Agricultural Systems 184 (2020) 102887

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

An environmental assessment of grass-based dairy production in the northeastern United States

C. Alan Rotz[a,*], Michael Holly[a,1], Aaron de Long[b], Franklin Egan[b], Peter J.A. Kleinman[a]

[a] USDA/Agricultural Research Service, Building 3702 Curtin Rd, University Park, PA 16802, USA
[b] Pennsylvania Association for Sustainable Agriculture, Harrisburg, PA 17102, USA

ARTICLE INFO

Keywords:
Dairy farm
Carbon footprint
Greenhouse gas
Nitrogen loss
IFSM

ABSTRACT

Demand for grass-based dairy production, which relies heavily on grazing and use of forage crops, is growing in the United States, primarily due to reported human health benefits of the milk produced as well as perceived environmental and animal welfare benefits. We used a whole-farm model to evaluate environmental footprints of all-grass, grass supplemented with grain, and confinement dairy production systems in the temperate climate of the northeastern U.S. Model results were depicted per unit of farmland and per unit of milk produced to provide alternate perspectives from the viewpoint of land management and commodity production. For most environmental indicators, the grass-based systems had smaller environmental impacts per unit of farmland but larger impacts per unit of milk produced compared to confinement fed systems. To verify the simulation of grass-based operations, eight dairy farms - ranging from herds that were grazed and fed only forage to herds that received some grain supplementation - were surveyed and modeled. Due to variation in climate, soil characteristics and management practices, a comparison of the two grass-based farm types showed no significant differences in environmental impacts. Farms of the same size using each production strategy along with a more traditional confinement production system were then simulated using the same climate and soil conditions for a better comparison. Predicted nitrogen and phosphorus losses to the environment, fossil energy use, water use, and greenhouse gas emissions were less from the grass-based farms compared to the confinement operation. Due to lower milk production on the grass-based dairies, nutrient losses and greenhouse gas emissions expressed per unit of milk produced were generally greater than those of the confinement system. Within the grass-based dairy systems, the system that supplemented with grain had slightly lower nitrogen and phosphorus losses per unit of farmland compared to the grass-only system, and much lower losses and emissions when expressed per unit of milk produced. Total production cost was less for the all-grass dairy than the grass with grain dairy. With a greater milk price, the all-grass system provided greater profitability per unit of land used and per unit of milk produced compared to the confinement farm of similar size. These data indicate that grass-based dairy farms can provide environmental benefits to a local watershed, but due to a lower efficiency in milk production, they may increase the aggregate environmental impacts of regional and global supply chains.

1. Introduction

The market for milk produced by cows on a predominately-grass or all-grass diet has increased rapidly in the the U.S. in recent years, even as consumption of other milk sectors has declined (Gerdes, 2019). Growth in demand for grass-based dairy products reflects, in part, findings of nutritional and human health benefits associated with all-forage dairy cattle diets. For instance, a U.S.-wide study of milk from cows fed a nearly 100% forage-based diet concluded that differences in the fatty acid profile compared with that from organic and conventional cows fed grain and forage diets could lower the risk of cardiovascular and other metabolic diseases of dairy consumers (Benbrook et al., 2018).

Consumer preference for grass-based dairy products extends beyond human health concerns and often includes interests in animal welfare, local food production and environmental sustainability. A survey of U.S. consumers not associated with the dairy industry revealed that perceptions regarding the quality of life of the animals and the indirect effect of their welfare on milk quality are important decision-making factors (Cardoso et al., 2016). Factors such as weaning age and hock

* Corresponding atthor.
E-mail address: al.rotz@usda.gov (C.A. Rotz).
[1] Present address: Research School of Engineering, University of Wisconsin–Green Bay, Green Bay, WI 54311, USA.

https://doi.org/10.1016/j.agsy.2020.102887
Received 27 February 2020; Received in revised form 8 May 2020; Accepted 2 June 2020
Available online 12 June 2020
0308-521X/

health have been found to differ between grazing dairies (both conventional and organic) and confinement operations (Bergman et al., 2014).

Environmental concerns related to dairy production vary widely, from local impacts on soil, water and air resources to global contributions of greenhouse gas (GHG) and energy footprints. Recent studies have quantified environmental impacts of dairy production systems using intensive confinement feeding practices (ex. Kim et al., 2019; Veltman et al., 2018). With specific interest in grass-based production, Müller-Lindenlauf et al. (2010) evaluated the environmental impacts of organic dairy farms in Germany where farms were classified by the percentage of grassland area used on the farm and feeding intensity. Farms with more intensive feeding practices tended to show ecological advantages in the impact categories of climate change and land demand. In contrast, lower-input grass-based farms showed benefits in animal welfare, milk quality and reduced ammonia losses. They concluded that within the range of dairy farms studied, those using intensive mixed cropping systems tended to have less negative environmental effects than the more extensive systems relying on grass production and grazing.

