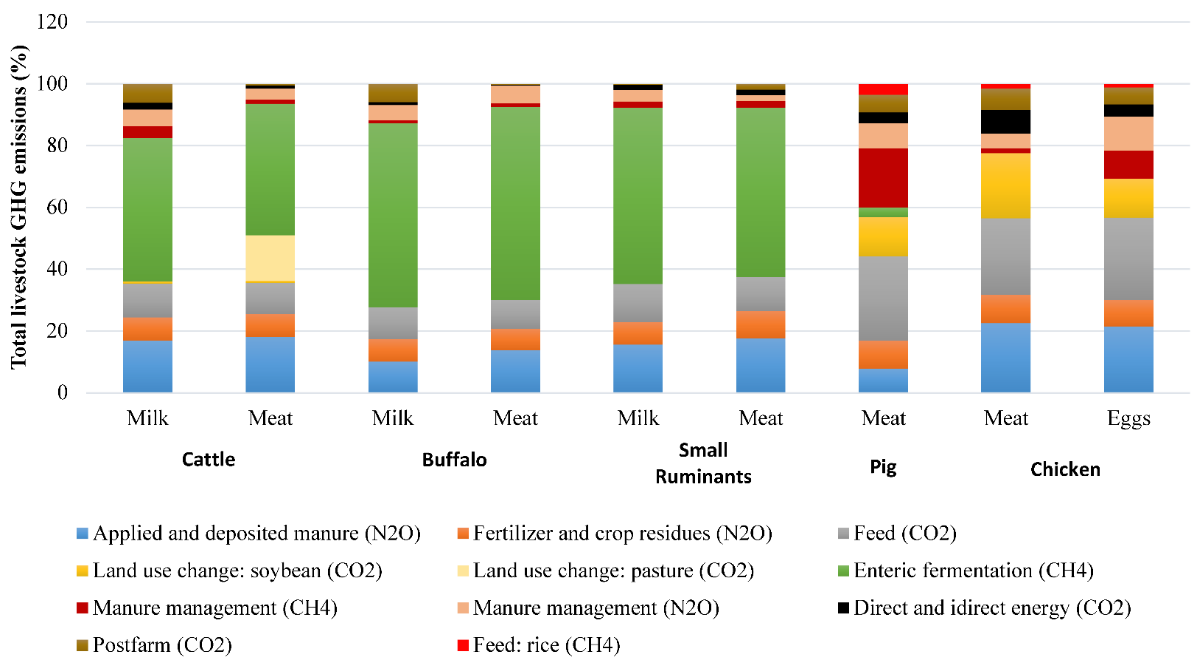

Figure 5. Total global livestock GHG emission by specie and product (Adapted from Gerber et al., 2013)

2.2.2.5 Manure

Livestock manure releases CH_4 and N_2O gas. The decomposition of the organic materials found in manure under anaerobic conditions releases methane (EPA, 1999). Liquid manure found in lagoons or holding tanks releases more methane than dry manure (Burke, 2001).

Manure methane emissions are a function of air temperature, moisture, pH, storage time, and animal diet (EPA, 1999; IFAD, 2010). Steinfeld et al. (2006) estimated global methane emissions from manure decomposition of 17.5 million tonnes of CH_4 per year. Pig manure comprises almost half of global manure-related methane emissions. At the country level, China has the highest global methane manure-related emissions, primarily due to pig manure (Steinfeld et al., 2006).

N_2O emissions from manure storage are dependent on environmental conditions, handling systems, and duration of waste management. Manure must be handled aerobically and then anaerobically to release N_2O emissions, which is more likely to occur in dry waste-handling systems. Steinfeld et al. (2006) reported that N_2O emissions from stored manure are equivalent to 10 million tonnes N per year.

Nitrous oxide soil emissions from manure application are the largest source of global N_2O emissions (Steinfeld et al., 2006). Nitrogen emissions from applied or deposited manure are dependent on soil infiltration, organic carbon amount, pH, soil temperature, precipitation, and the plant/crop uptake rate (Mosier et al., 2004). Steinfeld et al. (2006) estimated that 1.7 million tonnes of manure soil N_2O are released per year. N_2O emissions from applied manure are 40% higher in mixed crop-livestock systems than the N_2O emissions from excreted manure deposited on pasture systems. Industrial production systems have 90% less N_2O emissions than mixed crop-livestock systems (Steinfeld et al., 2006).

2.2.2.6 *Processing and transport*

Energy costs of processing animals and their products combined with global livestock production from "market-oriented intensive systems" can be used to obtain global processing emissions. However, the source of the energy and its variation in the world is uncertain (WEC, 2015). Energy use depends on the type of livestock system and if they are small or large scale. More than half of the energy used in confinement systems is for feed production, including seed, herbicides, pesticides, and machinery. Substantial energy is also used for heating, cooling, and ventilation systems (USDA-NRCS, 2006).

Nonetheless, some approximate estimations of energy use in the livestock sector have been developed. Based on a study performed in Minnesota by Sainz (2003) of energy use for processing, Steinfeld et al. (2006) estimated that the United States produces a "few million" tonnes of CO_2 emissions related to total animal product and feeding processing. Following the same trend, they estimated that the world produces "several tens of millions" tonnes CO_2 emissions in animal-product processing.

Transportation of livestock products to retailers and transport of feed to livestock farms contribute to GHG emissions. Long distance shipping is the most significant GHG emitter in this category. For example, high volumes of soybean are transported long distances to be used as feed (Steinfeld et al., 2006). Annual CO_2 emissions in meat transportation based on FAO statistics for 2001-2003 was estimated to be between 800-850 thousand tonnes of CO_2 (Steinfeld et al., 2006). These estimations lead to a greater understanding of the contribution of processing and transportation to the livestock sector GHG burden. However, more research is needed to obtain approximate estimations of CO_2 emissions related to processing and transport of livestock products.

2.2.3 Summarizing Adaptation and Mitigation Practices

There are several climate change adaptation and mitigation recommendations that can be made based on the above discussion. Adaptation strategies can improve the resilience of crop and livestock productivity to climate change (USDA, 2013). Mitigation measures could significantly reduce the impact of livestock on climate change (Dickie et al., 2014). Adaptation and mitigation can make significant impacts if they become part of national and regional policies (FAO, 2009b).

2.2.3.1 *Adaptation measures*

Adaptation measures involve production and management system modifications, breeding strategies, institutional and policy changes, science and technology advances, and changing farmers' perception and adaptive capacity (IFAD, 2010; Rowlinson et al., 2008; USDA, 2013). Research is needed on assessments for implementing these adaptation measures and tailoring them based on location and livestock system. This could be accomplished with GIS and remote sensing technologies applicable at broad and local scales (Thornton et al., 2008).

2.2.3.1.1 Livestock production and management systems

An adaptation such as the modification of production and management systems involves diversification of livestock animals and crops, integration of livestock systems with forestry and crop production, and changing the timing and locations of farm operations (IFAD, 2010).

Diversification of livestock and crop varieties can increase drought and heat wave tolerance, and may increase livestock production when animals are exposed to temperature and precipitation stresses. In addition, this diversity of crops and livestock animals is effective in fighting against climate change-related diseases and pest outbreaks (Batima et al., 2005; IFAD, 2010; Kurukulasuriya and Rosenthal, 2003).

Agroforestry (establishing trees alongside crops and pastures in a mix) as a land management approach can help maintain the balance between agricultural production, environmental protection and carbon sequestration to offset emissions from the sector.

Agroforestry may increase productivity and improve quality of air, soil, and water, biodiversity, pests and diseases, and improves nutrient cycling (Jose, 2009; Smith et al., 2012).

Changes in mixed crop-livestock systems are an adaptation measure that could improve food security (Herrero et al., 2010; Wani et al., 2009). This type of agricultural system is already in practice in two-thirds of world, producing more than half of the milk, meat, and crops such as cereal, rice and sorghum (Herrero et al., 2012). Changes in mixed crop-livestock systems can improve efficiency by producing more food on less land using fewer resources, such as water (Herrero et al., 2012; Steinfeld et al., 2006).

Shifting locations of livestock and crop production could reduce soil erosion and improve moisture and nutrient retention (Kurukulasuriya and Rosenthal, 2003). Another adaptive measure could be adjusting crop rotations and changing timing of management operations (e.g. grazing, planting, spraying, irrigating). This measure can be adapted to changes in duration of growing seasons, heat waves and precipitation variability (Batima et al., 2005; IFAD, 2010; Kurukulasuriya and Rosenthal, 2003).

2.2.3.1.2 Breeding strategies

Changes in breeding strategies can help animals increase their tolerance to heat stress and diseases and improve their reproduction and growth development (Henry et al., 2012; Rowlinson, 2008). Therefore, the challenge is in increasing livestock production while maintaining the valuable adaptations offered by breeding strategies, all of which will require additional research (Thornton et al., 2008). In addition, policy measures that improve adaptive capacity by facilitating implementation of adaptation strategies will be crucial (USDA, 2013). For example, developing international gene banks could improve breeding programs and serve as an insurance policy, such as has been done for plants with the *In-Trust* plant collections in the

CGIAR gene banks (Thornton et al., 2008). This would be a major breakthrough that requires significant investment and international collaboration to succeed.

2.2.3.1.3 Farmers' perception and adaptive capacity

One of the limiting factors for these changes to succeed is the disposition and capability of farmers to recognize the problem and adopt climate change adaptation and mitigation measures (Jones et al., 2013). Because of this, it is important to collect information about farmers' perceptions to mitigation and adaptation measures. One approach for collecting information about farmers' perceptions that has been used for mitigation and adaptation research is qualitative; using open-ended survey questions or group discussion at workshops to understand individual and group opinions (Barnes et al., 2013). By understanding farmers' perceptions and including them in rural policy development, there is a greater chance of accomplishing food security and environmental conservation objectives (Barnes et al., 2013; Oliver et al., 2012).

Risk perception within farmer decision-making can be increased through education, family farm succession, and social interaction among farmers and farming communities. Barnes et al. (2013) applied a latent class clustering approach (which uses statistical methodology to construct results) to evaluate the heterogeneity of dairy farmers' risk perception of climate change. Their results show that the drivers of risk perception due to climate change are family members and the influence of succession planning. They recommended increasing the social capital of farming communities to promote acceptance of communication strategies for climate change adaptation and mitigation measures.

2.2.3.2 Mitigation measures

There is potential to reduce livestock sector GHG emissions through the implementation of different technologies and practices. However, they are not widely used (Gerber et al., 2013).

Some of the technical options for mitigating the impact of livestock on climate change are carbon sequestration, improving diets to reduce enteric fermentation, improving manure management, and more efficient use of fertilizers (Steinfeld et al. 2006; Thornton and Gerber, 2010; UNFCCC, 2008). Mitigation measures need public policy support to be effective (Dickie et al., 2014).

2.2.3.2.1 Carbon sequestration

Carbon sequestration can be achieved through decreasing deforestation rates, reversing of deforestation by replanting (Carvalho et al., 2004), targeting for higher-yielding crops with better climate change adapted varieties, and improvement of land and water management (Steinfeld et al., 2006). A beef sector study performed in Brazil estimated a reduction of up to 25% of GHG emissions related to grazing land use and land use change, accomplished by improving animal and herd efficiency (Gerber et al., 2013).

Soil organic carbon can be restored in cultivated soils through conservation tillage, erosion reduction, soil acidity management, double-cropping, crop rotations, higher crop residues, mulching and more (Paustian et al., 1997; Steinfeld et al., 2006). Improving pasture management can also lead to carbon sequestration by incorporating trees, improving plant species, legume interseeding, introducing earthworms, and fertilization (Conant et al., 2001). In addition, grass productivity and soil carbon sequestration could be improved by increasing grazing pressure in grasslands that have a lower amount of grazing animals than the livestock carrying capacity (Holland et al., 1992). Improving grazing land management could sequester around 0.15 gigatonnes CO_2-eq yr^{-1} globally (Henderson et al., 2015).

2.2.3.2.2 Enteric fermentation

Enteric fermentation is a source of methane emissions that can be reduced through practices such as improvement of animal nutrition and genetics (EPA, 1999). Examples of practices for mitigating enteric fermentation are: increasing dietary fat content (Beauchemin et al., 2008; Martin et al., 2010), providing higher quality forage (Hristov et al., 2013), increasing protein content (ICF International, 2013), providing supplements (e.g. bovine somatotropin, feed antibiotics) (Boadi et al., 2004), and the use of antimethanogens (vaccines to suppress methane emissions) (EPA, 2013). However, there is high uncertainty in the efficacy of these practices because various studies have demonstrated that the initial reductions of enteric fermentation achieved are only temporary (ICF International, 2013).

A one percent increase of dietary fat can decrease enteric methane emissions between 4 to 5% (Beauchemin et al., 2008; Martin et al., 2010). However, rumens need to limit fat content to 8% of dry matter to avoid a decrease in livestock performance (Hales et al., 2012). Providing higher quality forage also results in a reduction of methane emissions because it increases digestibility (Hristov et al., 2013). An increase of protein content of feed can also improve digestibility and reduce overall methane emissions per unit of product (ICF International, 2013).

Providing supplements, such as feed antibiotics, which tend to increase weight gain and reduce feed intake per metric ton of meat produced, can reduce enteric fermentation (Boadi et al., 2004). In the case of milk, bovine somatotropin (a bovine growth hormone) increases production. An increase in milk production leads to less animals needed to produce the same amount of milk and less emissions produced (EPA, 2013). Antimethanogen vaccines are another practice that directly reduces methane emissions in the rumen. However, this is a new technology with limited research on emission reduction efficiency and animal health (EPA, 2013).

2.2.3.2.3 Manure management

Most methane emissions from manure management are related to storage and anaerobic treatment. Although manure deposited on pasture can produce nitrous oxide emissions, the mitigation measures are often difficult to apply because of the manure dispersion on pasture (Dickie et al., 2014). Therefore, most mitigation practices involve shortening storage duration, improving timing and application of manure, used of anaerobic digesters, covering the storage, using a solids separator, and changing the animal diets (ICF International, 2013).

Anaerobic digestion can reduce methane emissions while producing biogas (Gerber et al., 2008). Anaerobic digesters are lagoons or tanks that maintain manure under anaerobic conditions to capture biogas and combust it for producing energy or flaring. This process reduces the potential of GHG emissions by converting methane into CO_2 (ICF International, 2013). Unfortunately, anaerobic digesters are costly for producers; the best approach for implementing digesters is through policies that create enough incentive for adaptation (Dickie et al., 2014). Similar to digesters, the covering of ponds, tanks or lagoons reduces emissions by capturing and destroying methane (ICF International, 2013).

Other storage and handling practices can also reduce GHG emissions. Such practices include reducing storage time, improving housing and waste management systems to handle manure, and removing bedding from manure by using a solids separator (Dickie et al., 2014). The solids separator is mostly used in confinement systems to remove solids from manure streams that are entering the treatment or storage systems. By removing the solids from manure streams methane emissions are reduced, the time between storage system cleaning is increased, and crust formation is prevented (ICF International, 2013). These practices, compared to anaerobic digesters, are usually low-cost and low-tech. However, they require more time and effort from the producer (Dickie et al., 2014).

Adjusting animal diets can also be used as a mitigation measure, by changing the volume and composition of manure. GHG emissions can be reduced by balancing dietary proteins and feed supplements. If protein intake is reduced, the nitrogen excreted by animals can also be reduced. Supplements such as tannins are also known to have the potential to reduce emissions. Tannins are able to displace the nitrogen excretion from urine to feces to produce an overall reduction in emissions (Dickie et al., 2014; Hess et al., 2006).

2.2.3.2.4 Fertilizer management

Fertilizer application on animal feed crops increases nitrous oxide emissions (Bouwman, 1996). Therefore, mitigation measures such as increasing nitrogen use efficiency, plant breeding and genetic modifications (Dickie et al., 2014), using organic fertilizers (Denef et al., 2011), regular soil testing, using technologically advanced fertilizers, and combining legumes with grasses in pasture areas may decrease GHG emissions in feed production (Dickie et al., 2014).

Nitrogen use efficiency can be improved by applying the required amount that the crop will absorb and when it needs the nutrients, and placing it where the plant can easily reach it. Regular soil testing can be a part of a nutrient management plan depending on the region and crop, and improve efficiency of nitrogen use (Dickie et al., 2014). Plant breeding and genetic modifications can reduce the use of fertilizers by increasing a crop’s nitrogen uptake (Dickie et al., 2014). Increasing the use of organic fertilizers would also decrease emissions because organic fertilizers do not produce as much nitrogen oxide as synthetic fertilizers (Denef et al., 2011). Furthermore, fertilizer technology has improved through regulating the release of nutrients from the fertilizer and inhibiting nitrification to slow the degradation of the fertilizer and maintain the nutrients available for the plant. However, these technologically advanced fertilizers are more costly than the other practices mentioned above (Dickie et al., 2014). In the case of pasturelands, the use of synthetic nitrogen can be reduced by combining legumes with grasses. Legumes fix nitrogen through Rhizobium bacteria; therefore, the need for supplementary nitrogen is reduced (USDA-NRCS, 2007).

2.2.3.2.5 Shifting human dietary trends

Most studies are focused on reducing GHG emissions on the supply-side of the livestock production system. However, less research has focused on the demand section related to consumption of livestock products. This mitigation measure goes along with the policy related to a reduction in meat consumption, which may significantly reduce GHG emissions. Because beef accounts for a large portion of GHG emissions from the livestock sector and it is the least resource-efficient animal protein producer (Stehfest et al., 2009), the mitigation potential is high for the beef component of the livestock sector. Research to understand why populations feel compelled to increase animal protein consumption when they rise above the poverty line is needed, as well as why those at the top of the economic ladder are compelled to improve their diets by reducing meat consumption and returning to a more vegetarian diet. This conundrum stands at the center of the challenge faced by the state of knowledge and policies surrounding the livestock sector.

2.3 Summary

Climate change will affect livestock production and consequently food security. Livestock production will be negatively impacted (due to diseases, water availability, etc.), especially in arid and semiarid regions. In addition, climate change will affect the nutritional content of livestock products, which are one of the suppliers of global calories, proteins and essential micronutrients. Conversely, livestock production also influences climate change. Deforestation due to expansion of pasturelands and croplands for livestock production contributes 9.2% of total livestock GHG emissions (Gerber et al., 2013). However, the feed production stage contributes the greatest fraction (almost half) of GHG emissions across the complete livestock production process. It is expected that this stage will further increase its contribution due to intensification of livestock production. Meanwhile, enteric fermentation is the largest GHG contributor in the animal production stage. Therefore, if livestock numbers continue to increase and feeding practices are not changed, global emissions due to livestock production will continue to increase.

Climate change adaptation, mitigation practices, and policy frameworks are critical to protect livestock production. Among the reviewed studies, diversification of livestock animals (within species), using different crop varieties, and shifting to mixed crop-livestock systems seem to be the most promising adaptation measures. By diversifying animal and crop varieties, the tolerance to climate variability (e.g. drought, heat waves) and to diseases and pest outbreaks will be improved. In addition, shifting to mixed crop-livestock systems can improve efficiency by increasing production with the use of fewer resources. On the mitigation side, improvement of animal nutrition and genetics are important because enteric fermentation is a major GHG emitter in livestock production. However, the efficacy of these practices in reducing emissions is uncertain and more research is needed concerning effective mitigation practices related to enteric fermentation.

If we want effective adaptation and mitigation measures to address climate change and livestock production, these measures should be scaled up through policy. For example, understanding farmers' perceptions and including them in policy development can improve food security and environmental conservation by promoting widespread practice adoption. In addition, a comprehensive view of costs, time, and effort required from the producer needs to be included to the policy framework to maintain sustainable production systems.

Interactions between climate change and livestock production are still not well understood, despite the amount of research performed. First, most studies were performed at a continental or regional level; to assess the most vulnerable areas, local studies will be critical. Second, most of the research concerning livestock production focuses on cattle; more studies must be performed on non-ruminants. Third, there is a gap in research related to water availability for livestock production. With projected increases in drought and declining water quality in many places on earth, it is critical to identify the regions with the best conditions for livestock production and improve the conditions for those that do not. Fourth, climate change may induce livestock diseases (e.g. outbreaks of severe diseases or new diseases), affecting animals that are not usually exposed to those diseases; there is a need to evaluate the dynamics of those diseases on livestock and how animals adapt to them. Fifth, there is a gap in knowledge related to the nutritional and metabolic processes of livestock; addressing this can improve management practices that increase animal performance. Sixth, because breeds and species are not a renewable resource, it is important to identify breeds with inherent genetic capabilities to adapt to climate change. Seventh, there are large uncertainties in using only energy costs of processing and transporting animals and their products to estimate GHG emissions at this stage of the livestock production process. Therefore, a better approximate estimation of CO_2 emissions related to processing and transport of livestock products is needed. Eight, there is a lack of information related to the current use of adaptation and mitigation measures defined by location and livestock system.

3 INTRODUCTION TO METHODOLOGY AND RESULTS

This dissertation consists of two research papers that have been published and submitted to scientific journals. The first study focuses on the development of a sensitivity analysis for evaluating the impacts of climate change on grazing dairy systems, while identifying an efficient adaptation measure. The second study builds upon the first study by introducing a new measure called food footprint to evaluate sustainable practices on grazing dairy systems by considering water, energy, carbon, and economic footprints.

The first paper, entitled “Pasture diversification to combat climate change impacts on grazing dairy production”, introduces a new concept for evaluating the resiliency of pasture diversification as an adaptation measure on grazing systems to reduce the negative impacts of climate change. To accomplish this, a representative farm was developed based on grazing dairy farm practices surveys within the Michigan Lower Peninsula. Using a farm system model, the impacts of current and future climate scenarios were evaluated at the farm level. For each climate model scenario, the adaptation measure was tested for 48 different pasture compositions based on the four typical grass and two legume species within the study area. Statistical analysis was performed to understand the effectiveness of the adaptation measures based on economic and resource use criteria. Finally, in order to understand the resiliency of each pasture composition, a sensitivity analysis was performed based on each criterion.

The second paper, entitled “Food Footprint as a Measure of Sustainability for Grazing Dairy Farms” uses the same representative grazing dairy farm and 48 pasture compositions introduced in the first study to evaluate the sustainability of the farm by considering water, energy, carbon, and economic footprints in 10 different locations in Michigan. The farm model IFSM was employed to estimate milk production and required information to calculate energy, water, carbon, and economic footprints for different combinations of pasture compositions, target milk productions, and locations scenarios. A multi-criterion decision making method was used to calculate the new sustainability measure called food footprint. By obtaining the food footprint and performing the cluster analysis, the most sustainable milk production and appropriate pasture composition for each location was identified.

4 PASTURE DIVERSIFICATION TO COMBAT CLIMATE CHANGE IMPACTS ON GRAZING DAIRY PRODUCTION

4.1 Introduction

Climate change refers to long-term changes in patterns of temperature, precipitation, wind, and other climatological factors (EPA, 2016). The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report identified the “likely range” of increase in global average surface temperature between 0.3°C and 4.8°C by the end of this century (IPCC, 2013). Increase in temperature will have a domino effect on hydrological cycle elements that ultimately increase the frequency of extreme events such as heat waves, droughts, and floods (Melillo et al., 2014).

The global impacts of climate change on societies and nature are already evident and are expected to increase in frequency during this century and beyond (Melillo et al., 2014). In the agricultural sector, significant change in both production and crop/animal health can be expected. Climate change will influence temperature and precipitation patterns, which can result in changes in production levels, shifts in production length and time, and severe damages due to extended drought or flood. Furthermore, each change can affect agricultural products price and producers’ income. Climate change may also impact animal and crop health by changing the quantity and spread of different pests and diseases (FAO, 2010a; Hatfield et al., 2014). Several studies have indicated that climate change could reduce agriculture production mainly in areas that currently suffer from high levels of food insecurity (FAO, 2010a; Hatfield et al., 2014; Adhikari et al., 2015). Meanwhile, increased agricultural production is needed to support the projected population growth from 7.2 to 9.6 billion by 2050 (FAO, 2009a).

Livestock is one of the major agricultural subsectors and the demand for livestock products is expected to double by 2050 (Garnett, 2009). At the same time, livestock production will be impacted by climate change. The impacts of climate change on livestock production include variations in: quality and quantity of feed crop and forage (Calvosa et al., 2009; Thornton et al., 2009; Chapman et al., 2012; Polley et al., 2013), availability of water (Thornton et al., 2009; Nardone et al., 2010; Henry et al., 2012), quantity and quality of livestock products (Thornton et al., 2009; Nardone et al., 2010; Henry et al., 2012), plant and animal diseases (Thornton et al., 2009; Nardone et al., 2010), and animal reproduction (Nardone et al., 2010). Among livestock systems, grazing is likely to be more affected by climate change than confinement systems because: a) pasture composition is one of the main components of a grazing system (Heckman et al., 2007) and b) feed quality and availability on pastureland will be determined by the climate conditions' impacts on the growing season (Hatfield et al., 2014). Meanwhile, few studies have been performed on the impacts of climate change on grazing livestock systems (Gauly et al., 2013; IPCC, 2014) due to the fact that these impacts are usually of a local concern.

Graux et al. (2013) used the Pasture Simulation model (PaSim) to evaluate climate change impacts on the agronomic and environmental services at 12 grassland sites in France. They evaluated the interaction of intensive and extensive managements on permanent and sown grasslands under past (1970-1999) and future climate scenarios (2020-2049 and 2070-2099). Results showed that by the end of the century all sites will shift to more arid climates resulting in an increased interannual and seasonal variability of production and decreased milk production. However, the role of economics or adaptation options, which may offset the impacts of climate change on the production were not considered in this study. Höglind et al., (2013) evaluated the impacts of climate change on the yield of two grass species in 14 locations in Northern Europe (Iceland, Scandinavia, Baltic countries) by using local-scale near-future climate scenarios (2040-2065). The two selected species were (1) timothy, which is the most important grass species of the region due to its ability to survive winter and (2) perennial ryegrass, which is better fitted for warmer conditions that are expected due to climate change. Results showed an increase in yield for both grass species under future climate scenarios. However, the risk for frost damage is still in place, which makes it difficult to justify using perennial ryegrass as an alternative to timothy for this region. Shrestha et al. (2015) used grass and economic models to determine the regional impacts of climate change on the yield and family farm income in Ireland. Concerning yield, results showed 56% increase for perennial ryegrass under future climate scenarios (2061-2090) due to increased rainfall, temperature and CO_2 concentration. Meanwhile, the overall income will decrease due to an increase in production costs. However, for farms using concentrate feed for livestock, income can be improved by substituting the concentrate feed with grass feed. Moore and Ghahramani (2013) used the GRAZPLAN simulation model to evaluate the impact of climate change on the net primary productivity (ANPP) of five livestock enterprises in 25 locations in southern Australia. Results indicated that ANPP will decrease in future scenarios (2030, 2050, and 2070) with larger reductions occurring in low-rainfall locations. The average reductions of ANPP were 9% in 2030, 7% in 2050 and 14% in 2070. Kalaugher et al. (2013) used a theoretical integrated research methodology to evaluate common adaptation strategies for the dairy sector in New Zealand. Results showed that the integrated bottom-up social research and top-down biophysical modeling have the potential of providing a more complete adaptation strategy for the farming system.

In this study, we are mainly focused on the impacts of climate change on grazing livestock systems. Most of the grazing livestock systems are for beef and dairy production. The United States is the second largest milk producer of the world and 41% of its production is concentrated in the Great Lakes region (USDA-NASS, 2014c; FAO, 2016a). Milk production, under a grazing system, is dependent on pasture intake (Muller, 2004). Therefore, a reduction of pasture yield, which consequently reduces pasture intake, can have a significant impact on milk production. Meanwhile, in the past few decades more farmers are transitioning from dairy confinement systems to grazing systems, especially in the Great Lakes Region, because of the increase in profitability compared with confinement operations (Nott, 2003; Kriegl and McNair, 2005). A study by Kriegl and McNair (2005) showed that grazing systems produced $887 net farm income from operations (NFIFO) per cow, compared to confined systems which produced $640 NFIFO per cow (Kriegl and McNair, 2005). The dairy grazing systems requires less feed, startup cost, labor, equipment, and fuel costs compare to confinement systems and; therefore, are more appealing to smallholder farmers (Aschmann and Cropper, 2007). Meanwhile, it is important to point out that there is no general agreement on the definition of smallholder dairy farmers in the US; however, in this study, a farm with less than a 100-lactating-cow was considered a small farm.

In order to reduce the impact of climate change on livestock production, adaptation strategies should be implemented. Adaptation strategies can increase the resilience of agricultural production to climate change (Walthall et al., 2012). Adaptation strategies for livestock production involve: 1) diversification of plant and animal species (Kurukulasuriya and Rosenthal, 2003; Batima et al., 2005; Calvosa et al., 2009), 2) incorporation of forestry and crop productions to the livestock systems (Steinfeld et al., 2006; Wani et al., 2009; Jose, 2009;

Herrero et al., 2010; Herrero et al., 2012; Smith et al., 2012), 3) adjustment of the timing for farm operations (Kurukulasuriya and Rosenthal, 2003; Batima et al., 2005; Calvosa et al., 2009;), 4) shifting locations of livestock and crop production (Kurukulasuriya and Rosenthal, 2003) and, 5) improving breeding strategies (Rowlinson, 2008; Henry et al., 2012).

In this study, diversification of plant species will be the main adaptation strategy explored. This strategy was selected due to its high probability of selection by producers since it only requires changing the seeding practices. In this study, we will identify the most resilient composition for a representative grazing dairy farm in Michigan in order to minimize the negative impacts of climate change. The study assesses the effectiveness of pasture compositions by evaluating: a) economic and b) resource use of the grazing dairy farms. In the economic category, we evaluated the net return per cow over milk production and the whole farm profit. In the resource use category, we evaluated grazed forage consumption and the harvested forage production. In order to achieve the goal of this study three objectives were sought: 1) identify the best pasture composition under current and future climate scenarios concerning farm economics and resource use, 2) assess economic and resources use impacts of pasture compositions under future climate scenarios, and 3) evaluate the resiliency of pasture compositions to climate change. Considering the number of combination of pasture species, climate scenarios, and the extend of analysis from economic and resource use standpoints, this study is the most comprehensive study that has ever been performed on grazing dairy farms in the Great Lakes region. Studies such as this are important to guide policy makers and stakeholders to address the negative impacts of climate change in the largest milk-producing region of the United States.

4.2 Materials and Methods

The goal of this study is to evaluate and propose an adaptation strategy based on pasture composition for common grazing dairy farms in Michigan under future climate change scenarios. A representative farm was developed based on a livestock practices survey. The farms where selected based on Michigan pastureland distribution and United States Department of Agriculture (USDA) - National Agricultural Statistics Service (NASS).

In order to evaluate the impact of climate change, the representative farm was tested using both current and future climate scenarios. The livestock model, IFSM, was used to simulate the representative grazing dairy farm performance. Two climate conditions were evaluated: a) *Current:* 21 climate models for the period of 1985 to 2005 and b) *Future:* 42 climate models for the period of 2040 to 2060. The climate conditions were obtained from the National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP).

For each climate model scenario, the adaptation strategy was tested for 48 different pasture compositions for a total of 2064 runs. The 48 pasture compositions were based on the four most common grass species and the two most common legume species.

4.2.1 Study Area

Five of the top 10 milk-producing states are in the Great Lakes region, including the state of Michigan (USDA-NASS, 2014c). In recent years, there has been an increase in the transition from confinement dairy systems to grazing dairy systems (Nott, 2003) within this region. This study will focus on grazing dairy farms in the state of Michigan.

Two criteria were defined in selecting the study area for the representative grazing dairy farm: a) pastureland distribution and b) number of dairy farms at a county level. The pastureland distribution was obtained from the USDA Crop Data Layer (USDA-NASS, 2014b). In general, pasturelands are mainly concentrated in the Southern portion of Lower Peninsula of Michigan. The number of dairy farms at the county level was obtained from USDA-NASS (2014a) and the majority was found in the Southern portion of Lower Peninsula of Michigan (Figure 6). The area of concentrated pasturelands and dairy farms is aligned with the agricultural region of Michigan (Nejadhashemi et al., 2012). Therefore, this region was selected as the study area.

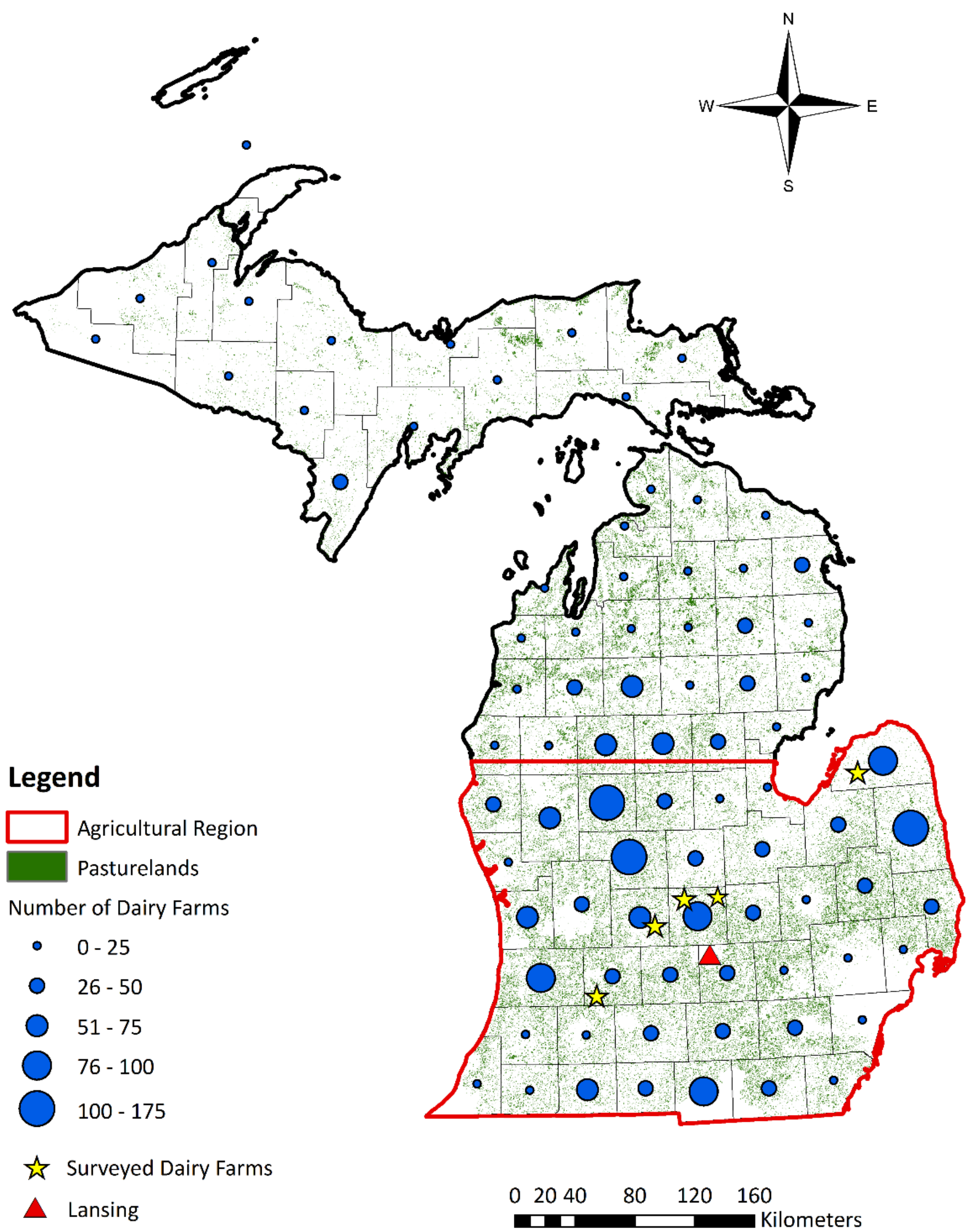

Figure 6. Study area and the location surveyed dairy farms

4.2.2 Data Collection

4.2.2.1 Grazing Farm Survey

In order to capture different grazing farm practices, ground surveys were performed in the spring and summer of 2013 throughout the study area (Rojas-Downing et al., 2017a). The surveyed farms were selected considering regional distribution, size, and management style. MSU extension advice was also sought for identifying the representative grazing dairy farms in the region. Ultimately, five different farms were surveyed in the western, eastern, and central part of the Michigan agricultural region (Figure 6). Direct field observations and structured questionnaires based on IFSM input data requirements where used to obtain the information during a single-visit. To maximize survey compliance, farmers were reminded to return answers to the questions that they were not able to respond to during the in-person interview. The information collected on the surveys by Rojas-Downing et al., (2017a) was used to develop a representative grazing dairy farm in Michigan. The selected data for the representative farm was reviewed by MSU extension and specialists in order to confirm the representativeness of the farm and validating the input data that will later use in modeling exercise. This information included farm management, pasture area, machinery operations, grazing strategy, equipment, structures, number and type of animals, and associated prices for several farm inputs and outputs. A summary of survey information is provided in Table S1 and S2 in the Supplementary Materials.

