



# Food Footprint as a Measure of Sustainability for Grazing Dairy Farms

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## Abstract

Livestock productions require significant resources allocation in the form of land, water, energy, air, and capital. Meanwhile, owing to increase in the global demand for livestock products, it is wise to consider sustainable livestock practices. In the past few decades, footprints have emerged as indicators for sustainability assessment. In this study, we are introducing a new footprint measure to assess sustainability of a grazing dairy farm while considering carbon, water, energy, and economic impacts of milk production. To achieve this goal, a representative farm was developed based on grazing dairy practices surveys in the State of Michigan, USA. This information was incorporated into the Integrated Farm System Model (IFSM) to estimate the farm carbon, water, energy, and economic impacts and associated footprints for ten different regions in Michigan. A multi-criterion decision-making method called VIKOR was used to determine the overall impacts of the representative farms. This new measure is called the food footprint. Using this new indicator, the most sustainable milk production level (8618 kg/cow/year) was identified that is 19.4% higher than the average milk production (7215 kg/cow/year) in the area of interest. In addition, the most sustainable pasture composition was identified as 90% tall fescue with 10% white clover. The methodology introduced here 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.

**Keywords** Grazing dairy farm · Sustainable · Footprint · Multi-criterion decision-making · IFSM · VIKOR

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## Introduction

Anthropogenic greenhouse gas (GHG) emissions are the dominant cause of the global warming (IPCC 2014). Among anthropogenic activities, livestock production plays a major role by contributing 14.5% of global anthropogenic GHG emissions. In addition, the livestock sector negatively affects the environment through land degradation, water pollution, water shortage, and biodiversity destruction (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).

Sustainability, in general terms, refers to the ability to progress by meeting the needs of the present while considering the needs of future generations (WCED 1987). Therefore, sustainability requires the balanced consideration of environmental, economic, and social components of a system (OECD 2004). Therefore, farm sustainability is usually evaluated using whole-farm models such as the

Integrated Farm System Model (IFSM), SIMSDairy, and DairyWise (Del Prado et al. 2011; Schils et al. 2007; Rotz 2004) in which the interactions among farm management and the surrounding environment are considered. In addition, the overall farm sustainability can be measured by indicators known as sustainability measures such as sustainable intensification and footprints. Sustainable intensification comprises of both environmental (productivity and environment) and non-environmental (economic, human condition, and social domains) elements (Musumba et al. 2017). The sustainable intensification system is built based on the framework introduced by Olsson et al. (2009) in which indicators are classified at any scale in a balanced manner. Meanwhile, footprints are usually calculated through life cycle assessment (LCA) techniques (Čuček et al. 2012). Footprint refers to the quantitative measurement of the human activities' burdens on sustainability (Hoekstra 2008). Each type of footprint has its own definition, units of measurement, and tools for 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 global dairy farming sustainability. However, using a single footprint is not always the right approach for measuring overall sustainability, especially for the area of food production (Finkbeiner 2009). For example, Dyer et al. (2014) performed an LCA where carbon footprint along with the impacts on non-carbon footprints, such as water, energy, and diseases, were considered to measure the environmental impacts of livestock production in Canada. Vasilaki et al. (2016) also used an LCA-based water and carbon footprint to assess the environmental impact of different types of yogurt productions in a dairy plant. Most recently, Cecchini et al. (2016) also performed a sustainability analysis of dairy farms using the LCA-based carbon footprint to perform an environmental assessment. In order to select the best practice, these studies included economic assessment considering all costs associated with the production process.

The results of these studies showed that improvement in the overall sustainability outcomes can be achieved when considering inter-relationships between carbon, water, energy, and economic aspects. Therefore, a comprehensive sustainability study should consider all of these aspects at the same time. This study is unique since the combination of carbon, energy, water, and economic footprints are considered as a sustainability metric of agriculture-based production systems, such as grazing dairy farms. Here we

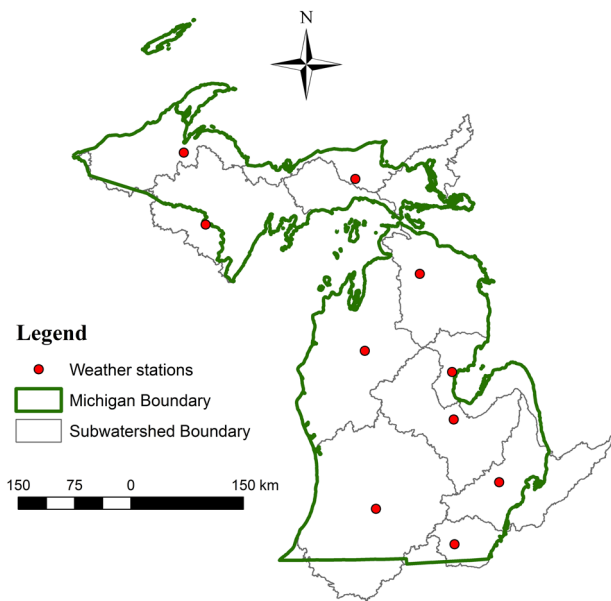
propose to use multi-criterion decision-making (MCDM) to determine the balanced options between conflicting criteria (footprints). A new measure named food footprint was introduced to indicate the overall impacts of grazing dairy farms and helps with identifying the most sustainable production systems. Using this new measure, the most sustainable pasture composition and milk production can be identified for a region of interest. The specific objectives of this study were to: (1) identify the most sustainable milk production level in different regions; (2) identify the most sustainable pasture composition in different regions; and (3) understand the spatial variability of sustainable pasture compositions and milk productions. Objectives 1 and 2 try to improve individual goals (e.g., milk production or pasture composition) while objective 3 will highlight the importance of considering combined goals to achieve the best overall outcome. We hypothesized that considering a single goal for decision-making can be misleading when the problem at hand has multiple dimensions.

## Materials and Methods

### Study Area

The United States is the number one cows' milk producer in the world, producing on average about 91 billion kilograms of liquid milk annually (FAO 2016). Meanwhile, the state of Michigan is one of the top five milk-producing states in the USA which is why the state has been considered for this study (USDA 2014). 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 based on major watershed boundaries. This approach is aligned with the natural division of the land surface as influenced by geology and climate factors. The U.S. Geological Survey used a national standard hierarchical system based on surface hydrologic features to delineate the watersheds in the United States and classify them into hydrologic unit codes (HUC) (USGS 2017). For this study, the six-digit HUC was used, which divides the entire state of Michigan into ten different watersheds (Fig. 1). Data from a weather station located close to the centroid of the watershed was used to represent the average climatological condition (Viessman and Lewis 2003).

Twenty years of daily weather data for the period of 1985–2005 was obtained from the National Climatic Data Center. The average maximum temperature, minimum temperature, and precipitation for each watershed range



**Fig. 1** State of Michigan and its watershed boundaries

**Table 1** 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

from 10.6 to 15.3 °C, −1.5 to 4.0 °C, and 757.3 mm to 904.8 mm, respectively, within the study area (Table 1).

Besides daily temperature and precipitation, solar radiation was also required for farm system modeling, which was obtained using a stochastic weather generator, WXGEN (Sharpley and Williams 1990; Wallis and Griffiths 1995).