Our objective was to quantify important environmental aspects of grass-based dairy farms in the northeastern U.S., including nitrogen and phosphorus losses and life cycle assessments of water use, fossil energy use, total reactive nitrogen loss and GHG emission. Specifically, we sought to provide insight into the variability of grass-based production systems found in the state of Pennsylvania. Then, we compared representative grass-based systems with other dairy production systems common to the state and a previous assessment over all dairy farms in the state.

2. Materials and methods

Actual and representative farms were modeled using the Integrated Farm System Model (IFSM) to quantify the environmental impacts of dairy production systems in Pennsylvania. To provide insight into variability in grass-based enterprises, we evaluated eight dairies participating with the Pennsylvania Association for Sustainable Agriculture. Four of the farms fed only forage (all-grass) and four fed primarily forage with some grain supplementation (grass with grain). Grass-based management represents a small portion of all farms in Pennsylvania (Holly et al., 2019) where our sample farms are very representative of the size and management practices used. There is interest in this type of management in the northeastern U.S. as a means for maintaining small profitable dairy farms.

Each farm was visited in late 2017 or early 2018 to gather information on management practices used over recent years. Data such as feed production and use reflected typical or long-term averages rather then the conditions of a specific year. Characteristics of these grass-based dairies were used to set up simulations of representative farms. Simulated environmental impacts of the grass-based production systems were then compared to those of other representative dairy production systems in the region, derived using data from the Agricultural Resource Management Survey (Holly et al., 2019).

2.1. Integrated Farm System Model

The IFSM is a process-level farm simulation tool used to assess the performance, environmental impacts and economics of dairy or beef production systems (USDA-ARS, 2018). Feed production and intake, animal growth and production, and the cycling of nutrients through the production system are simulated for many years of weather (Rotz et al., 2018). Crop growth and harvest are predicted daily to represent feed quality and losses as influenced by weather. Feeds produced are supplemented with purchased feeds to meet animal requirements and predict milk production. For a better comparison across systems, milk production is adjusted to 4.0% fat and 3.3% protein (FPCM; Rotz et al., 2018). The herd includes the feeding, growth and manure handling of replacement heifers, dry cows and up to three groups of lactating cows (Rotz et al., 1999). Simulated performance is used to determine production costs, incomes, and net return for each year of weather. A whole-farm budget includes important fixed and variable costs. Production costs are subtracted from the total income received for milk, cull animal and excess feed sales to determine a net return. Family members provide most of the labor on these small farms; therefore, the labor cost was ignored to provide a net return to management and labor as a measure of profitability.

Nutrient movements are tracked to predict soil accumulation or attenuation and losses to the environment (Rotz et al., 2018). Losses include nitrogen, phosphorus and carbon. Common pathways of nitrogen loss are ammonia (NH_3) volatilization, nitrous oxide (N_2O) and nitrogen oxide (NOx) emissions through nitrification and denitrification processes, and leaching and runoff of nitrate (NO_3^-). Phosphorus pathways of loss are sediment bound and soluble runoff with minor amounts of leaching to ground water. Process-based simulation predicts volatilization on an hourly time step and nitrification, denitrification, leaching and runoff on a daily basis as influenced by temperature, wind speed, precipitation, soil conditions and management practices (Rotz et al., 2018; Rotz et al., 2014). Carbon emissions are methane and carbon dioxide primarily from enteric fermentation and respiration of animals and microbial decomposition of manure. Numerous studies have verified the model's ability to represent feed crop production, animal performance, emissions, and other model components of dairy production (ex. Leytem et al., 2018; Bonifacio et al., 2015; Jego et al., 2015; Rotz et al., 2014; Belflower et al., 2012).

Following guidelines of the Livestock Environmental Assessment and Performance partnership (LEAP, 2016), a cradle-to-farm gate partial life cycle assessment (LCA) is performed within IFSM to determine annual carbon (net GHG) emission, fossil energy use, blue (non-precipitation) water use, and total reactive N loss (Rotz et al., 2018). Carbon emission includes the sum of important emissions of methane (CH_4), N_2O and carbon dioxide (CO_2) converted to CO_2 equivalents (CO_2e) using 100 year global warming potentials of 28 for biogenic CH_4 and 265 for N_2O (Myhre et al., 2013). Emissions include both direct emissions from the production system as well as indirect N_2O emissions that occur elsewhere in the environment through a transformation of NH_3 and NO_3^- lost from the production system (IPCC, 2006). For this analysis, we assumed steady-state soil organic matter where long-term carbon sequestration would not occur. Fossil energy use includes that of fuel and electricity used in milking and housing of animals, farm operations and general truck use. In this region where crop irrigation is rarely used, blue water is that used for parlor cleaning, cattle consumption, and cooling of cattle. Reactive N is the sum of all N leaving the production system in the forms of NH_3, N_2O, NOx and NO_3^-. Environmental impacts are expressed both on a per hectare of farmland and per kg of FPCM basis.