The five surveyed grazing dairy farms represent different farm size and management operations that are common in the study area. The farm sizes range between 83 ha to 146 ha. Most of the farms have alfalfa areas for forage production and a grazing area with a variety of pasture compositions. Based on this information and inputs from extension specialists, the typical grass and legume species and compositions were identified.

The surveyed farms had between 90 and 750 lactating cows. The cattle frame for four of the farms were small Holsteins and one farm had New Zealand Friesian. The target milk production ranges from 6,804 to 10,866 kg/cow/year, while the average milk production in Michigan is 9,500 kg/cow/year. Most of the cattle feed of the surveyed farms had high relative forage to grain ratios, with pasture as the main feed and grain as an energy supplement.

All of the surveyed farms have a rotational grazing system with a stocking rate that ranges between 0.4 to 2.1 animals per acre. The grazing strategy is similar for the five surveyed farms with a labor for grazing management of 10 hours per week and all animals are grazed 22 hours per day. Regarding animal facilities, all farms had a milking center, cow housing, heifer housing, feed facility, short-term manure storage, and forage storage.

4.2.2.2 Representative Grazing Dairy Farm Description

Based on the data obtained from the statewide survey, the representative grazing farm was established in IFSM. The simulated farm has small frame Holsteins (454 kg), where 100 were lactating cows and 80 were replacement stock. The grazing area was 54 ha with a stand life of 10 years and additional 27 ha forage production area that includes alfalfa, with a stand life of 5 years. The tillage and planting operations were performed between mid-October and mid-April, using a chisel plow and a seedbed conditioner. Eighty percent of the manure collected in the milking facilities was applied to the alfalfa area and the remaining twenty percent was applied to the grazing area. Beside the collected manure, no additional fertilizers were applied on the grass and alfalfa areas.

As part of the grazing strategy, all cows where grazed for the entire day during the growing season (April to October), with a labor for grazing management of 20 hours per week. The grazing area varied during spring (27 ha), summer (49 ha), and fall (49 ha) to account for area harvested for hay or silage. Alfalfa was harvested as silage and hay four times a year beginning around the end of the May while grass was harvested once a year as silage around the same period.

The annual target milk production was 7,252 kg per cow corrected to 4.2% fat content. All animals were fed with a rotation that provided a relatively high forage-to-grain ratio. Additional supplements were given to animals besides the feed produced on the farm. Soybean meal 48% was given as crude protein supplement, distiller grain was given as undegradable protein and grain was given as the energy supplement.

The animal facilities included a bedded pack barn for cow housing, calf hutches and dry lot for heifer housing, a short-term storage premix as a feed facility, and a double four parlor as a milking center. The manure was collected in the facilities throughout the year using scrapers with slurry pumps and stored in a top-loaded concrete tank for a four-month period.

The economic analysis included all major operations based on 2013 representative prices. Any resources grown on or brought onto the farm were considered as costs, while any sale of milk, forage, and animals were considered as income. All income and costs for producing milk, feed and animals occurred in the same year. Therefore, the annual accounting considers all resources used during a one-year production (Rotz et al., 2014). Important prices include diesel fuel at $0.98/L, electricity at $0.13/KWh, labor wage at $16/h, new forage stand at $494/ha, high quality hay at $265/tonne DM, hay at $198/tonne DM, and milk at $0.36/kg.

4.2.2.3 Climate Data

Three sets of climatological data were used to evaluate the impact of climate change on the representative grazing dairy farm. These included: a) one historical data set based on observed daily records obtained from a weather station and b) two future climate scenarios based two representative concentration pathways obtained from NASA NEX-GDDP. The three sets of climatological data include daily precipitation and minimum and maximum temperature.

The historical data based on observed daily records (1985 to 2005) were obtained from the National Climatic Data Center (NCDC) for station number 725390 located at the Lansing Capital City Airport. The station was selected since it represents the annual average precipitation (720 mm) and temperature (8.6°C) of the study area.

The future climate conditions from NASA NEX-GDDP are global downscaled climate scenarios that were obtained from the General Circulation Model (GCM) simulations under the Coupled Model Intercomparison Project Phase 5 (CMIP5). These climate scenarios provide worldwide projected changes on a regional level in response to two different GHG emissions simulated by 21 models (Thrasher et al., 2012). The two different GHG emissions scenarios, also known as Representative Concentration Pathways (RCP) include current and future climate conditions. The current climate conditions are simulated by 21 climate models for the period from 1985 to 2005. The future climate conditions are simulated by 42 climate projections derived from 21 climate models and two RCP scenarios (RCP 4.5 and 8.5) for the period of 2040 to 2060 (Table 1). The annual average precipitation and temperature were increase by 63.8 mm and 2.2 °C for RCP 4.5 and 74.1 mm and 2.8 °C for RCP 8.5, respectively.

The NASA NEX-GDDP dataset provides worldwide high resolution (0.25 degrees x 0.25 degrees) and bias-corrected climate scenarios. The Bias-Correction Spatial Disaggregation

(BCSD) method was used for generating the NASA NEX-GDDP dataset (Thrasher et al. 2012). BCSD is a statistical downscaling logarithm that addresses the GCM limitations, such as coarse resolution grids and local bias projections (Wood et al., 2002; Wood et al., 2004; Maurer et al., 2008; Thrasher et al., 2012). The BSCD algorithm adjusts the offset of climate trends by applying a linear shift based on the observational climate data from weather stations of the Global Meteorological Forcing Dataset (GMFD) (Thrasher et al., 2012). However, since the location of the study area does not overlap with one of the GMFD stations, additional downscaling using the Delta method (Woznicki and Nejadhashemi, 2014) was performed between the 21 current climate models and the historical data based on observed daily records.

In addition to daily temperature and precipitation, solar radiation data are also a required parameter for IFSM but not available through NASA NEX-GDDP data set. Therefore, solar radiation was estimated for the climate scenarios using a weather generator. The weather generator used in this study is called WXGEN (Sharpley and Williams, 1990; Wallis and Griffiths, 1995). WXGEN is a stochastic weather generator model embedded in the Soil and Water Assessment Tool (SWAT) to fill-in gaps of weather data (Jeong et al., 2015). WXGEN is based on monthly statistics estimated from daily weather data (Jeong et al., 2015). Therefore, daily temperature and precipitation data were used as inputs in WXGEN to estimate daily solar radiation data for the location of study. WXGEN has been extensively used in other studies in different parts of the world and it has proven to be a powerful tool (Wallis and Griffiths, 1995; Harmel et al., 2000; Sourkova and Pona, 2002; Birhanu et al., 2007; Lee and Kim, 2013; Baker and Miller, 2013).

Table 1. Summary of climate models used in NEX-GDDP and their average temperature and precipitation projections for the study area for the period of 2040 to 2060 (IPCC, 2013; PCMDI, 2015)

Model number	Modeling Center/ID	Model Name	RCP 4.5		RCP 8.5	
			Average Temperature (°C)	Average Precipitation (mm)	Average Temperature (°C)	Average Precipitation (mm)
1	Institute for Numerical Mathematics/ INM	INM-CM4	9.7	793.2	10.1	783.4
2	Beijing Climate Center, China Meteorological Administration/ BCC	BCC-CSM1.1	11.0	734.4	11.4	797.9
3	Norwegian Climate Centre/ NCC	NorESM1-M	11.0	720.1	11.6	781.2
4	Meteorological Research Institute /MRI	MRI-CGCM3	10.1	808.5	10.5	863.4
5	Max Planck Institute for Meteorology/ MPI-M	MPI-ESM-MR	10.1	866.2	11.0	801.5
6		MPI-ESM-LR	10.2	737.0	11.3	751.5
7	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology /MIROC	MIROC5	11.3	771.7	12.0	839.1
8		MIROC-ESM	11.6	800.1	12.9	817.6
9		MIROC-ESM-CHEM	12.1	811.0	13.0	785.9
10	Institute Pierre-Simon Laplace/IPSL	IPSL-CM5A-MR	10.7	714.0	11.5	726.1
11		IPSL-CM5A-LR	10.7	770.6	11.4	759.4
12	Geophysical Fluid Dynamics Laboratory/NOAA GFDL	GFDL-ESM2M	9.7	774.8	10.1	759.2
13		GFDL-ESM2G	10.1	823.5	10.6	885.4
14		GFDL-CM3	11.5	914.6	12.1	912.2
15	Canadian Centre for Climate Modelling and Analysis/ CCCma	CanESM2	11.2	795.0	11.9	767.2

Table 1 (cont'd)

16	Commonwealth Scientific and Industrial Research Organization in collaboration with the Queensland Climate Change Centre of Excellence/ CSIRO-QCCCE	CSIRO-Mk3.6.0	10.8	851.5	11.1	858.2
17	Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique/CNRM-CERFACS	CNRM-CM5	10.6	816.2	11.3	772.4
18	National Science Foundation, Department of Energy, National Center for Atmospheric Research/ NSF-DOE-NCAR	CESM1-BGC	10.7	772.6	11.5	818.5
19	National Center for Atmospheric Research/NCAR	CCSM4	11.3	669.2	11.4	742.6
20	College of Global Change and Earth System Science, Beijing Normal University/ GCESS	BNU-ESM	11.3	808.5	11.7	815.1
21	CSIRO (Commonwealth Scientific and Industrial Research Organization, Australia), and BOM (Bureau of Meteorology, Australia)/ CSIRO-BOM	ACCESS1.0	11.2	706.3	12.2	638.0

4.2.3 Modelling Process

4.2.3.1 Integrated Farm System Model (IFSM)

The IFSM is a whole-farm simulation model developed by the USDA-Agricultural Research Service (ARS) for over 35 years. IFSM can evaluate the resource use and the environmental and economic sustainability of livestock and crop production systems (USDA-ARS, 2014). The model was developed and validated for temperate regions of the northern United States (such as Michigan) and Southern Canada (USDA-ARS, 2014). However, the model has been used in many regions where long-term weather data is available (Wachendorf and Golinski, 2006; Bryant and Snow, 2010). IFSM model performance has been extensively validated with real farming practices (Rotz, 2004; Rojas-Downing et al., 2017a, b). In addition, the model accuracy has been evaluated under both dry and wet years with different pasture mixtures (Corson et al., 2007).

IFSM is distinguished from other similar models because it is a process-based model (USDA-ARS, 2014). Therefore, it is able to represent the interactions between farm components and major biological and physical process throughout the simulation period (USDA-ARS, 2014). For a livestock system, the major components simulated in IFSM include feed production and disappearance, grazing management, animal performance, feed storage, manure handling, tillage, planting and harvest operations, and costs and returns. IFSM comprises nine major submodels that are: crop and soil, grazing, machinery, tillage and planting, crop harvest, crop storage, herd and feeding, manure handling, and economic analysis.

Several assumptions were considered during the IFSM model development, such as disregarding market considerations (e.g. the amount of livestock production does not affect commodity prices) and that the production and accounting period is one year (e.g. at the end of the year, crop inventories are sold and feed shortages are purchased). In addition, the impact of climate variabilities on farm performance can be evaluated if all parameters remain constant. This assumption allows evaluation of climate change impacts on farm performances.

The required input parameters for the IFSM model include: soil type, crop areas and characteristics, grazing management, equipment and structures used, harvest, tillage, numbers of animals at various ages, herd feeding, manure handling strategies, and prices for various farm inputs and outputs (Table S1). IFSM simulation is daily, but the outputs can be presented as long-term annual averages and standard deviations. Meanwhile, some outputs can be presented in higher temporal resolution including annual (e.g. production costs), monthly (e.g. grazed forage yield), weekly (e.g. labor information), and daily basis (e.g. forage crop yield and quality) (USDA-ARS, 2014).

4.2.3.2 Selection of pasture compositions

The representative grazing dairy farm was developed based on the survey information collected from the five farms, a literature review, and expert opinion. The representative farm simulated in IFSM had two variables: a) pasture composition and b) climate condition.

The pasture composition varies depending on the grazing management goal and the location. Producers select the species of the pasture composition based on: biomass production, seasonal biomass distribution, animal palatability and nutrition, and persistency over time (Sullivan et al., 2000). In Michigan, the most common functional groups are cool-season grasses and legumes. Based on the information collected from the survey, the most common cool-season grasses are orchardgrass (*Dactylis glomerata*) and perennial ryegrass (*Lolium multiflorum*). The most common legumes are white clover (*Trifolium repens*) and red clover (*Trifolium pratense*) and the percentage in the pasture composition varies between 0% and 50%. However, the most common pasture composition in Michigan is 60% orchardgrass and 40% white clover. Based on the aforementioned information, these four pasture species were selected.

The two typical grass species used in Michigan have different characteristics that made them favorable (Table 2). For the orchardgrass, the overall yield is high, and it is resistant to the cold climate of Michigan (winter hardiness). In addition, orchardgrass is easy to establish due to fast germination (seedling vigor), while it makes ‘excellent’ hay production. Meanwhile, perennial ryegrass is an ‘excellent’ pasture crop and is easy to manage. In addition, it can be quickly established (excellent seedling vigor) but cannot survive a cold weather; and therefore, is mostly planted in the southern part of the state, which is, in general, warmer than the rest of the state. In regard to adaptability of the aforementioned grass species to climate change, orchardgrass has ‘fair’ resistance to flooding but a ‘good’ resistance to droughts while perennial ryegrass has ‘poor’ drought resistance but a ‘good’ tolerance to flooding.

In addition to the above species, alternative varieties were evaluated since the typical grass species in Michigan have ‘good’ or ‘poor’ adaptability to extreme events (Table 2). The two other alternative cool-season grasses in Michigan are Kentucky bluegrass (*Poa pratensis*) and Tall Fescue (*Lolium arundinaceum*). Both species are ‘excellent’ for pasture and have resistance to the cold Michigan environment (winter hardiness). In addition, tall fescue can be characterized as a ‘very good’ drought and flood resistant species, while Kentucky bluegrass cannot tolerate drought (poor) but is considered a ‘good’ flood resistant grass.

Table 2. Cool-season grasses characteristics (Barnes et al., 2007; Cassida et al., 2014)

Grass	Forage yield for Michigan (Kg/ha)	Seedling vigor	Pasture	Drought resistant	Flood resistant	Winter hardiness	Hay
Orchardgrass	7,173 -10,088	G	F	G	F	E	E
Perennial Ryegrass	4,035 -6,725	E	E	P	G	F	P
Kentucky Bluegrass	-	P	E	P	G	E	P
Tall Fescue	5,380-10,760	F	E	VG	VG	E	E

E = Excellent, VG = Very Good, G = Good, F = Fair, P = Poor

4.2.3.3 Simulation of pasture compositions and climate scenarios in IFSM

Figure 7 illustrates the overall modeling process of pasture compositions and climate scenarios for the representative grazing dairy farm. All possible combinations of the four cool-season grass species (Orchardgrass, Perennial ryegrass, Kentucky bluegrass and, Tall Fescue) with the two legumes (white clover and red clover) where simulated (Figure 7). The percentage of legume in the pasture composition varies between 0% and 50%, in 10% increments. Overall, 48 different pasture compositions where simulated. Each of the 48 pasture combinations were simulated under the current condition and under the 42 climate models of the future condition of NASA NEX-GDDP (21 climate models of RCP 4.5 and 21 climate models of RCP 8.5). Consequently, 2064 scenarios where simulated in IFSM (Figure 7). The representative grazing dairy farm information from Table S1 was used as the main input to IFSM with the variables of pasture composition and climate conditions (Figure 7).

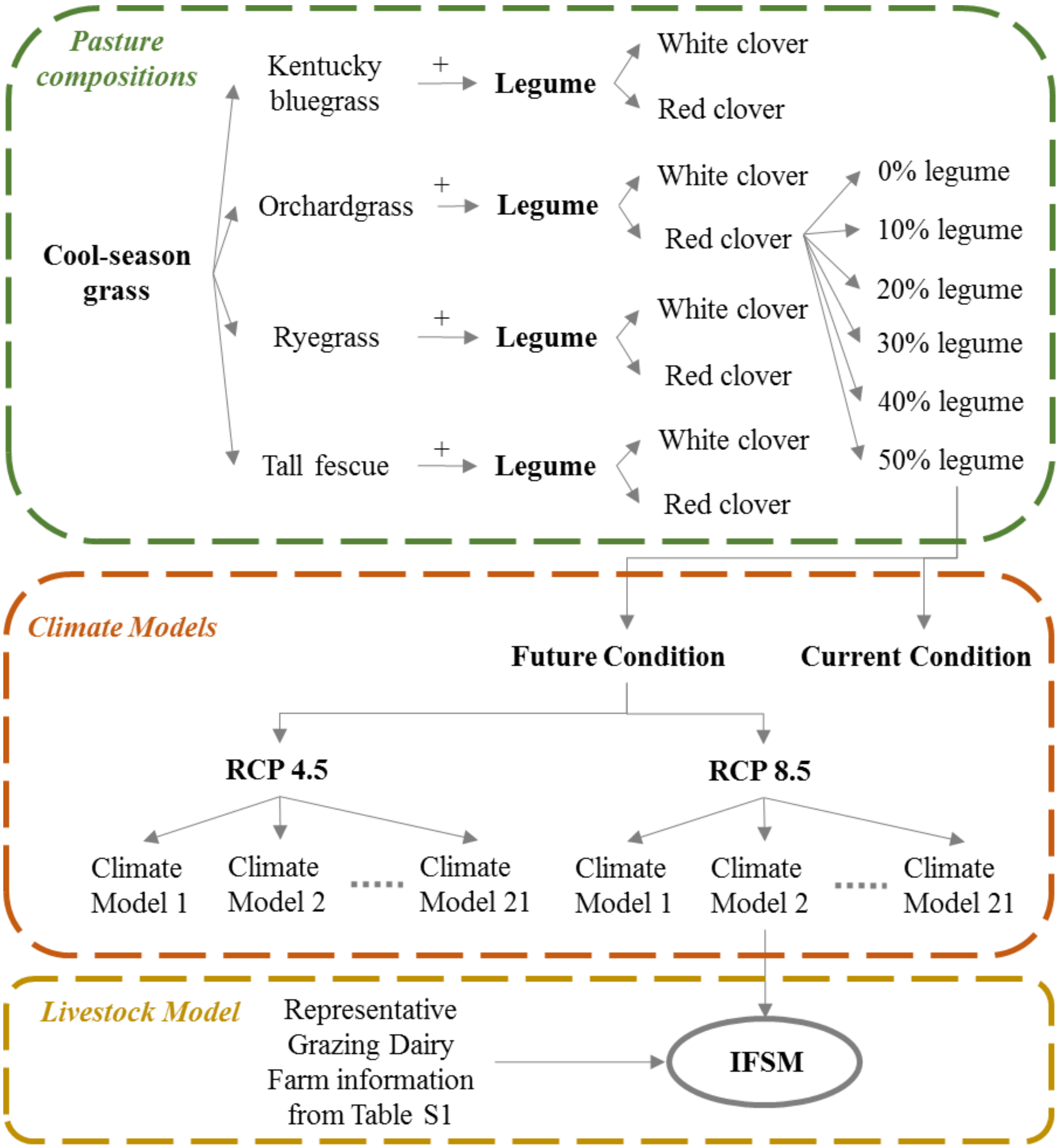

Figure 7. Modeling process of the representative grazing dairy farm

4.2.3.4 *Identifying the impact of pasture compositions and climate change on economic and resource use of a livestock grazing system*

Statistical analysis was performed to understand the significance of grass and legume species compositions concerning the economic and resource use criteria and future climate scenarios (RCP 4.5 and RCP 8.5). The Fisher's Least Significant Difference test (Fisher, 1935) was used to perform a multiple pairwise comparison among grass and legume species at a 5%

significance level (α=0.05) using MATLAB version 8.2.0.701 (R2013b). The pairwise comparison analysis was performed to identify the impact of: (1) legumes percentages with four different grass species in the pasture composition, (2) grass species at different percentages of legumes in the pasture composition, (3) two legumes for each grass species, (4) four grass species for each legume species, and (5) climate scenarios (RCP 4.5 and RCP 8.5).

4.2.3.5 Sensitivity analysis to identify the most resilient pasture composition

In order to understand the resiliency of each pasture composition under the current and future climate scenarios (RCP 4.5 and RCP 8.5), a sensitivity analysis was performed. Equation (1) was used to calculate the relative sensitivity index (Luo and Zhang, 2009; Woznicki and Nejadhashemi, 2012):

$$S_{(T,P)} = \frac{(y_i - y_0)x_0}{(x_i - x_0)y_0} \quad (1)$$

where, $S_{(T,P)}$ is the relative sensitivity index based on average temperature (T) or precipitation (P), x_o is the 20-year average temperature or precipitation based on current climate scenario, x_i is the 20-year average temperature or precipitation for the i^{th} future climate model/scenario, y_o is the criteria value (the economic and resource use) under the current climate scenario, and y_i is the criteria value under the *i*th future climate model/scenario. Greater magnitude of the relative sensitivity index indicates higher sensitivity of the pasture composition to the temperature or precipitation variations under future climate scenarios.

A minimum of 50 model simulations are required for each pasture composition (Luo and Zhang, 2009). Therefore, for each pasture composition, the percentage of legume was randomly altered within the selected legume range. Since the legume percentage ranges between 0% and 50% and IFSM only accepts integer values, all legume percentages were simulated within the range. Therefore, the two legumes (Red Clover and White Clover) were varied 51 times (1%

intervals) for each grass species (Perennial ryegrass, Tall Fescue, Kentucky bluegrass, and Orchardgrass) and one current and 42 future climate model/scenario combinations, resulting in 17,544 simulations.

After calculating the relative sensitivity index for each criterion under future climate scenarios, the Euclidean norm was calculated using Equation (2):

$$S = \sqrt{S_P^2 + S_T^2} \tag{2}$$

where, S is the relative sensitivity index. The Euclidean norm provides the sensitivity of the pasture composition to both temperature and precipitation.

4.2.3.6 Economic and resource use sensitivity under future climate change scenarios

Second-order response surface models (Bradley, 2007) were fitted to different sensitivity indices. The second-order response surface model analyzes the factor level combinations (precipitation and temperature) that provide the maximum and minimum sensitivity index in each criterion with different pasture compositions.

To present the fitted response surface model results, three dimensional response surface plots and two dimensional contour plots were created (Supplementary material, Figures S1 to S28). Regarding the response surface plots, the z-axis represents the sensitivity index (response variable), the y-axis the temperature (explanatory variable), and the x-axis the precipitation (explanatory variable). Contour lines were added at the base of the surface plots to better display the structure of the response surface. Regarding the contour plots, x- and y-axes represented the explanatory variables (temperature and precipitation, respectively) while the contour lines represented the levels of the response variable (sensitivity index).

Two factors were evaluated in both the response surfaces and contour plots. First, the area with the highest sensitivity index, and second, the fraction representing the change of temperature in Celsius for every 100 mm of precipitation. The fraction represents the importance of temperature to precipitation on the sensitivity indices between the different pasture compositions.

The change of the sensitivity index was presented with a color gradient as the background combined with the contour lines. Each color in Figure 8 represents the area of a certain range of sensitivity index from white-pink (high sensitivity) to pink-yellow (medium sensitivity) to yellow-green (low sensitivity). The contour plots provided a clear identification of the most sensitive area based on temperature and precipitation for all the pasture compositions. The fraction of the change of temperature in Celsius for every 100 mm of precipitation was obtained by drawing two lines from the highest value on the graph. One line is drawn parallel to the x-axis (A) and the second line connects the inflexion points of the concave contour lines (B) as shown in Figure 9. The vertical difference between the lines at the far right of the graph, named ‘C’, represents the difference in temperature for the entire range of the precipitation. By using the rule of three, where the nominator is temperature and the denominator is precipitation, the fraction of the change of temperature in Celsius for every 100 mm of precipitation was calculated.

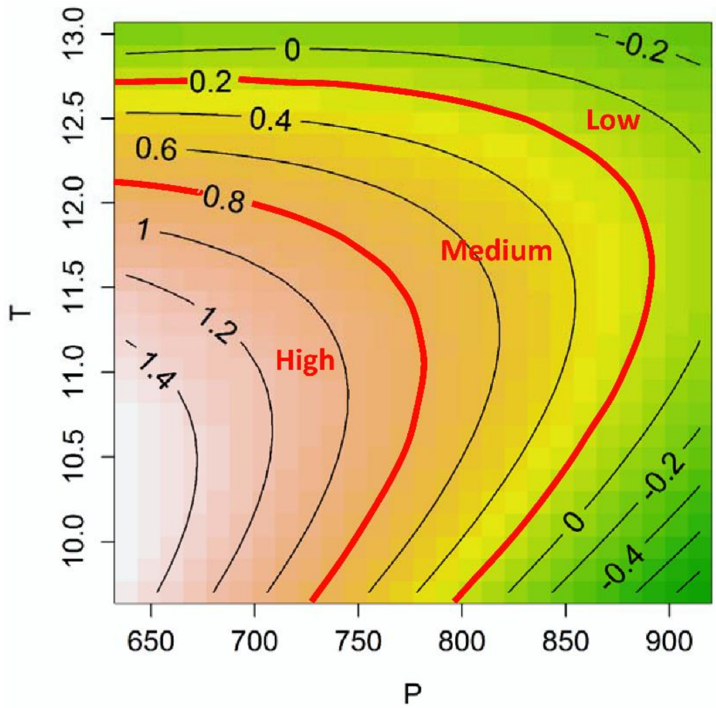

Figure 8. Sensitivity index area

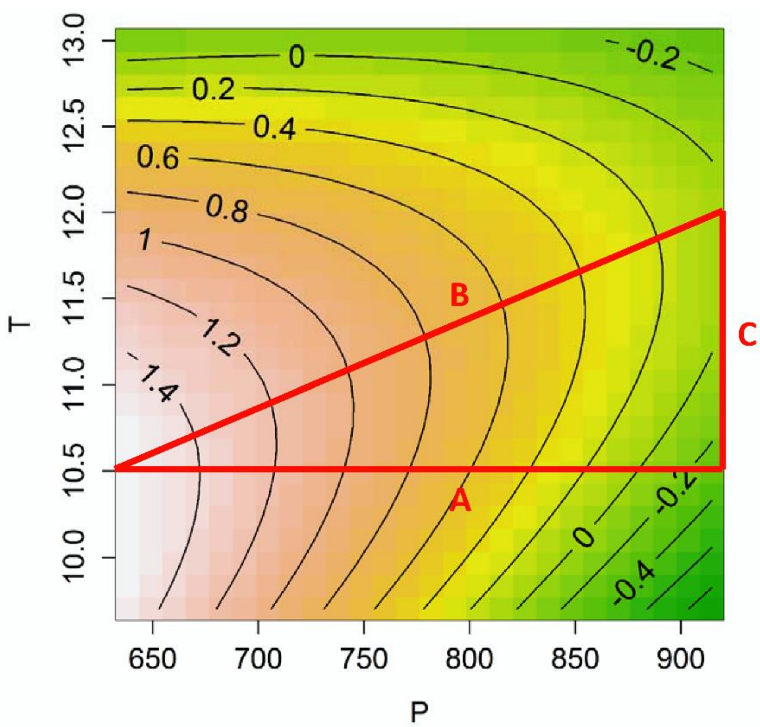

Figure 9. Calculating the fraction of temperature to precipitation

4.3 Results and Discussion

4.3.1 Identification of the best pasture composition based on resource use and economics

4.3.1.1 Net return per cow over milk production

The net return per cow for milk production is determined by IFSM as the sum of all revenues minus the sum of all costs related to milk production (Rotz et al., 2014). The revenues include incomes from feed production and milk sales while the costs include purchased feed and activities associated with crop production such as equipment, fuel, electricity, facility, labor, seeds, fertilizers, and chemicals.

Among evaluated pasture composition scenarios, the one with 50% perennial ryegrass and 50% red clover was identified with the highest net return per cow over milk production for both the current and future climate scenarios. In fact, we saw improvement in net return under future climate scenarios. For example, on average the highest net return per cow ($2,149/cow-yr) was observed under the RCP 8.5 climate scenario, followed by the RCP 4.5 climate scenario ($2,123/cow-yr), and then the current scenario ($2,106/cow-yr), respectively. This is mainly due to increases in the annual average temperature and precipitation in the region as the current average temperature is expected to rise from 8.6˚C to 10.8˚C under RCP 4.5 and to 11.5˚C under RCP 8.5 by the middle of this century. Similarly, the current annual average precipitation is expected to increase from 720 mm to 784 mm and 794 mm for RCP 4.5 and 8.5 climate scenarios, respectively. This resulted in increased performances in perennial ryegrass, as the ryegrass does not generally perform well under low rainfall and high soil temperature conditions (MacFarlane, 1990).

In general, the differences between the best-case scenario (50% perennial ryegrass and 50% red clover) and other top ranked pasture compositions (different grass species with 50 %

legume) were small and less than 10 dollars (Table 3). Therefore, it can be concluded that the percentage of legume is the main factor, besides climate scenario, influencing the net return per cow over milk production. Meanwhile, among the evaluated legume species and beside the overall profit, red clover is a preferred choice since it has a better potential for hay production (Lacefield, 2013).

Looking more in depth into the costs and incomes associated with milk production reveled similar trends between current and future climate scenarios. In general, within the same climate scenario, the higher ranked pasture composition scenarios had higher incomes and costs and vice versa. Meanwhile, for all climate scenarios, a pasture composition with 50% red clover combined with perennial ryegrass had the highest net return per cow over milk production, followed by tall fescue, Kentucky bluegrass, and orchardgrass. For example under RCP 8.5 climate scenario, the highest costs and incomes were associated with the most profitable scenario (50% perennial ryegrass and 50% red clover) in which the average annual costs for equipment, fuel and electricity, feed and machinery facilities, and seed, fertilizer and chemical are \$39,686, \$5,653, \$11,294, and \$11,326 respectively. However, the perennial ryegrass also presented the lowest purchased feed cost (\$66,336/yr) and the highest income from feed sales (\$29,173/yr). Labor is considered an income for the representative farm, because the majority of dairy farmers in Michigan (97%) are family owned, and thus family members tend to perform most of the labor on the farm (United Dairy Industry of Michigan, 2016). Therefore, by subtracting the costs (\$134,295/yr) from the feed sales (\$29,173/yr), labor incomes (\$27,188/yr) and milk incomes (\$292,850/yr), the perennial ryegrass had the highest net return per cow over milk production (\$2,149/yr) compared to tall fescue (\$2,143/yr), Kentucky bluegrass (\$2,142/yr), and orchardgrass (\$2,139/yr). Comparing to the current scenario, the average net return per cow for the perennial ryegrass, tall fescue, Kentucky bluegrass, and orchardgrass were improved by 2.04%, 1.85%, 1.90%, and 1.86% under RCP 8.5 scenarios, respectively.

Table 3. Summary of the top four pasture compositions with the highest net return per cow over milk production

Pasture composition		Net return per cow ($/cow-year)		
		Current	Future Scenario	
Grass	Legume	Scenario	RCP 4.5	RCP 8.5
		Mean (SD*)	Mean (SD*)	Mean (SD*)
50% Perennial Ryegrass	50% Red Clover	2,106 (809)	2,123 (431)	2,149 (473)
50% Tall Fescue	50% Red Clover	2,104 (816)	2,118 (437)	2,143 (474)
50% Kentucky Bluegrass	50% Red Clover	2,102 (815)	2,117 (433)	2,142 (474)
50% Orchardgrass	50% Red Clover	2,100 (817)	2,114 (441)	2,139 (472)

*SD: Standard Deviation

4.3.1.2 Whole Farm profit

The whole farm profit is obtained from IFSM as a return to management and unpaid factors. IFSM calculates this by subtracting costs for feed, manure handling, animal housing, animal care, and milking from the incomes of milk, excess feed and animal sales (Rotz et al. 2014).

The pasture composition that had the highest whole farm profit was 50% perennial ryegrass and 50% red clover for all climate scenarios. The climate scenario that had the highest whole farm profit was RCP 8.5 ($174,672/yr), followed by RCP 4.5 ($172,059/yr) and then the current scenario ($170,406/yr), respectively.

In all climate scenarios, the top four pasture compositions with the highest whole farm profit are all the four grass species combined with 50 % legume (Table 4). These top four pasture compositions have a similar whole farm profit, and major differences are dependent on the percentage of legume. Therefore, similar to the net return per cow, the percentage of legume is the main factor affecting farm profit.

Overall, the higher ranked pasture composition scenarios had the highest incomes and costs, and vice versa in all climate scenarios. This trend is the same as for the criterion of net return per cow, where a pasture composition with 50% red clover combined with perennial ryegrass has the highest whole farm profit and orchardgrass has the lowest. For example, under RCP 8.5 the average annual costs associated with this scenario are equipment ($47,121/yr), facilities ($47,228/yr), energy ($13,091/yr), seed, fertilizer and chemical ($11,326/yr), animal purchase and livestock expense ($48,200/yr), milk hauling and marketing fees ($12,801/yr) and property tax ($4,435/yr). However, the perennial ryegrass presented the lowest net purchased feed and bedding cost ($38,018/yr). Therefore, by subtracting the costs ($222,220/yr) from the labor ($59,601/yr), animal sales ($44,442/yr) and milk incomes ($292,850/yr), the perennial ryegrass had the highest whole farm profit of $174,672/yr compared to tall fescue ($174,087/yr), Kentucky bluegrass ($173,978/yr), and orchardgrass ($173,678/yr).