### Modeling Process

The modeling process involves data processing, performing model simulations, and footprint analysis to identify the most sustainable milk production and pasture composition

for each region within the study area (Fig. 2). Under the data processing, typical farm management, size, pasture compositions, yield, and target milk productions were collected through a survey from producers and extension specialists within the study area. However, for cases that the actual data could not be obtained from the farm survey (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. Next, long-term (20 years) weather data for each region were obtained to understand the climate variabilities. In addition, 48 pasture composition and 32 target milk production levels were identified. The aforementioned information provided the inputs to the IFSM in order to simulate a representative grazing dairy farm, which was defined as the system boundary. The results from IFSM simulations were also checked with extension specialists to confirm the model robustness. 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. An MCDM 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, which is a new sustainability measure that represents 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 pasture composition of each region was identified. More details regarding each of the modeling processes are provided as follows.

### Data Processing

**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 comprised of 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. A summary of the key survey data collected is provided in Table 2. 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

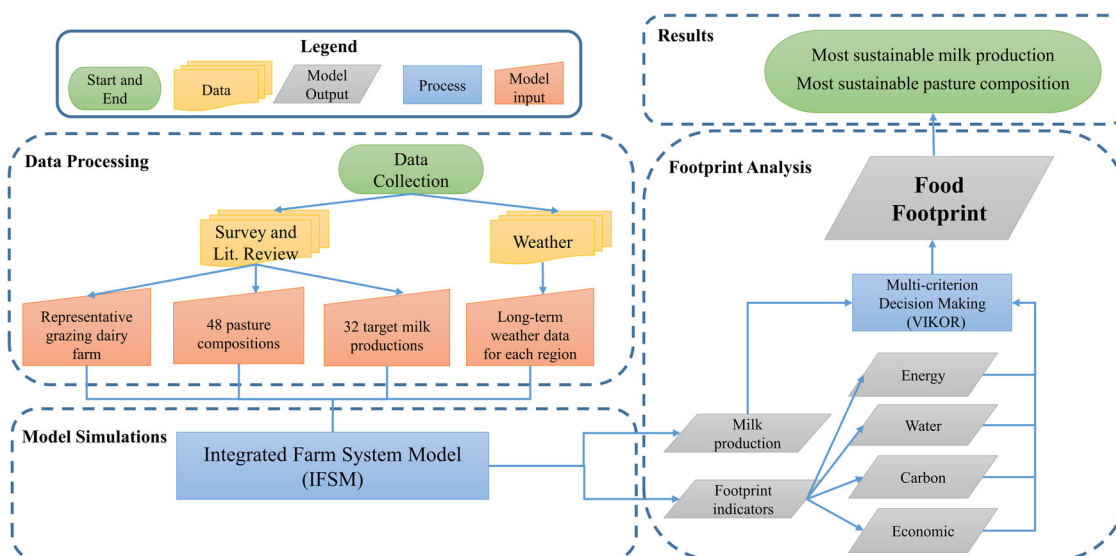


Fig. 2 The conceptual framework of the modeling process

farm data is provided in Table 3 along with published agricultural statistics in Supplementary Materials (Tables 4 and 5). 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 6).

**Selection of Pasture Composition** 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 weather (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.

Owing 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 (*Festuca arundinacea*). 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).

The pasture composition affects the nutritive content of the forage. The IFSM can simulate different nutritive contents, including crude protein, protein degradability, acid detergent insoluble protein, net energy for lactation, neutral detergent fiber, phosphorus, and potassium. The model assigns different values for nutritive content that varies during the grazing season to different pasture species.

**Selection of Target Milk Production Level** 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 are 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 amounts of milk, butterfat, and protein (EPA 2015). However, producers with grazing systems prefer small-framed over large-framed cattle because they are more efficient in converting grass to milk (Flanders and Gillespie 2015).

Based on the farm surveys, the target milk production level ranges between 6804 and 10,866 kg/cow/year.

**Table 2** Key survey data collected from gazing dairy farms in Michigan

Survey item	Description	Range (median)
Farm size	—	83–146 ha (114)
Grazing area	—	22–91 ha (57)
Alfalfa area	—	24–53 ha (38)
Harvested forage crops	Alfalfa and clovers	80% Alfalfa
Grazing forage crops	Variety of pasture compositions including mostly perennial ryegrass, orchardgrass, white clover, and red clover	Combinations of 60–70% cool-season grass with 30–40% legume
Lactating cows	—	90 to 120 cows (105)
Replacement stock	—	60–100 (80)
Cattle frame	Small Holsteins and New Zealand Friesian	80% Small Holsteins
Target milk production	—	6804–10,866 kg/cow/year (8835)
Cattle feed	High relative forage-to-grain ratios, with pasture as the main feed and grain as an energy supplement. Crude protein supplement (soybean meal 48% or 44%). Undegradable protein (distillers grain or roasted soybean)	Crude protein: 50% of farmers use “soybean meal 48%”; 20% of farmers use “soybean meal 44%”; 30% of farmers use no crude protein supplement Undegradable protein: 80% of farmers use distillers grain; 20% of farmers use roasted soybean
Cow housing	Bedded pack barn or Free stall barn	50% Bedded pack barn 50% Free stall barn
Heifer housing	Calf hutches and dry lot or bedded pack barn	80% Calf hutches and dry lot 20% Bedded pack barn
Feed facility	Short-term storage premix	100% Short-term storage premix
Milking center	Double parlor or multi stall Automatic Robotic System	60% Double parlor 40% Multi stall Automatic Robotic System
Manure collection	Scrapers with slurry pumps or with bucket loading	80% Scrapers with slurry pumps 20% Scrapers with bucket loading
Manure storage type	Top-loaded concrete tank or bottom-loaded tank	80% Top-loaded concrete tank 20% Bottom-loaded tank
Manure storage period	—	3–6 months (4.5)
Grazing system	Rotational	100% rotational
Stocking rate	—	1.0–5.2 animals/ha (3.1)
Labor for grazing management	—	6–10 h/week (8)
Grazing time	22 h per day	100% 22 h/day

However, in this study, we used a wider range (1361–15,876 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 production levels.

### Model Simulations

**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 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

**Table 3** Representative grazing dairy farm description

Main IFSM inputs	Value/description
<i>Cows</i>	
Lactating cows	100
Replacement stock	80
Cattle	Small frame Holsteins (454 kg)
Culling rate	30%
<i>Feed</i>	
Relative forage-to-grain ratio	High
Crude protein supplement	Soybean meal 48%
Undergradable protein	Distiller grain
<i>Facilities</i>	
Cow housing	Bedded pack barn
Heifer housing	Calf hutches and dry lot
Feed facility	Short-term storage premix
Milking center	Double four parlor
<i>Manure</i>	
Manure collection	Scrapers with slurry pumps
Manure storage	Top-loaded concrete tank for a 4-month period
Manure applied to the grazing area	20%
Manure applied to the alfalfa area	80%
<i>Forage areas</i>	
Grazing area	54 ha
Alfalfa area	27 ha
Fertilizers application	No
<i>Grazing strategy</i>	
Animals grazed	All cows
Time on pasture	Full days during the grazing season (April–October)
Labor for grazing management	20 h per week
<i>Tillage and planting</i>	
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
<i>Economics<sup>a</sup></i>	
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

**Table 3** (continued)

Main IFSM inputs	Value/description
Structures economic life	20 years
Real interest rate	6%

<sup>a</sup>All major operations based on 2013 representative prices

(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 processes 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; nutritive content and consumption; grazing management; animal performance; feed storage; manure management; tillage, planting, and harvest operations; and economics (Rotz et al. 2014).