Emissions associated with the production of resources used on dairy operations (upstream sources) are included in the LCA (Rotz et al., 2018). Upstream sources include the production of fuel, electricity, fertilizer, purchased feed, machinery, seed and pesticide. Emission or consumption values used for these upstream sources are listed in Table 1. Estimates for purchased grain and forage were obtained using IFSM simulations of crop farms where the environmental impacts were divided by the feed dry matter produced and added to that for transport. Simulations of heifer production operations were used to determine footprints for any replacement heifers purchased or sold from the farm.

A biophysical allocation method was used to remove the impacts of animals sold to the beef industry (IDF, 2015). The portion allocated to milk varied among farms from 73% to 95% depending upon the mass of milk sold from the farm relative to the mass of animals sold. Averaged over all production systems, about 87% of each environmental impact was allocated to the milk produced with no effect directly related to the

Table 1
Emission or use factors for production of purchased resources and feeds, including transport and upstream sources, used in IFSM to determine cradle-to-farm gate footprints of dairy production systems in Pennsylvania.

Resource	Unit	Greenhouse gas emission, kg CO_2e	Fossil energy use, MJ	Blue water use, L	Reactive N loss, g N
Energy[a]					
Fuel	/L	0.522	4.01	–	0.48
Electricity	/kWh	0.629	5.00	–	0.27
Fertilizer[a]					
Nitrogen	/kg N	3.11	62.4	–	0.91
Phosphate	/kg P_2O_5	1.84	32.5	–	1.87
Potash	/kg K_2O	1.30	18.4	–	0.53
Lime[a]	/t	14	190	–	9.0
Machinery[b]	/kg mass	3.54	42.6	–	1.22
Seed[c]	/kg	0.30	85.0	2.0	3.0
Pesticide[b]	/kg a.i.	22.0	275	–	11
Plastic wrap[d]	/kg	2.0	50.0	–	–
Purchased or sold heifers[c]	/kg BW	14.0	25.0	100	0.16
Purchased feed					
Maize grain[c]	/kg DM	0.37	3.58	10.0	4.9
Hay[c]	/kg DM	0.18	1.16	1.0	0.9
Soybean meal[e]	/kg DM	0.37	4.27	10.0	2.2
Protein mix[f]	/kg DM	0.82	6.25	10.0	1.0
Fat[f]	/kg DM	1.52	12.2	5.0	1.0
Mineral and vitamin mix[f]	/kg DM	1.62	16.2	6.0	0.0

[a] Obtained from BASF's Eco-efficiency analysis tool representative of U.S. national values (BASF, Ludwigshafen, Germany).
[b] Obtained from the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model (Argonne National Laboratory, Argonne, IL).
[c] Obtained from simulated farms using the Integrated Farm System Model (USDA, 2018). Phosphorus loss in maize grain production was 0.12 g/kg DM produced.
[d] Rotz et al. (2010).
[e] Derived from simulations of maize and soybean crop farms using the Integrated Farm System Model (USDA, 2018) and processing resource use with an economic allocation among the coproducts of the grains produced.
[f] Unpublished data (Greg Thoma, University of Arkansas, Fayetteville, AR).

production strategy used.

2.2. Grass-based dairy farms

We gathered information on management practices from eight, grass-based farms spread from northern to southern areas of the eastern half of Pennsylvania. All farms followed organic production practices, but not all were certified organic. To determine significant differences in the characterisitics of the all-grass and grass with grain farm types, values from the four farms of each type were treated as replicates in a single-factor analysis of variance with a probability less than 0.05 considered as significant.

Using the information gathered, each farm was simulated with IFSM to verify long-term performance and to quantify nutrient flows and losses from the farm and other environmental footprints. Simulations used historical daily weather data and soil characteristics representative of the location of each farm. Weather data were obtained from the Integrated Surface Database of the National Climatic Data Center of the National Oceanic and Atmospheric Administration (NOAA, 2019). Daily data included solar radiation; minimum, maximum and mean temperature; precipitation; and average wind speed (Table 2). Soil characteristics were obtained from the Web Soil Survey (USDA-NRCS, 2019). An "area of interest" was defined over land where the farm was located and predominant soils were identified. Soil characteristics used were clay, silt and sand contents, bulk density and available water holding capacity (Table 3). This region has karst topography where soils are well-drained with a moderate clay content and moderate to low available water holding capacity.