Table 4. Top four pasture compositions with the highest whole farm profit

Pasture composition		Whole farm profit ($/year)		
			Future Scenario	
Grass	Legume	Current Scenario Mean (SD*)	RCP 4.5 Mean (SD*)	RCP 8.5 Mean (SD*)
50% Perennial Ryegrass	50% Red Clover	170,406 (8223)	172,059 (5375)	174,672 (5577)
50% Tall Fescue	50% Red Clover	170,173 (8432)	171,540 (5402)	174,087 (5573)
50% Kentucky Bluegrass	50% Red Clover	170,006 (8368)	171,457 (5401)	173,978 (5573)
50% Orchardgrass	50% Red Clover	169,735 (8420)	171,157 (5348)	173,678 (5607)

*SD: Standard Deviation

4.3.1.3 Grazed forage consumed

The grazed forage consumed is the amount of pasture consumed by herds. The availability of pasture is predicted by IFSM and is based on the season, pasture species characteristics, soil type, and weather conditions. In general, 60% of the pasture production is kept for herd consumption and the remaining 40% is used for pasture regrowth (Rotz et al., 2014).

For the grazed forage consumed criterion, the top four pasture compositions had the same value for each climate scenario (current = 186 tonne DM/yr; RCP 4.5 = 185 tonne DM/yr; RCP8.5 = 184 tonne DM/yr). In general and regardless of grass species, a combination of 30%, 40% and 50% of red clover produced between 184 (RCP 8.5) to 186 (current) tonne of dry matter (DM) per year in all climate scenarios. Therefore, to maintain a high grazed forage production for future scenarios, it is important to maintain at least 30% red clover in the pasture composition. This finding is also supported by previous studies that demonstrated that at least 30% legume is required to improve pasture productivity (Rayburn, 2007). This can be explained due to the fact that the red clover on average is able to produce two-thirds more forage than white clover and tolerates wetter soils (Griffin, 2004), which is the case in the study area.

In general, the grazed forage consumption decreases with the future scenarios because of an increase in average rainfall and temperature. Cool-season grasses tolerate a cooler and wetter environment. The optimum growth of cool-season grasses is between 10 ˚C and 21 ˚C and the growth decreases to zero as the average temperature increases to 32 ˚C (Rayburn, 2007). Therefore, an increase in temperature in the future scenarios reduces the amount of grass forage produced.

4.3.1.4 Harvested forage production

To meet animal nutrients needs and maintain the desired production level, harvested forage is provided to livestock in addition to pasture and supplemental feeds. Therefore, the source of the harvested forage production was a combination of harvested pasture composition and alfalfa to produce enough hay and silage to meet the animals feeding requirements. The pasture composition that had the highest annual harvested forage production was 50% perennial ryegrass and 50% red clover for the current and future climate scenarios. However, the RCP 8.5 climate scenario presented the highest harvested forage production (337 tonne DM), followed by the current scenario (330 tonne DM) and RCP 4.5 (326 tonne DM). This trend is similar to the forage yield. Alfalfa yield in the current scenario, RCP 4.5 and RCP 8.5 is 11.2 tonne/ha, 11.2 tonne/ha and 11.5 tonne/ha, respectively. Grass yield in the current scenario, RCP 4.5 and RCP 8.5 is 5.5 tonne/ha, 5.0 tonne/ha and 5.3 tonne/ha, respectively. The reduction of harvested forage production of grass in the future scenarios is related to the increase in temperature, which lowers the cool-season grass performance (MacFarlane, 1990; Rayburn, 2007). Despite the decrease of grass yield in future scenarios, the highest harvested forage production was observed for RCP 8.5 (337 tonne DM), mostly due to an increase in the alfalfa yield.

The top four pasture compositions with the highest harvested forage production have 50% red clover for all climate scenarios. This is related to the higher potential of red clover for hay production compared to white clover (Lacefield, 2013). The forage production ranges from 327 to 330 tonne DM under current climate scenario. However, it is expected to decrease to 321 to 326 tonne DM under RCP 4.5 but increase to 332 to 337 tonne DM under RCP 8.5 scenario.

The harvested forage is classified into high and low quality based on nutrient availability and concentration. The forage quality is influenced by several factors such as maturity of the plant at the time of harvesting, plant species, climate, soil fertility, disease and insect pests, and harvesting and storage losses (Rayburn, 2007). The high quality forage production follows the same trend as the harvested forage production. The pasture composition that had the highest annual high quality forage production contains 50% perennial ryegrass and 50% red clover for all climate scenarios. The current scenario presented the highest high quality forage production (233 tonne DM), followed by RCP 4.5 (136 tonne DM), and RCP 8.5 (128 tonne DM).

Neutral Detergent Fiber (NDF) and Crude Protein (CP) are widely used to determine forage quality. The NDF is the portion of the forage that is insoluble in neutral detergent, which contains the primary components of the plant cell wall. An increase in NDF decreases dry matter intake. Legumes with an NDF lower than 40% and grasses with less than 50% NDF will be considered high quality forage (Rayburn, 2007; Rayburn, 2008). The CP is the amount of nitrogen and amino acids in the forage. The amino acids are used by the animals for growth and milk production. A forage that has higher CP will usually be considered high quality (Rayburn, 2007; Rayburn, 2008). Based on the aforementioned criteria, the forage quality of alfalfa decreases under future scenarios. Alfalfa CP decreases from 20.3% in the current scenarios to 19.0% and 18.7% in RCP 4.5 and RCP 8.5, respectively, which reduces the forage quality (Table 5). Meanwhile, the NDF level increases from 41.9% (current) to 47.6% (RCP 8.5) under the future scenario (Table 5), which reduces the forage quality. However, a different trend was observed with forage quality in regard to pasture composition. The pasture composition that presented the highest CP in all climate scenarios was 50% perennial ryegrass and 50% red clover. Red clover is commonly added to the forage to increase the protein level (Griffin, 2004). The CP for this pasture composition increases from 31.7% (current) to about 33% for the future scenarios (Table 5). This represents an improvement in forage quality under future climate scenarios. The pasture composition that presented the highest NDF in all climate scenarios was 50% Perennial ryegrass and 50% White Clover. The NDF increases from 32.6% in the current scenario to about 35% for the future scenarios (Table 5). This represents a decline in forage quality under future climate scenarios.

Table 5. CP and NDF for alfalfa and the pasture compositions with the highest quality

Forage	Forage quality factors	Current scenario	Future scenario RCP 4.5	Future scenario RCP 8.5
Alfalfa	CP [a] (%)	20.3	19.0	18.7
	NDF [b] (%)	41.9	47.0	47.6
50% Perennial Ryegrass and 50% Red Clover	CP (%)	31.7	32.9	33.0
50% Perennial Ryegrass and 50% White Clover	NDF (%)	32.6	34.6	34.8

[a] Crude Protein (CP): higher CP, higher forage quality
[b] Neutral Detergent Fiber (NDF): Legumes with an NDF lower than 40% and grasses with less than 50% NDF are considered high quality forage.

4.3.2 Impact of pasture compositions and climate change on economic and resource use of a livestock grazing system

In this section, a pairwise comparison analysis was performed to identify the significant difference between grass and legume species in the pasture composition under two climate scenarios (RCP 4.5 and RCP 8.5).

Comparison of the four types of grass species, while the legume percentages were held constant in the pasture composition (Table S3), did not present any significant difference (α= 0.05) in the three criteria of (1) net return over milk production, (2) whole farm profit, and (3) harvested forage production. Therefore, the implementation of perennial ryegrass, tall fescue, Kentucky bluegrass, or orchardgrass with either red clover or white clover did not have significant impact on the profits or forage production of the farm. However, for the grazed forage consumed criterion, perennial ryegrass had significantly lower grazed forage consumed than the other three grass species when legumes were not considered. However, under RCP 4.5 and with 10% red clover added to the pasture composition, orchardgrass was found to have significantly lower grazed forage consumed than ryegrass. Therefore, while perennial ryegrass had less grazed forage consumed than orchardgrass with no legume, the situation is reverse when 10% of red clover was incorporated into the perennial ryegrass. Overall, the grass species did not have significantly difference in any of the four criteria evaluated under the two climate scenarios (Table 6).

The comparison of the percentage of the two legume species is presented in Table S4. Overall, as the percentage of legume increased in the pasture composition the value of all four criteria increased. This result can be explained by the importance of legume benefits including: i) being a source of nitrogen due to their ability of fixing nitrogen through Rhizobium bacteria (Aschmann and Cropper, 2007); ii) improvement of forage quality in the pasture (Aschmann and Cropper, 2007); and iii) reduction of the summer slump of grass-only pasture (Aschmann and Cropper, 2007). The following sections discuss the significant level of legume percentages that affect economic and resource use criteria (Table S4):

The economic criteria: Under RCP 4.5 and 8.5 climate scenarios, a 10% increases in legume has significant impacts on economic criteria (net return per cow and the whole farm profit) up to 20% for the red clover and up to 30% for the white clover. Above these points, no significant economic impacts were observed.

The resource use criteria: Regarding the grazed forage consumed and red clover, no significant impact was observed for the legume increase above 30% regardless of grass species; however, for white clover this number was increased to 40%. Regarding the harvested forage production, a 10% increase in legume has significant impacts on this criterion up to 20% for the red clover; however, this range is 20% to 30% for the white clover.

Overall, the presence of red clover in the pasture composition resulted in significantly higher values for the four criteria compared to the white clover (Table 7). These results can be explained by the higher biomass yield of red clover in comparison to white clover (Griffin, 2004), which consequently increases the forage production and thus the farm profits.

Finally, the impacts of the climate scenarios on economic and resource use of a dairy grazing system are presented in Table 8. Overall, it can be concluded that increases in precipitation and temperature under more intensive climate scenario (RCP 8.5) can significantly improve the net return per cow and whole farm profit while having no significant impact on resource use criteria.

Table 6. Statistical comparison of net return, whole farm profit, grazed forage consumed, and harvested forage produced by different grass and legume species (horizontal comparison)*

Criteria	Legume	RCP 4.5				RCP 8.5			
		Perennial Ryegrass	Tall Fescue	Kentucky Bluegrass	Orchardgrass	Perennial Ryegrass	Tall Fescue	Kentucky Bluegrass	Orchardgrass
Net Return ($/cow/yr)	Red Clover	1,983[a]	1,978[a]	1,976[a]	1,973[a]	2,009[a]	2,003[a]	2,002[a]	1,999[a]
	White Clover	1,843[a]	1,841[a]	1,838[a]	1,837[a]	1,874[a]	1,871[a]	1,869[a]	1,868[a]
Whole Farm Profit ($/yr)	Red Clover	158,168[a]	157,661[a]	157,480[a]	157,225[a]	160,785[a]	160,205[a]	160,055[a]	159,790[a]
	White Clover	144,297[a]	144,118[a]	143,848[a]	143,726[a]	147,357[a]	147,133[a]	146,911[a]	146,781[a]
Grazed Forage Consumed (tonne/yr)	Red Clover	156[a]	155[a]	155[a]	155[a]	155[a]	155[a]	155[a]	155[a]
	White Clover	133[a]	132[a]	132[a]	131[a]	136[a]	136[a]	136[a]	135[a]
Harvested Forage Produced (tonne/yr)	Red Clover	298[a]	296[a]	295[a]	294[a]	308[a]	305[a]	305[a]	303[a]
	White Clover	263[a]	263[a]	262[a]	262[a]	270[a]	270[a]	269[a]	269[a]

* Values followed by the same letters are not significantly different (α=0.05).

Table 7. Statistical comparison of net return, whole farm profit, grazed forage consumed, and harvested forage produced by different grass and legume species (vertical comparison)*

Criteria	Legume	RCP 4.5				RCP 8.5			
		Perennial Ryegrass	Tall Fescue	Kentucky Bluegrass	Orchardgrass	Perennial Ryegrass	Tall Fescue	Kentucky Bluegrass	Orchardgrass
Net Return ($/cow/yr)	Red Clover	1,983[a]	1,978[a]	1,976[a]	1,973[a]	2,009[a]	2,003[a]	2,.002[a]	1,999[a]
	White Clover	1,843[b]	1,841[b]	1,838[b]	1,837[b]	1,874[b]	1,871[b]	1,869[b]	1,868[b]
Whole Farm Profit ($/yr)	Red Clover	158,168[a]	157,661[a]	157,480[a]	157,225[a]	160,785[a]	160,205[a]	160,055[a]	159,790[a]
	White Clover	144,297[b]	144,118[b]	143,848[b]	143,726[b]	147,357[b]	147,133[b]	146,911[b]	146,781[b]
Grazed Forage Consumed (tonne/yr)	Red Clover	156[a]	155[a]	155[a]	155[a]	155[a]	155[a]	155[a]	155[a]
	White Clover	133[b]	132[b]	132[b]	131[b]	136[b]	136[b]	136[b]	135[b]
Harvested Forage Produced (tonne/yr)	Red Clover	298[a]	296[a]	295[a]	294[a]	308[a]	305[a]	305[a]	303[a]
	White Clover	263[b]	263[b]	262[b]	262[b]	270[b]	270[b]	269[b]	269[b]

* Values followed by the same letters are not significantly different (α=0.05).

Table 8. Statistical comparison of net return, whole farm profit, grazed forage consumed and, harvested forage produced by different climate scenarios (horizontal comparison)*

Criteria	RCP 4.5	RCP 8.5
Net Return ($/cow/yr)	1,909[a]	1,937[b]
Whole Farm Profit ($/yr)	150,815[a]	153,627[b]
Grazed Forage Consumed (tonne/yr)	143[a]	145[a]
Harvested Forage Produced (tonne/yr)	279[a]	287[a]

* Values followed by the same letters are not significantly different (α=0.05).

4.3.3 Economic and resource use sensitivity under future climate change scenarios

4.3.3.1 Surface Analysis

A sensitivity analysis was performed to understand the resiliency of the different pasture compositions under the future climate scenarios. In general, the greater the magnitude of the sensitivity index the higher the sensitivity and the lower the resilience of the pasture composition to the temperature and precipitation variations under future climate scenarios. From 42 future climate scenarios (21 climate models for each RCP 4.5 and RCP 8.5), only one climate scenario under RCP 4.5 (NorESM1-M) resulted in very high sensitivity indexes for all the pasture combinations. This is due to the minimal increase (0.1 mm) in precipitation under this scenario compared to current condition. This makes the ratio very large in Equation (1) since the denominator is much smaller than the numerator. Therefore, the climate scenario of NorESM1-M was considered as an anomaly since the results deviated significantly from the results of other scenarios and was removed from further analysis.

In order to understand the sensitivity index pattern for each criterion, a second-order response surface model was used. Three-dimensional response surface plots and two-dimensional contour plots were created for each pasture composition and criterion, resulting in 32 surface plots and 32 contour plots (Figures 10 to 13 and S1 to S28). In these figures, the precipitation (x-axis) varies between 631 mm and 922 mm and the temperature (y-axis) range varies between 9.6˚C and 13˚C. The two factors evaluated in these plots are: (1) the area with the highest sensitivity index and (2) the importance of temperature to precipitation between two or more different pasture compositions.

The following sections discuss the results of the sensitivity analysis in the context of economic and resource use:

The economic criteria: Based on the results presented in Figures 10, 11 and S1 to S14, the area with a sensitivity index greater than 0.8 was identified as area in which the combination of temperature, precipitation, and pasture compositions resulted in high sensitivity or low resiliency. The area with the highest sensitivity index was on average larger for the whole farm profit than the net return per cow over milk production. The whole farm profit was more sensitive to ranges of average temperature and precipitation between 9.6˚C and 12.1˚C and 631 mm and 785 mm, respectively (e.g. Figure 11). Meanwhile, the net return per cow over milk production was more sensitive to ranges of average temperature and precipitation between 9.6˚C and 11.7˚C and 631 mm and 741 mm, respectively (e.g. Figure 10). This can be explained due to the fact that the net return per cow was estimated based only on the milk production, while the whole farm profit includes additional factors such as manure handling, animal housing, and animal care and sales, which makes the criteria more sensitive to climatological variabilities.

Regarding the importance of temperature to precipitation on sensitivity indices, both economic criteria had similar results. The pasture composition that was more sensitive to temperature was the perennial ryegrass with red clover with the fraction above 0.5˚C/100 mm. Meanwhile, the pasture composition that was less sensitive to temperature was the orchardgrass with red clover with the fraction below 0.3 ˚C/100. However, for the grass species combinations with different legumes, the results were mixed. For example, perennial ryegrass is more sensitive to temperature changes when is mixed with red clover than white clover for the economic criteria. However, in the case of the Kentucky bluegrass and orchardgrass mixtures with legumes, more sensitivity to temperature was observed for white clover than red clover. In the case of tall fescue, both red and white clover had the same sensitivity to temperature.

The resource use criteria: For both resource use criteria, the area with a sensitivity index greater than 6.0 was identified as the area in which the combination of temperature, precipitation, and pasture compositions resulted in high sensitivity or low resiliency (Figures 12, 13 and S15 to S28). The high sensitive area is usually larger for the grazed forage than the harvested forage. The area for the grazed forage consumption ranges between 9.6˚C and 11.6˚C and 631 mm and 738 mm for average temperature and precipitation, respectively (e.g. Figure 12). Meanwhile, the area for the harvested forage production ranges between 9.6˚C and 11.3˚C and 631 mm and 686 mm for average temperature and precipitation, respectively (e.g. Figure 13). The grazed forage only includes the consumption of the different pasture compositions, while the harvested forage production involves mostly alfalfa harvest. Therefore, the decrease of the sensitivity index area of the harvested forage production can be explained by the alfalfa's excellent heat and drought tolerance compared to other grass and legume species in this study, which range between poor and good tolerance (Cassida et al., 2014).

Regarding the importance of temperature to precipitation on sensitivity indices, the results are mixed for the resource use criteria. In the case of grazed forage consumption, the Kentucky bluegrass or orchardgrass combined with white clover were more sensitive to temperature (1.1˚C/100 mm) than perennial ryegrass, tall fescue, and orchardgrass mixed with red clover (0.9 ˚C/100 mm). In general, the combinations of all grass species with red clover were less sensitive to temperature than white clover. In the case of harvested forage production, the pasture composition compromising perennial ryegrass with red clover was more sensitive to temperature

(1.1˚C/100 mm). However, in general, all combinations of grass species with red clover were more sensitive to temperature and had higher production rates than the combinations with white clover. Meanwhile, the pasture composition that was the least sensitive to temperature changes (0.7˚C/100 mm) was the tall fescue with white clover.

Overall, the area identified with the highest sensitivity index for all criteria is located within the temperature range of 9.6˚C and 12.1˚C, and the precipitation range of 631 mm and 785 mm. Therefore, this area will be highly impacted by climate change regardless the pasture compositions or the economics and resource use criteria. In general, the mixture of perennial ryegrass and red clover had the highest sensitivity to temperature to precipitation ratio in the majority of criteria (net return per cow over milk production, whole farm profit and harvested forage production), while the mixture of orchardgrass with red clover had the least sensitivity to temperature to precipitation ratio in three criteria, which are net return per cow over milk production, whole farm profit, and grazed forage consumption.

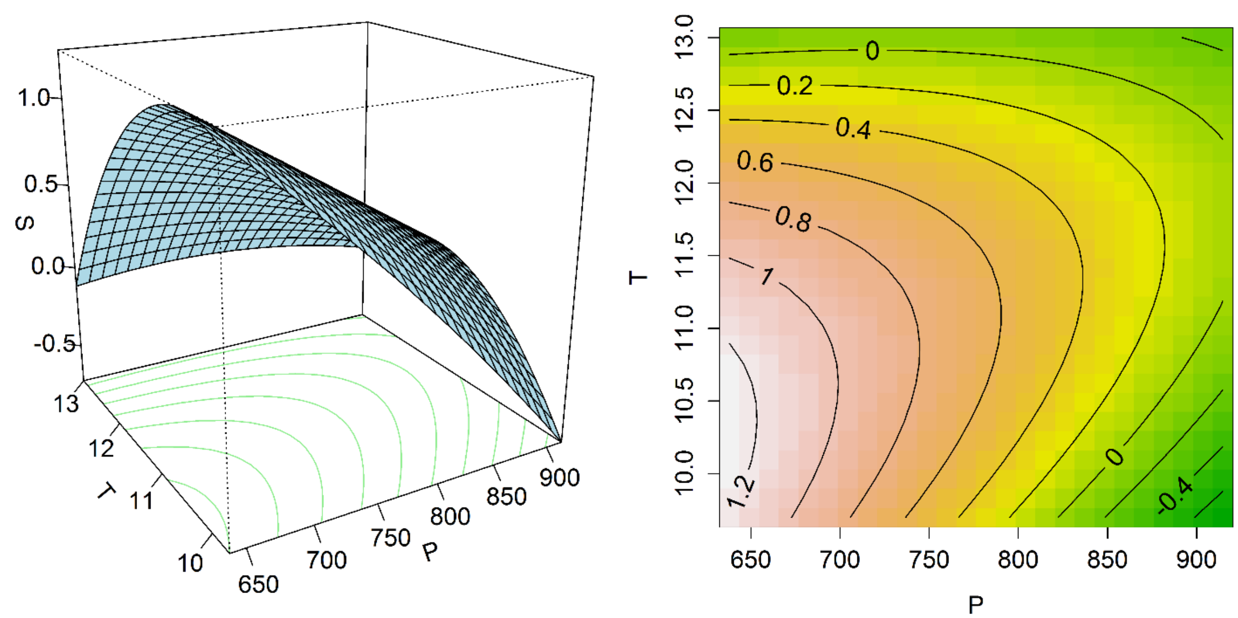

Figure 10. Net return per cow over milk production sensitivity index for perennial ryegrass and red clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

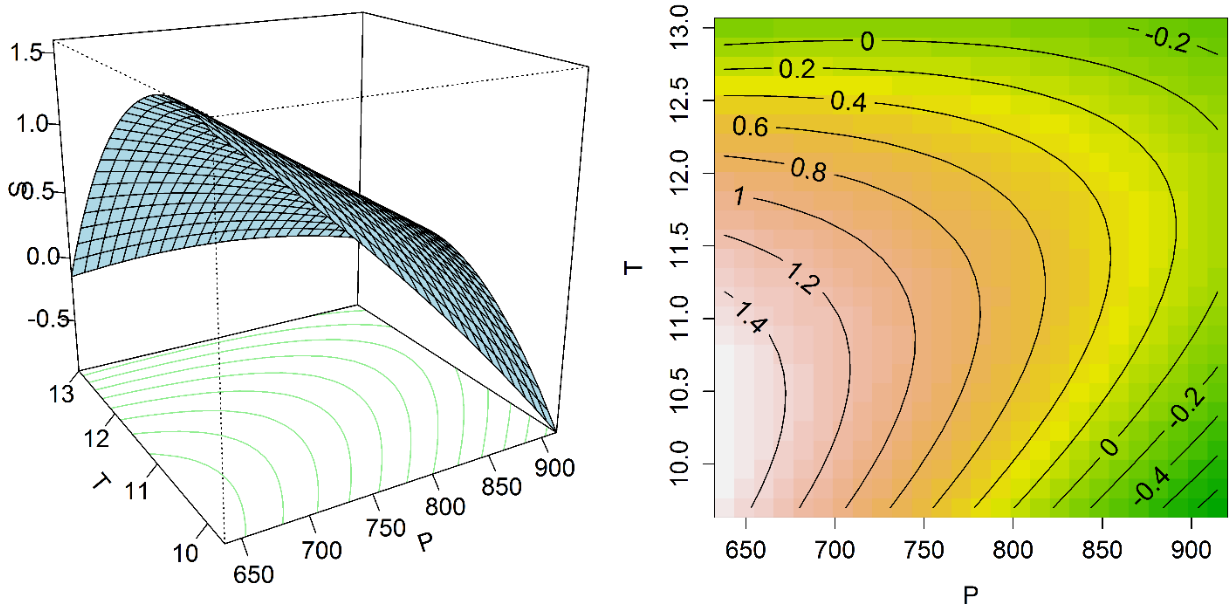

Figure 11. Whole farm profit sensitivity index for perennial ryegrass and red clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

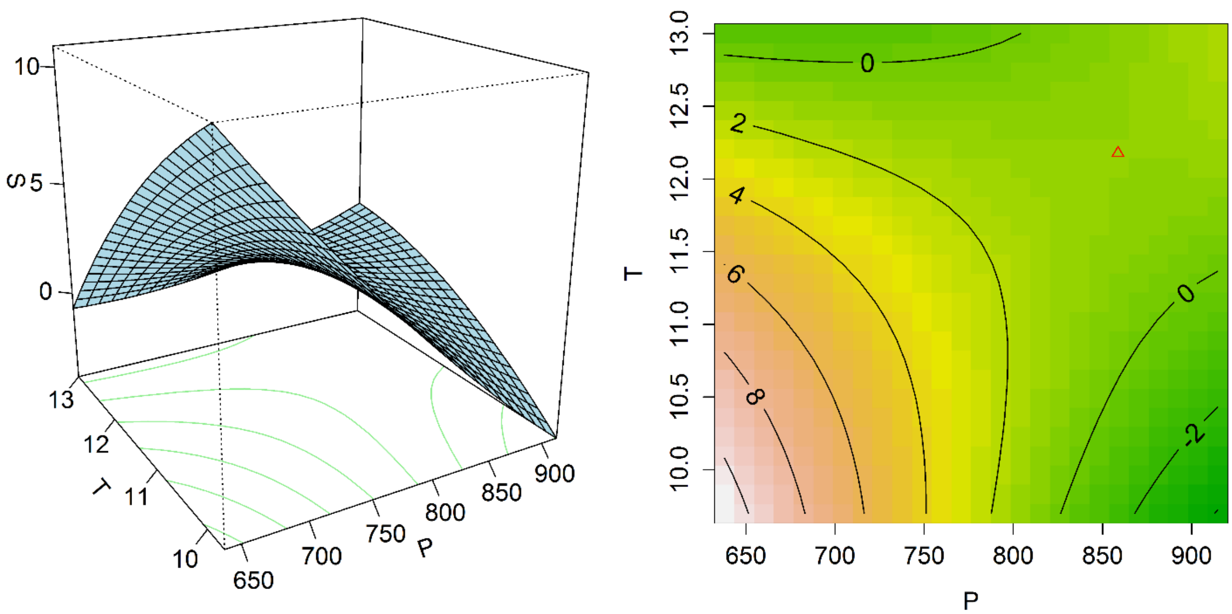

Figure 12. Grazed forage consumed sensitivity index for perennial ryegrass and red clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

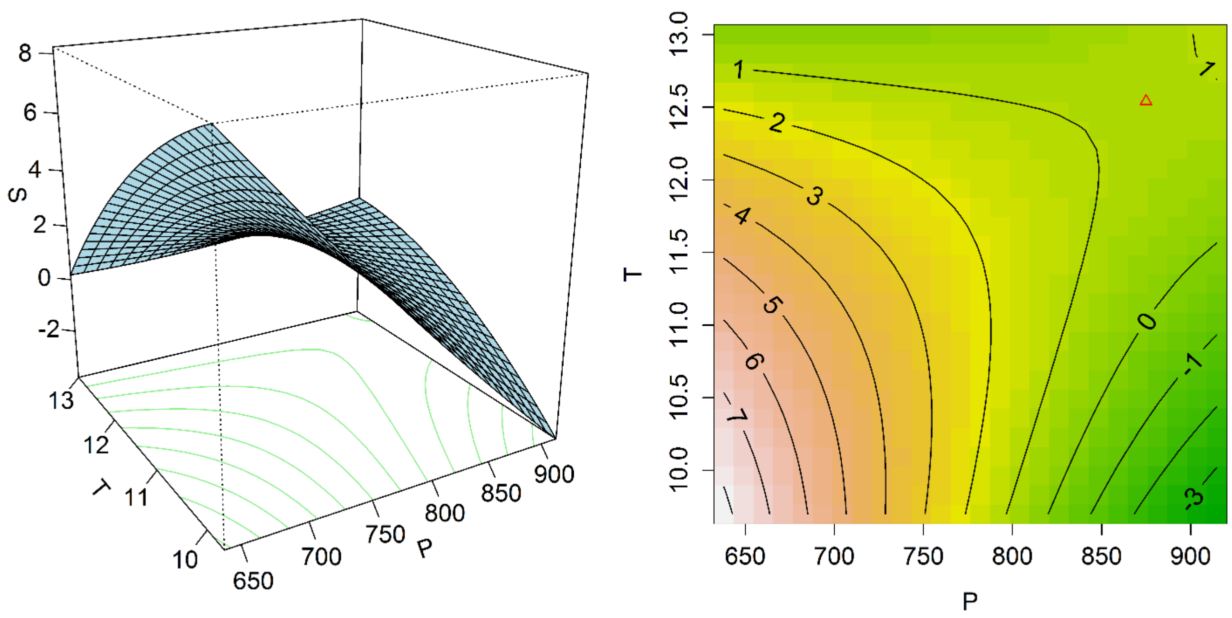

Figure 13. Harvested forage produced sensitivity index for perennial ryegrass and red clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

4.3.3.2 Overall Sensitivity Assessment

The overall sensitivity assessment was performed based on the results of 1,312 sensitivity indices (Section 4.2.3.5). This allows obtaining the absolute highest and the lowest sensitivity index for each criterion along with the most and the least resilient pasture composition under future climate scenarios.

Overall, the resource use criteria had a greater sensitivity indexes range (0.0 to 18.2) than the economic criteria (0.0 to 3.4). The criterion with highest sensitivity indexes was the grazed forage consumed, which ranged between 0.5 and 18.2. The pasture composition that had the maximum sensitivity index from the grazed forage consumed criterion was orchardgrass with white clover. The criterion with lowest sensitivity indexes was the net return per cow over milk production, which ranged between 0.0 and 2.7, where perennial ryegrass combined with red clover was the pasture composition with the maximum sensitivity index. While the least resilient pasture composition was orchardgrass mixed with white clover.

The overall most resilient pasture composition and most and least resilient grass and legume species are listed in Table 9. In this table, each cell with a white background represents the average sensitivity indexes of 42 future climate scenarios. In addition, the Euclidean operator norm was used to estimate the overall sensitivity index for each criterion, grass species, and legume species (Table 9, cells with gray background). The following sections discuss the results of Table 9 in the context of economic and resource use for each criterion:

The economic criteria: The results of the sensitivity analysis from the average condition (background with white cells) revealed that the trend in both economic criteria were the same, with perennial ryegrass presenting the highest sensitivity index, followed by tall fescue, Kentucky bluegrass, and orchardgrass. In addition, white clover presented higher sensitivity indexes than red clover. Overall, the whole farm profit criterion presented higher sensitivity indexes than the net return per cow over milk production, which supports previous findings from the second-order response surface model analysis.

The resource use criteria: In contrast with the economic criteria, resource use criteria followed the opposite trend, where Orchardgrass presented the highest sensitivity index, followed by Kentucky bluegrass, tall fescue, and perennial ryegrass (Table 9). Regarding the legume species, in the grazed forage consumed criterion, white clover had higher sensitivity indexes than red clover. However, the opposite trend was observed by the harvested forage produced criterion. Overall, the grazed forage consumed criterion presented higher sensitivity indices than the harvested forage produced, which is aligned with the discussion in Section 4.3.3.1.

Overall, the grazed forage consumed criterion presents the overall highest sensitivity index of all criteria and pasture compositions. Meanwhile, net return per cow over milk production presents the overall lowest sensitivity index. Regarding grass species, orchardgrass had the overall highest sensitivity index for both red clover (2.87) and white clover (3.54), while perennial ryegrass had the overall lowest sensitivity index (red clover = 2.71 and white clover = 3.35). Concerning legumes species, white clover had an overall higher sensitivity index (6.91) than red clover (5.60). Therefore, the most resilient pasture composition under future climate scenarios was perennial ryegrass with red clover and the least resilient pasture composition was orchardgrass with white clover.

Table 9. Average and overall sensitivity indices for all criteria, grass species, and legume species

	Red Clover					White Clover				
	Net Return per Cow (NR)	Whole Farm Profit (WP)	Grazed Forage Consumed (GF)	Harvested Forage Produced (HF)	Overall** (S_G)	Net Return per Cow (NR)	Whole Farm Profit (WP)	Grazed Forage Consumed (GF)	Harvested Forage Produced (HF)	Overall** (S_G)
Perennial Ryegrass (R)	0.47	0.58	1.96	1.72	2.71	0.53	0.67	2.79	1.65	3.35
Tall Fescue (T)	0.43	0.54	2.00	1.84	2.80	0.52	0.67	2.90	1.65	3.44
Kentucky Bluegrass (K)	0.42	0.53	2.00	1.88	2.82	0.52	0.67	2.92	1.70	3.48
Orchardgrass (O)	0.40	0.50	2.02	1.94	2.87	0.52	0.67	2.99	1.69	3.54
Overall* (S_C)	0.86	1.08	3.98	3.69	5.60	1.05	1.34	5.80	3.34	6.91

*$S_c = \sqrt{R^2 + T^2 + K^2 + O^2}$, where S_C overall sensitivity index for a criterion

** $S_G = \sqrt{NR^2 + WP^2 + GF^2 + HF^2}$, where S_G= overall sensitivity index for a grass

4.4 Conclusions

The overall goal was to identify the best pasture composition for a representative grazing dairy farm in Lower Peninsula of Michigan to reduce the impacts of climate change. Three objectives were pursued: 1) identify the best pasture composition concerning the economic and resource use criteria, 2) assess economic and resources use impacts of pasture compositions under future climate scenarios, and 3) evaluate the resiliency of pasture compositions under current and future climate scenarios.

Regarding the selection of the best pasture composition, concerning the economic and resource use criteria, 50% perennial ryegrass and 50% red clover was identified as the best option under current and future climate scenarios. This is mainly due to increases in the future annual average temperature and precipitation in the region under future climate scenarios, which increases the performance of perennial ryegrass. In general, and under all climate scenarios, the top pick is always a pasture composition with 50% red clover combined with perennial ryegrass, followed by tall fescue, Kentucky bluegrass, and orchardgrass. However, the grazed forage consumed criterion was an exception where the top four pasture compositions had the same value for each climate scenario.

In order to assess economic and resources use impacts of pasture compositions under future climate scenarios, a pairwise comparison analysis was performed. The comparison of the four types of grass species, while legume percentage was held constant, showed no significant differences. However, when both grass and legume species were considered, it was revealed that the presence of red clover could significantly improve outcomes under all climate scenarios. In general, increasing the percentage of the two legume species resulted in improvement of indicators for all criteria. Finally, evaluation of climate scenarios showed that under intensive climate scenario (RCP 8.5), the net return per cow and whole farm profit were significantly improved in comparison with RCP 4.5, but no significant impacts were observed for the resource use criteria.

In order to evaluate the resiliency (capacity to adapt to external stresses) of pasture compositions under the future climate scenarios, a sensitivity analysis was performed. The surface and contour plots were used to identify the most sensitive conditions for the simulated livestock grazing system. This condition was identified between 9.6˚C and 12.1˚C of temperature and 631 mm and 785 mm of precipitation. Regarding the sensitivity of pasture compositions to the ratio of temperature to precipitation, the pasture composed of perennial ryegrass and red clover had the highest sensitivity to temperature in three criteria: net return per cow over milk production, whole farm profit, and harvested forage production. Furthermore, the pasture composed of orchardgrass with red clover had the least sensitivity to temperature in three criteria: net return per cow over milk production, whole farm profit, and grazed forage consumption.