Figure 3 presents the overall modeling frame for the IFSM model. The model is comprised of nine submodels that are seamlessly integrated and work together. These include annual weather data repository, spring and fall farm operations, crop growth and harvest, crop storage, animal operations, manure management, and economic and environmental assessments. In order to run the IFSM model, first one needs to provide detailed information about the farm and machineries operations. This information is initialized in the form of arrays to assure that the model is ready for simulation. Next, different operation tasks (e.g., tillage) are assigned to the farm machineries. Now that the farm is setup in the IFSM model, the submodels are activated to simulate all aspects of farm operations for the entire year. Depending on the predefined period of simulation, this process can be repeated and variabilities on the farm operations and results are recorded. After the termination criterion (period of simulation) is met, the results are summarized and presented in three primary forms, including an average performance of the farm, a cost/benefit analysis of farm operations, and a detailed environmental impact assessment in the form of footprints (Rotz et al. 2014).

**Scenario Analysis of the Impacts of Climate Variabilities, Pasture Compositions, and Target Milk Production Levels on Sustainability Grazing Dairy Farms** Within each of the ten climatological regions (Fig. 1), 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

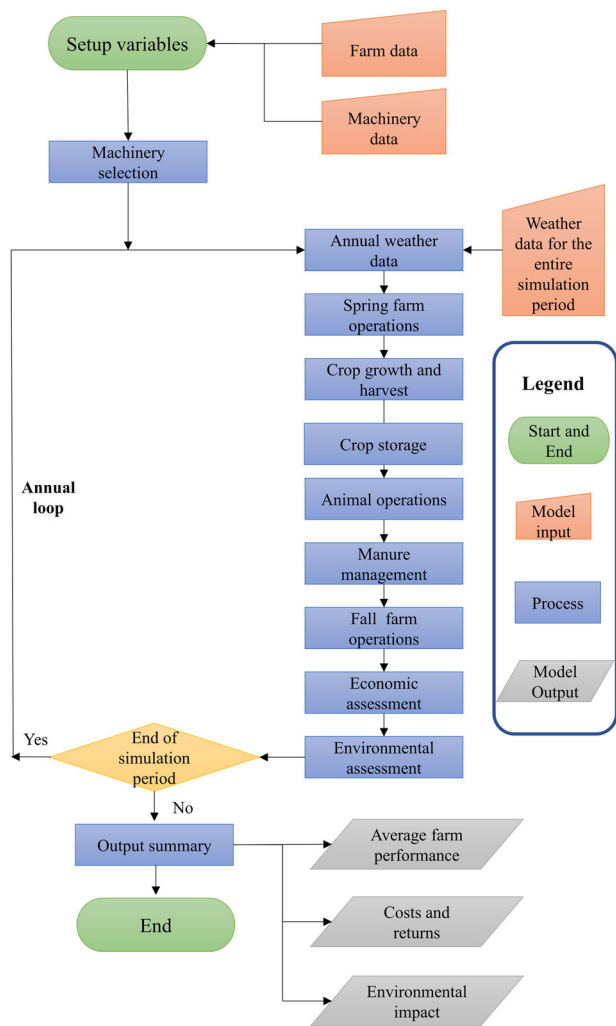


Fig. 3 IFSM modeling framework (modified from Rotz et al. 2014)

varying the legume percentage in the composition between 0% and 50%, in 10% increments. These combinations resulted in 48 different pasture compositions. In addition, for each pasture composition, each of the 32 target milk production levels, ranging from 1361 to 15,876 kg/cow/year, were simulated. The combination of 10 regions, 48 pasture compositions, and 32 target milk production levels, resulted in 15,360 different scenarios that were simulated in IFSM.

**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 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 (FPCM) 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 metric tonnes of CO<sub>2</sub> equivalents (CO<sub>2</sub>-eq), which is based on the global warming potential (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) (Flysjö et al. 2011; de Léís et al. 2015; O’Brien et al. 2014; Zehetmeier et al. 2014); and evaluating different feeds (e.g. grain, forage) (Adom et al. 2012). IFSM determines the carbon footprint as the net emission (assimilated and emitted) of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O while considering all sources and sinks of CO<sub>2</sub>. In addition, a carbon balance is enforced, so a portion of the CO<sub>2</sub> 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 LCA by assuming the GWP of 25 CO<sub>2</sub>-eq/kg for CH<sub>4</sub> and 298 CO<sub>2</sub>-eq/kg for N<sub>2</sub>O (IPCC 2001). In this study, the unit CO<sub>2</sub>-eq/kg of FPCM 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 an LCA (Galli et al. 2011, 2012). Water footprint provides a better understanding of water management and usage of 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 (surface water, groundwater, and rainwater) in the dairy farm system. The unit of measurement is kg of water per kg of FPCM. 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 FPCM.

**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 the 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 1 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 FPCM). In this study, the whole-farm profit is calculated by subtracting total costs from income. The income includes 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). However, this does not mean that no additional labor is needed to perform the job. Then, in cases where the total labor required is more than a family's capacity, the cost of additional laborers was included. Therefore, the costs include feed, manure handling, animal housing, animal care, cost of additional labor, and milking.

**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 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) and have been used to explore the ecological and economic sustainability of various Dutch farms (Van Calker et al. 2006).

The MCDM method that was 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. The VIKOR optimization method can provide efficient ranking regarding the selection of the best scenario (alternative).

A generic form of an MCDM matrix for a set of conflicting criteria  $\{g_1, g_2, \dots, g_j, \dots, g_n\}$  and a set of possible alternatives  $\{A_1, A_2, \dots, A_j, \dots, A_m\}$  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  $\sum_{j=1}^n w_j = 1$ .

Alternatives	Criteria (factors)			
	$g_1$	$g_2$	...	$g_n$
$A_1$	$f_{11}$	$f_{12}$	...	$f_{1n}$
$A_2$	$f_{21}$	$f_{22}$	...	$f_{2n}$
...	...	...	...	...
$A_m$	$f_{m1}$	$f_{m2}$	...	$f_{2n}$

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. These are named as 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 an 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 (Eq. 1):

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

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.

*Step 1.* The best and worst values of all the criterion functions ( $f_j^*$  and  $f_j^-$ ) are determined according to the benefit or cost criteria.

*Step 2.* The  $S_i$  and  $R_i$  values are determined for all alternatives using the following relations.

$$S_i = \sum_{j=1}^n w_j \cdot \left( \frac{|f_j^* - f_{ij}|}{|f_j^* - f_j^-|} \right) \quad (2)$$

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

*Step 3.* The minimum and maximum values of  $S_i$  and  $R_i$  are estimated using Eq. 4:

$$S^* = \min_i S_i, S^- = \max_i S_i, R^* = \min_i R_i, R^- = \max_i R_i \quad (4)$$

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

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

where, the parameter of  $\vartheta$  is initiated as a strategy weight for the majority of criteria (or the maximum group utility) and  $(1 - \vartheta)$  is the weight of individual regret. The compromise can be selected with consensus ( $\vartheta = 0.5$ ), voting by majority ( $\vartheta > 0.5$ ), or veto ( $\vartheta < 0.5$ ). Usually, the

value of  $\vartheta$  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  $\vartheta$ . In this study, we considered consensus, which is commonly used for a compromise solution (Opricovic and Tzeng 2007; Sayadi et al. 2009).