Simulated production costs and incomes were included in our analysis using long-term relative prices in current dollars (Rotz et al., 2018). This analysis provided a relative cost comparison of the production practices, but values should not be viewed as the actual costs or returns for the producers. Important prices included fuel ($0.85/l), electricity ($0.12/kWh), organic grain ($518/t DM), hay ($330/t DM), minerals and vitamins ($496/t) and bedding material ($110/t). Crop seeding costs were $198/ha for perennial grassland and $86/ha for annual forage crops. Equipment used on the farms was amortized over 14 years with a remaining value of 30% of the initial cost. Facilities were amortized over 30 years with no remaining value after that period. Milk prices received were set to that reported by the producer and cull cows were sold for $0.44/kg of body weight. Milk price varied among farms dependent upon their market as all-grass fed, certified organic or regular milk.

2.3. Comparison of dairy production systems

Since weather and soils varied among farms, further simulations were conducted for a more standardized comparison of production systems. Farms of the same size representing all-grass and grass with grain production systems were simulated with IFSM using the same weather data (Harrisburg, PA) and soil characteristics. A generic soil was used with characteristics similar to the average of the actual farm soils. This soil had clay, silt and sand contents of 20, 51 and 29%, respectively with a bulk density of 1.33 g/cm^3 and available water holding capacity of 108 mm.

The average or most typical conditions found on the actual farms were used to set model parameters for the different production systems. Parameters were the same for the two farm types except where the observed conditions were significantly or substantially different. Each farm managed 100 cows and 67 heifers on 134 ha of pasture and cropland. The land area included 120 ha of perennial grassland and 13.4 ha of an annual small-grain forage. Cow replacement rates were set to 14% and 26% for the all-grass and grass with grain farms, respectively. Each farm produced just enough forage to meet their long-term needs, i.e. no purchasing or selling of forage. For those that supplemented with grain, all grain was purchased and imported to the farm.

An additional simulation was added to represent a common production system in Pennsylvania where cows are maintained and fed in confinement. For consistency, the farm had a 100-cow herd on 134 ha of land, and the farm was simulated using the same daily weather and soil characteristics used for the grass-based production systems. Following the characterisitcs of most Pennsylvania dairy farms (Holly et al., 2019), cropland included 64.7 ha of maize producing both silage and grain with 28.3 ha of alfalfa and 40.5 ha of perennial grassland. The annual cow replacement rate was 38% with 82 heifers produced on the farm including those greater than and those less than one year of age. Annual milk production was set at the state average of 9459 kg per cow (USDA-NASS, 2019). Milk fat content was 3.5% giving a yield of 8725 kg FPCM. Cows were housed in free stall barns where manure was removed daily and stored as slurry in a bottom-loaded tank. Replacement heifers were housed in a bedded pack barn. All manure was removed and applied to cropland in the spring and fall.

A final comparison was to a summary of all dairy farms in Pennsylvania. In a previous study, dairy farms were characterized and evaluated throughout the state to determine the environmental impacts of dairy production (Holly et al., 2019; Rotz et al., 2020). Total and average state-wide impacts were determined weighted by the amount of milk produced by individual farms. The average of all dairy farms in the state had 71 cows and 58 replacement heifers on 113 ha of crop and pasture land. Farms produced most of their forage and some of the

Table 2
Summary of 25 years of weather data (daily solar radiation, daily mean temperature, annual precipitation and daily wind speed)[a] used in simulating grass-based dairy farms in Pennsylvania.

City	Solar radiation, MJ/m^2		Temperature, °C		Precipitation, mm		Wind, m/s	
	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.
Chambersburg	13.8	1.25	11.7	0.67	1084	216	3.4	0.46
Harrisburg	14.3	0.40	12.1	0.68	1066	182	3.4	0.44
Lancaster	13.3	1.33	12.1	0.85	1074	167	3.6	0.38
Lewistown	13.4	0.68	11.0	0.68	1067	197	2.8	0.28
State College	13.4	0.68	10.2	0.80	1006	197	2.8	0.28
Williamsport	13.2	0.70	10.5	0.66	1059	164	3.0	0.38

[a] Obtained from the Integrated Surface Database of the National Climatic Data Center, National Oceanic and Atmospheric Administration (NOAA, 2019).

Table 3
Soil characteristics used for locations simulated across Pennsylvania.

Farm	Predominant soil type	Soil texture,[a] %			Density, g/cm^3	Available water, mm
		Clay	Silt	Sand		
All-grass						
1	Ungers loam	15.6	44	40.4	1.31	130
2	Volusia channery silt	17	60	23	1.30	90
3	Berks-Weikert complex	21	48	31	1.36	90
4	Covegap cobbly sandy loam	18	32	50	1.30	140
Grass with grain supplementation						
1	Berks channery silt loam	15	61	24	1.36	80
2	Duffield silt loam	24	54	22	1.32	130
3	Mardin channery silt loam	15	60	25	1.30	88
4	Hagerstown silty clay loam	33	52	15	1.36	120

[a] Soil characteristics based upon common soils found in each region as obtained from the Web Soil Survey (NRCS, 2019).

maize grain required to feed their cattle. Most of the milk in the state was produced on farms with cows fed total mixed rations in confinement. This comparison to all Pennsylvania dairy farms provided a broader perspective of grass-based systems relative to all dairy farms throughout the state. The number of grass-based farms and the milk produced by them was small compared to all farms in the state, so they had little effect on the overall results for the state.