The results of the overall sensitivity analysis revealed that the grazed forage consumed criterion is the most sensitive criterion under future climate scenarios. In addition, the most resilient pasture composition was perennial ryegrass with red clover while the least resilient pasture composition was orchardgrass with white clover. Overall, the pasture composition of 50% perennial ryegrass and 50% red clover was identified as the best pasture composition for all criteria while being the most resilient composition.

Future studies should consider expanding of this work in different climatological regions to better understand the impacts of climate change on grazing livestock systems. However, the concept of sensitivity analysis that was introduced in this study has global implications and can help with understanding the resiliency of the different pasture compositions under the future climate scenarios. This can provide the scientific basis for decision-making while providing knowledge to policy makers and stakeholders to reduce the negative impacts of climate change. Meanwhile, the concept of pasture diversification introduced in this study as an adaption measure has global implications. This study found that 1) the percentage of legume is the main factor, besides climate, influencing the criteria. Overall, as the percentage of legume increased in the pasture composition, the value of all four criteria increased. This means that adding more legume to the composition can be beneficial for grazing dairy farms; 2) grass species combined with 50% legume was identified as the best composition to reduce the negative impacts of climate change while improving the farm economics; however, providing more than 50% legume may increase risk of illness to dry cows; and 3) to maintain a high grazed forage production for future scenarios, it is important to maintain at least 30% legume in the pasture composition.

5 FOOD FOOTPRINT AS A MEASURE OF SUSTAINABILITY FOR GRAZING DAIRY FARMS

5.1 Introduction

Greenhouse gas emissions are the major cause of global climate change, leading to an increase in global average temperature (IPCC, 2014). Anthropogenic GHG emissions are the dominant cause of the increase in global warming since mid-20th century, resulting in the highest atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), in the last 800,000 years (IPCC, 2014). Among anthropogenic activities, livestock productions play a major role by contributing 14.5% of global anthropogenic GHG emissions. In perspective, the livestock sector is a larger contributor to GHG emission than the transportation sector (14%) (Gerber et al., 2013; IPCC, 2014). The GHG emission from the livestock sector is due to activities including enteric fermentation (39%), manure management, application, and direct deposit (26%), feed production (21%), land use change (9%), post-farm gate (3%), and direct and indirect energy usage (2%) (Gerber et al., 2013). Furthermore, emissions from the livestock sector accounts for 5%, 44%, and 53% of the total human emissions for CO_2, CH_4, and N_2O, respectively (Gerber et al., 2013). In addition to contributing to climate change, the livestock sector negatively affects the environment through land degradation, water pollution, water shortage, and biodiversity destruction (Steinfeld et al., 2006; Rojas-Downing et al., 2017c). Meanwhile, livestock product demand (mostly dairy and meat) is also expected to double by 2050 (Garnett, 2009). Therefore, there is a need to fulfill the demand in a sustainable manner (Thornton, 2010).

In this study, sustainability refers to the ability to progress by considering the environment, economic feasibility, and socially acceptable practices to meet the needs of the present and future generations. Therefore, sustainability requires consideration of environmental, economic, and social components of a system while finding the balance point of this system (OECD, 2004). To study these components, different indicators have been used that are known as sustainability measures (footprints) and usually calculated through life cycle assessment (LCA) techniques (Čuček et al., 2012). The use of footprints has become so popular that a simple search of this word in the Google Scholar resulted in more than a million hits. Footprint refers to the quantitative measurement of the human activities burdens on sustainability (Hoekstra, 2008; Čuček et al., 2012). Each type of footprint has its own definition, units of measurement, and tools for its estimation. Footprints can be categorized as environmental (e.g., carbon, water, and energy footprints), social (e.g., human rights, corruption, poverty, health, job footprints), economic (e.g., financial, economic footprint), and composite footprints (e.g., ecological footprint) (Čuček et al., 2012).

A single footprint or a combination of them have been used to measure sustainability in the livestock sector. For example, FAO (2010) used a carbon footprint obtained from LCA to examine the global dairy farming sustainability. Through this analysis, methane was identified as the largest contributor to GHG emissions from the dairy sector. However, using a single footprint is not always the right approach for measuring the overall sustainability, especially for the area of food production (Finkbeiner, 2009). Dyer et al. (2014) performed a LCA where carbon footprint along with the impacts on non-carbon footprint, such as water, energy, and diseases, were considered to measure the environmental impacts of livestock production in Canada. An environmental impact matrix and a network diagram were used to consider the non-carbon footprint. Next, the crop areas and non-carbon footprint elements were associated to different types of livestock using the area-reference index. Results suggested that a sustainable solution that reduces the current level of carbon footprint cannot be met. However, an increase in grass-fed beef while using grains for the non-ruminants can reduce CO_2 loss from the soil (Dyer et al., 2014). Vasilaki et al. (2016) also used a combination of water and carbon footprints to assess the environmental impact of different types of yogurt productions in a dairy plant. They used a LCA-based water and carbon footprint 'cradle to gate' approach. The results showed that the major $CO_{2\text{-eq}}$ contributors (over 80%) are raw milk and milk-based ingredients while cleaning operations account for 70% of the water usage. However, the carbon and water footprint can still be reduced by minimizing waste during the processing stage. Cecchini et al. (2016) performed environmental and economic sustainability analysis of five dairy farms in Italy. The LCA-based carbon footprint was used to perform an environmental assessment while the economic assessment was done considering all costs associated the production process. To identify the relationship between the environmental and economic impacts, a regression analysis was conducted. The results showed improvement in the overall sustainability outcomes can be achieved when considering interrelationships between carbon footprint and economic aspects. In general, only a limited number of studies have considered multiple footprints (usually two environmental footprints) to assess the environmental impact or sustainability, while the majority of studies only used carbon footprint as a measure of sustainability (Adom et al., 2012; de Léis et al., 2015; FAO, 2010b; Flysjö et al, 2011; Mc Geough et al., 2012; O'Brien et al., 2014). However, a comprehensive sustainability study should consider different aspects that are impacted by a proposed activity such as water and energy requirements and economic feasibility. This study is unique since for the first-time carbon, energy, water, and economic footprints are considered to assess the sustainability of grazing dairy farms. Here, we propose to use multi-criterion decision making to determine the balanced options between conflicting criteria (footprints). A new measure named food footprint was introduced to mimic the overall impacts of grazing dairy farms and helps with identifying the most sustainable production systems. Using this new measure, the most sustainable milk production can be identified for a location of interest. The specific objectives of this study were to: (1) identify the most sustainable milk production in different locations; (2) identify the pasture composition for each targeted milk production in different locations; and (3) understand the spatial variability of milk productions and associated pasture compositions for different locations.

5.2 Materials and Methods

5.2.1 Study Area

The United States is the number one cows' milk producer in the world by producing on average about 91 billion kilograms of liquid milk annually (FAO, 2016b). Meanwhile, the state of Michigan is one of the top five milk-producing states in the USA which is why it has been considered for this study (USDA-NASS, 2014c). Among dairy systems, the grazing dairy is more likely to be impacted by climate variability because of dependency on forage quality and quantity (Hatfield et al., 2014; Heckman et al., 2007). Therefore, to understand the impacts of climate variability on grazing systems in Michigan, the study area was divided into several regions. The National Oceanic and Atmospheric Administration (NOAA) Climate Division Boundaries were initially considered for this purpose. However, these boundaries do not represent areas of climatological homogeneity. Instead, the division boundaries were defined initially (between 1909 and 1949) based on drainage basins or major crops, and then in the late 1950s into structured boundaries that would coincide with the political boundaries, most which do not relate to climate (Guttman and Quayle, 1996).

Due to limitations of the NOAA Climate Division Boundaries, an alternative approach was considered in which Michigan is divided into 10 regions based on the watershed boundaries. This approach is aligned with the natural division of the land surface that were mainly influenced by geology and climate factors. Considering a watershed as a subunit for pasture study is also useful since the soil types and distributions within a watershed are determined by the geology, climate, and vegetation within a watershed (OWEB, 1999). In addition, the vegetation patterns are influenced by the local climate, which determines the timing and amount of precipitation and solar energy that falls into the watershed (OWEB, 1999). The U.S. Geological Survey used a national standard hierarchical system based on surface hydrologic features to delineate the watersheds in United States and classify them into hydrologic unit codes (HUC) (USGS, 2017). For this study, the six-digit HUC was used. The study area was divided into 10 regions (Figure 14) and data from a weather station located close to the centroid of the watershed was used (Viessman and Lewis, 2003). However, this location does not represent the spatial climate variability within the watershed but rather climate variability for a single point.

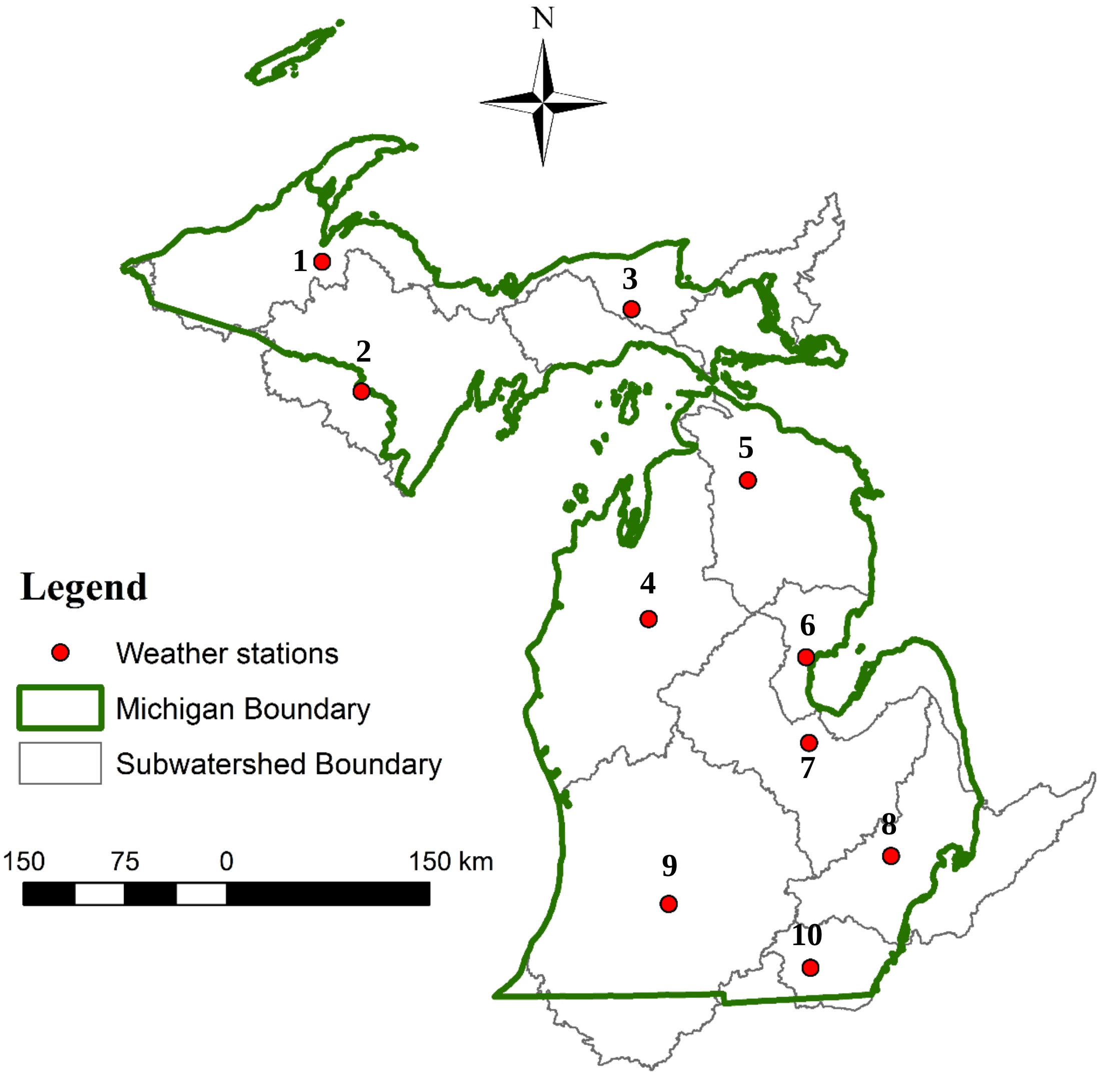

Figure 14. State of Michigan and its watershed boundaries

Twenty years of daily weather data for the period of 1985 to 2005 were obtained from the NCDC. The maximum temperature, minimum temperature and precipitation range from 10.6 ˚C to 15.3 ˚C, -1.5 ˚C to 4.0 ˚C, and 757.3 mm to 904.8 mm, respectively within the study area (Table 10).

Table 10. Average daily temperature and precipitation for the weather stations within the study area

Region	Station number	Average Max. Temperature		Average Min. Temperature		Average Precipitation	
		(˚C)	SD*	(˚C)	SD*	(mm)	SD*
1	USC00200089	10.6	12.8	-1.5	11.6	824.8	5.6
2	USC00204090	12.0	12.4	-0.6	11.7	764.4	5.6
3	USC00205816	10.8	11.8	0.0	10.4	857.2	7.2
4	USW00014817	12.3	11.7	0.9	10.5	891.5	6.2
5	USC00208417	12.3	12.3	-1.4	10.9	780.5	5.3
6	USC00207820	13.3	11.5	1.2	10.1	761.4	5.8
7	USC00207222	14.1	12.2	3.2	10.2	823.2	6.1
8	USC00206658	14.3	11.7	4.0	10.0	757.3	5.7
9	USC00200552	14.9	11.4	3.7	10.0	904.8	6.3
10	USC00200032	15.3	11.5	3.4	9.8	901.4	6.5

*SD: Standard deviation

Besides daily temperature and precipitation, solar radiation was also required for a farm system modeling. In order to obtain daily solar radiation for each location, a widely used stochastic weather generator called WXGEN was used (Sharpley and Williams, 1990; Wallis and Griffiths, 1995). WXGEN used the daily temperature and precipitation data to calculate the solar radiation (Jeong et al., 2015).

5.2.2 Modeling Process

The modeling process involves data processing, performing model simulations, and footprint analysis to identify the most sustainable milk production and appropriate pasture composition for each location within the study area (Figure 15). Under the data processing, typical farm management, size, pasture compositions, and target milk productions were collected through a survey from producers and extension specialists within the study area. However, for cases that actual data cannot be obtained from farm surveys (e.g., manure characteristics, structures initial costs, investment in fences and watering systems, animal fiber intake capacity), reported data from literature were used to create a representative farm for the study area (Rojas-Downing, 2013). In addition, long-term (20 years) weather data for each location were obtained to understand the climate variabilities, 48 pasture composition, and 32 target milk productions were identified. The aforementioned information provided the inputs to IFSM. IFSM can estimate milk production and required information to calculate energy, water, carbon, and economic footprints for different combinations of pasture compositions, target milk productions, and location (watershed) scenarios. A multi-criterion decision making method called VIKOR was used to determine the balanced options between different footprints. The results from VIKOR analysis was used to determine the food footprint representing the overall impacts of a grazing dairy farm management practice on energy, water, carbon, and farm economics. By obtaining the food footprint, the most sustainable milk production and appropriate pasture composition of each location was identified.

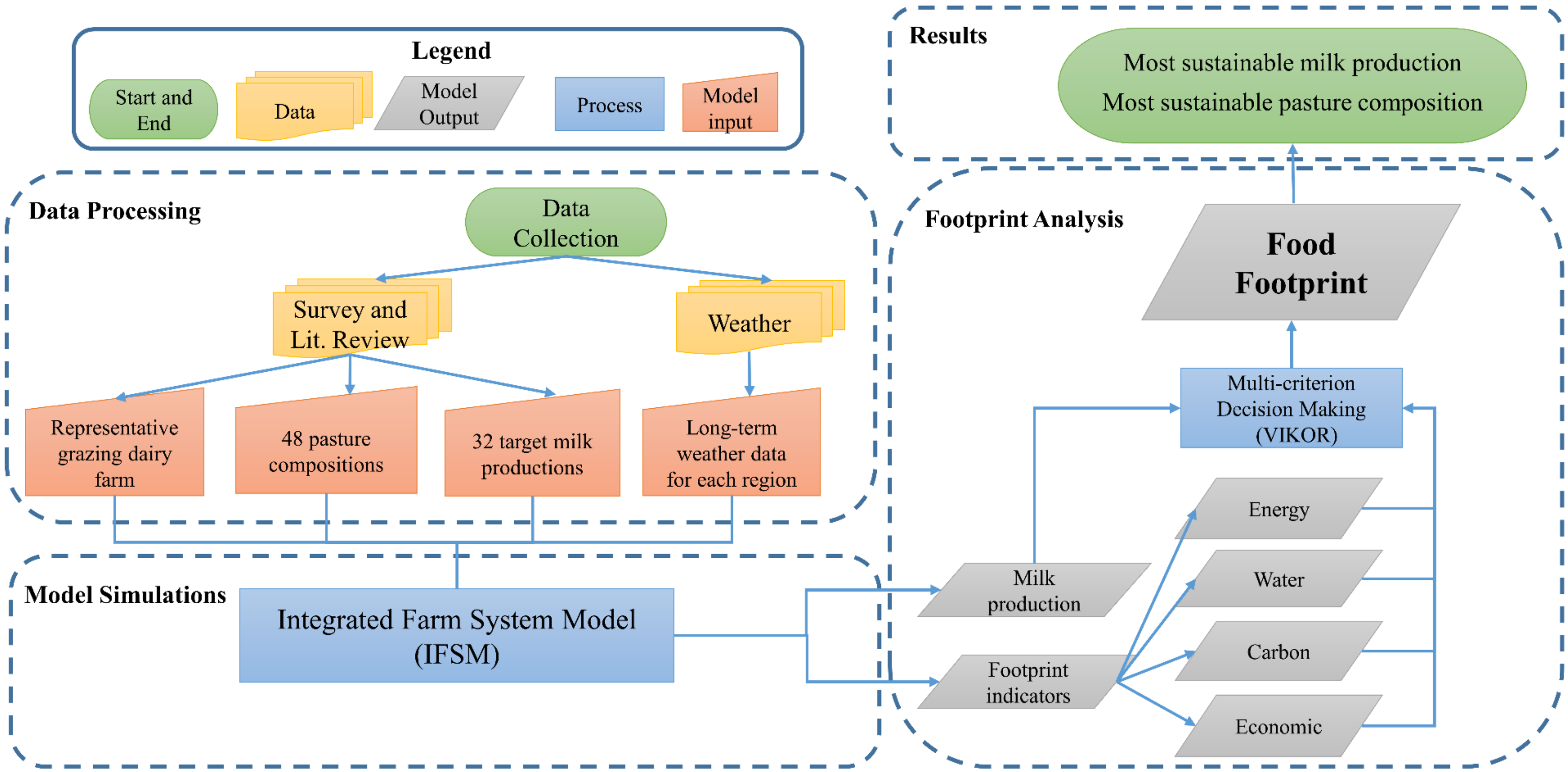

Figure 15. The conceptual framework of the modeling process

5.2.2.1 Data Processing

5.2.2.1.1 Grazing Farm Survey and Review

Since it is not practical to perform modeling analysis for each individual farm within the study area, a representative farm was developed. Five different grazing dairy farms throughout the study area were surveyed to collect data regarding the typical farm management, size, pasture compositions, and target milk productions (Rojas-Downing et al., 2017a). The surveys, which included field observations, were performed in the spring and summer of 2013 and the farms were selected considering location, size, and farming practice. The survey questionnaires were structured based on IFSM data requirements and performed during a single-visit. The survey questionnaires cover a variety of topics including farm management, pasture area, alfalfa area, machinery operations, grazing strategy, equipment, structures, number and type of animals, and prices for several farm inputs and outputs (Supplementary Materials, Table S1). A summary of the key survey data collected is provided in Table S2. In the case that the required data for the IFSM could not be obtained from the survey, additional means including literature review and discussions with Michigan State University extension specialists were used to obtain the data. A summary of the key representative grazing dairy farm data is provided in Table 11.

Table 11. Representative grazing dairy farm description

Main IFSM inputs	Value/Description
Cows	
Lactating cows	100
Replacement stock	80
Cattle	Small frame Holsteins (454 kg)
Feed	
Relative forage-to-grain ratio	High
Crude protein supplement	Soybean meal 48%
Undergradable protein	Distiller grain
Facilities	
Cow housing	Bedded pack barn

Table 11 (cont'd)

Heifer housing	Calf hutches and dry lot
Feed facility	Short-term storage premix
Milking center	Double four parlor
Manure	
Manure collection	Scrapers with slurry pumps
Manure storage	Top-loaded concrete tank for a four-month period
Manure applied to the grazing area	20%
Manure applied to the alfalfa area	80%
Forage areas	
Grazing area	54 ha
Alfalfa area	27 ha
Fertilizers application	No
Grazing strategy	
Animals grazed	All cows
Time on pasture	Full days during the grazing season (April to October)
Labor for grazing management	20 hours per week
Tillage and planting	
Operations time	Mid-October and mid-April
Machinery	Chisel plow and a seedbed conditioner
Silage and hay harvest	Alfalfa harvested as silage and hay four times a year; grass harvested once a year as silage
Economics*	
Diesel fuel	$0.98/L
Electricity	$0.13/Kwh
Labor wage	$16/h
New forage stand	$494/ha
High quality hay	$265/tonne DM
Hay	$198/tonne DM
Milk	$0.36/kg
Machinery economic life	10 years
Structures economic life	20 years
Real interest rate	6%

*All major operations based on 2013 representative prices

5.2.2.1.2 Selection of pasture compositions

The pasture composition varies depending on the grazing management goal (e.g., biomass production, animal nutrition), seasonal biomass distribution, animal palatability, and persistency over time (Sullivan et al., 2000). Based on survey data, literature review, and inputs from extension specialists, the typical grass and legume species and compositions of the study area were identified. The most typical pasture composition in Michigan includes 60% orchardgrass and 40% white clover. However, the typical functional groups (functional features of an ecosystem service) are cool-season grasses, such as orchardgrass (*Dactylis glomerata*) and perennial ryegrass (*Lolium multiflorum*) and legumes, such as white clover (*Trifolium repens*) and red clover (*Trifolium pratense*). The percentage of legume in the pasture composition varies between 0% and 50% within the study area. Orchardgrass, white clover, and red clover are resistant to cold weathers (winter hardiness), while perennial ryegrass is tolerant to wet soils. Perennial ryegrass and white clover tolerate heavy grazing, while orchardgrass and red clover can be used as a hay crop or grazed by animals (Barnes et al., 2007; Ogle and St. John, 2008; USDA-NRCS, 2002). Meanwhile, all of the aforementioned pasture species are high in nutritive value when harvested appropriately.

Due to global warming and change in climate trends, two additional species were also evaluated with relatively better adaptability to extreme events than current typical pasture species. These species are Kentucky bluegrass (*Poa pratensis*) and tall fescue (*Lolium arundinaceum*). Both species have good winter hardiness in Michigan and moderate tolerance of wet soils, while tall fescue is also tolerant of drought. Kentucky bluegrass is suitable for pastures, while tall fescue can be used for either hay or animal grazing (Barnes et al., 2007).

5.2.2.1.3 Selection of Target Milk Productions

Milk production, under any dairy system, depends on the animal genetic constitution, type of management, diet, and environmental factors (EPA, 2015). However, under a grazing system, milk production is mainly dependent on pasture intake while pasture quantity and quality is primarily dependent on climate variability (Hatfield et al., 2014; Heckman et al., 2007; Muller, 2004). Regarding the animal genotype, most of the U.S. dairy cows (90%) are black and white Holsteins because they can produce large amount of milk, butterfat, and protein (EPA, 2015). However, producers with grazing systems prefer small framed Holsteins because they are more efficient in converting grass to milk (Flanders and Gillespie, 2015).

Based on the farm surveys, the target milk production ranges between 6,804 to 10,866 kg/cow/year. However, in this study we used a wider range (1,361 to 15,876 kg/cow/year) that allowed the model to examine the impacts of introducing new pasture compositions on milk productions. The range was simulated in steps of 454 kg/cow/year, resulting in 32 scenarios for the target milk productions.

5.2.3 Model Simulations

5.2.3.1 Integrated Farm System Model (IFSM)

IFSM is a whole-farm simulation model developed by the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS). IFSM integrates livestock and crop production systems to evaluate resource use, economics, and environmental sustainability of the farm practices (USDA-ARS, 2016). IFSM has been extensively used in around the world, although the model was developed for temperate regions of the northern United States (e.g. Michigan) and Southern Canada (Bryant and Snow, 2008; USDA-ARS, 2016; Wachendorf and Golinski, 2006). The model has been validated with various farm practices and pasture compositions under different climate conditions (Corson et al., 2007; Rojas-Downing et al., 2017b; Rotz, 2004).

IFSM is a process-based model that integrates the farm components with major biological and physical process over a period of time (USDA-ARS, 2016). The main input data for IFSM include: soil characteristics, crop areas and type, grazing management, equipment and structures, harvest, tillage, types of animals, feed, manure handling, and prices related to the whole-farm. Using this information, IFSM simulates feed production and consumption, grazing management, animal performance, feed storage, manure management, tillage, planting, and harvest operations, and economics (Rotz et al., 2014).

5.2.3.1.1 Scenario analysis of the impacts of climate variabilities, pasture compositions, and target milk productions on sustainability grazing dairy farms

Figure 16 presents the integrated scenario analysis used in this study to evaluate the impacts of climate variabilities, pasture compositions, and target milk productions on sustainability of grazing dairy farms. For each of the 10 locations (Figure 14), the sustainability of a representative grazing dairy farm was evaluated considering different pasture compositions and target milk productions. The pasture compositions include all possible combinations of the four cool-season grass species with two legumes by varying the legume percentage in the composition between 0% and 50%, at 10% increments. These combinations resulted in 48 different pasture compositions. In addition, for each pasture composition, each of the 32 target milk productions, ranging from 1,361 to 15,876 kg/cow/yr, were simulated. The combination of 10 locations, 48 pasture compositions, and 32 target milk productions, resulted in 15,360 different scenarios that where simulated in IFSM.

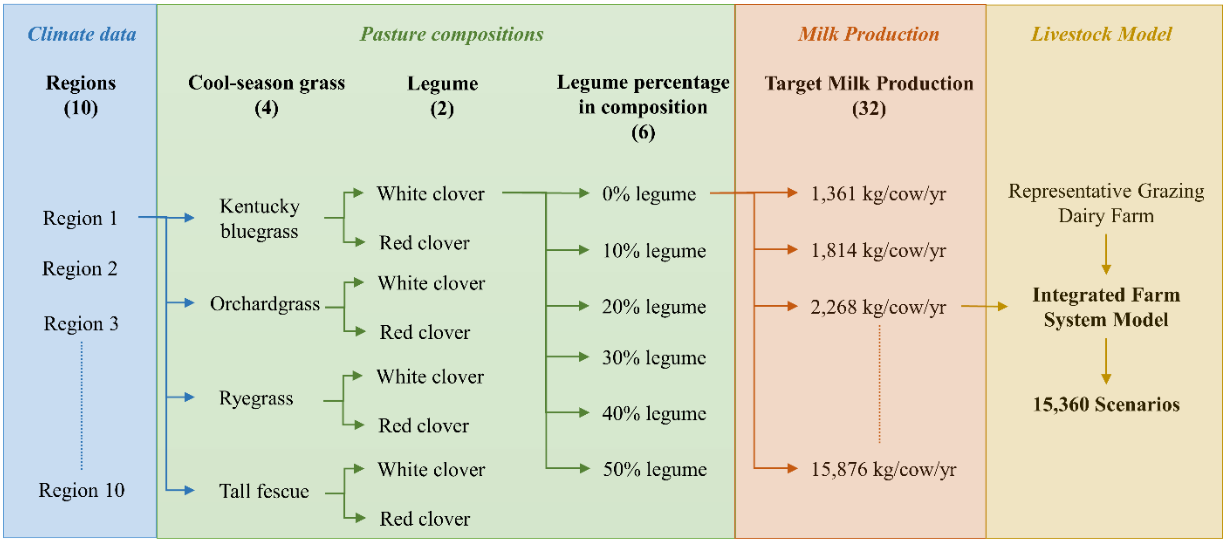

Figure 16. Schematic representation of the integrated scenario analysis

5.2.4 *Footprint Analysis*

Beside economic footprint, IFSM can directly be used to determine carbon, water, and energy footprints of the representative grazing dairy farm. However, in order to calculate the economic footprint, the IFSM model outputs are still necessary to account for the whole farm profits and the milk productions. All footprints are ultimately normalized to the total amount of milk production. Milk production is estimated as the maximum amount of milk that can be produced per cow in a year. The maximum milk production is calculated based on the desired target milk production, amount of feed, forage nutritional value, and type of concentrates fed (Rotz, et al., 2014). The milk production was converted to the fat and protein corrected milk (FCPM) using milk fat content of 4.2% and milk protein content of 3.3% (Rojas-Downing et al., 2017a). Below, more detailed information is provided for each footprint used in this study:

Carbon footprint: Carbon footprint is one of the key environmental indicators that presents the amount of GHG emissions over the lifecycle of a product or process (BSI, 2008). The unit of measurement is tonnes of CO_2 equivalents (t CO_2-eq), which is based on the GWP indicators

(EC, 2007). Several studies have applied carbon footprint to assess the sustainability of the dairy sector in regard to: allocating GHG emissions between meat and milk (Mc Geough et al., 2012); comparing emissions of different production systems (e.g., confinement, grazing) (de Léis et al., 2015; Flysjö et al, 2011; O'Brien et al., 2014; Zehetmeier et al., 2014); and evaluating different feeds (e.g. grain, forage) (Adom e t al., 2012). IFSM determines the carbon footprint as the net emission of CO_2, CH_4, and N_2O while considering all sources and sinks of CO_2. In addition, a carbon balance is enforced, so a portion of the CO_2 assimilated in the feed production (grazed and harvested forage) is exported through feed (harvested forage), milk, and animal productions. Finally, the net emission is determined through a partial life cycle assessment by assuming the GWP of 298 $CO_{2\text{-eq}}$/kg for CH_4 and 298 $CO_{2\text{-eq}}$/kg for N_2O (IPCC, 2001). In this study, the unit $CO_{2\text{-eq}}$ per kg of FCPM is used for the carbon footprint since it was normalized to the total amount of milk production.

Water footprint: Water footprint refers to the volume of water consumed per unit of time or per functional unit in a LCA (Galli et al., 2011, 2012). Water footprint provides a better understanding of water management and usage in a system. Therefore, it has been frequently applied to assess: techniques to improve water usage on dairy farms (Palhares and Pezzopane, 2015; Murphy et al., 2017; Zonderland-Thomassen and Ledgard, 2012), water availability for large-scale production systems (Huang et al., 2014), water scarcity (Owusu-Sekyere et al., 2016), and different types of dairy products (Vasilaki et al., 2016). IFSM determines the water footprint as the total amount of water used in the dairy farm system. The unit of measurement is kg of water per kg of FCPM. The major use of water in the grazing dairy farm include the production of feed crops, drinking water for animals, animal cooling, and cleaning of the parlor and holding areas on the farm (Rotz, et al., 2014).

Energy footprint: Energy footprint is defined as the amount of energy required (fossil- and renewable-based energy) per functional unit (Sobhani et al., 2012). Both the units of energy (e.g., Megajoule (MJ)) and global area (e.g., global hectare (gha)) can be used to report energy footprint (Hermann et al., 2011). Energy footprint can provide valuable information about the energy usage for different types of dairy systems, which ultimately can be used to identify different energy saving strategies (Pagani et al., 2016). IFSM determines the energy footprint as the total energy required to produce feed and milk while excluding the solar energy used to grow feed crops. This includes all fuel and electricity used for milking, ventilation, and lighting, as well as energy requirements for resources used on the farm (e.g., tractor, equipment used for feed production, feeding, and manure handling). The unit of measurement is MJ per kg of FCPM.

Economic footprint: Čuček et al. (2012) defined the economic footprint as the net economic impact of a product or process, where the unit of measurement is currency. Meanwhile, this footprint is mainly used by organizations, institutions, companies, and universities and its application in agriculture sector is scarce (Čuček et al., 2012; Clayton-Matthews and Watanabe, 2012). The accounting period in the IFSM model for performing the economic analysis is one year. The model determines all costs and benefits associated with productions (e.g., milk, feed). The economic analysis also includes fixed (e.g., equipment and structures) and variable (e.g., labor, resources) production costs. However, no interaction between the farm and the surrounding markets is allowed. As a result, the efficiency of the technical and economic production of the farm for a set of relative prices can be evaluated (Rotz, et al., 2014). The economic footprint was determined by considering the whole-farm profit per kg of milk production ($ per kg of FCPM). The whole farm profit is calculated by subtracting incomes from the total costs. Incomes include, milk, animals and feed sales, and saving through usage of family labor. Labor was considered as income for this study because 97% of dairy farmers in this region are family owned, where most of the labor is performed by the family members (United Dairy Industry of Michigan, 2016). The costs include feed, manure handling, animal housing, animal care, and milking.

5.2.4.1 Food Footprint

In this study, the food footprint measure was used to mimic the overall impacts of grazing dairy farms and helps with identifying the most sustainable production systems. This new measure was calculated using a multi-criterion decision-making (MCDM) in which lower values represent a more sustainable scenario. MCDM help with determining the best overall solution considering multiple criteria (Zanakis et al., 1998).

The MCDM method used in this study is called multi-criteria optimization and compromise solution (VIKOR). VIKOR was selected since it can solve complex decision-making problems with conflicting criteria (benefit and cost criteria) and non-commensurable (different units) criteria, which is the case in this study (Opricovic and Tzeng, 2004). VIKOR employs an aggregated function representing "closeness to the ideal", which originated in the compromise programming method and determines a compromise solution, providing a maximum "group utility" for the "majority" and a minimum of an individual regret for the "opponent" (Opricovic and Tzeng, 2007; Opricovic, 2009). As a result, the highest ranked alternative by the VIKOR method is the closest to the ideal solution (Opricovic, 2011).

In this study, there are four criteria entailing three cost criteria (water, energy, and carbon footprint), and one benefit criterion (economic footprint) in relation to environmental and economic factors. Thus, the VIKOR optimization method can provide efficient ranking regarding the selection of the best scenario (alternative).

A generic form of a MCDM matrix for a set of conflicting criteria $\{g_1, g_2, \dots, g_j, \dots, g_n\}$ and a set of possible alternatives $\{A_1, A_2, \dots, A_i, \dots, A_m\}$ can be constructed with the performance ratings of f_{ij}. The weight vector, which refers to the relative importance of criteria, is modeled as $W = [w_1, w_2, \dots, w_j, \dots, w_n]$ where $\sum_{j=1}^{n} w_j = 1$.