*Step 5.* The alternatives are ranked in separate lists based on ascending  $S, R$ , and  $Q$  values.

*Step 6.* 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 the “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 Eq. 6.

$$Q(A'') - Q(A') \geq DQ \quad (6)$$

where  $DQ = 1/(\# \text{ of alternatives} - 1)$ .

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

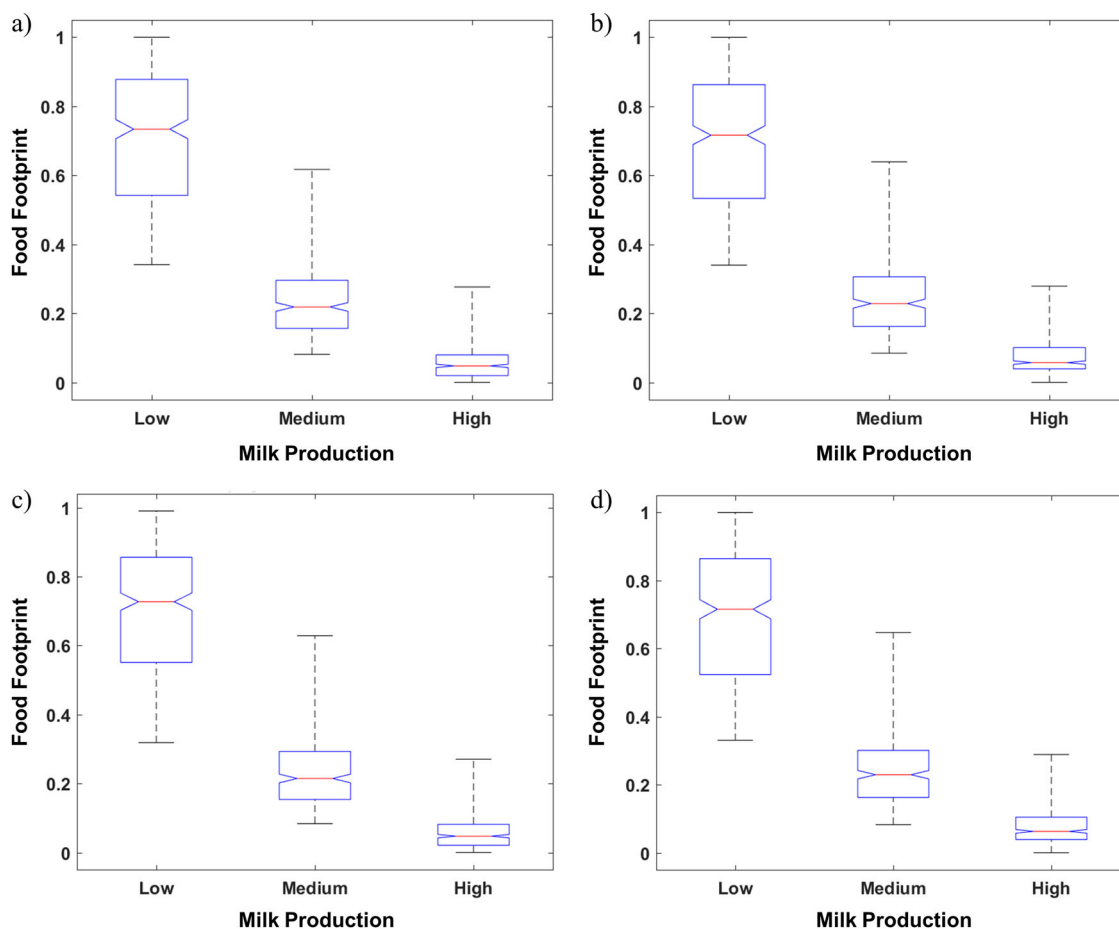
If one of these two conditions is not satisfied, then a set of compromise solutions are recommended as follows:

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

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

### Spatial Variability of Sustainable Pasture Composition and Milk Production

In order to identify the spatial variability of the most sustainable pasture composition and milk production in the ten regions 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 recalculating each center as the mean of all assigned points (Celebi et al. 2013).



**Fig. 4** Food footprint for different combinations of red clover with **a** Kentucky bluegrass, **b** orchardgrass, **c** perennial ryegrass, and **d** tall fescue for low (1361–3629 kg/cow/year), medium (4082–5897 kg/cow/year), and high (6350–8618 kg/cow/year) milk production

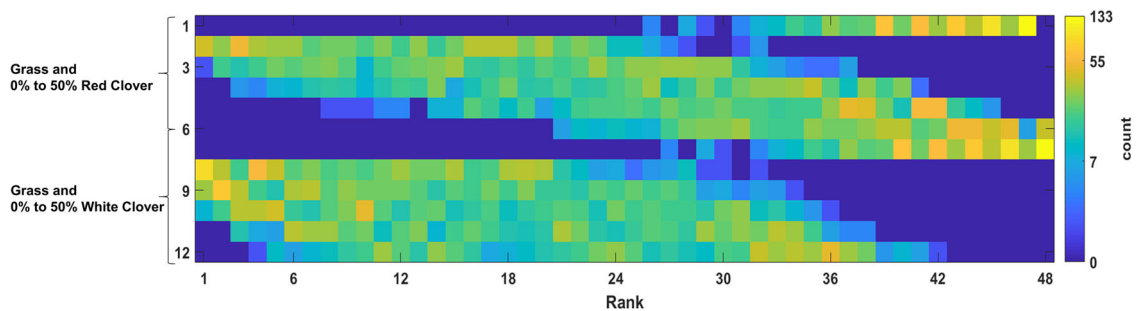
## Results and Discussion

### 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 a lower value represents a more sustainable milk production level. As discussed in the Materials and Methods section, the range between 1361 and 15,876 kg/cow/year of target milk production was evaluated in this study. This is the allowable range for the IFSM model; however, in practice, the range is narrower due to climate variabilities and cattle characteristics in regard to efficiency-level conversion of grass to milk (EPA 2015). This was the case in this study as the range of milk production level was reduced to 1361 from 8618 kg/cow/year for the region.

Box and whisker plots (Fig. 4 and Fig. 11 in the Supplementary Materials) present the variability of the food

footprint for three ranges of milk production: low (1361–3629 kg/cow/year), medium (4082–5897 kg/cow/year), and high (6350–8618 kg/cow/year). Figure 4 shows the pasture compositions of the four grass species with red clover while Fig. 11 (Supplementary Materials) shows the pasture compositions of the four grass species with white clover considering all percentages of legume (0 to 50%). However, both Fig. 4 and Fig. 11 (Supplementary Materials) present a similar trend, where the high range of milk production presents lower values of food footprint (median = 0.0573), while having less variability among the pasture compositions and regions (minimum = 0.0000 and maximum = 0.3069). Conversely, the low range of milk production presents higher values of food footprint (median = 0.7180), while having more than triple of the variability among the pasture compositions and regions compared to the high range of milk production (minimum = 0.3117 and maximum = 1.0000). This suggests that the most sustainable range of milk production for any of the pasture compositions for this study is between 6350 and 8618 kg/cow/



**Fig. 5** Histogram map for legume variations with grass species

year, while having the least variability. Since all the footprints under study (energy, water, carbon, and economic) were weighted equally by choice, the low variability under high range of milk production represents the limited improvement in sustainability that is gained by increasing the target milk production from 6350 to 8618 kg/cow/year.