3. Results and discussion

IFSM simulations indicated environmental and economic tradeoffs for grass-based dairy farms. Grass-based production systems generally showed lower nutrient losses and environmental footprints than confinement systems. However when considered as an intensity expressed per kg FPCM produced, grass-based production often showed greater nutrient losses and environmental footprints than confinement systems. With current pricing, grass-based farms showed clear economic advantage, both in terms of returns per hectare and per kg FPCM.

3.1. Characteristics of grass-based dairy farms

The eight grass-based dairy farms varied in size from 26 to 240 cows with an average around 100 cows (Table 4). This size was representative of dairy farms in the state, where the recent average herd was 71 cows (Holly et al., 2019). As is often reported for grazing herds, the annual cow replacement rate was relatively low varying from 8 to 35% with an average of 20%. Replacement heifers were produced on all farms with an average of 0.58 heifers maintained per cow.

Cattle breed included Jersey, Ayrshire and Holstein genetics with most cattle being a mixed breed of Jersey and Holstein. With these different genetics, fat content of the milk produced varied among farms from 3.8 to 4.5%. Cows on the all-grass farms averaged 4.4% fat and those supplemented with grain averaged less at 4.05% fat ($P < .05$). Annual milk production varied from 3039 to 6785 kg FPCM/cow. Herds fed only grass had lower production ($P < .05$) averaging 3651 kg FPCM/cow while those supplemented with grain averaged 6049 kg FPCM/cow.

Housing facilities varied with some difference between the all-grass and grass with grain farm types. On farms that supplemented with grain, animals spent more time in barns where free stalls were commonly used for cows with a bedded pack used in heifer housing. For the all-grass farms, cows were typically housed in a bedded-pack barn with no housing for heifers. Manure from free stall barns was stored and applied as a slurry and bedded pack manure was handled as a solid. Most of the manure was surface applied to perennial grassland without incorporation into the soil.

Farm areas varied from 40.5 to 251 ha with an average of 124 ha. Land areas per cow were similar across both types of farms averaging 1.4 ha/cow (Table 4). Essentially all land was used to produce forage. One farm included an oat grain crop where the grain was sold and the straw was harvested and used for bedding of cattle. Most of the land was in perennial grassland. Five of the farms reported this as permanent grassland while three reported reestablishing 10–15% of the grassland per year.

Legumes were reported in the grassland with the predominant species being white clover. The portion of legume in the sward was reported between 10 and 40% with an average about 25% for both farm types. Annual forage crops were grown on half of the farms of each type. Annual crops included triticale, field peas and oats, sorghum, sorghum-sudan grass, and maize silage. Annual crops were established using moderate (disk and/or harrow) to heavy (plow with disk and harrow) tillage operations.

Each of the surveyed farms was simulated to verify that the model properly represented the performance of the operation. Actual farm and simulated performance data compared were crop yield and feed production, feeds bought and sold, animal numbers, and milk production. Although hard numbers were not available for grass yield and supplemental feed use, we confirmed that simulated data generally agreed with what the producers felt represented long-term production of their farm (Table 4). Producers were asked to provide values that represented this information over multiple years of weather, not necessarily what was happening that particular year. This was particularly true for feed production and use, which can be quite variable from year to year as influenced by weather. This verification helped support that predicted nutrient flows, emissions and production costs were properly represented.

Most of the grass-based farms maintained a long-term balance of forage production with that used, but one farm purchased some forage most years and a couple farms had excess forage to sell during some

Table 4
Farm size, reported milk price, and simulated feed use for grass-based dairy farms in Pennsylvania.