Criteria (factors)

Alternatives	g_1	g_2	…	g_n
A_1	f_{11}	f_{12}	…	f_{1n}
A_2	f_{21}	f_{22}	…	f_{2n}
…	…	…	…	…
A_m	f_{m1}	f_{m2}	…	f_{2n}

The main goal of the VIKOR optimization method is to determine the best and worst values of alternatives in accordance with the cost/benefit criteria. There are named positive-ideal solution (f_j^*) and the negative-ideal solution (f_j^-), respectively. Moreover, the compromise rankings are performed by comparing the measure of closeness to the ideal alternative (Opricovic and Tzeng, 2007). The multi-criteria measure for compromise ranking is developed from a LP- metric proposed by Yu (1973) used as an aggregating function in a compromise programming method. Development of the VIKOR method started with the following form of LP- metric (Equation 1):

$$L_{P,i} = \left\{ \sum_{j=1}^{n} [w_j . \frac{(f_j^* - f_{ij})}{(f_j^* - f_j^-)^P}] \right\}^{1/P} \quad ; \quad 1 \leq P \leq \infty \qquad (1)$$

where, $L_{P=1,i}$ (also known as S_i) computes the sum of deviations and evaluates the maximum group utility or majority (concordance), whereas $L_{P=\infty,i}$ (also known as R_i) measures the maximum deviations and signifies the minimum individual regret of the opponent (discordance)

(Opricovic and Tzeng, 2004). The detailed procedure of the compromise ranking algorithm of the VIKOR optimization method are described below.

Step1. The best and worst values of all the criterion functions (f_j^* and f_j^-) are determined according to the benefit or cost criteria.

Step2. The S_i and R_i values are determined for all alternatives using the following relations.

$$S_i = \sum_{j=1}^{n} w_j \,.\, (\frac{|f_j^* - f_{ij}|}{|f_j^* - f_j^-|}) \tag{2}$$

$$R_i = \max_{j=1,2,..,n} [w_j . \left(\frac{|f_j^* - f_{ij}|}{|f_j^* - f_j^-|}\right)] \tag{3}$$

Step3. The minimum and maximum values of S_i and R_i are estimated using equation 4:

$$S^* = \min_i S_i \;,\; S^- = \max_i S_i \;,\; R^* = \min_i R_i \;,\; R^- = \max_i R_i \tag{4}$$

Step4. Computing the values of Q_i for all alternatives (in this case, *i* = 4) using Equation 5. Q_i is a measure that simultaneously takes S_i, R_i, and their best and worst values into consideration.

$$Q_i = \vartheta . \frac{(S_i - S^*)}{(S^- - S^*)} + (1 - \vartheta) . \frac{(R_i - R^*)}{(R^- - R^*)} \tag{5}$$

where, the parameter of ϑ is initiated as strategy weight for majority of criteria (or the maximum group utility) and $(1 - \vartheta)$ is the weight of individual regret. The compromise can be selected with consensus (ϑ=0.5), voting by majority (ϑ>0.5), or veto (ϑ<0.5). Usually, the value of ϑ is taken as 0.5. This means that the decision maker considers the same weights for the effect of S_i (50%) and R_i (50%). However, any value between 0 and 1 can be considered for ϑ. In this study, we considered consensus that are commonly used for a compromise solution (Opricovic and Tzeng, 2007; Sayadi et al., 2009).

Step5. The alternatives are ranked in separate lists based on ascending S, R, and Q values.

Step6. The following conditions are checked. If both conditions are satisfied, alternative A' that has minimum Q value, is proposed as a compromise solution.

Condition 1: It is known as "acceptable advantage" condition in decision making, denoting that the difference of the first two ranks of alternatives by Q (A$'$: the first rank, $A"$: the second rank) satisfies Equation 6.

$$Q(A") - Q(A') \geq DQ \tag{6}$$

where, $DQ = 1/(\#of\ alternatives - 1)$.

Condition 2: It is known as "acceptable stability" condition in decision-making, meaning that A' alternative must also be the best ranked alternative by the S or/and R measures.

If one of these two conditions is not satisfied, then a set of compromise solutions are recommended as follows:

- Alternatives A' and $A"$ are proposed if only *Condition 2* is not satisfied, or
- Alternatives $\{A', A", \ldots, A^{(M)}\}$ are proposed if *Condition 1* is not satisfied. Where, $A^{(M)}$ is determined by the Equation 7 for maximum M:

$$Q(A^{(M)}) - Q(A') < DQ \tag{7}$$

5.2.5 Spatial Variability of Sustainable Pasture Composition and Milk Production

In order to identify the spatial variability of the most sustainable milk production and appropriate pasture composition in the 10 locations of the study area, a cluster analysis was performed. A cluster analysis involves classifying, without supervision, patterns into groups by acquiring insight into data (e.g., identifying irregularities) (Celebi et al., 2013; Woznicki et al., 2015). The most widely used clustering algorithm is called *k*-means (Jain, 2010). This algorithm is selected here due to its versatility (e.g., algorithm can be modified), simplicity of application, and invariance to data ordering (Celebi et al., 2013). The procedure in this algorithm starts with random selection of centers for arbitrary clusters, follows by assigning each data point to the nearest center, and finalizes by reassigning the means (Celebi et al., 2013).

5.2.6 The Social Component of Grazing Dairy Farms

The ultimate goal of sustainability assessment is to provide valuable information to producers as they are making management decisions. Meanwhile, even the most sustainable solution may be rejected by producers' due to negative social implications (OECD, 2004). One way to include the social implication of a management practice is to calculate the social footprint. However, this measure has not been introduced in the concept of the grazing dairy farm and because of variability in management practices and preferences of dairy farmers, it is very difficult to achieve a standardization (Čuček et al., 2012). Therefore, the social measure of sustainably was not included in determining the food footprint, but should be considered when making management recommendation that are both sustainable and socially acceptable.

In general, and in order to incorporate the social aspect of a management scenario, an extensive stakeholder feedback is required (von Keyserlingk et al., 2013). For this study, this information was collected from extension specialists. Critical public issues related to grazing dairies include food safety, animal health and welfare, landscape quality, and labor (van Calker et al., 2005; von Keyserlingk et al., 2013). The public increasingly views access to pasture as a key component of acceptable welfare and health for dairy cattle (von Keyserlingk et al., 2013; Schuppli et al., 2014), and often views dairy products produced from pastured cattle as safer and more desirable (von Keyserlingk et al., 2013). This should help grazing dairies, but unfortunately there is a disconnect between what consumers say they value and how much they are willing to pay for it at the moment of food purchase (von Keyserlingk et al., 2013). Many specialty dairy processors in the Great Lakes region are currently saturated with milk, which limits opportunities for new grazing dairies to get access to price premiums related to specialty product labeling.

Labor management was cited by von Kreyserlingk et al. (2013) as one of the greatest immediate threats to sustainability of the US dairy industry. While this is partly an economic consideration, there is also a strong social aspect related to perceived desirability of this type of work. Immigrant laborers are often recruited, many of them undocumented (Martin, 2002) and poor working conditions are a concern. Potential loss of the undocumented immigrant labor pool due to proposed changes to immigration enforcement policies presents a severe challenge to conventional dairy systems (von Keyserlingk et al., 2013). Grazing dairy systems may possibly avoid part of this labor challenge because farms are generally smaller than large confinement dairies and may be able to hire family members to accomplish most work. However, when hired labor is needed, grazing dairies may be less able to compete with large dairies for competitive wage rates in a shrinking labor pool.

5.3 Results and Discussion

5.3.1 Identification of the Most Sustainable Milk Production

The goal of this section is to identify the most sustainable milk production for the study area considering the food footprint measure in which the lower value represents a more sustainable milk production. As it was discussed in the Materials and Methods section, the range between 1,361 and 15,876 kg/cow/year of target milk production was evaluated in this study. However, after simulating the IFSM model for all locations, the maximum milk production was 8,618 kg/cow/year. The number looks reasonable since a previous study showed that the typical target milk production level for grazing cows is about 7,700 kg/cow/year (Conner, et al., 2007).

Box and whisker plots (Figures 17 and S29) present the variability of the food footprint for three ranges of milk production: low (1,361 to 3,629 kg/cow/year), medium (4,082 to 5,897 kg/cow/year), and high (6,350 to 8,618 kg/cow/year). Figure 17 shows the pasture compositions of the four grass species with red clover while figure S29 shows the pasture compositions of the four grass species with white clover considering all percentages of legume (0% to 50%). However, both Figures 17 and S29 present a similar trend, where the high range of milk production presents lower values of food footprint, while having less variability among the pasture compositions and locations. Since all the footprints under study (energy, water, carbon, and economic) were weighted equally, the low variability under the high range of milk production represents the limited improvement in sustainability that is being gained by increasing the target milk production from 6,350 to 8,618 kg/cow/year. Conversely, the low range of milk production presents higher values of food footprint, while variability is much greater among the pasture compositions and locations. This suggests that the most sustainable range of milk production for any of the pasture compositions for this study is between 6,350 to 8,618 kg/cow/year, while having the least variability.

Moreover, the most appropriate pasture composition for each range of milk production was identified. The most appropriate pasture composition for the high range of milk production for all 10 locations is perennial ryegrass combined with red clover. This composition had the lowest median food footprint (0.0473). Perennial ryegrass was also identified as the most appropriate grass for the pasture composition in the medium range of milk production. However, the most appropriate composition was achieved when it is combined with white clover (median food footprint =0.2037). In the case of the low range of milk production, the most appropriate pasture composition was identified as tall fescue with white clover, with a median value of

0.7069. Therefore, by identifying the most sustainable range of milk production and its respective pasture composition, the sustainability of the grazing dairy farm can be considerably improved.

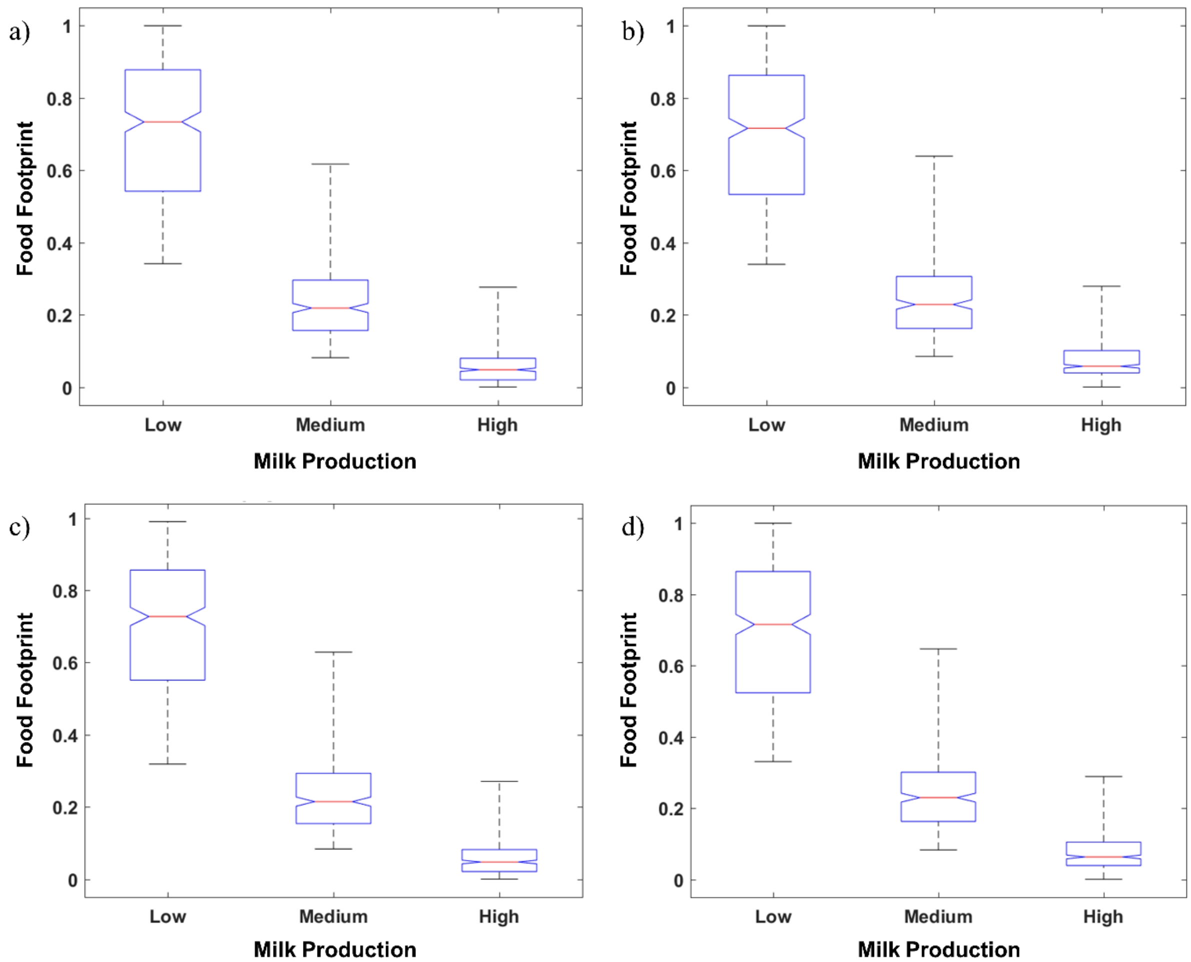

Figure 17. Food footprint for different combinations of red clover with a) Kentucky bluegrass, b) orchardgrass, c) perennial ryegrass, and d) tall fescue for low (1,361 to 3,629 kg/cow/year), medium (4,082 to 5,897 kg/cow/year), and high (6,350 to 8,618 kg/cow/year) milk production

5.3.2 Identification of the Most Appropriate Pasture Composition

To identify the most appropriate pasture composition for the study area, all compositions were ranked from 1 to 48 based on their food footprint score in which lower scores ranked higher. Figures 18 to 20 shows a summary histogram map of the pasture compositions ranking based on the results from all locations within the study area. The y-axis represents the pasture compositions, were each row signifies steps of 10% legume ranging from 0% to 50%. The x-axis represents the pasture compositions food footprint ranking from 1 to 48, were 1 indicates the most appropriate pasture composition and 48 the least appropriate. The color bar at the right side of histogram map shows how frequently a certain rank for a specific pasture composition has been obtained. The yellow color indicates the maximum amount of counts in which a pasture composition obtained that rank. As the color spectrum moves from yellow to dark blue (top-down), it indicates that the pasture composition obtained that rank less frequently than the other ranks. The dark blue color indicates that the pasture composition did not obtained that rank. As an example, on row one in Figure 18 (grass with 0% red clover), rank 47 happened more frequently than any other ranking. In addition, this composition is one of the least appropriate compared to any other grass and red clover mixtures (10% to 50%).

In general, having white clover in the pasture composition helps with improving sustainability as the grass and white clover composition ranked higher than the grass and red clover composition (Figure 18). In addition, the milk production becomes less sustainable when no legume is added (Figure 18, rows 1 and 7). The best rankings for both red clover and white clover are when 10% of these legumes are combined with a grass (Figure 18, rows 2 and 8). However, white clover resulted in higher sustainability in milk production with 20%, 30%, and even 40% in the composition than red clover (Figure 18, rows 9, 10, and 11, respectively).

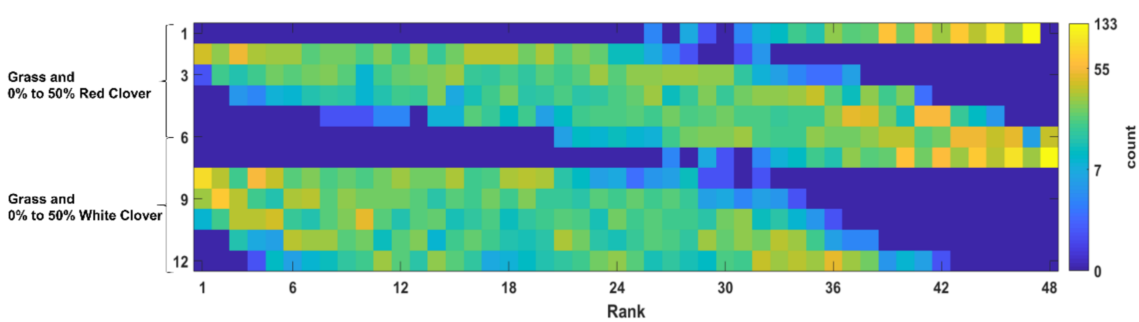

Figure 18. Histogram map for legume variations with grass species

As presented in Figure 19, the least appropriate pasture compositions are Kentucky bluegrass with no legume (row 1), orchardgrass with 0% legume (row 7), and perennial ryegrass with 0% and 50% legume (rows 13 and 18, respectively). Among all grasses, the presence of tall fescue resulted in the most sustainable milk production especially when it is combined with 10% of legume (Figure 19, row 20). However, milk production becomes less sustainable with an increase of legume percentage in the pasture composition with tall fescue.

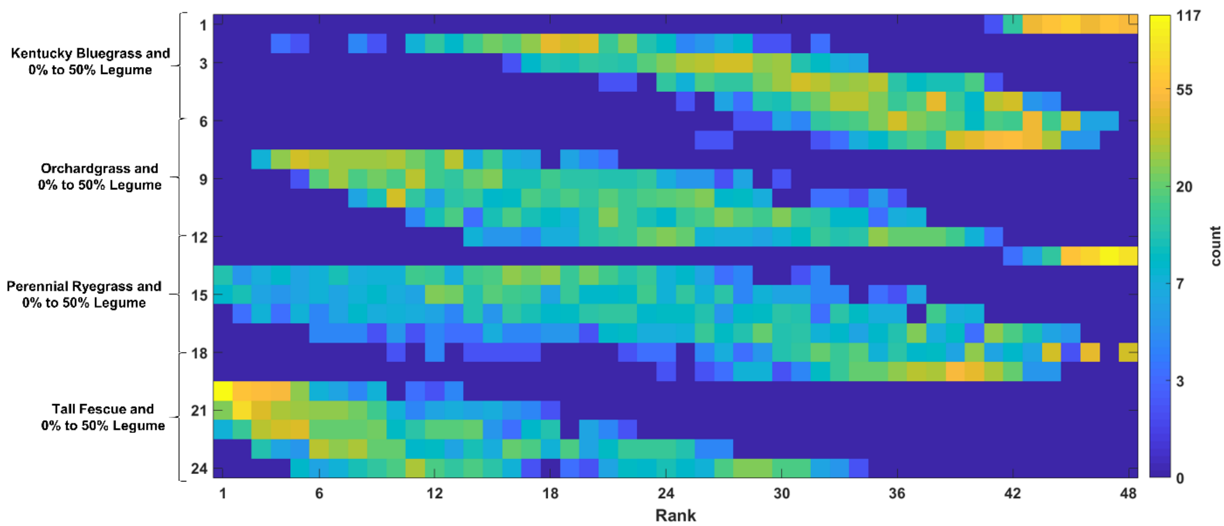

Figure 19. Histogram map for grass species for different variations of legume

Comparing all compositions of pastures, Figure 20 shows that as legume percentage increases (between 10% to 50%) the overall grazing dairy farm practice becomes less sustainable. However, when grasses are not combined with legume, the pastures are ranked the lowest. This indicates when a legume is not present in the pasture composition, the farm is less sustainable. In summary, the least appropriate pasture composition was perennial ryegrass with no legume (Figure 20, row 25) and the most appropriate pasture composition is tall fescue with 10% white clover (Figure 20, row 20). In addition, tall fescue with white clover in general presents the best rankings (Figure 20, rows 44 to 48), making it the most sustainable milk production.

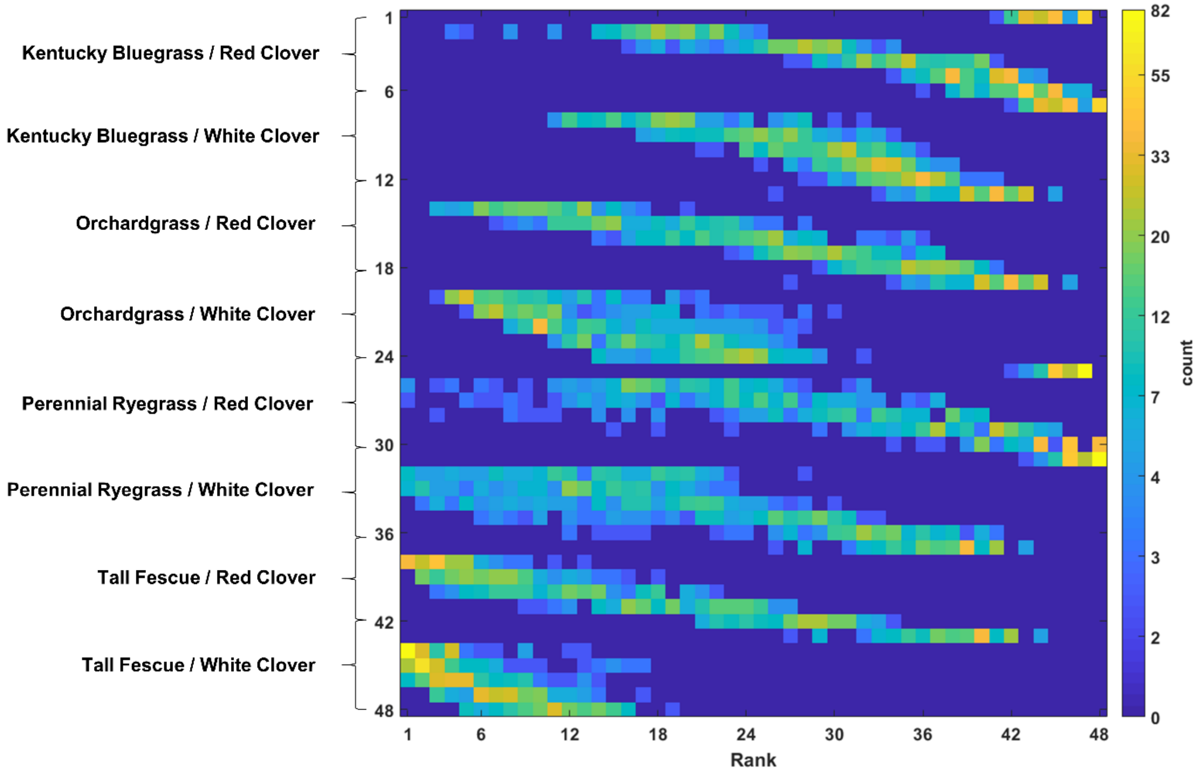

Figure 20. Histogram map of all pasture compositions

5.3.3 Spatial Variability of Sustainable Milk Productions and Associated Pasture Compositions

In order to understand climate variability of grazing dairy farms, 10 locations were identified within the study area. For each location, the most sustainable milk production and associated pasture composition was identified and presented in Figures 21, 22, and 23. Figure 21 shows the most appropriate composition of grass and legume for each location. Tall fescue with white clover was identified as the most suitable pasture composition in eight locations, positioned mostly in the Lower Peninsula of Michigan. Meanwhile, the most appropriate pasture compositions of the locations 1 and 3 (the Upper Peninsula) are perennial ryegrass with white clover and tall fescue with red clover, respectively. Nine of the locations identified white clover as the most appropriate legume in the pasture composition, which can be related to the high tolerance for heavy grazing and its high quality, especially for pastures (Ogle and St. John, 2008). Whereas, red clover has more potential for hay production as it can be quickly depleted if grazed continuously (USDA-NRCS, 2002). In addition, tall fescue was identified in nine of the locations as the most appropriate grass in the pasture composition, which can be related to its high tolerability of extreme weather conditions (drought and flood) (Cassida et al., 2014).

The legume percentages of the pasture compositions for each location were also identified (Figure 23). Ten percent legume in the pasture compositions was identified as the most suitable legume percentage in nine locations and 20% in the remaining location. In another study performed in the Lower Peninsula of Michigan, 50% legume in the pasture composition was identified as the best scenario for forage production and economics of a grazing dairy farm (Rojas-Downing et al., 2017b). However, Rojas-Downing et al. (2017b) did not considered carbon generation and energy usage in their study. This highlights the importance of performing a comprehensive sustainability study to make more informed decisions.

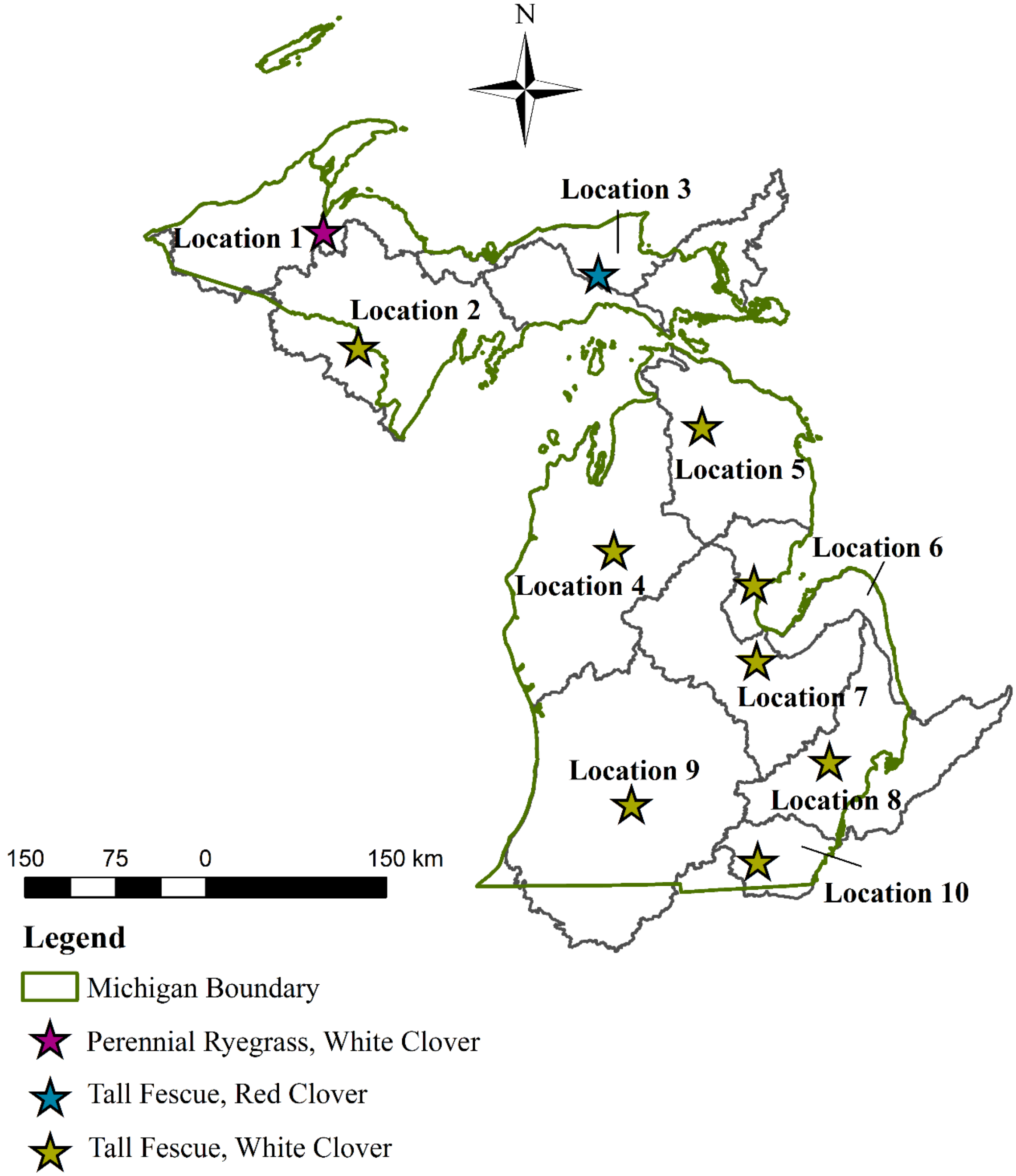

Figure 21. Spatial variability of most appropriate pasture compositions in Michigan

Regarding the most sustainable milk production, 8,618 kg/cow/year was identified as the most sustainable production for all locations (Figure 22), which is the highest produced among all the simulated scenarios. This result is promising since it shows that sustainability is achievable even at high levels of milk production, while having a balanced use of resources.

Finally, a cluster analysis was performed to develop the overall sustainability map for the location in which both pasture composition and milk production were considered (Figure 23). The study area was divided into three clusters, where 90% tall fescue combined with 10% white clover and 8,618 kg/cow/year were identified as the most appropriate practices for the majority of the locations. These maps can be used by policymakers to develop a strategy for grazing dairy farms that involves reducing water, energy, and environmental footprints, while maximizing the profit and production of dairy farmers.

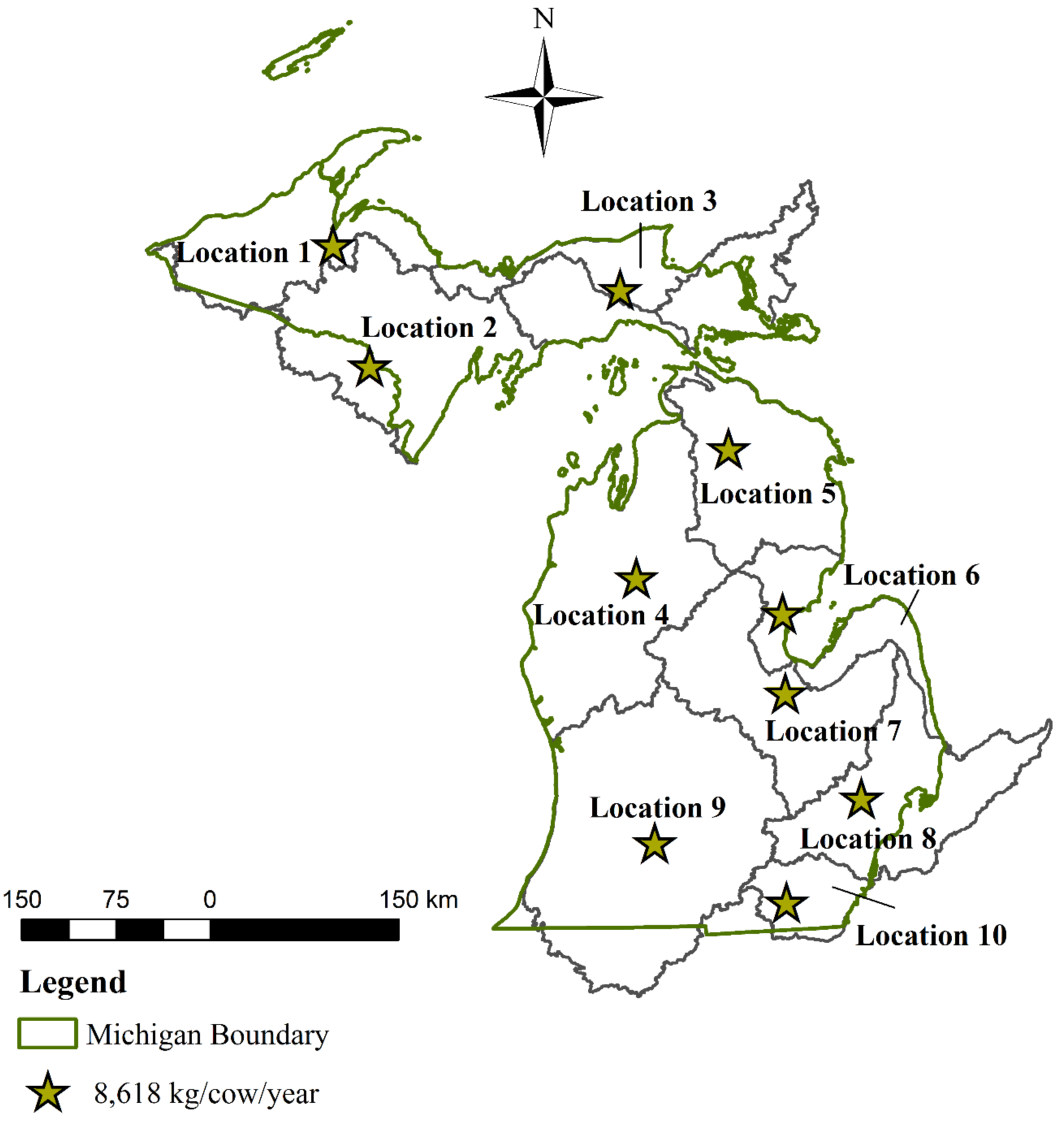

Figure 22. Spatial variability of most sustainable milk productions in Michigan

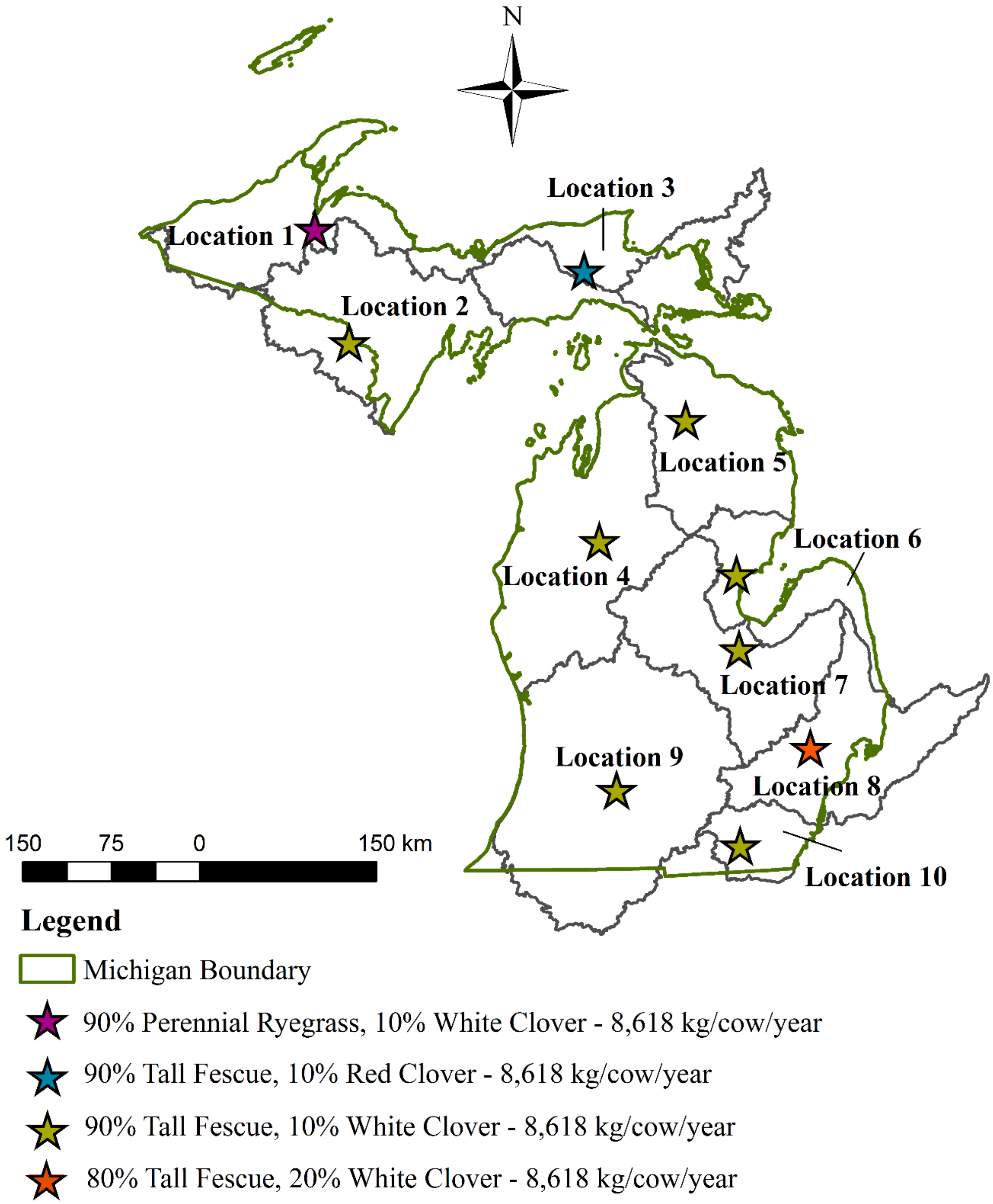

Figure 23. Spatial variability of most sustainable milk productions and associated pasture compositions in Michigan (Cluster analysis)

5.4 Conclusions

The overall goal of this study was to identify the most sustainable milk production for grazing dairy farms in Michigan by using a new measure named food footprint that was calculated using a multi-criterion decision making method.