Moreover, the most suitable pasture composition for each range of milk production was identified. The most suitable pasture composition for the high range of milk production for all ten regions 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 suitable grass for the pasture composition in the medium range of milk production. However, the most suitable 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 suitable 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.

### Identification of the Most Sustainable Pasture Composition

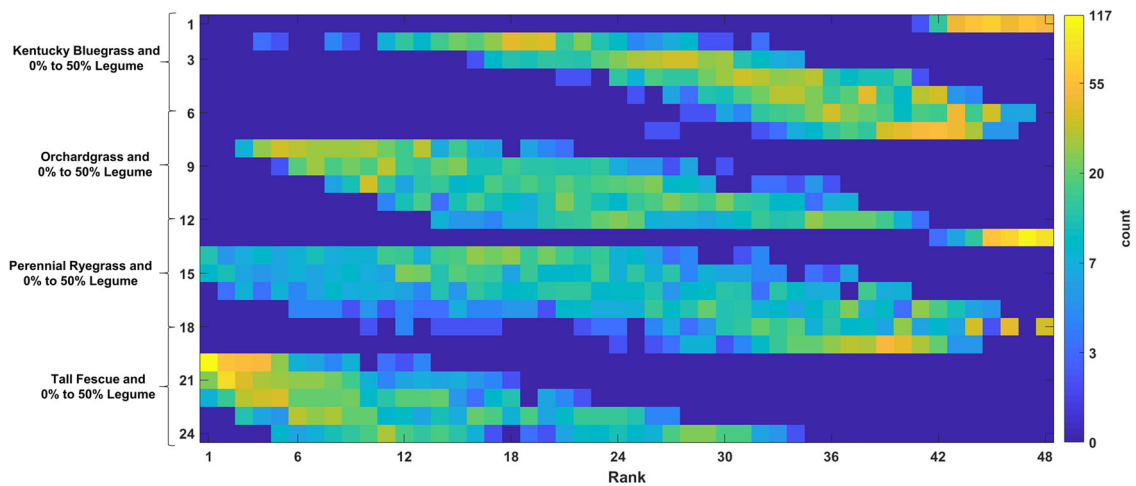
To identify the most sustainable pasture composition for the study area, all compositions were ranked from 1 to 48 based on their food footprint score in which lower scores ranked higher. Figures 5–7 shows a summary histogram map of the pasture compositions ranking based on the results from all regions within the study area. The y axis represents the pasture compositions, where 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, where 1 indicates the most sustainable pasture composition and 48 the least sustainable. 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 obtain that rank. As an example, in row one in Fig. 5 (grass with 0% red clover), rank 47 happened more frequently than any other ranking. In addition, this composition is one of the least sustainable compared to any other grass and red clover mixtures (10–50%).

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 (Fig. 5). In addition, the pasture becomes less sustainable when no legume is added (Fig. 5, 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 (Fig. 5, rows 2 and 8). However, white clover had higher sustainability with 20, 30%, and even 40% in the composition than red clover (Fig. 5, rows 9, 10, and 11, respectively).

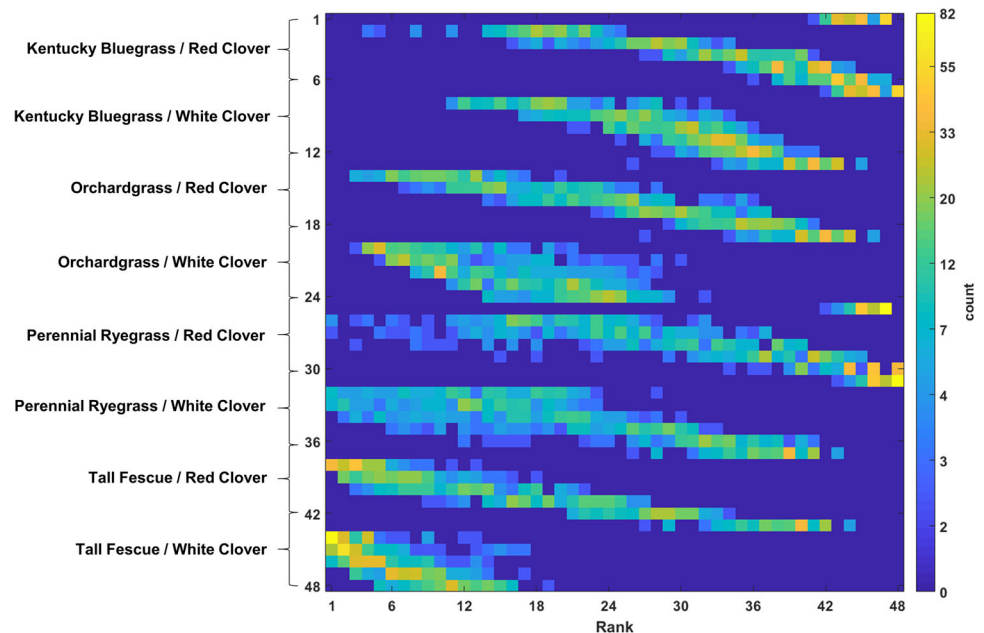
As presented in Fig. 6, the least sustainable pasture compositions are Kentucky bluegrass with no legume (row 1), orchardgrass with 0% legume (row 7), and perennial ryegrass with 0% and 50% legume (rows 13 and 18, respectively). Among all grasses, tall fescue resulted in the most sustainable pasture composition especially when it is combined with 10% of legume (Fig. 6, row 20). Tall fescue also becomes less sustainable with an increase of legume percentage in the pasture composition.

Comparing all compositions of pastures, Fig. 7 shows that as legume percentage increases (between 10% and 50%) the overall grazing dairy farm practice becomes less sustainable. However, when grasses are not combined with a legume, the pastures are ranked the lowest. This indicates that, when a legume is not present in the pasture composition, the farm is less sustainable. In summary, the least sustainable pasture composition was perennial ryegrass with no legume (Fig. 7, row 25) and the most sustainable pasture composition is tall fescue with 10% white clover (Fig. 7, row 20). In addition, tall fescue with white clover, in



**Fig. 6** Histogram map for grass species for different variations of legume

**Fig. 7** Histogram map of all pasture compositions

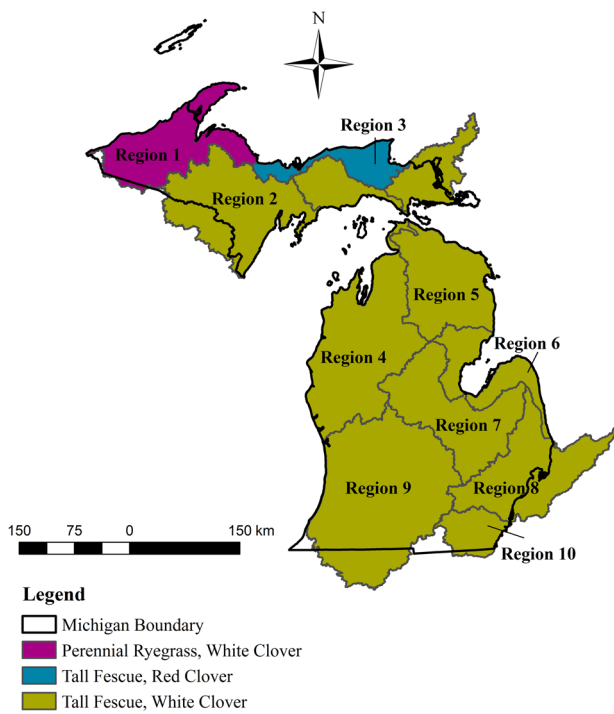


general, presents the best rankings (Fig. 7, rows 44 to 48), making it the most sustainable pasture composition.