Farm characteristic[a]	All grass farms				Grass with grain farms				Average	Average
	1	2	3	4	1	2	3	4	All-grass	Grass with grain
Total fam area, ha	85.0	179.3	146.9	121.4	60.7	250.9	106.8	40.5	133.1	114.7
Grass area, ha	85.0	149.7	132.3	121.4	40.5	202.4	106.8	40.5	122.1	97.5
Stand life, years	100	10	100	15	10	100	100	100	56	78
Legume portion in sward, %	25	30	20	25	30	30	10	40	25	28
Other crop area, ha	0.0	29.5	14.6	0.0	20.2	48.6	0.0	0.0	11.0	17.2
Number of cows	85	80	133	85	95	240	43	26	96	101
Number of heifers	45	29	44	60	45	200	31	18	45	74
Heifers/cow	0.53	0.36	0.33	0.71	0.47	0.83	0.72	0.69	0.48	0.68
Replacement rate, %	8	12	12	24	35	33	24	10	14	26
Annual milk production, kg FPCM/cow	3039	4396	4237	2931	6785	5988	5112	6312	3651	6049*
Milk fat content, %	4.2	4.5	4.4	4.5	4.1	4.1	3.8	4.2	4.4	4.1*
Land use, ha/animal	0.65	1.64	0.83	0.84	0.43	0.57	1.44	0.92	0.99	0.84
Land use, ha/cow	1.00	2.24	1.10	1.43	0.64	1.05	2.48	1.56	1.44	1.43
Milk price, $/kg	0.77	0.78	0.82	1.06	0.55	0.66	0.75	0.55	0.86	0.61*
Grazed forage consumed, t DM	306	181	438	187	229	445	62	100	278	209
Forage bought (sold), t DM	0	0	38	(12)	0	0	(19)	(40)	5	(16)
Concentrate fed, t DM	3	3	5	3	194	415	62	39	3	178*
Feed consumed, kg DM/animal/day	9.7	11.5	12.5	9.7	12.4	11.2	10.4	12.4	10.8	11.6
Feed consumed, kg DM/cow/day	14.8	15.7	16.7	16.5	18.2	20.6	18.0	20.9	15.9	19.4*
Herd feed efficiency, kg FPCM/kg DM	0.56	0.77	0.70	0.49	1.02	0.80	0.78	0.83	0.60	0.86*

* Indicates a significant difference between the all-grass and grass supplemented with grain farms ($P < .05$).
[a] Most farm characterisitcs were obtained through farm visits. Feed production and use data are simulated results confirmed by the producer as typical annual use.

weather years. On the all-grass farms, the only concentrate fed was that of supplemental minerals and vitamins. For farms where grain and protein supplements were fed, simulated daily concentrate use averaged 5.5 kg DM/cow during lactation or 4.6 kg DM/cow over the full year (Table 4). Total annual feed consumption for the whole herd, including all forage and pasture, averaged 15.9 kg DM/cow per day for the all-grass farms and 19.4 kg DM/cow per day for those supplementing with grain and protein feeds ($P < .05$). This indicated significantly different ($P < .05$) whole-herd feed efficiencies of 0.63 and 0.86 kg FPCM/kg of feed dry matter consumed for the all-grass and grass with grain farms, respectively.

3.2. Environmental impacts of grass-based farms

For most environmental metrics considered, there were large variations among farms (Table 5). In comparing values for the two farm types of all-grass and grass with grain, differences were observed but there was often overlap among individual farm values, and few differences were determined as statistically significant.

Among farms, simulated ammonia emissions ranged from 7.3 to 20.4 g N/kg FPCM (Table 5). Emissions from the all-grass farms averaged less than those from farms supplementing with grain when expressed per unit of farmland and greater when expressed per unit of milk produced with no significant differences. Most of the difference was due to a farm that reported a high (40%) legume content in their pasture (Table 4, grass with grain farm 4). This contributed to less efficient use of protein by the cattle, greater urea excretion, and thus more ammonia emission from pastures and other manure sources on the farm (Rotz et al., 2014). Due to the high protein intake on this farm, similar increases relative to other farms were found for nitrate leaching, denitrification losses and nitrate runoff (Table 5).

Predicted phosphorus runoff losses were primarily influenced by soil erosion, which in turn, was determined by the amount of annual forage crops grown and the tillage practices used to establish those crops (Table 5). The greatest simulated phosphorus loss and soil erosion came from the all-grass farm 2 that included annual crops of triticale, sorghum and field peas, and these crops were established using heavy tillage with moldboard plow, disk and harrow operations. For farms that used permanent pastures with little renovation, simulated phosphorus runoff was low. Averaged over farms, similar losses occurred from both farm types. For the grass with grain system, losses expressed per unit of milk included losses associated with producing the purchased grain. This inclusion offset by greater milk production through grain supplementation produced losses per unit of milk similar to those from all-grass farms where no grain was purchased.

Long-term accumulation of soil phosphorus was relatively low on both types of grass-based farms and the amount accumulated was related to the amount of poultry manure brought onto the farm, primarily for nitrogen fertilization (Table 5). Although the all-grass operations showed greater accumulation, the levels were small and not related to farm type.

There was a trend toward less energy and water use on all-grass farms (Table 5). With less reliance on purchased feed, less energy and water were used by this type of farm when expressed per unit of farmland or per unit of milk. Because of the large variation among farms though, these differences were not significant. The average of all reactive nitrogen losses, including that lost in producing resources used on the farm, indicated less loss per unit of land area for the all-grass farms, but less for the grass with grain farms when expressed per unit of milk produced. Total GHG emission averaged less for the all-grass farms. With the lower milk production though, the GHG emission intensity or carbon footprint expressed per unit of milk produced was 26% greater ($P < .05$) than that averaged over the four farms supplementing with grain.