Regarding the most sustainable milk production, the result of this study showed that the high range (6,350 to 8,618 kg/cow/year) is the most sustainable for any combination of the pasture compositions and locations, while having the least variability in terms of food footprint. These results are promising since it encourages high levels of milk production while promoting the most sustainable approach for the grazing farm management. However, in order to achieve these levels of milk production (6,350 to 8,618 kg/cow/year), one should consider the perennial ryegrass with red clover composition (Figure 17).

Regardless of the level of milk production, the results of the multi-criterion decision making procedure (food footprint estimation) provide three major findings: 1) white clover in the pasture composition helps with improving sustainability more than with red cover; 2) farm sustainability improves with maintaining low percentages of legume (10% and 20%) in the pasture mixture; 3) among all grasses, tall fescue resulted in the most appropriate pasture composition for any target milk production and location, especially when is combined with 10% of white clover.

The cluster analysis helped with identifying the most sustainable grazing farm practice within the study area. In general, the highest level of milk production (8,618 kg/cow/year) was identified as the most sustainable for all the 10 locations. However, the most appropriate pasture composition varied among the locations. For most locations (locations 2, 4, 5, 6, 7, 9, 10), 90%

tall fescue combined with 10% white clover was identified as the most suitable pasture composition.

The results of this study can be further customized to address the needs of both policy makers and stakeholders including identification of: a) the most sustainable milk production for a specific pasture composition, b) the most appropriate pasture composition for a specific milk production level, and c) the most suitable legume percentage in the pasture composition for a specific milk production. In addition, the concept of the food footprint, which refers to the impacts of a food product on carbon, energy, water, and economics, can be expanded to other agricultural sectors including livestock and crops. However, the social aspects were not considered into final recommendation due to locality of these aspects (e.g. variability in management practices, labor, and preferences of dairy farmers) in each location. Future work should consider the locality of social aspects into the decision making. This will ultimately help policy makers with implementation of sustainable farm management practices that have a higher probability of adaptation by farmers.

6 CONCLUSIONS

This research introduced new concepts for evaluating the sustainability of a grazing dairy system in Michigan and impacts of climate change/variability on this system while identifying the most appropriate adaptation and mitigation strategies. These new concepts where tested in the state of Michigan. In the first study, a sensitivity analysis was performed to measure the resiliency of an adaptation measure to mitigate the impacts of future climate scenarios. In the second study, a new measure called food footprint was introduced as a measure which sustainable farm practices can be evaluated considering water, energy, carbon, and economic footprints. Using this new measure, we identified the most sustainable milk production and appropriate pasture composition for a study area. Overall, summary of the major findings of first and second study are presented in Table 12.

The results of the first study provided four major findings concerning the use of legume in the pasture composition: 1) an increased ratio of legume to grass species in a pasture composition, can be beneficial to both farm economy and resource use; 2) grass species combined with 50% legume was identified as the best composition to reduce likely impacts of climate change while improving the farm economics; 3) to maintain a high-grazed forage production under future climate scenarios, it is important to incorporate at least 30% legume in the pasture composition; and 4) the presence of red clover in a pasture composition could significantly improve the farm economics and production under all future climate scenarios. In addition, the sensitivity analysis applied in this study have policy implications for understanding the resiliency of the different pasture compositions. Overall, the pasture composition of 50% perennial ryegrass and 50% red clover was identified as the best pasture composition while being the most resilient to climate change. Summary of the major findings are presented in Table 13.

The food footprint measure that was introduced in the second study provided four major findings: 1) the high range of target milk production (6,350 to 8,618 kg/cow/year) is the most sustainable practice regardless of the pasture compositions; 2) white clover in the pasture composition helps improve sustainability more than with red cover; 3) farm sustainability is improved by maintaining low percentages of legume (10% to 20%) in the pasture mixture; and 4) among all grasses, tall fescue was considered as the best choice in the pasture composition for any level of sustainable target milk production. The food footprint that was introduced in this study can be adopted in other regions to improve sustainability by reducing water, energy, and environmental impacts of grazing dairy farms, while maximizing the farm profit and productions. Summary of the major findings are presented in Table 14.

Table 12. Overall findings

Study time period	Criteria	Finding
1985-2005 / 2040-2060	Economic	50% perennial ryegrass and 50% red clover was identified as the best pasture composition
1985-2005 / 2040-2060	Resource Use	50% perennial ryegrass and 50% red clover was identified as the best pasture composition
1985-2005 / 2040-2060	Resilience to climate change	Perennial ryegrass and red clover had the overall lowest sensitivity index
1985-2005	Milk production sustainability	90% tall fescue combined with 10% white clover and 8,618 kg/cow/year were identified as the most appropriate practices for most of the locations

Table 13. Summary of findings of first study

Analysis	Criteria	Criterion	Current	RCP 4.5	RCP 8.5
Ranking	Economic	Net Return per cow over milk production	50% perennial ryegrass and 50% red clover	50% perennial ryegrass and 50% red clover	50% perennial ryegrass and 50% red clover
		Whole Farm profit	50% perennial ryegrass and 50% red clover	50% perennial ryegrass and 50% red clover	50% perennial ryegrass and 50% red clover
	Resource Use	Grazed forage consumed	Grass with 50% red clover	Grass with 50% red clover	Grass with 50% red clover
		Harvested forage production	50% perennial ryegrass and 50% red clover	50% perennial ryegrass and 50% red clover	50% perennial ryegrass and 50% red clover
Statistical	Economic	Net Return per cow over milk production	-The implementation of any grass, with either red clover or white clover did not have significant impact - As the percentage of legume increased in the pasture composition the criteria values increased - The presence of red clover in the pasture composition resulted in significantly higher criteria values compared to the white clover	Remains same as current	Improves
		Whole Farm profit		Remains same as current	Improves
	Resource Use	Grazed forage consumed		Remains same as current	Remains same as current
		Harvested forage production		Remains same as current	Remains same as current
Sensitivity	Economic	Net Return per cow over	-Perennial ryegrass presented		

Table 13 (cont'd)

		milk production	higher sensitivity indexes -White clover presented higher sensitivity indexes		
		Whole Farm profit			
	Resource Use	Grazed forage consumed	-Orchardgrass presented the highest sensitivity indexes -White clover presented higher sensitivity indexes		
		Harvested forage production	- Orchardgrass presented the highest sensitivity indexes -Red clover presented higher sensitivity indexes		
Overall sensitivity			-Perennial ryegrass and red clover had the overall lowest sensitivity index		

Table 14. Summary of findings of second study

Analysis	Finding
Identification of the most sustainable milk production	-The most sustainable range of milk production for any of the pasture compositions is between 6,350 to 8,618 kg/cow/year - The most appropriate pasture composition for the high range of milk production for all 10 locations is perennial ryegrass combined with red clover
Identification of the most appropriate pasture composition	- White clover in the pasture composition helps with improving sustainability - Tall fescue in the pasture composition helps with improving sustainability - When a legume is not present in the pasture composition, the farm is less sustainable - As legume percentage increases (between 10% to 50%) the grazing farm practice becomes less sustainable - The most appropriate pasture composition is tall fescue with 10% white clover
Spatial variability of sustainable milk productions and associated pasture compositions	- Majority of locations identified white clover as the most appropriate legume in the pasture composition - Tall fescue was identified in majority of locations as the most appropriate grass in the pasture composition - Ten percent of legume in the pasture compositions was identified as the most suitable legume percentage in the majority of locations -8,618 kg/cow/year was identified as the most sustainable production for all locations -90% tall fescue combined with 10% white clover and 8,618 kg/cow/year were identified as the most appropriate practices for the majority of locations

7 FUTURE RESEARCH RECOMMENDATIONS

This research introduced new measures for evaluating the resiliency and sustainability of grazing dairy systems under current climate variabilities and future climate scenarios. However, additional research should be performed on the applicability and limitations of these methods. The following are suggestions for future research:

- It is important to consider the local and regional agri-environmental policies and crop insurance subsidies into the selection of the most resilient pasture compositions. This will help identify the most feasible grazing management scenario(s) for a specific location/region.
- The food footprint analysis should also consider additional factors such as farmer preferences to account for acceptability of the recommended approach.
- The spatial distribution and variability of climate and soil textures should be considered in support of a statewide analysis.
- The methods developed under this study can be incorporated within an online decision support tool to help dairy farmers with sustainability and resiliency evaluation of their farms.
- Remotely sensed data can play a major role for the farm model parametrization. This will reduce time for data collection/surveys while improving the accuracy of the input datasets.
- Future work should consider the local social norms concerning grazing dairy farms. This will ultimately help policy makers with implementation of sustainable farm management practices that have a higher probability of adoption by farmers.
- This study was innovative in that for the first time a comprehensive indicator was defined to measure the level of sustainability in the context of milk production in a grazing farm. Future studies can use this method to help policy makers in defining the acceptable level for sustainable farming using the food footprint indicator. A threshold value can be identified for

different regions based on the stakeholder preferences concerning energy and water usage, GHG emissions, and economic returns while considering regional limitations.

APPENDIX

Table S1. Major survey components (Rojas-Downing et al., 2017a)

Farm Management Component	Survey Category	Survey Item
Crop	Grazed Forage	• Area • Stand life • Manure/Fertilizer applied and rates • Initial sward dry matter and composition
	Harvested Forage	• Area • Stand life • Manure/Fertilizer applied and rates

Grazing	Management	• Spring, Summer, and Fall grazing area
		• Grazing management costs
		  ○ Investment in fence and watering systems
		  ○ Annual seeds and chemicals cost

	Strategy	• Labor • Animals grazed • Time on pasture • Grazing period
Farm Operations	Machinery	• Harvest/ Feeding • Tillage/ Planting • Miscellaneous

	Tillage/planting
	Harvest
		• Sequence and dates of operations
		• Preferred harvest schedule
		• Harvest type and operations
		• Harvest parameters
		  ○ Maximum moisture content
		  ○ Neutral Detergent Fiber

Structures	Storage	• Type, capacity and cost of storage for:
		  ○ High and low quality forage
		  ○ Dry hay

	Animal Facilities	• Milking Center • Cow and Heifer housing • Feed Facility
Animals	Herd	• Type • Number of lactating and young stock over/under one year animals • Target milk production • Milking and animal handling labor • Annual livestock expenses

Table S1 (cont'd)

	Herd feeding	• Feeding method for grain, silage and hay • Ration constituents ○ Minimum dry hay ○ Relative forage: grain ○ Crude protein supplement ○ Undegradable protein supplement ○ Energy supplement
	Manure	• Collection and use method • Manure characteristics • Average hauling distance • Storage period, type, and initial cost • Type and amount of bedding use
Economic	Buying prices	• Seed and chemicals per acre • Supplements • Hay • Minerals and vitamins • Bedding
	Selling prices	• High quality hay • Milk • Cull cow • Bred heifer • Suckling calf

Table S2. Key survey data collected (Rojas-Downing et al., 2017a)

Survey item	**Description**	**Range**
Farm size	-	83 to 146 ha
Harvested forage crops	Mostly alfalfa	-
Grazing forage crops	Variety of pasture compositions including mostly perennial ryegrass, orchardgrass, white clover, and red clover	-
Lactating cows	-	90 to 750 cows
Cattle frame	Small Holsteins and New Zealand Friesian	-
Target milk production	-	6,804 to 10,866 kg/cow/year
Cattle feed	High relative forage to grain ratios, with pasture as the main feed and grain as an energy supplement	-
Grazing system	Rotational	-
Stocking rate	-	1.0 - 5.2 animals/ha
Labor for grazing management	-	6 to 10 hours/week
Grazing time	22 hours per day	-
Animal facilities	Milking center, cow housing, heifer housing, feed facility, short-term manure storage, and forage storage	-

Table S3. Statistical comparison of net return, whole farm profit, grazed forage consumed and, harvested forage produced by different grass species and legume percentages in the pasture composition (horizontal comparison)*

Criteria	Legume	Legume %	RCP 4.5				RCP 8.5			
			Perennial Ryegrass	Tall Fescue	Kentucky Bluegrass	Orchard-grass	Perennial Ryegrass	Tall Fescue	Kentucky Bluegrass	Orchard-grass
Net Return ($/cow/yr)	Red Clover	0	1,497[a]	1,501[a]	1,499[a]	1,501[a]	1,514[a]	1,519[a]	1,517[a]	1,519[a]
		10	2,013[a]	2,006[a]	2,003[a]	1,999[a]	2,043[a]	2,034[a]	2,032[a]	2,028[a]
		20	2,063[a]	2,056[a]	2,053[a]	2,049[a]	2,092[a]	2,083[a]	2,082[a]	2,077[a]
		30	2,091[a]	2,084[a]	2,082[a]	2,078[a]	2,118[a]	2,110[a]	2,109[a]	2,105[a]
		40	2,110[a]	2,102[a]	2,101[a]	2,099[a]	2,136[a]	2,129[a]	2,128[a]	2,125[a]
		50	2,123[a]	2,118[a]	2,117[a]	2,114[a]	2,149[a]	2,143[a]	2,142[a]	2,139[a]
	White Clover	0	1,497[a]	1,501[a]	1,499[a]	1,501[a]	1,514[a]	1,519[a]	1,517[a]	1,519[a]
		10	1,761[a]	1,754[a]	1,751[a]	1,747[a]	1,810[a]	1,803[a]	1,801[a]	1,797[a]
		20	1,894[a]	1,888[a]	1,885[a]	1,881[a]	1,930[a]	1,923[a]	1,921[a]	1,917[a]
		30	1,949[a]	1,947[a]	1,944[a]	1,943[a]	1,979[a]	1,976[a]	1,973[a]	1,972[a]
		40	1,971[a]	1,971[a]	1,969[a]	1,968[a]	1,997[a]	1,996[a]	1,993[a]	1,993[a]
		50	1,986[a]	1,986[a]	1,983[a]	1,983[a]	2,013[a]	2,012[a]	2,009[a]	2,009[a]
Whole Farm Profit ($/yr)	Red Clover	0	110,455[a]	110,917[a]	110,679[a]	110,915[a]	112,244[a]	112,693[a]	112,503[a]	112,681[a]
		10	160,966[a]	160,236[a]	159,990[a]	159,589[a]	164,024[a]	163,058[a]	162,890[a]	162,459[a]
		20	166,019[a]	165,247[a]	165,022[a]	164,557[a]	168,908[a]	167,995[a]	167,840[a]	167,432[a]
		30	168,797[a]	168,085[a]	167,924[a]	167,540[a]	171,553[a]	170,744[a]	170,589[a]	170,230[a]
		40	170,712[a]	169,939[a]	169,809[a]	169,592[a]	173,310[a]	172,652[a]	172,531[a]	172,258[a]
		50	172,059[a]	171,540[a]	171,457[a]	171,157[a]	174,672[a]	174,087[a]	173,978[a]	173,678[a]
	White Clover	0	110,455[a]	110,917[a]	110,679[a]	110,915[a]	112,244[a]	112,693[a]	112,503[a]	112,681[a]
		10	136,448[a]	135,693[a]	135,474[a]	135,054[a]	141,314[a]	140,634[a]	140,422[a]	140,001[a]
		20	149,326[a]	148,680[a]	148,382[a]	148,074[a]	152,817[a]	152,196[a]	151,954[a]	151,618[a]
		30	154,577[a]	154,400[a]	154,088[a]	153,980[a]	157,520[a]	157,249[a]	157,030[a]	156,933[a]
		40	156,710[a]	156,780[a]	156,500[a]	156,403[a]	159,344[a]	159,221[a]	158,969[a]	158,943[a]
		50	158,266[a]	158,238[a]	157,964[a]	157,930[a]	160,906[a]	160,806[a]	160,590[a]	160,512[a]

Table S3 (cont'd)

		0	23^{a}	24^{b}	24^{b}	24^{b}	22^{a}	24^{b}	23^{b}	24^{b}
Grazed Forage Consumed (tonne/yr)	Red Clover	10	173^{a}	172^{ab}	171^{ab}	171^{b}	174^{a}	173^{a}	173^{a}	172^{a}
		20	182^{a}	182^{a}	182^{a}	181^{a}	182^{a}	182^{a}	182^{a}	181^{a}
		30	185^{a}	184^{a}	184^{a}	184^{a}	184^{a}	184^{a}	184^{a}	184^{a}
		40	185^{a}	185^{a}	185^{a}	185^{a}	184^{a}	184^{a}	184^{a}	184^{a}
		50	185^{a}	185^{a}	185^{a}	185^{a}	184^{a}	184^{a}	184^{a}	184^{a}
	White Clover	0	23^{a}	24^{b}	24^{b}	24^{b}	22^{a}	24^{b}	23^{b}	24^{b}
		10	118^{a}	116^{a}	116^{a}	114^{a}	130^{a}	128^{a}	128^{a}	127^{a}
		20	148^{a}	147^{a}	146^{a}	145^{a}	153^{a}	152^{a}	152^{a}	151^{a}
		30	161^{a}	160^{a}	160^{a}	159^{a}	164^{a}	163^{a}	163^{a}	162^{a}
		40	170^{a}	169^{a}	169^{a}	168^{a}	171^{a}	171^{a}	171^{a}	171^{a}
		50	175^{a}	174^{a}	174^{a}	174^{a}	176^{a}	176^{a}	176^{a}	175^{a}
Harvested Forage Produced (tonne/yr)	Red Clover	0	245^{a}	246^{a}	245^{a}	246^{a}	250^{a}	251^{a}	250^{a}	251^{a}
		10	284^{a}	281^{a}	280^{a}	278^{a}	295^{a}	291^{a}	290^{a}	288^{a}
		20	301^{a}	298^{a}	298^{a}	296^{a}	312^{a}	308^{a}	307^{a}	306^{a}
		30	312^{a}	309^{a}	308^{a}	307^{a}	323^{a}	320^{a}	319^{a}	317^{a}
		40	319^{a}	317^{a}	317^{a}	315^{a}	330^{a}	327^{a}	327^{a}	326^{a}
		50	326^{a}	323^{a}	323^{a}	321^{a}	337^{a}	334^{a}	334^{a}	332^{a}
	White Clover	0	245^{a}	246^{a}	245^{a}	246^{a}	250^{a}	251^{a}	250^{a}	251^{a}
		10	254^{a}	254^{a}	253^{a}	253^{a}	260^{a}	260^{a}	259^{a}	259^{a}
		20	260^{a}	260^{a}	259^{a}	259^{a}	268^{a}	268^{a}	267^{a}	267^{a}
		30	267^{a}	267^{a}	266^{a}	266^{a}	275^{a}	275^{a}	273^{a}	273^{a}
		40	272^{a}	272^{a}	271^{a}	271^{a}	281^{a}	280^{a}	279^{a}	279^{a}
		50	277^{a}	277^{a}	276^{a}	276^{a}	286^{a}	286^{a}	285^{a}	285^{a}

* Values followed by the same letters are not significantly different (α=0.05).

Table S4. Statistical comparison of net return, whole farm profit, grazed forage consumed and, harvested forage produced by different grass species and legume percentages in the pasture composition (vertical comparison)*

			RCP 4.5				RCP 8.5			
Criteria	Legume	Legume %	Perennial Ryegrass	Tall Fescue	Kentucky Bluegrass	Orchard-grass	Perennial Ryegrass	Tall Fescue	Kentucky Bluegrass	Orchard-grass
Net Return ($/cow/yr)	Red Clover	0	1,497^{a}	1,501^{a}	1,499^{a}	1,501^{a}	1,514^{a}	1,519^{a}	1,517^{a}	1,519^{a}
		10	2,013^{b}	2,006^{b}	2,003^{b}	1,999^{b}	2,043^{b}	2,034^{b}	2,032^{b}	2,028^{b}
		20	2,063^{c}	2,056^{c}	2,053^{c}	2,049^{c}	2,092^{c}	2,083^{c}	2,082^{c}	2,077^{c}
		30	2,091^{cd}	2,084^{cd}	2,082^{d}	2,078^{d}	2,118^{cd}	2,110^{cd}	2,109^{cd}	2,105^{cd}
		40	2,110^{de}	2,102^{de}	2,101^{de}	2,099^{de}	2,136^{d}	2,129^{d}	2,128^{d}	2,125^{d}
		50	2,123^{e}	2,118^{e}	2,117^{e}	2,114^{e}	2,149^{d}	2,143^{d}	2,142^{d}	2,139^{d}
	White Clover	0	1,497^{a}	1,501^{a}	1,499^{a}	1,501^{a}	1,514^{a}	1,519^{a}	1,517^{a}	1,519^{a}
		10	1,761^{b}	1,754^{b}	1,751^{b}	1,747^{b}	1,810^{b}	1,803^{b}	1,801^{b}	1,797^{b}
		20	1,894^{c}	1,888^{c}	1,885^{c}	1,881^{c}	1,930^{c}	1,923^{c}	1,921^{c}	1,917^{c}
		30	1,949^{d}	1,947^{d}	1,944^{d}	1,943^{d}	1,979^{d}	1,976^{d}	1,973^{d}	1,972^{d}
		40	1,971^{de}	1,971^{de}	1,969^{de}	1,968^{de}	1,997^{d}	1,996^{d}	1,993^{d}	1,993^{d}
		50	1,986^{e}	1,986^{e}	1,983^{e}	1,983^{e}	2,013^{d}	2,012^{d}	2,009^{d}	2,009^{d}
Whole Farm Profit ($/yr)	Red Clover	0	110,455^{a}	110,917^{a}	110,679^{a}	110,915^{a}	112,244^{a}	112,693^{a}	112,503^{a}	112,681^{a}
		10	160,966^{b}	160,236^{b}	159,990^{b}	159,589^{b}	164,024^{b}	163,058^{b}	162,890^{b}	162,459^{b}
		20	166,019^{c}	165,247^{c}	165,022^{c}	164,557^{c}	168,908^{c}	167,995^{c}	167,840^{c}	167,432^{c}
		30	168,797^{cd}	168,085^{cd}	167,924^{d}	167,540^{d}	171,553^{cd}	170,744^{cd}	170,589^{cd}	170,230^{cd}
		40	170,712^{de}	169,939^{de}	169,809^{de}	169,592^{de}	173,310^{d}	172,652^{d}	172,531^{d}	172,258^{d}
		50	172,059^{e}	171,540^{e}	171,457^{e}	171,157^{e}	174,672^{d}	174,087^{d}	173,978^{d}	173,678^{d}
	White Clover	0	110,455^{a}	110,917^{a}	110,679^{a}	110,915^{a}	112,244^{a}	112,693^{a}	112,503^{a}	112,681^{a}
		10	136,448^{b}	135,693^{b}	135,474^{b}	135,054^{b}	141,314^{b}	140,634^{b}	140,422^{b}	140,001^{b}
		20	149,326^{c}	148,680^{c}	148,382^{c}	148,074^{c}	152,817^{c}	152,196^{c}	151,954^{c}	151,618^{c}
		30	154,577^{d}	154,400^{d}	154,088^{d}	153,980^{d}	157,520^{d}	157,249^{d}	157,030^{d}	156,933^{d}
		40	156,710^{de}	156,780^{de}	156,500^{de}	156,403^{de}	159,344^{d}	159,221^{d}	158,969^{d}	158,943^{d}
		50	158,266^{e}	158,238^{e}	157,964^{e}	157,930^{e}	160,906^{d}	160,806^{d}	160,590^{d}	160,512^{d}

Table S4 (cont'd)

Grazed Forage Consumed (tonne/yr)	Red Clover	0	23^{a}	24^{a}	24^{a}	24^{a}	22^{a}	24^{a}	23^{a}	24^{a}
		10	173^{b}	172^{b}	171^{b}	171^{b}	174^{b}	173^{b}	173^{b}	172^{b}
		20	182^{c}	182^{c}	182^{c}	181^{c}	182^{c}	182^{c}	182^{c}	181^{c}
		30	185^{d}	184^{d}	184^{d}	184^{d}	184^{d}	184^{d}	184^{d}	184^{d}
		40	185^{d}	185^{d}	185^{d}	185^{d}	184^{d}	184^{d}	184^{d}	184^{d}
		50	185^{d}	185^{d}	185^{d}	185^{d}	184^{d}	184^{d}	184^{d}	184^{d}
	White Clover	0	23^{a}	24^{a}	24^{a}	24^{a}	22^{a}	24^{a}	23^{a}	24^{a}
		10	118^{b}	116^{b}	116^{b}	114^{b}	130^{b}	128^{b}	128^{b}	127^{b}
		20	148^{c}	147^{c}	146^{c}	145^{c}	153^{c}	152^{c}	152^{c}	151^{c}
		30	161^{d}	160^{d}	160^{d}	159^{d}	164^{d}	163^{d}	163^{d}	162^{d}
		40	170^{e}	169^{e}	169^{e}	168^{e}	171^{e}	171^{e}	171^{e}	171^{e}
		50	175^{e}	174^{e}	174^{e}	174^{e}	176^{e}	176^{e}	176^{e}	175^{e}
Harvested Forage Produced (tonne/yr)	Red Clover	0	245^{a}	246^{a}	245^{a}	246^{a}	250^{a}	251^{a}	250^{a}	251^{a}
		10	284^{b}	281^{b}	280^{b}	278^{b}	295^{b}	291^{b}	290^{b}	288^{b}
		20	301^{c}	298^{c}	298^{c}	296^{c}	312^{c}	308^{c}	307^{c}	306^{c}
		30	312^{cd}	309^{cd}	308^{cd}	307^{cd}	323^{cd}	320^{cd}	319^{cd}	317^{cd}
		40	319^{d}	317^{de}	317^{de}	315^{de}	330^{d}	327^{d}	327^{d}	326^{d}
		50	326^{d}	323^{e}	323^{e}	321^{e}	337^{d}	334^{d}	334^{d}	332^{d}
	White Clover	0	245^{a}	246^{a}	245^{a}	246^{a}	250^{a}	251^{a}	250^{a}	251^{a}
		10	254^{ab}	254^{ab}	253^{ab}	253^{ab}	260^{ab}	260^{ab}	259^{ab}	259^{ab}
		20	260^{bc}	260^{bc}	259^{bc}	259^{bc}	268^{bc}	268^{bc}	267^{bc}	267^{abc}
		30	267^{cd}	267^{cd}	266^{cd}	266^{cd}	275^{bcd}	275^{bcd}	273^{bcd}	273^{bcd}
		40	272^{cd}	272^{cd}	271^{cd}	271^{cd}	281^{cd}	280^{cd}	279^{cd}	279^{cd}
		50	277^{d}	277^{d}	276^{d}	276^{d}	286^{d}	286^{d}	285^{d}	285^{d}

* Values followed by the same letters are not significantly different (α=0.05).

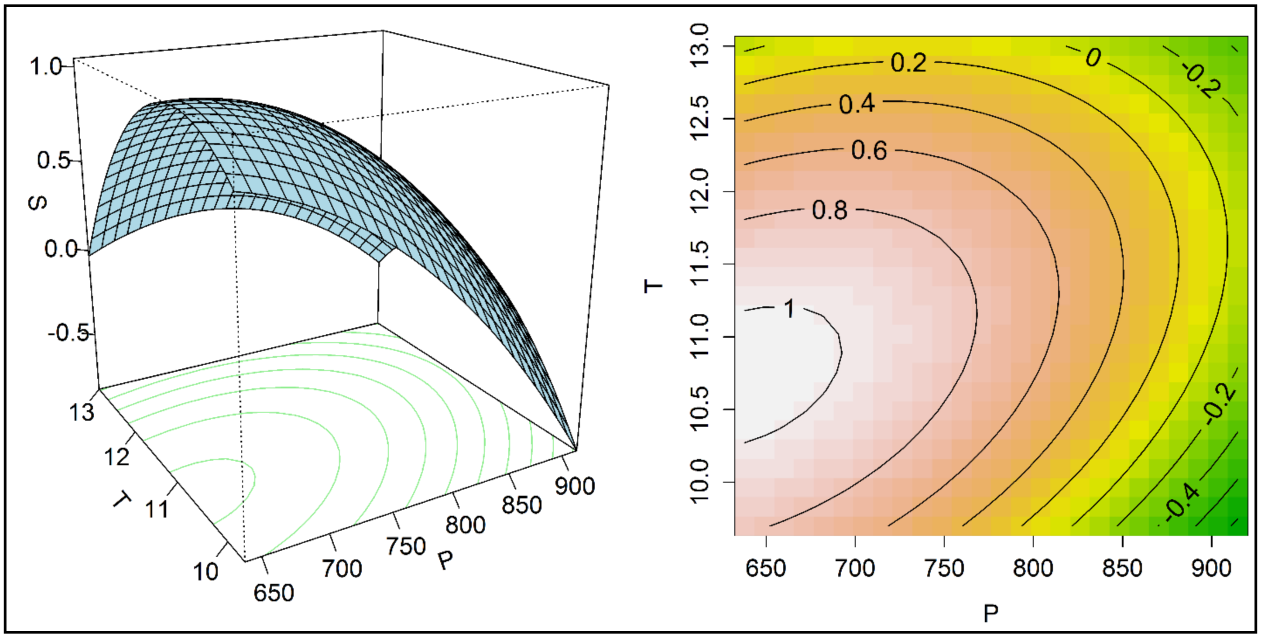

Figure S1. Net return per cow over milk production sensitivity index of Perennial ryegrass and white clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

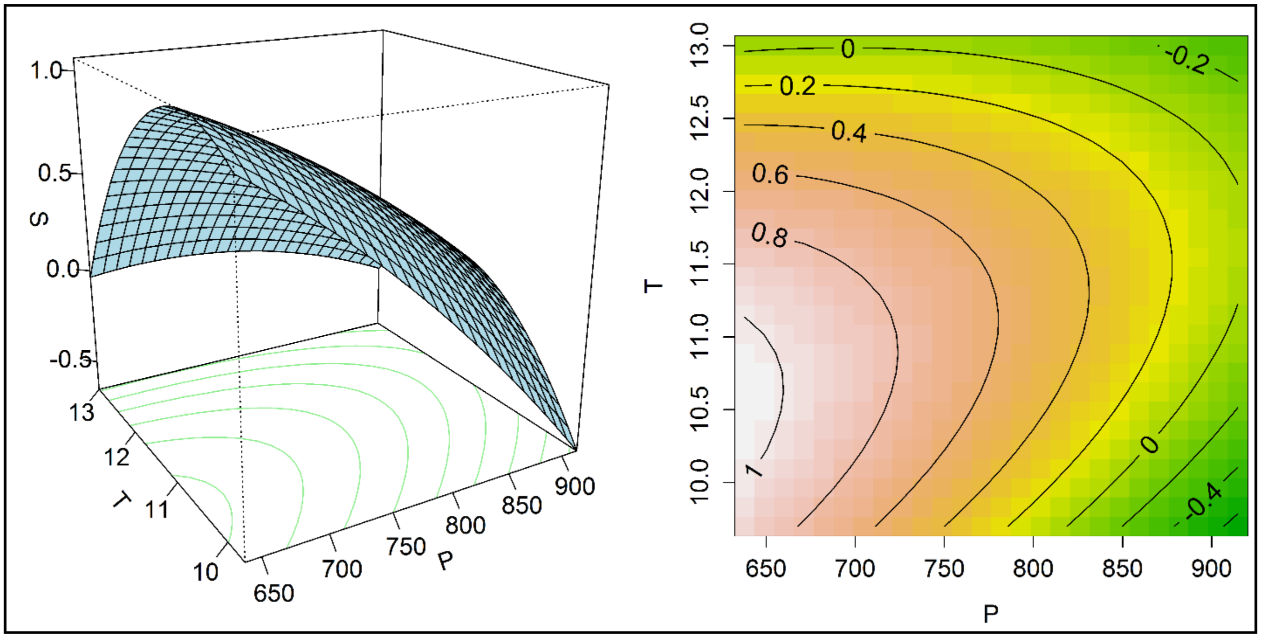

Figure S2. Net return per cow over milk production sensitivity index of Tall Fescue and red clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

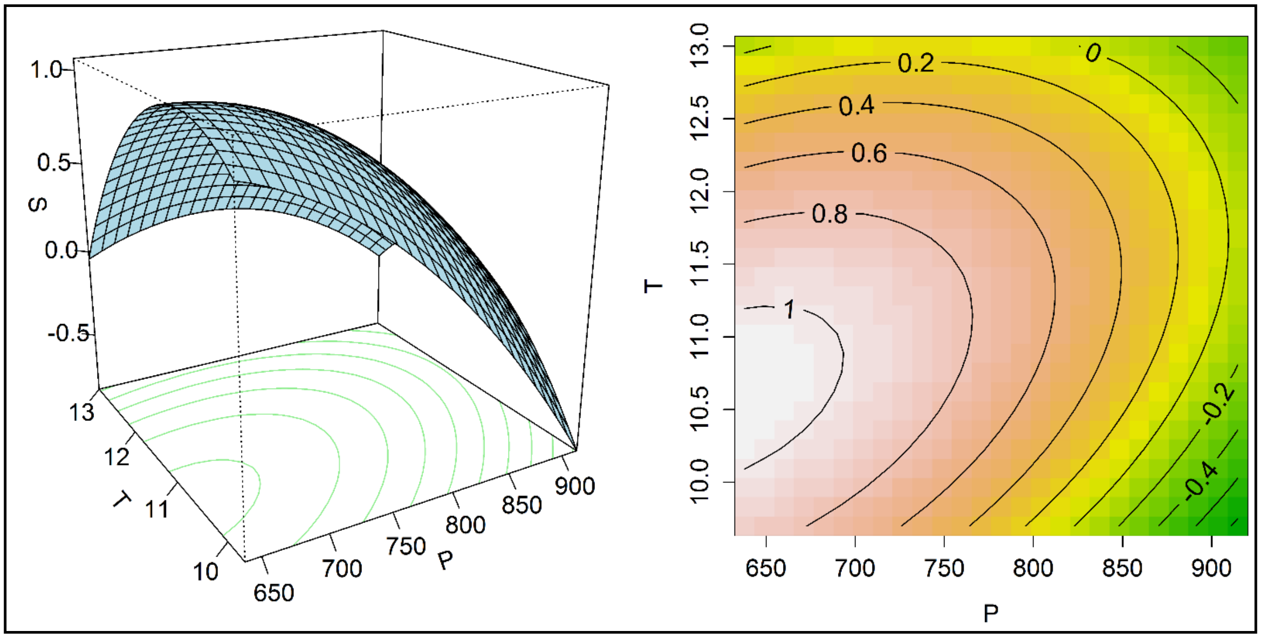

Figure S3. Net return per cow over milk production sensitivity index of Tall Fescue and white clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