### Spatial Variability of Sustainable Pasture Compositions and Milk Productions

In order to understand climate variability of grazing dairy farms, the study area was divided into ten regions. For each region, the most sustainable pasture composition and milk production was identified and presented in Figs. 8–10. Figure 8 shows the most sustainable composition of grass and legume for each region. Tall fescue with white clover was identified as the most sustainable pasture composition in eight regions, located mostly in the Lower Peninsula of

Michigan. Meanwhile, the most sustainable pasture compositions of the regions 1 and 3 (the Upper Peninsula) are perennial ryegrass with white clover and tall fescue with red clover, respectively. Nine of the regions identified white clover as the most sustainable 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 regions as the most sustainable grass in the pasture composition, which can be related to its high tolerability of extreme weather conditions (drought and flood) (Cassida et al. 2014).

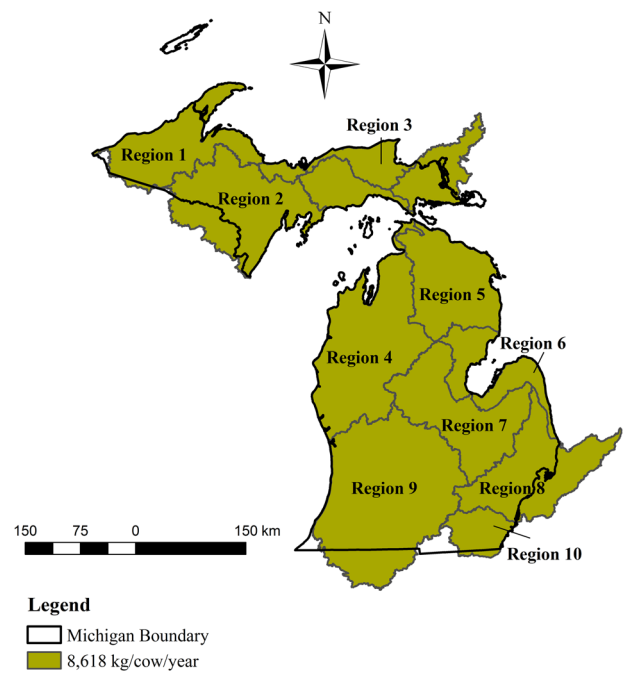


**Fig. 8** Spatial variability of most sustainable pasture compositions in Michigan

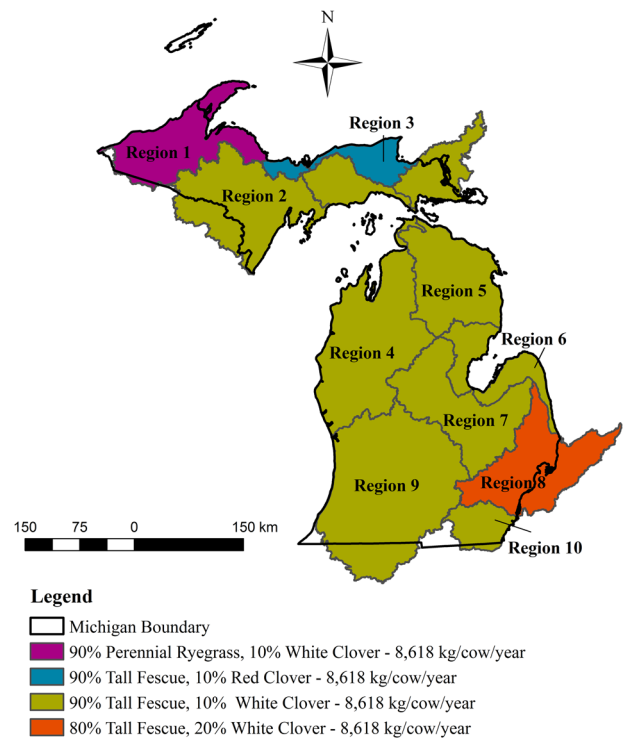
The legume percentage of the pasture composition for each region were also identified (Fig. 10). Ten percent of legume in the pasture composition was identified as the most sustainable legume percentage in nine regions and 20% in the remaining region. In another study performed in the Lower Peninsula 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 consider carbon generation and energy usage in their study. This highlights the importance of performing a comprehensive sustainability study to make more informed decisions.

Regarding the most sustainable milk production, 8618 kg/cow/year was identified as the most sustainable production for all regions (Fig. 9), 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 region in which both pasture composition and milk production were considered (Fig. 10). The study area was divided into three clusters, where 90% tall fescue combined with 10% white clover and 8618 kg/cow/year were identified as the most sustainable practices for the majority of the regions. These maps can be used by policy makers to develop a strategy for grazing



**Fig. 9** Spatial variability of most sustainable milk productions in Michigan



**Fig. 10** Spatial variability of most sustainable pasture compositions and milk productions in Michigan (cluster analysis)

dairy farms that involves reducing water, energy, and environmental footprints, while maximizing the profit and production of dairy farmers.

## Conclusions

Results of this study showed that the high range of milk production is the most sustainable for all pasture compositions and regions, 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.

For any level of milk production, the results from the food footprint estimation provide three major findings: (1) having white clover in the pasture composition helps with improving sustainability; (2) the pasture becomes less sustainable when no legume is added while maintaining low percentages of legume improves the farm sustainability; and (3) among all grasses, tall fescue resulted in the most sustainable pasture composition.

The cluster analysis helped with identifying the most sustainable grazing dairy farm practice. In general, the highest level of milk production (8618 kg/cow/year) was identified as the most sustainable. However, the most sustainable pasture composition varied among the regions. However, it is important to note that there are many other aspects of farming that can still make a system unsustainable (e.g., animal welfare, soil condition, biodiversity, and resilience against climate change) and therefore should be considered when making decisions about the most sustainable practices.

In summary, 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 sustainable pasture composition for a specific milk production level, and (c) the most sustainable legume percentage in the pasture composition for a specific milk production. 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.

Finally, despite the fact that the concept of the food footprint was developed and examined for a grazing dairy farm, this measure can be applied to other agricultural sectors to identify the most sustainable practices. However, it is important to note that the food footprint values obtained from the production of different foods (e.g., milk, meat, beans) cannot be compared against each other.