Our economic analysis revealed some advantage for the all-grass farms (Table 5). Cost of production expressed per hectare of farmland averaged 40% less for the all-grass farms, but due to lower milk yield, this cost was 20% greater than that of the grass with grain farms when expressed per unit of milk produced. Although these trends were found, they were not significantly different. With the greater price for milk from the all-grass farms ($p < .05$), net returns to management and labor were similar across the two farm types on a per hectare basis. Through direct sales of portions of their milk, two of the all-grass farms had a greater profit margin when expressed per unit of milk produced.

3.3. Comparision of dairy production systems

Characteristics of the grass-based and confinement dairy production systems using farms of the same size, soil type and weather conditions are provided in Table 6. Forage production and use was similar across

Table 5
Predicted environmental impacts of the grass-based dairy farms simulated in Pennsylvania.

	All grass farms				Grass with grain farms				Average of farms	
	1	2	3	4	1	2	3	4	All grass	Grass & grain
Ammonia volatilized, kg/ha	47.6	15.4	32.1	41.9	77.4	44.6	12.1	44.6	34.2	44.7
Ammonia volatilized, g N/kg FPCM	15.7	7.8	8.4	20.4	7.3	7.8	5.9	11.0	13.1	8.0
Nitrate leached, kg/ha	31.4	25.9	18.9	83.5	17.0	28.6	30.5	34.1	39.9	27.5
Nitrate leached, g N/FPCM	10.3	13.2	4.9	40.7	1.6	5.0	14.8	8.4	17.3	7.5
N denitrified, kg/ha	9.5	9.5	12.8	22.3	22.6	15.9	7.2	14.3	13.5	15.0
N denitrified, g N/FPCM	3.1	4.9	3.3	10.9	2.1	2.8	3.5	3.5	5.5	3.0
N runoff, g N/ha	0.0	0.8	1.1	2.2	1.7	0.4	0.4	0.5	1.0	0.8
N runoff, mg N/FPCM	15.9	432	283	1049	165	72.4	173	124	445	134
P runoff, g P/ha	0.06	0.86	0.53	0.04	0.42	0.46	0.31	0.16	0.37	0.34
P runoff, mg P/FPCM	20.6	441	137	19.7	75.8	115	186	68.6	155	111
Soil P accumulation, kg P/ha	7.1	4.4	1.2	9.2	3.8	9.0	2.9	0.1	5.5	4.0
Soil P accumulation, g P/FPCM	2.3	2.2	0.3	4.5	0.4	1.6	1.4	0.0	2.3	0.8
Sediment erosion, kg/ha	35	1479	692	16	657	581	275	83	555	399
Blue water use, Mg/ha	35.2	31.0	50.3	22.7	103	152	40.1	51.7	34.8	86.7
Blue water use, kg/kg FPCM	11.6	15.8	13.1	11	9.7	26.6	19.5	12.8	12.9	17.1
Energy use, GJ/ha	4.17	6.16	6.06	4.77	24.19	14.25	7.65	8.39	5.3	13.6
Energy use, MJ/kg FPCM	1.37	3.14	1.58	2.33	2.28	2.49	3.72	2.07	2.10	2.64
Reactive N footprint, g N/ha	58.5	36.6	46.0	75.4	120.	58.1	26.8	68.2	54.1	68.3
Reactive N footprint, g N/kg FPCM	19.2	18.7	12.0	36.8	11.3	10.1	13.0	16.8	21.7	12.8
Carbon footprint, Mg CO2e/ha	4.29	3.06	5.10	3.90	11.04	6.64	2.65	5.15	4.1	6.4
Carbon footprint, kg CO2e/kg FPCM	1.41	1.56	1.33	1.90	1.04	1.16	1.29	1.27	1.55	1.19*
Production cost, $/ha	2162	1201	1802	1683	5063	3323	1344	1851	1710	2895
Production cost, $/kg FPCM	0.71	0.61	0.47	0.82	0.48	0.58	0.65	0.46	0.65	0.54
Net return to management & labor, $/ha	309	259	1275	452	894	561	309	586	574	588
Net return to management & labor, $/kg	0.10	0.13	0.33	0.22	0.08	0.10	0.15	0.14	0.20	0.12

* Indicates a significant difference between the all-grass and grass-supplemented with grain farms ($P < .05$).

Table 6
Normalized all-grass, grass with grain supplementation, and confinement-fed dairy production systems.