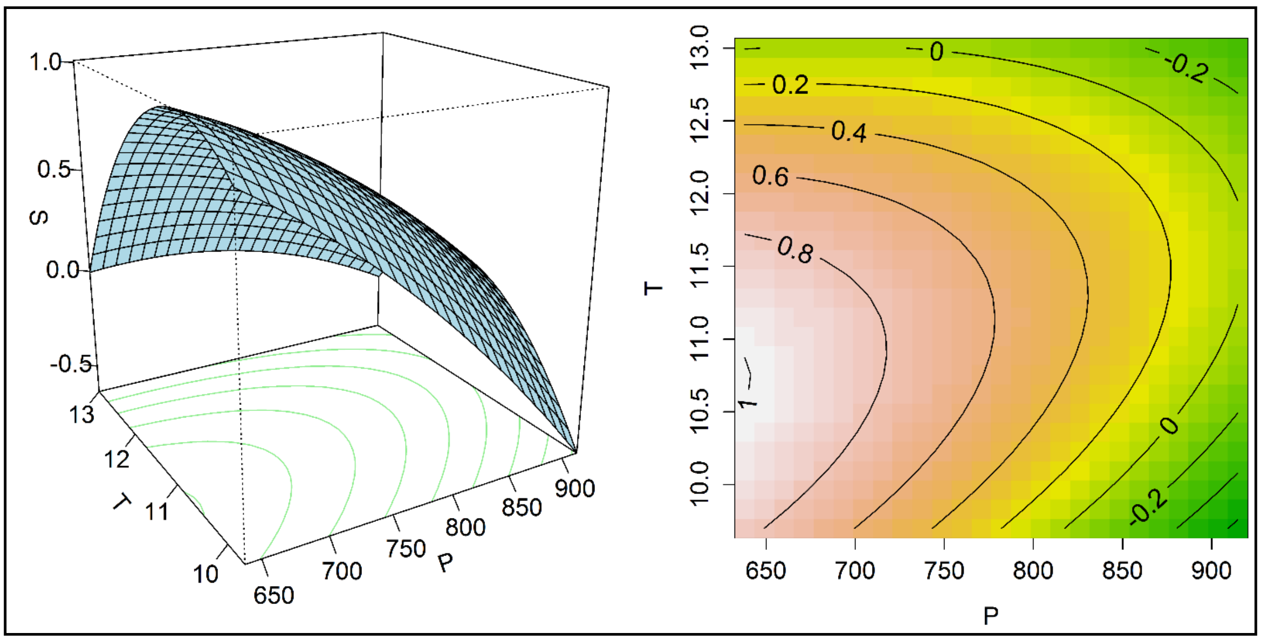

Figure S4. Net return per cow over milk production sensitivity index of Kentucky bluegrass and red clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

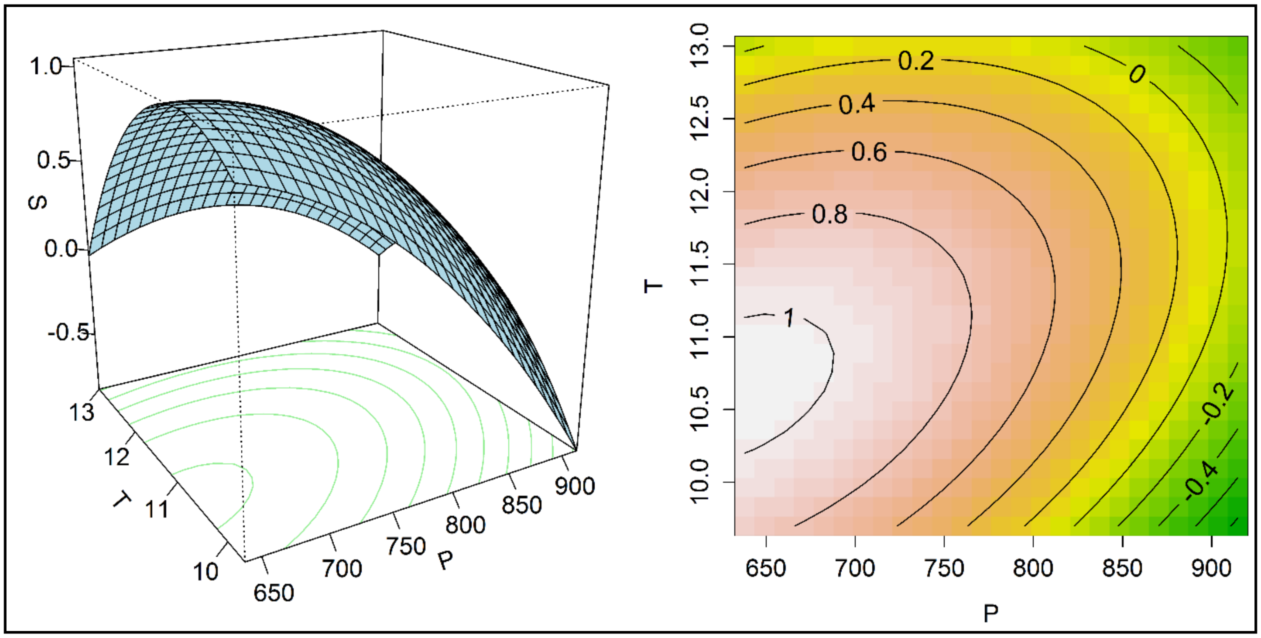

Figure S5. Net return per cow over milk production sensitivity index of Kentucky bluegrass and white clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

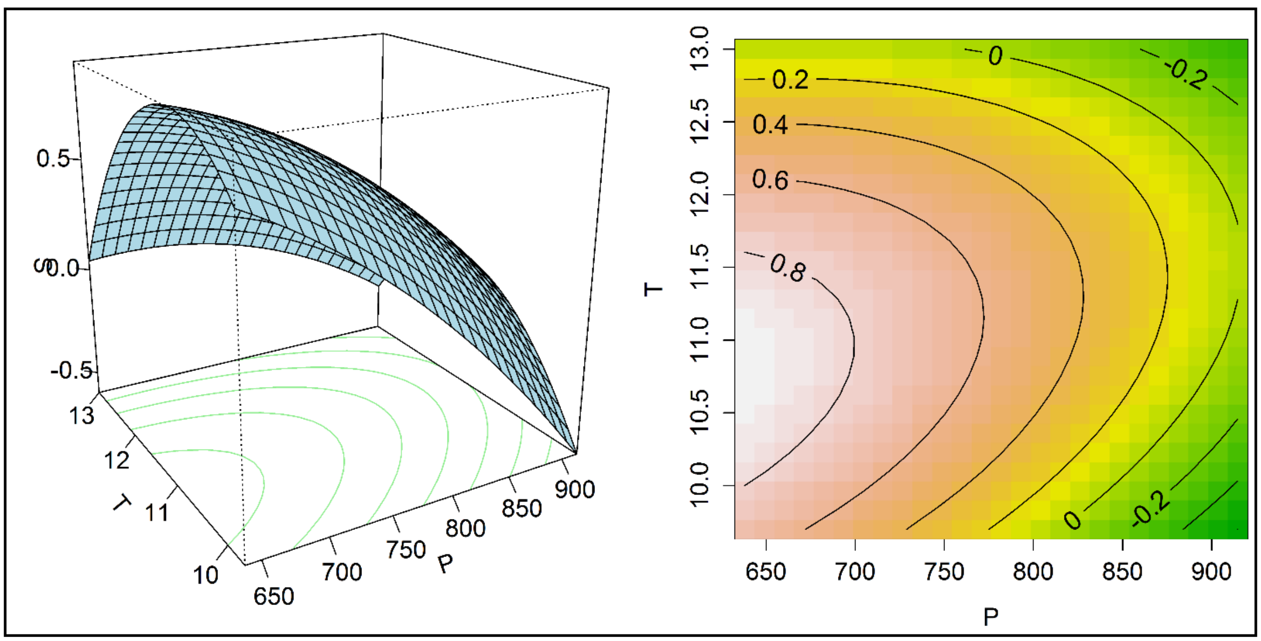

Figure S6. Net return per cow over milk production sensitivity index of Orchardgrass and red clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

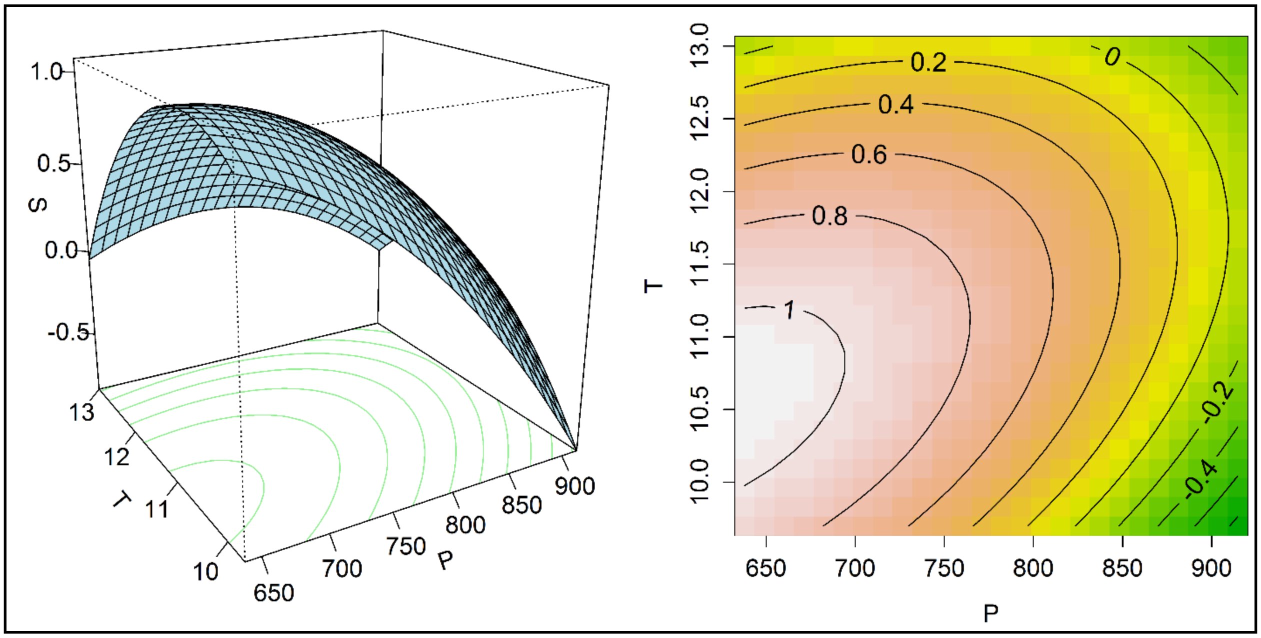

Figure S7. Net return per cow over milk production sensitivity index of Orchardgrass and white clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

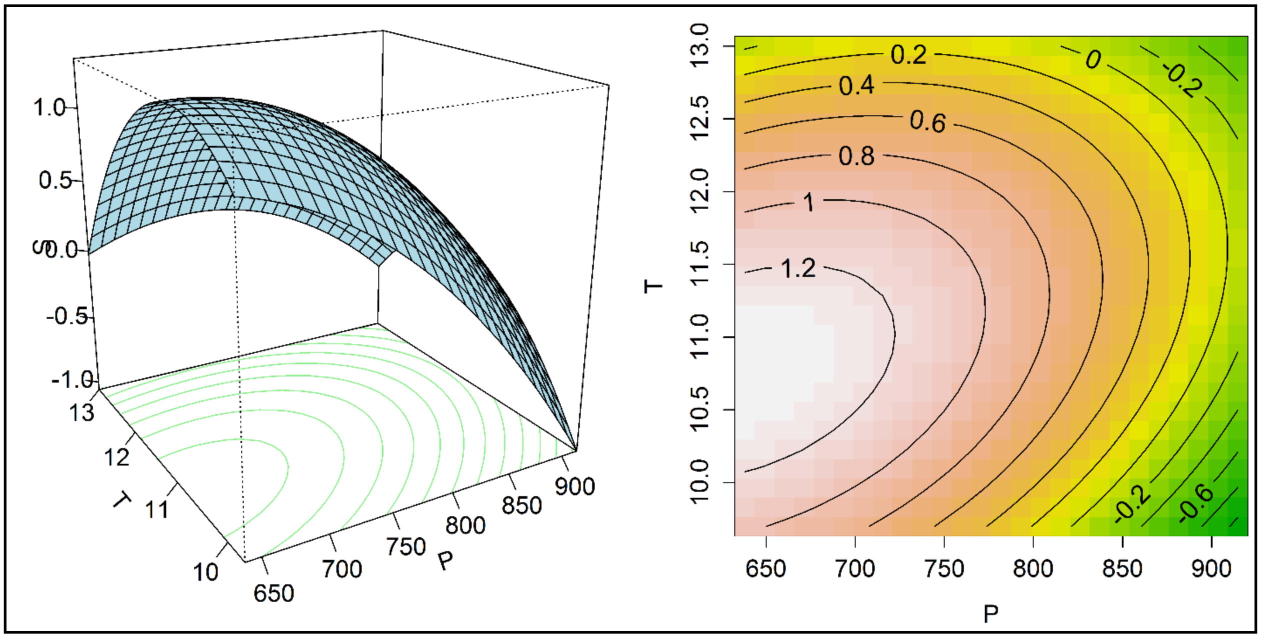

Figure S8. Whole farm profit sensitivity index of Perennial ryegrass and white clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

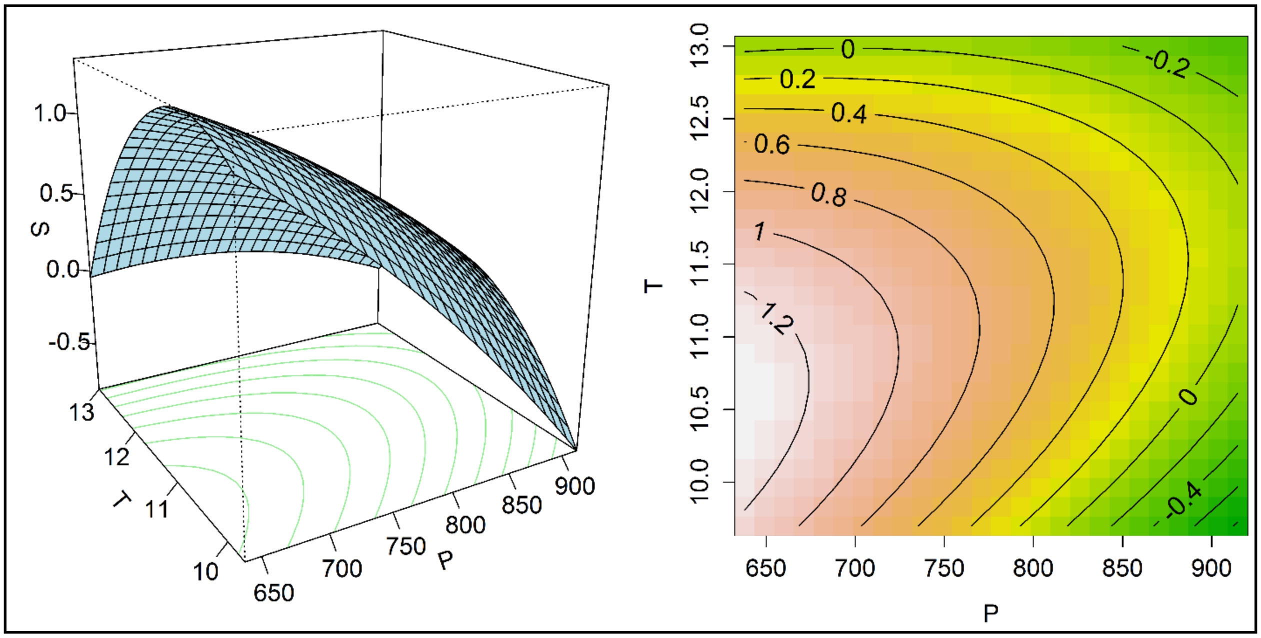

Figure S9. Whole farm profit sensitivity index of Tall Fescue and red clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

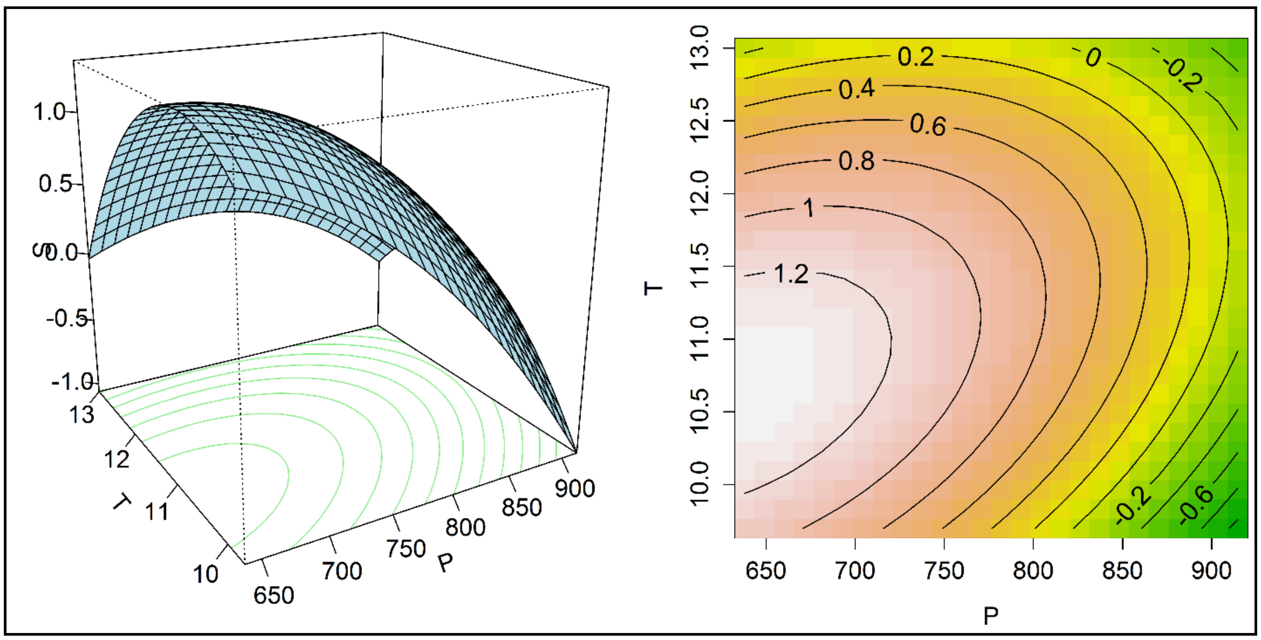

Figure S10. Whole farm profit sensitivity index of Tall Fescue and white clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

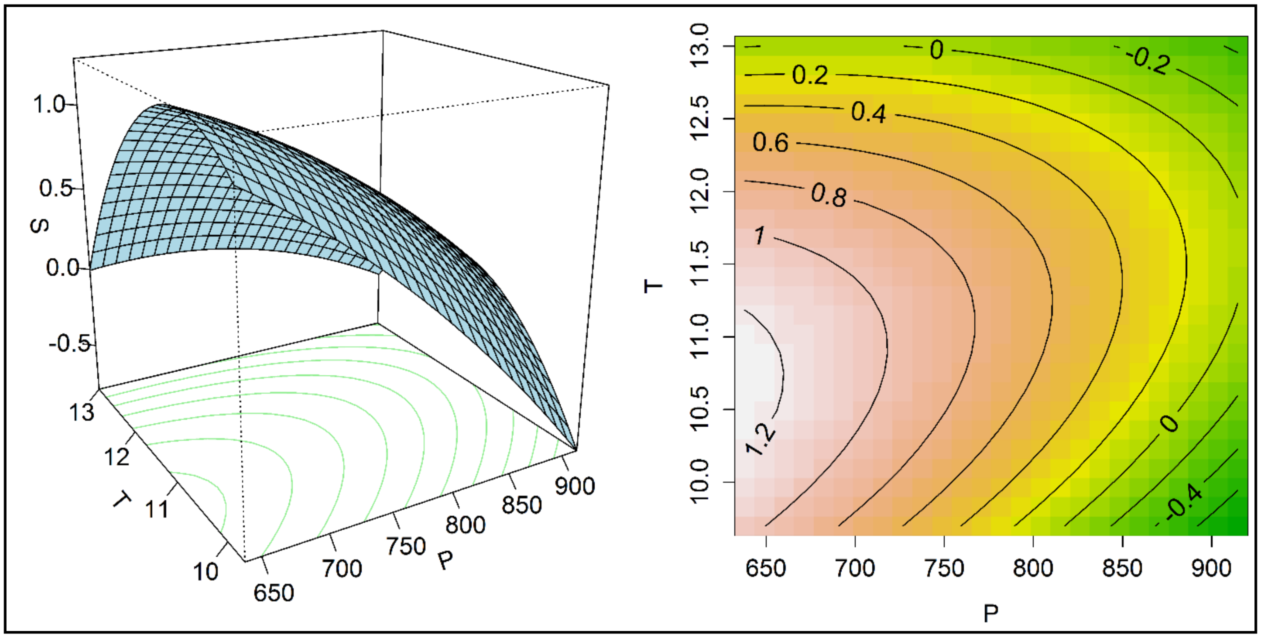

Figure S11. Whole farm profit sensitivity index of Kentucky bluegrass and red clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

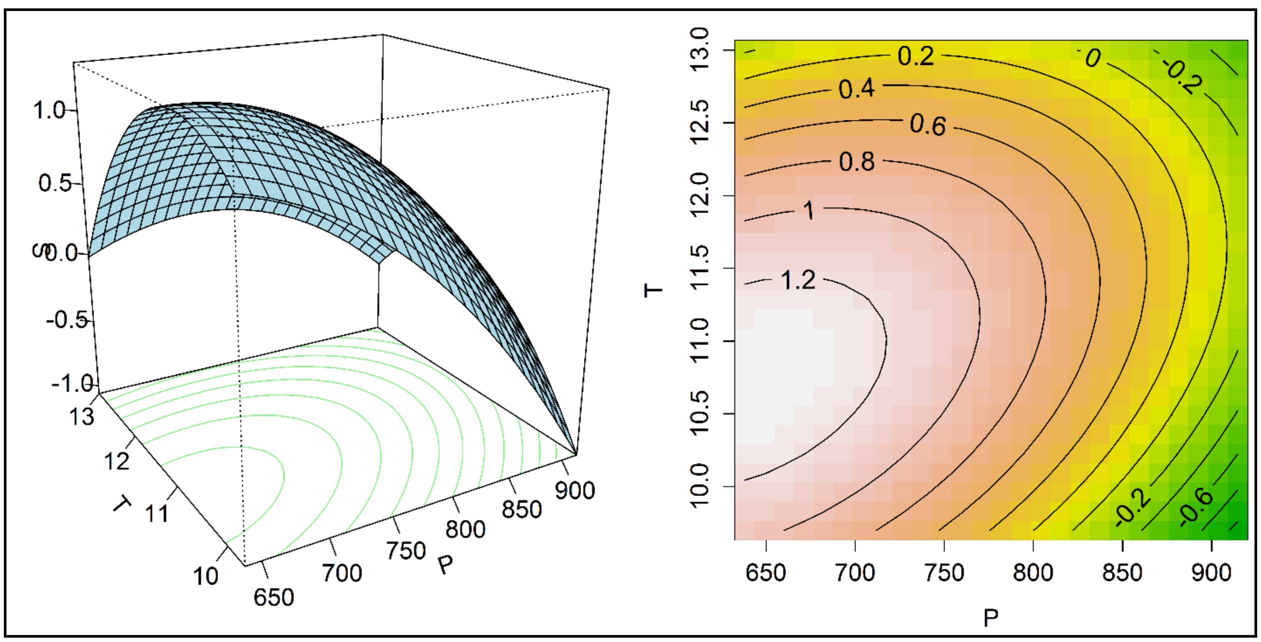

Figure S12. Whole farm profit sensitivity index of Kentucky bluegrass and white clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

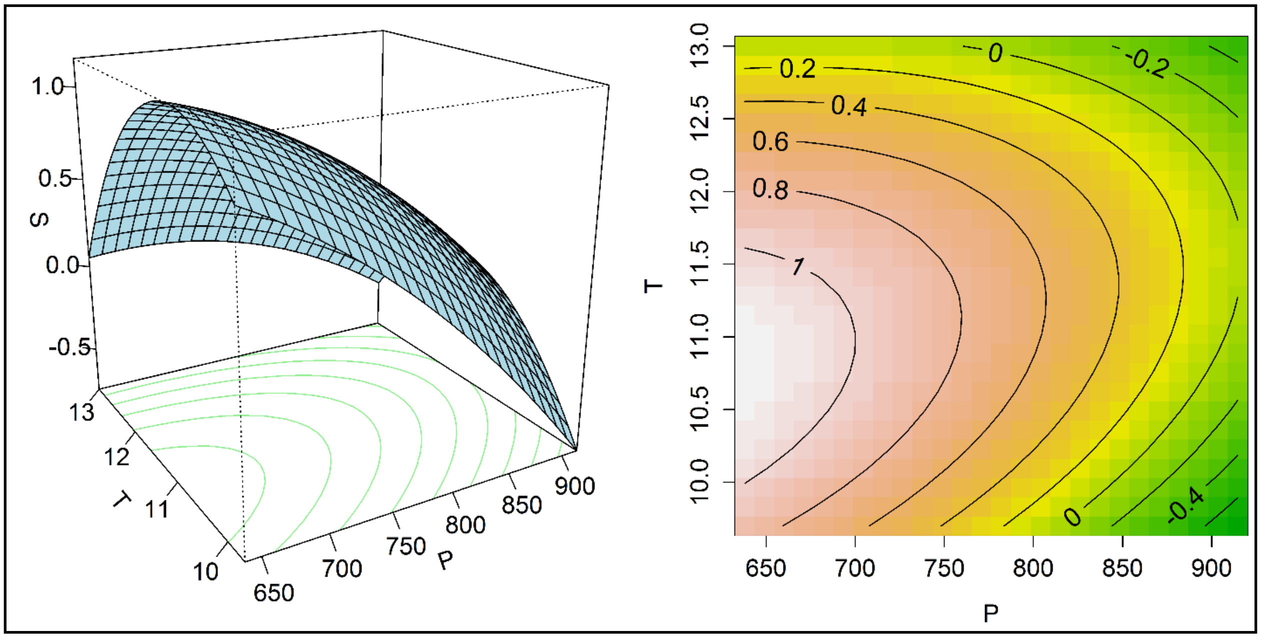

Figure S13. Whole farm profit sensitivity index of Orchardgrass and red clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

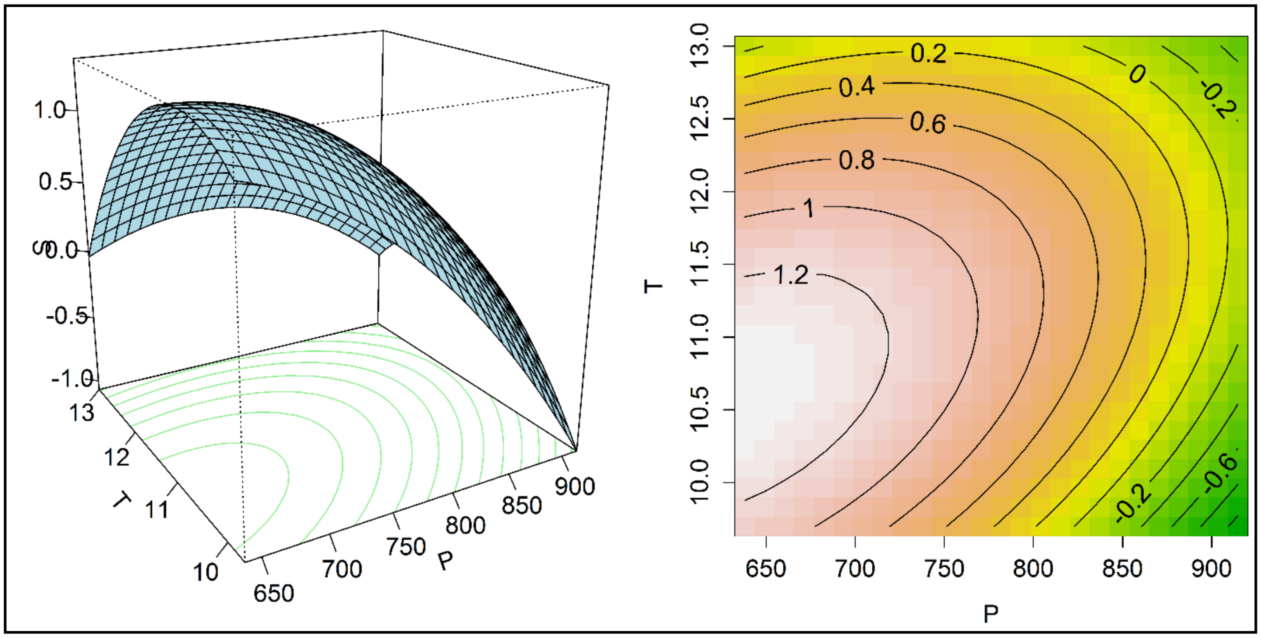

Figure S14. Whole farm profit sensitivity index of Orchardgrass and white clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

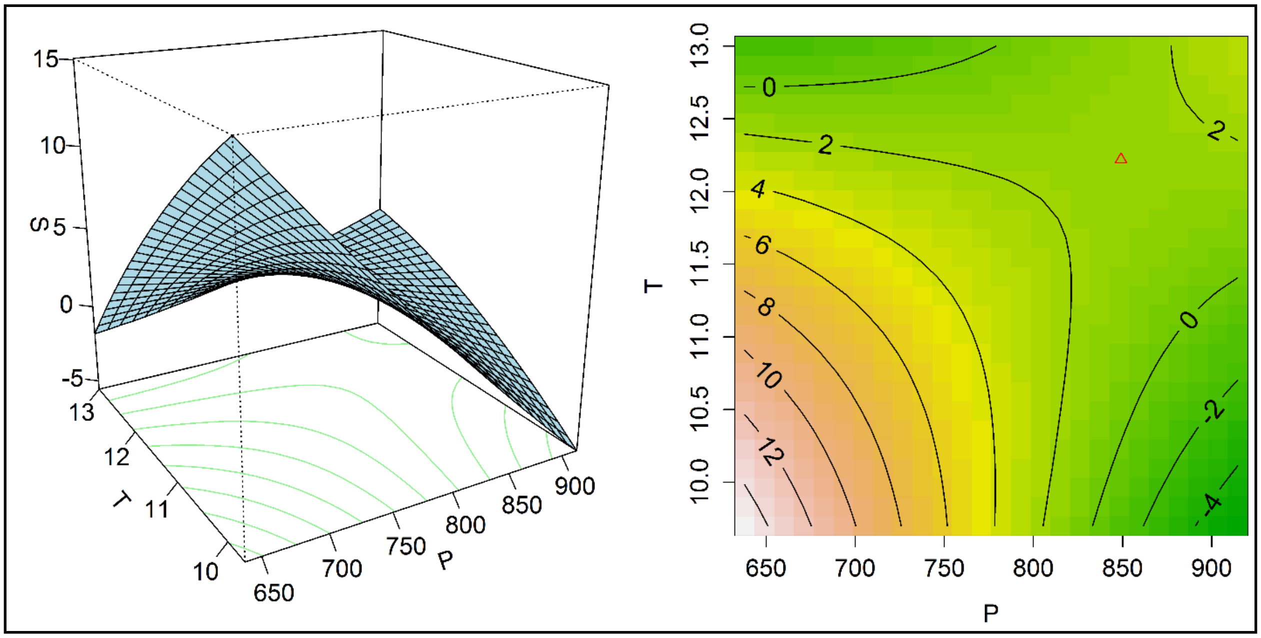

Figure S15. Grazed forage consumed sensitivity index of Perennial ryegrass and white clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

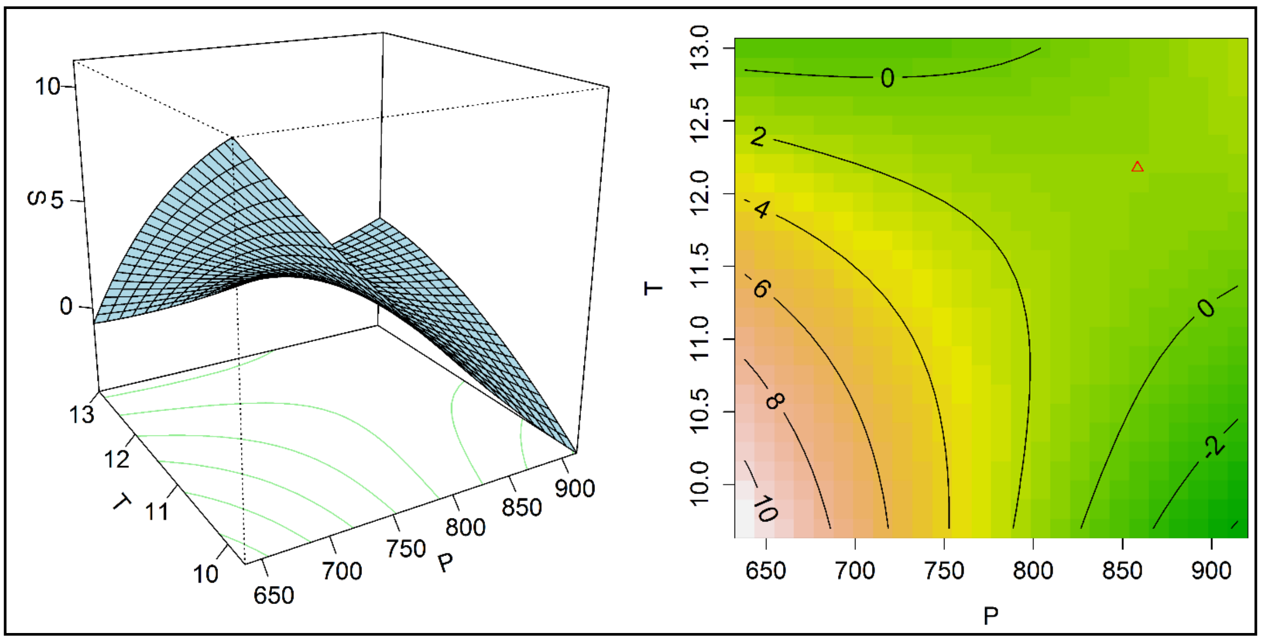

Figure S16. Grazed forage consumed sensitivity index of Tall Fescue and red clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