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## Compliance with ethical standards

**Conflict of Interest** The authors declare that they have no conflict of interest.

## References

- Adom F, Maes A, Workman C, Clayton-Nierderman Z, Thoma G, Shonnard D (2012) Regional carbon footprint analysis of dairy feeds for milk production in the USA. *Int J Life Cycle Assess* 17:520–534
- Barnes R, Nelson C, Moore K, Collins M (2007) *Forages: an introduction to grassland agriculture*, 6th edn. Iowa State University Press, Ames, Iowa
- Bryant JR, Snow VO (2008) Modelling pastoral farm agro-ecosystems: a review. *New Zeal J Agric Res* 51:349–363
- BSI (British Standard Institute) (2008) *Guide to PAS2050. How to assess the carbon footprint of goods and services*. British Standards, London, UK
- Cassida K, Paling J, Kapp C (2014) 2014 Michigan forage variety test report. Forage factsheet #15–01. Michigan State University Extension, East Lansing, MI
- Cecchini L, Torquati B, Paffarini C, Barbanera M, Foschini D, Chiorri M (2016) The milk supply chain in Italy's Umbria region: environmental and economic sustainability. *Sustainability* 8:728
- Celebi ME, Kingravi HA, Vela PA (2013) A comparative study of efficient initialization methods for the k-means clustering algorithm. *Expert Syst Appl* 40:200–210
- Clayton-Matthews A, Watanabe P (2012) *Massachusetts immigrants by the numbers: Demographic Characteristics and Economic Footprint*, 2nd edn. Immigrant Learning Center, Inc.: Malden, MA
- Corson MS, Rotz AC, Skinner HR, Sanderson MA (2007) Adaptation and evaluation of the Integrated Farm System Model to simulate temperate multiple-species pastures. *Agric Syst* 94:502–508
- Čuček L, Klemeš JJ, Kravanja Z (2012) A review of footprint analysis tools for monitoring impacts on sustainability. *J Clean Prod* 34:9–20
- de Léis CM, Cherubini E, Ruviano CF, Prudêncio da Silva V, do Nascimento Lampert V, Spies A, Soares SR (2015) Carbon footprint of milk production in Brazil: a comparative case study. *Int J Life Cycle Assess* 20:46–60
- Del Prado A, Misselbrook T, Chadwick D, Hopkins A, Dewhurst RJ, Davison P, Butler A, Schröder J, Scholefield D (2011) SIMS-DAIRY: a modelling framework to identify sustainable dairy farms in the UK. Framework description and test for organic systems and N fertiliser optimisation. *Sci Total Environ* 409(19):3993–4009
- Dyer JA, Vergé XPC, Desjardins RL, McConkey BG (2014) Assessment of the carbon and non-carbon footprint interactions of livestock production in Eastern and Western Canada. *Agroecol Sustain Food Syst* 38:541–572
- EC (European Commission) (2007) Carbon footprint: what it is and how to measure it. <http://www.to-be.it/wp-content/uploads/2015/07/Carbon-footprint.pdf>. Accessed 21 Feb 2018
- EPA (United States Environmental Protection Agency) (2015) Ag 101: dairy production [https://www.epa.gov/sites/production/files/2015-07/documents/ag\\_101\\_agriculture\\_us\\_epa\\_0.pdf](https://www.epa.gov/sites/production/files/2015-07/documents/ag_101_agriculture_us_epa_0.pdf). Accessed 21 Feb 2018
- FAO (Food and Agriculture Organization of the United Nations) (2010) Greenhouse gas emissions from the dairy sector: a life cycle assessment. Animal Production and Health Division, Rome

- FAO (Food and Agriculture Organization of the United Nations) (2016) FAOstat. Statistical databases-Livestock Primary, Rome
- Finkbeiner M (2009) Carbon footprinting: opportunities and threats. *Int J Life Cycle Assess* 14:91–94
- Flanders FB, Gillespie JR (2015) Modern livestock & poultry production, 9th edn. Cengage Learning, Boston, MA
- Flysjö A, Henriksson M, Cederberg C, Ledgard S, Englund JE (2011) The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden. *Agric Syst* 104:459–469
- Galli A, Wiedmann T, Ercin E, Knoblauch D, Ewing B, Giljum S (2011) Integrating ecological, carbon and water footprint: defining the “footprint family” and its application in tracking human pressure on the planet. Technical Document, Surrey, UK
- Galli A, Wiedmann T, Ercin E, Knoblauch D, Ewing B, Giljum S (2012) Integrating ecological, carbon and water footprint into a “Footprint Family” of indicators: definition and role in tracking human pressure on the planet. *Ecol Indic* 16:100–112
- Garnett T (2009) Livestock-related greenhouse gas emissions: impacts and options for policy makers. *Environ Sci Policy* 12:491–503
- Hatfield J, Takle G, Grotjahn R, Holden P, Izaurralde RC, Mader T, Marshall E, Liverman D (2014) Ch. 6: Agriculture. Climate change impacts in the United States: The Third National Climate Assessment. In: JM Melillo, Terese (TC) Richmond, GW Yohe (eds) U.S. Global Change Research Program, Washington, DC, p 150–174
- Heckman E, Hinds S, Johnson K, Perkins J, Shelton V, Zupancic R (2007) Management-intensive grazing in Indiana. Bulletin AY-328. USDA-NRCS Extension, Indiana
- Hermann BG, Debeer L, De Wilde B, Blok K, Patel MK (2011) To compost or not to compost: Carbon and energy footprints of biodegradable materials’ waste treatment. *Polym Degrad Stab* 96:1159–1171
- Hoekstra AY (2008) Water neutral: reducing and offsetting the impacts of water footprints. UNESCO-IHE, Delft, The Netherlands. Value of Water Research Report Series No. 28
- Huang J, Xu CC, Ridoutt BG, Liu JJ, Zhang HL, Chen F, Li Y (2014) Water availability footprint of milk and milk products from large-scale dairy production systems in Northeast China. *J Clean Prod* 79:91–97
- IPCC (Intergovernmental Panel on Climate Change) (2001) Climate change 2001: the scientific basis. In: Houghton JT, Ding Y, Griggs DJ, Noguera M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA
- IPCC (Intergovernmental Panel on Climate Change) (2014) Climate change 2014: impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds) Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp 1132
- Jain AK (2010) Data clustering: 50 years beyond K-means, Pattern Recognition Letters
- Mc Geough EJ, Little SM, Janzen HH, McAllister TA, McGinn SM, Beauchemin KA (2012) Life-cycle assessment of greenhouse gas emissions from dairy production in Eastern Canada: a case study. *J Dairy Sci* 95:5164–5175
- Muller LD (2004) Managing to get more milk and profit from pasture. PennState Extension, Pennsylvania State University, Pennsylvania
- Musumba M, Grabowski P, Palm C, Snapp S (2017) Guide for the sustainable intensification assessment framework. The U.S. Government’s Global Hunger & Food Security Initiative
- Murphy E, De Boer IJM, Van Middelaar CE, Holden NM, Shalloo L, Curran TP, Upton J (2017) Water footprinting of dairy farming in Ireland. *J Clean Prod* 140:547–555
- O’Brien D, Capper JL, Garnsworthy PC, Grainger C, Shalloo L (2014) A case study of the carbon footprint of milk from high-performing confinement and grass-based dairy farms. *J Dairy Sci* 97:1835–1851
- OECD (Organisation for Economic Co-operation and Development) (2004) Measuring sustainable development: integrated economic, Environmental and Social Frameworks, Paris, France
- Ogle D, St. John L (2008) Plant guide for white clover (*Trifolium repens* L.). USDA-Natural Resources Conservation Service, Idaho Plant Materials Center, Aberdeen, Idaho
- Olsson JA, Bockstaller C, Stapleton LM, Ewert F, Knäpen R, Therond O, Geniaux G, Bellon S, Correia TP, Turpin N, Bezlepkina I (2009) A goal oriented indicator framework to support integrated assessment of new policies for agri-environmental systems. *Environ Sci Policy* 12(5):562–572
- Opřicovic S (2011) Fuzzy VIKOR with an application to water resources planning. *Expert Syst Appl* 38:12983–12990
- Opřicovic S (2009) A compromise solution in water resources planning. *Water Resour Manag* 23:1549–1561
- Opřicovic S, Tzeng GH (2007) Extended VIKOR method in comparison with outranking methods. *Eur J Oper Res* 178:514–529
- Opřicovic S, Tzeng GH (2004) Compromise solution by MCDM methods: a comparative analysis of VIKOR and TOPSIS. *Eur J Oper Res* 156:445–455
- Owusu-Sekyer E, Scheepers M, Jordaan H (2016) Water footprint of milk produced and processed in South Africa: implications for policy-makers and stakeholders along the dairy value chain. *Water* 8:322
- Pagani M, Vittuari M, Johnson TG, De Menna F (2016) An assessment of the energy footprint of dairy farms in Missouri and Emilia-Romagna. *Agric Syst* 145:116–126
- Palhares JCP, Pezzopane JRM (2015) Water footprint accounting and scarcity indicators of conventional and organic dairy production systems. *J Clean Prod* 93:299–307
- Rojas-Downing MM, Harrigan T, Nejadhashemi AP (2017a) Resource use and economic impacts in the transition from small confinement to pasture-based dairies. *Agric Syst* 153:157–171
- Rojas-Downing MM, Nejadhashemi AP, Abouali M, Daneshvar F, Al Masraf SAD, Herman MR, Harrigan T, Zhang Z (2017b) Pasture diversification to combat climate change impacts on grazing dairy production. *Mitig Adapt Strateg Glob Chang* 23:405–431
- Rojas-Downing MM, Nejadhashemi AP, Harrigan T, Woznicki SA (2017c) Climate change and livestock: Impacts, adaptation, and mitigation. *Clim Risk Manage* 16:145–163
- Rotz CA (2004) The Integrated Farm System Model: a tool for developing more economically and environmentally sustainable farming systems for the Northeast. NABEC. 2004 Northeast Agricultural and Biological Engineering Conference Sponsored by ASAE. ASABE, St. Joseph, MI, p 4–22
- Rotz CA, Corson MS, Chianese DS, Montes F, Hafner SD, Bonifacio HF, Coiner CU (2014). The Integrated Farm System Model – reference manual, version 4.2. Pasture Systems and Watershed Management Research Unit, Agricultural Research Service, United States Department of Agriculture, University Park, PA, USA
- Sayadi MK, Heydari M, Shahanaghi K (2009) Extension of VIKOR method for decision making problem with interval numbers. *Appl Math Model* 33:2257–2262
- Schils RLM, Olesen JE, del Prado A, Soussana JF (2007) A review of farm level modelling approaches for mitigating greenhouse gas emissions from ruminant livestock systems. *Livest Sci* 112:240–251