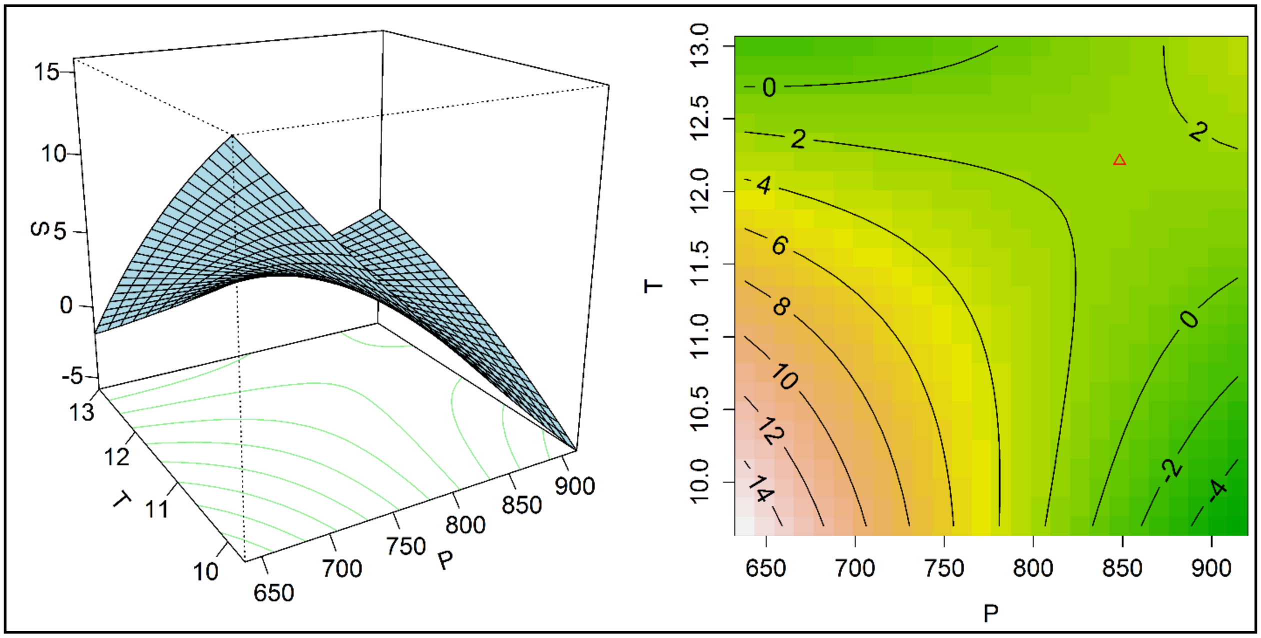

Figure S17. Grazed forage consumed sensitivity index of Tall Fescue and white clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

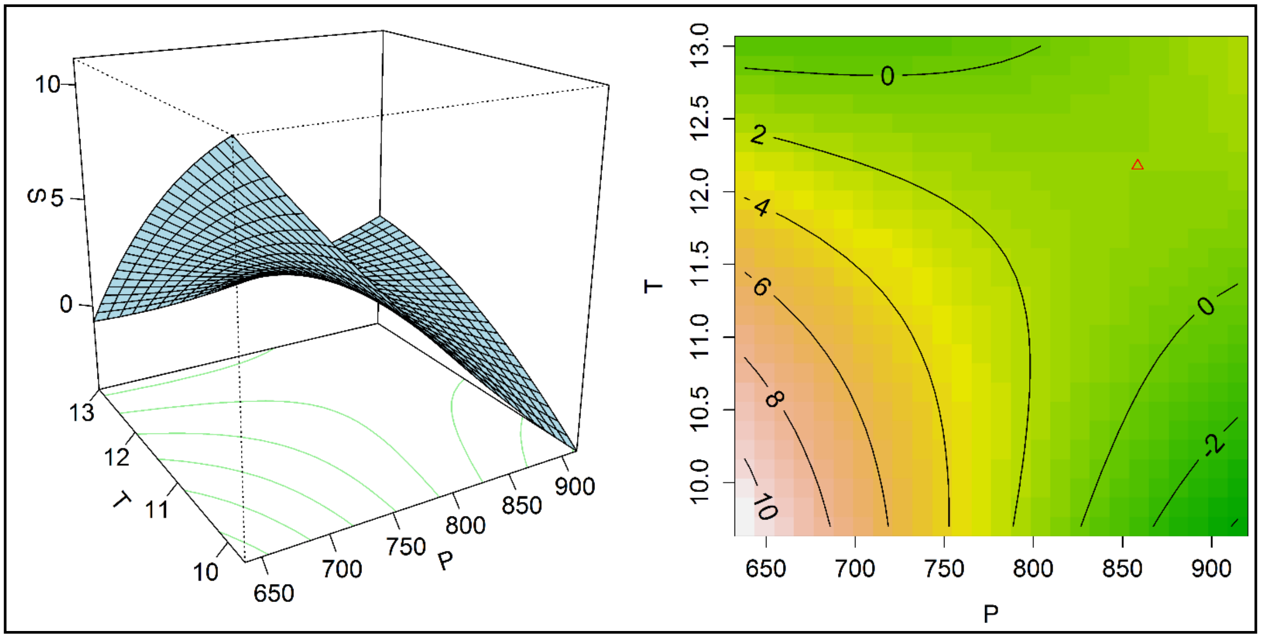

Figure S18. Grazed forage consumed sensitivity index of Kentucky bluegrass and red clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

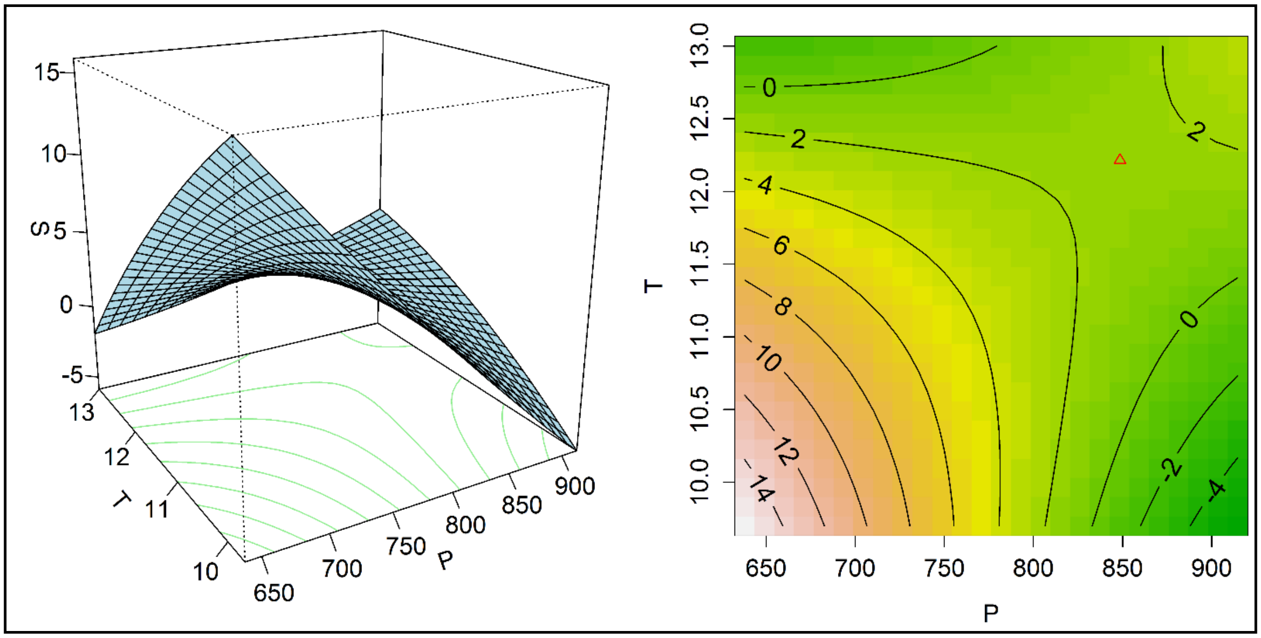

Figure S19. Grazed forage consumed sensitivity index of Kentucky bluegrass and white clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

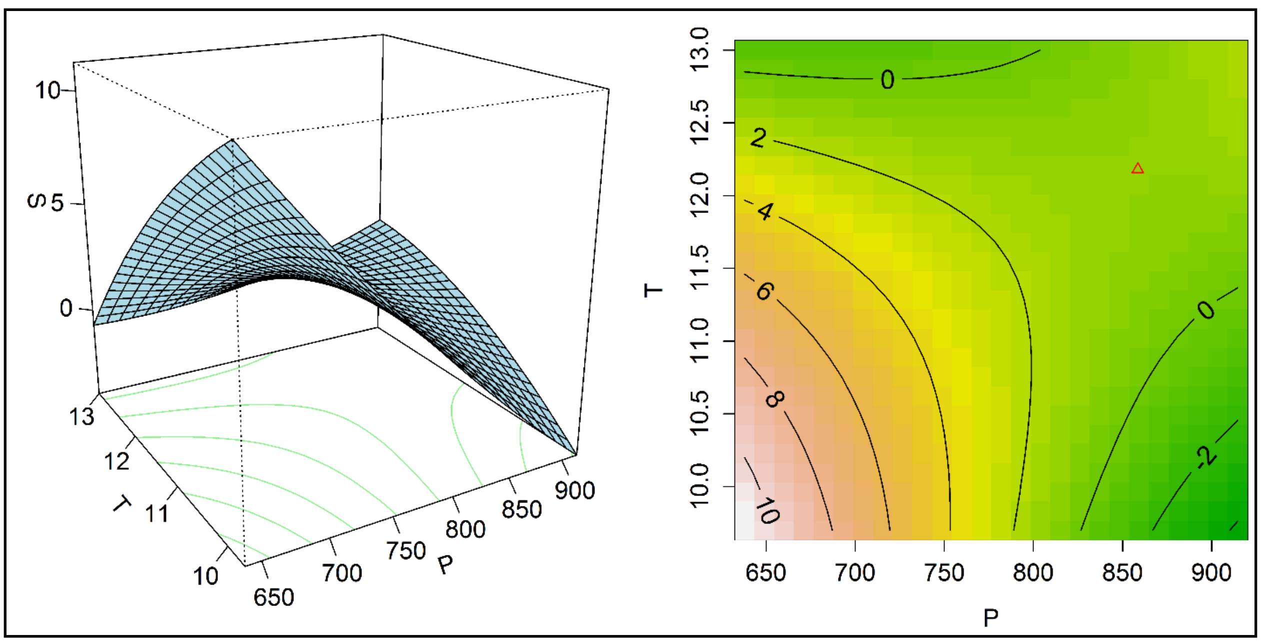

Figure S20. Grazed forage consumed sensitivity index of Orchardgrass and red clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

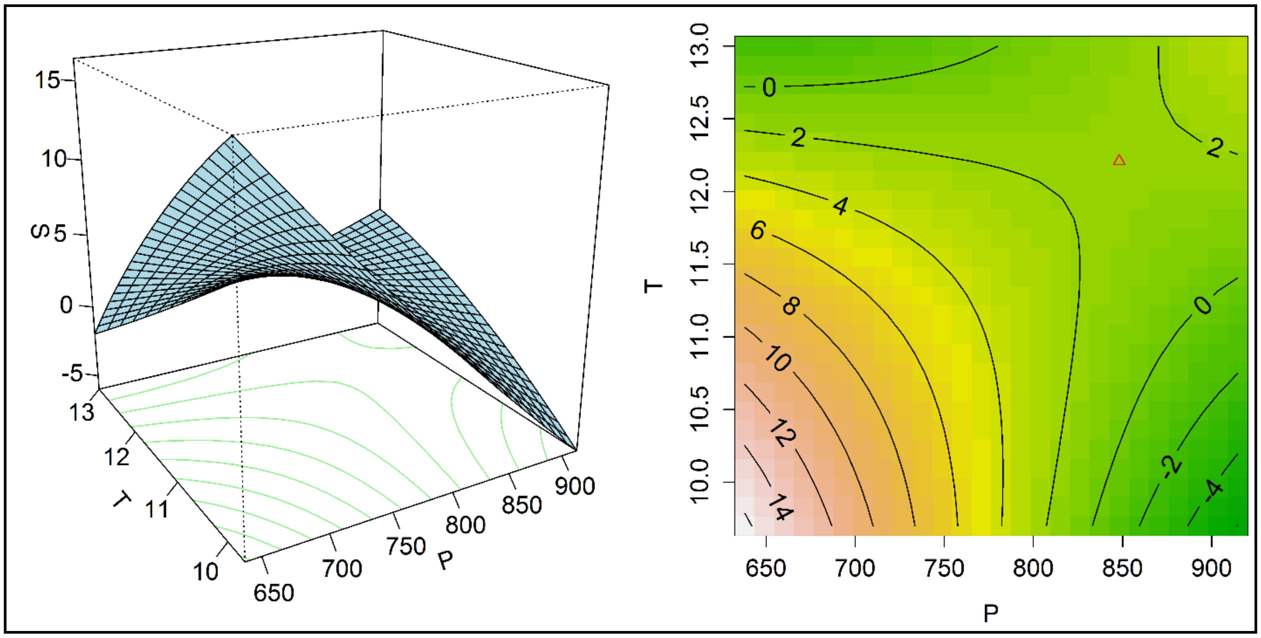

Figure S21. Grazed forage consumed sensitivity index of Orchardgrass and white clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

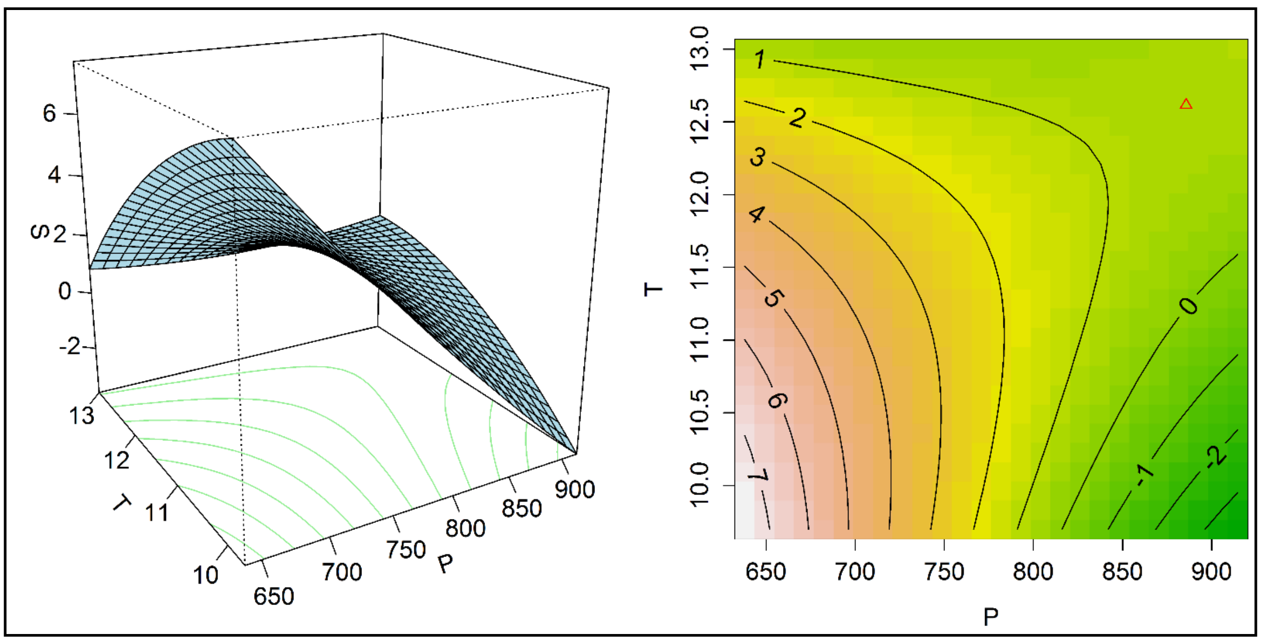

Figure S22. Harvested forage produced sensitivity index of Perennial ryegrass and white clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

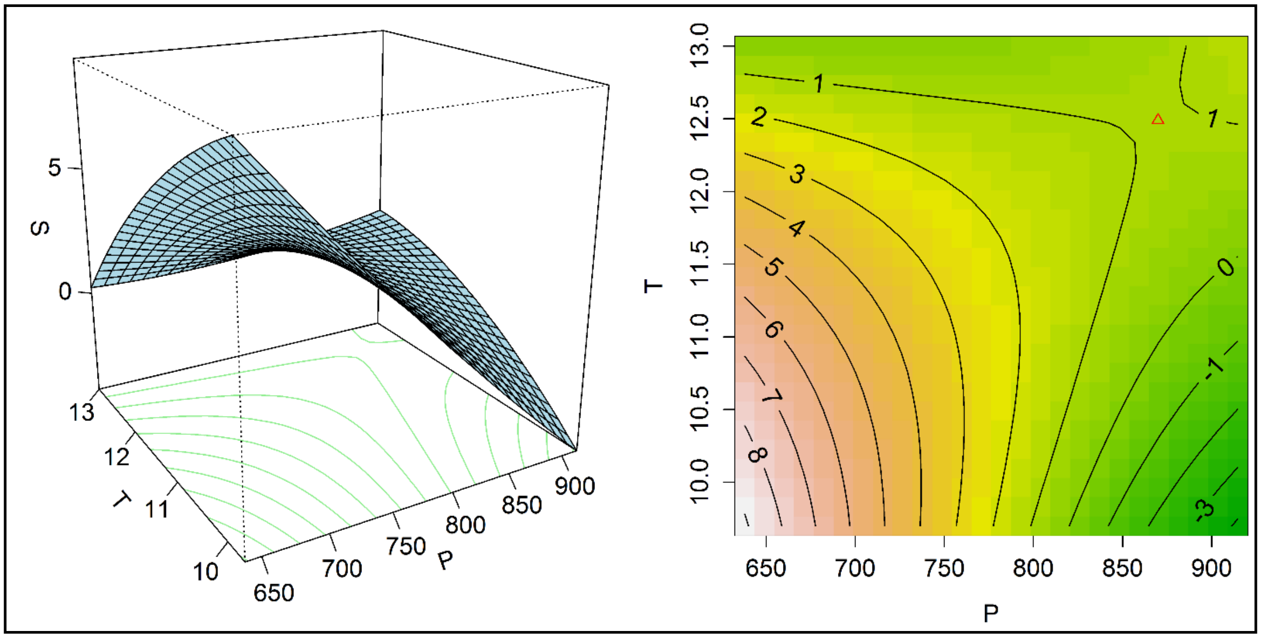

Figure S23. Harvested forage produced sensitivity index of Tall Fescue and red clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

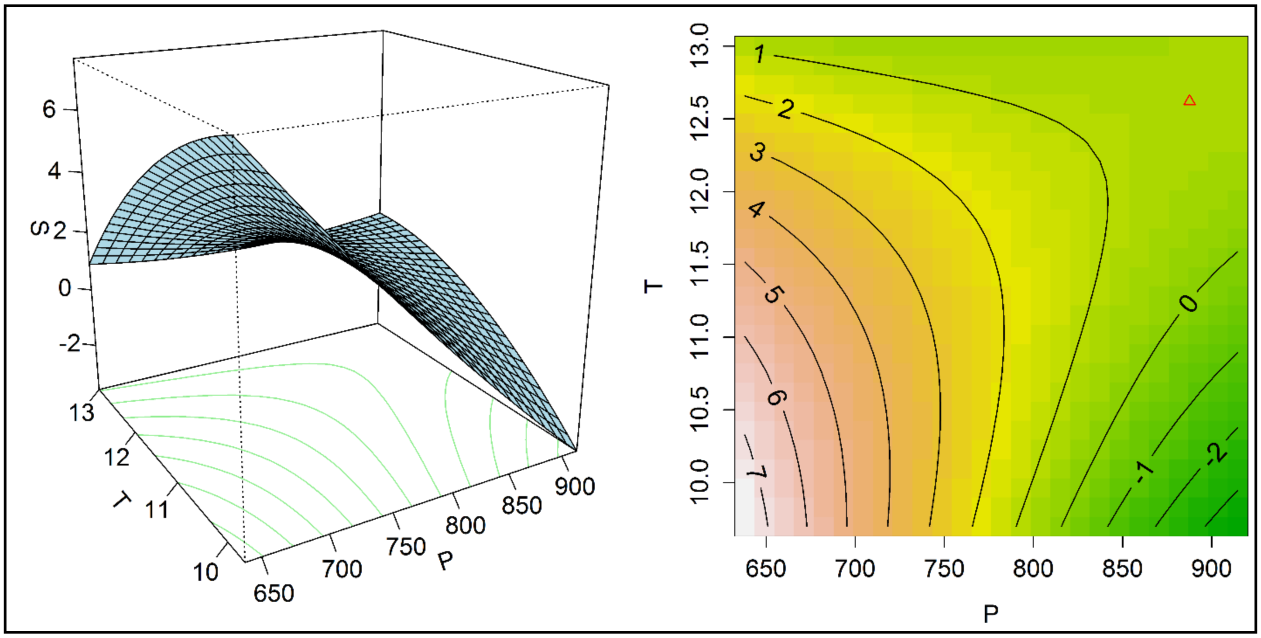

Figure S24. Harvested forage produced sensitivity index of Tall Fescue and white clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

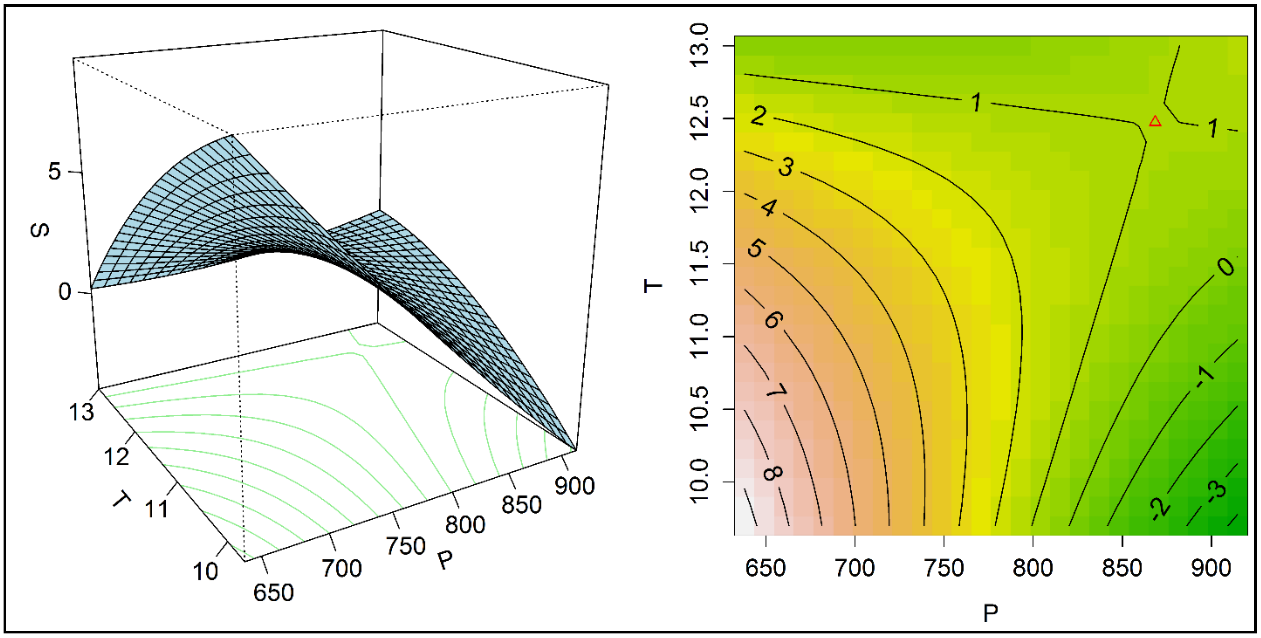

Figure S25. Harvested forage produced sensitivity index of Kentucky bluegrass and red clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

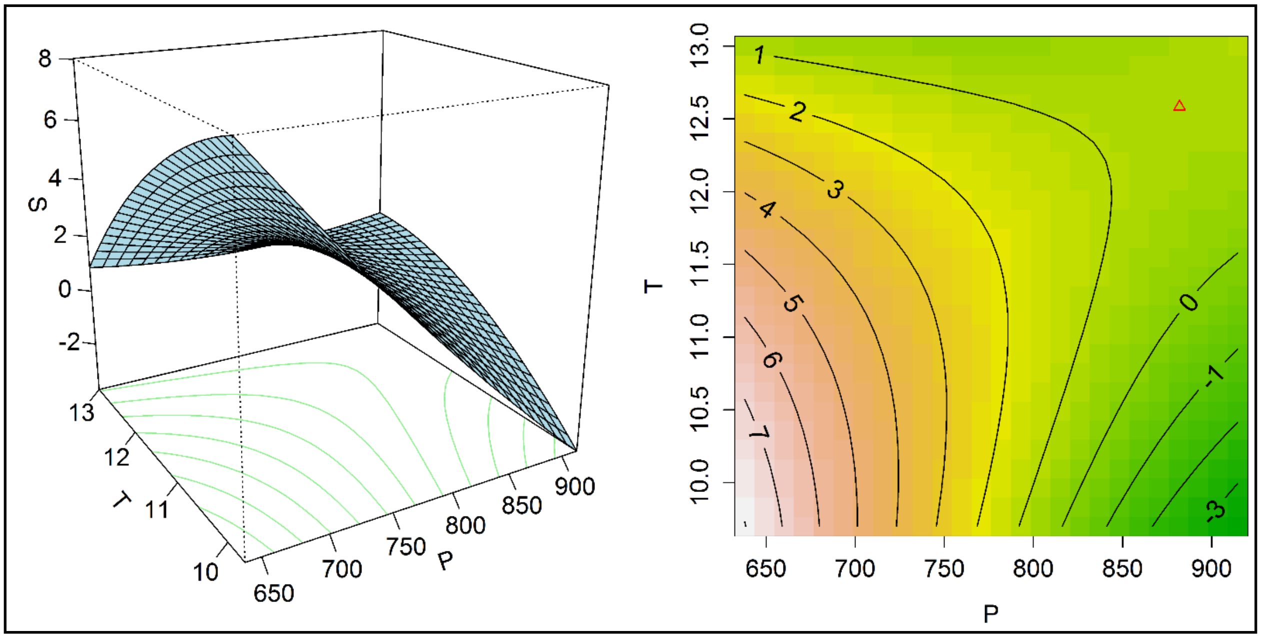

Figure S26. Harvested forage produced sensitivity index of Kentucky bluegrass and white clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

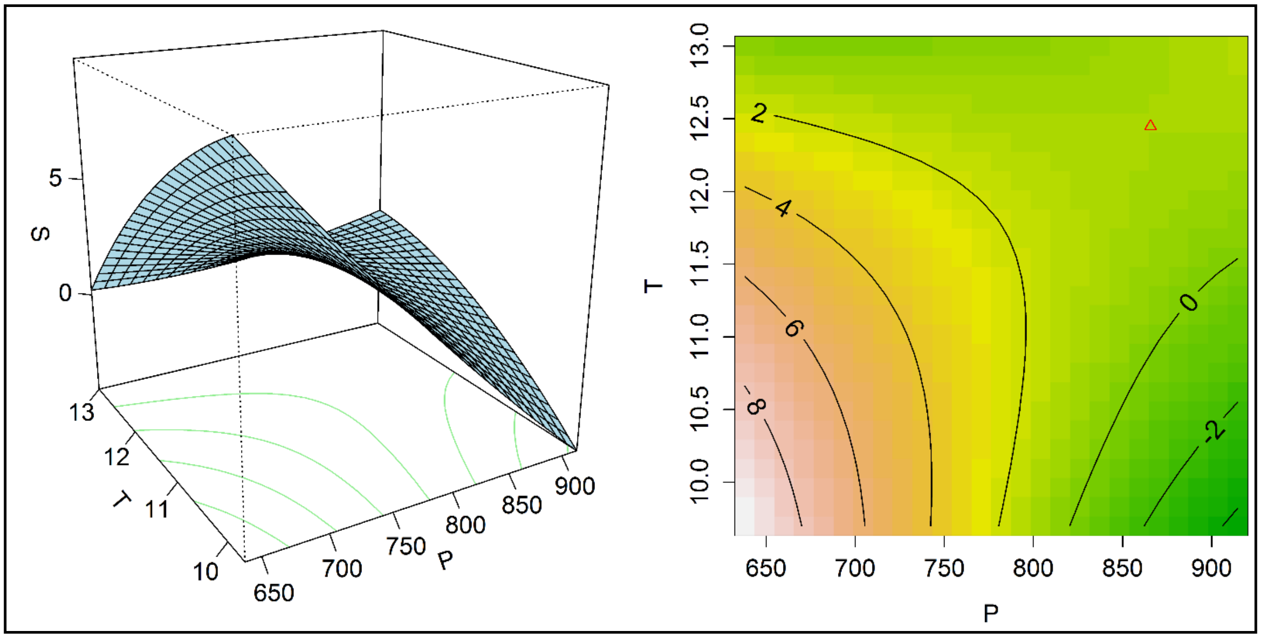

Figure S27. Harvested forage produced sensitivity index of Orchardgrass and red clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

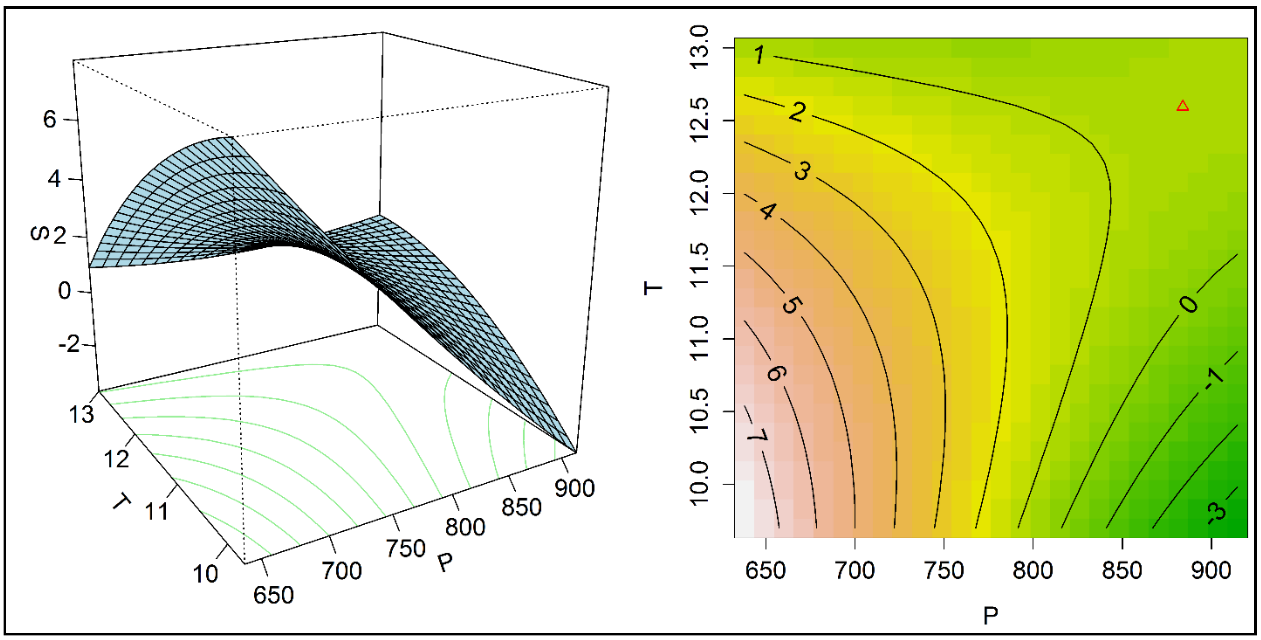

Figure S28. Harvested forage produced sensitivity index of Orchardgrass and white clover pasture composition. P= precipitation (mm), T= temperature (ºC), S= sensitivity index

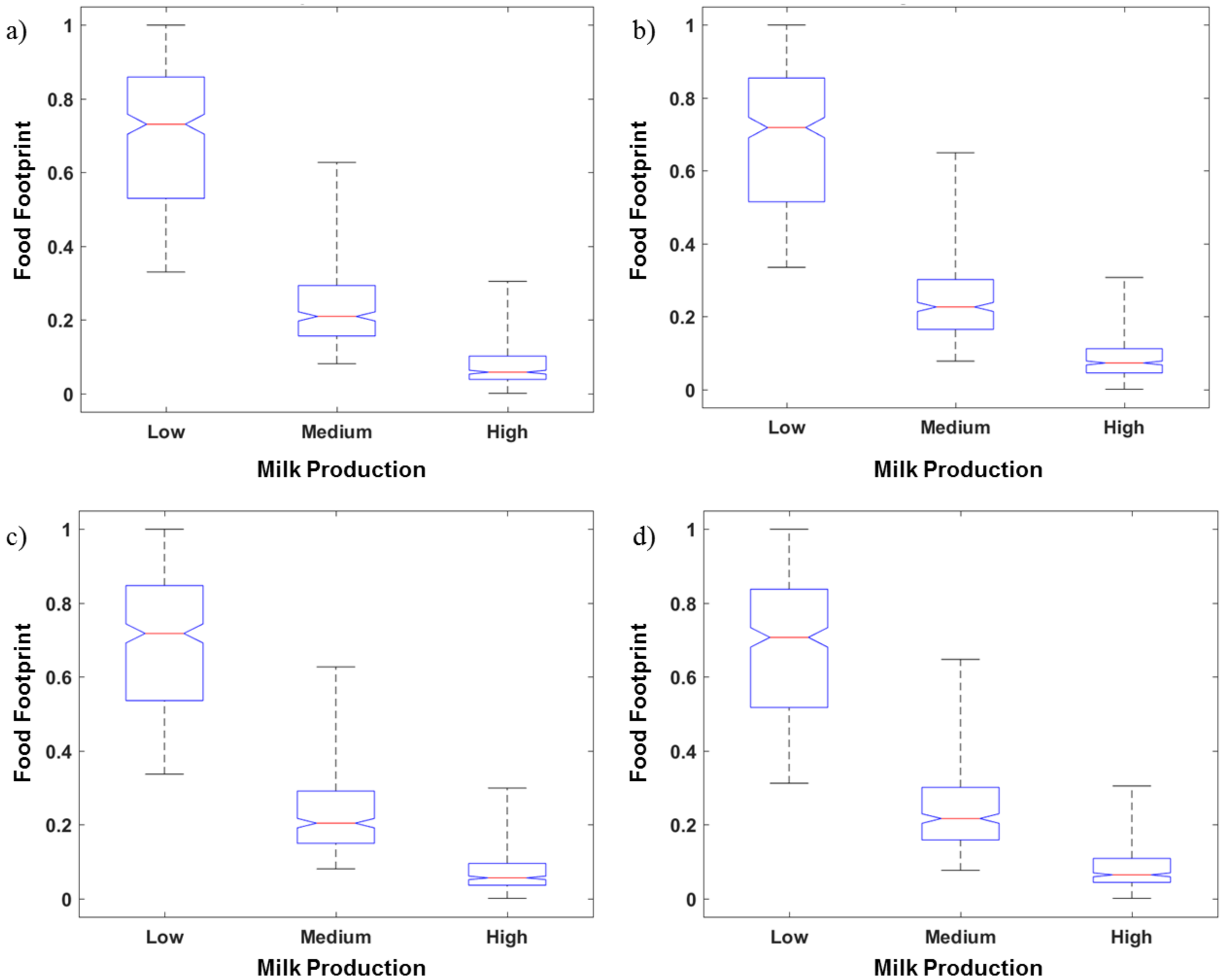

Figure S29. Food footprint for different combinations of white clover with a) Kentucky bluegrass, b) orchardgrass, c) perennial ryegrass, and d) tall fescue for low (1,361 to 3,629 kg/cow/year), medium (4,082 to 5,897 kg/cow/year), and high (6,350 to 8,618 kg/cow/year) milk production

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