- Sharpley AN, Williams JR (1990) EPIC-erosion/productivity impact calculator: 1. Model documentation, USDA-ARS Technical Bulletin 1768
- Sobhani R, Abahusayn M, Gabelich CJ, Rosso D (2012) Energy footprint analysis of brackish groundwater desalination with zero liquid discharge in inland areas of the Arabian Peninsula. *Desalination* 291:106–116
- Sullivan K, DeClue R, Emmick D (2000) Prescribed grazing and feeding management for lactating dairy cows. USDA-NRCS, Syracuse
- Thornton PK (2010) Livestock production: recent trends, future prospects. *Philos Trans R Soc B* 365:2853–2867
- United Dairy Industry of Michigan (2016) dairy facts. <https://www.milkmeansmore.org/milk-local/michigan-dairy-facts/>. Accessed 21 Feb 2018
- USDA (United States Department of Agriculture) (2014) Milk cows and production: Final estimates 2008-2012. [http://usda.mannlib.cornell.edu/usda/nass/milkcowest/2010s/2014/milkcowest\\_MilkCowsandProduction-FinalEstimates,2008-12.pdf](http://usda.mannlib.cornell.edu/usda/nass/milkcowest/2010s/2014/milkcowest_MilkCowsandProduction-FinalEstimates,2008-12.pdf)
- USDA-ARS (United States Department of Agriculture- Agricultural Research Service) (2016) Integrated Farm System Model. <https://www.ars.usda.gov/northeast-area/up-pa/pswmru/docs/integrated-farm-system-model/>. Accessed 21 Feb 2018
- USDA-NASS (United States Department of Agriculture-National Agricultural Statistics Service) (2014) 2012 Census of agriculture. Michigan, State and County Data. AC-12-A-22, Washington, D.C
- USDA-NRCS (United States Department of Agriculture-Natural Resources Conservation Service) (2002) Plant Fact Sheet for Red Clover (*Trifolium pratense* L.). Washington, DC
- USGS (United States Geological Survey) (2017) Hydrologic unit maps. <https://water.usgs.gov/GIS/huc.html>
- Van Calker KJ, Berentsen PBM, Romero C, Giesen GWJ, Huirne RBM (2006) Development and application of a multi-attribute sustainability function for Dutch dairy farming systems. *Ecol Econom* 57(4):640–658
- Vasilaki V, Katsou E, Ponsá S, Colón J (2016) Water and carbon footprint of selected dairy products: a case study in Catalonia. *J Clean Prod* 139:504–516
- Viessman Jr W, Lewis GL (2003) Introduction to hydrology, 5th edn. Pearson Education Inc, Upper Saddle River, NJ
- Wachendorf M, Golinski P (2006) Towards sustainable intensive dairy farming in Europe. *Grassl Sci Eur* 11:159–174
- Wallis TWR, Griffiths JF (1995) An assessment of the weather generator (WXGEN) used in the erosion/productivity impact calculator (EPIC). *Agric Meteorol* 73:115–133
- WCED (World Commission on Environment and Sustainable Development) (1987) Our Common Future (The Brundtland Report). Oxford University Press, Oxford, Bungay, Suffolk, UK
- Wittenberg E, Wolf C (2008) 2007 Michigan Dairy Grazing Farm Business Analysis Summary. Michigan State University, Staff Paper No. 2008-5.
- Woznicki SA, Nejadhashemi AP, Ross DM, Zhang Z, Wang L, Esfahanian AH (2015) Ecohydrological model parameter selection for stream health evaluation. *Sci Total Environ* 511:341–353
- Yu PL (1973) A class of solutions for group decision problems. *Manag Sci* 19:936–946
- Zanakis SH, Solomon A, Wishart N, Dubliss S (1998) Multi-attribute decision making: a simulation comparison of select methods. *Eur J Oper Res* 107:507–529
- Zehetmeier M, Gandorfer M, Hoffmann H, Muller UK, De Boer IJM, Heibenhuber A (2014) The impact of uncertainties on predicted greenhouse gas emissions of dairy cow production systems. *J Clean Prod* 73:116–124
- Zonderland-Thomassen MA, Ledgard SF (2012) Water footprinting: a comparison of methods using New Zealand dairy farming as a case study. *Agric Syst* 110:30–40