	All grass	Grass with grain	Confinement fed
Total crop and pasture area, ha	133.6	133.6	133.6
Grass area, ha	120.2	120.2	40.5
Other crop area, ha	13.4	13.4	93.1
Number of cows	100	100	100
Number of heifers	67	67	82
Heifers/cow	0.67	0.67	0.82
Replacement rate, %	14	26	38
Annual milk production, kg FPCM/cow	3879	6056	8725
Land use, ha/animal	0.80	0.80	0.73
Land use, ha/cow	1.34	1.34	1.34
Hay and silage produced, t DM	282	322	560
Grazed forage consumed, t DM	348	208	84
Forage bought (sold), t DM	0	0	0
Concentrate fed, t DM	4	190	312
Feed consumed, kg/animal/day	10.4	11.7	14.4
Feed consumed, kg/cow/day	17.3	19.6	26.2
Herd feed efficiency, kg FPCM/kg feed DM	0.61	0.85	0.91

the farm types with grain making up 0, 26, and 33% of total feed consumption for the all-grass, grass with grain and full confinement production systems, respectively. Total feed consumption increased with the increase in milk yield, but whole-herd feed efficiency also improved from 0.61 kg FPCM/kg DM of feed with all grass feeding to 0.91 kg FPCM/kg DM of feed with full confinement feeding (Table 6).

Nitrogen losses from the all-grass production system were somewhat greater, and when expressed per unit of milk produced, they were much greater than that from the grass with grain system (Table 7). This was primarily due to differences in manure handling. Following the practices of the actual farms, cows on the grass with grain system were housed in free stall barns with liquid manure handling, and bedded pack barns were used in the all-grass system with solid manure handling. With the liquid manure, more of the nitrogen infiltrated into the soil providing less runoff. Nitrogen losses from the grass with grain farms were similar to those found on the full confinement farm except that surface runoff losses were less. Greater runoff loss occurred from the confinement system due to greater use of annual crops, particularly maize, which required more fertilizer use with more frequent tilling of the land and less ground cover. The total of all reactive N losses was less for the grass-based dairies than that of the confinement dairy. When expressed per unit of milk produced, this nitrogen emission intensity was much greater for the all-grass production system.

Similar to nitrogen runoff, predicted phosphorus runoff loss was a little greater from the all-grass production system compared to the grass with grain system and much greater when expressed per unit of milk produced (Table 7). Phosphorus loss from both of the grass-based systems was much less than that predicted for the full confinement operation where much of the farmland was tilled each year. Expressed per unit of milk produced, the loss from the grass with grain system (which included loss from the farm producing purchased grain) was less than that of the other two production systems. A whole-farm balance, showed the lowest buildup of soil phosphorus for the confinement operation (Table 7). This was obtained through more efficient fertilizer use. The confinement operation used 56 kg/ha of phosphate fertilizer when alfalfa land was reestablished, which was enough to maintain a long-term balance. The grass-based systems used poultry manure, primarily to meet nitrogen needs, which led to over application of phosphorus. Although this buildup of soil phosphorus was relatively small, the accumulation over time would potentially lead to greater runoff losses in the future.

As indicated by the individual farm simulations, fossil energy use was much less for the all-grass production system than for the system using grain supplementation (Table 7) due primarily to the energy required to produce and transport the grain. As would be expected, the greatest energy use was with the confinement feeding system. When expressed per unit of FPCM produced, the lowest user was still the all-grass system where few machinery operations were used. The other two systems had similar energy use per unit of FPCM, 30% greater than that of the all-grass system. Due to water use in producing purchased feeds,

Agricultural Systems 184 (2020) 102887

Table 7
Predicted environmental impacts and economics of simulated grass-based and confinement dairy production systems and the weighted average of all dairy farms in Pennsylvania.

	Production system			All Pennsylvania farms*
	All grass	Grass with grain	Confined fed TMR	
Ammonia volatilized, kg/ha	51.0	43.7	62.4	33.8
Ammonia volatilized, g N/kg FPCM	17.6	9.6	9.6	6.3
Nitrate leached, kg/ha	23.0	21.3	33.9	15.6
Nitrate leached, g N/kg FPCM	7.9	4.7	5.2	2.9
Denitrified N, kg/ha	13.0	12.0	15.9	11.1
Denitrified N, g N/kg FPCM	4.5	2.6	2.4	2.1
Runoff N, kg/ha	1.2	0.7	2.2	0.7
Runoff N, mg N/kg FPCM	425	148	331	124
Runoff P, kg/ha	0.67	0.56	1.47	0.43
Runoff P, mg P/FPCM	232	161	268	128
Soil P accumulation, kg P/ha	5.5	9.1	1.5	3.7
Soil P accumulation, g P/FPCM	1.9	2.0	0.2	0.7
Blue water use, Mg/ha	46.5	58.9	86.9	75.5
Blue water use, kg/kg FPCM	16.0	13.0	13.3	14.0
Energy use, GJ/ha	5.81	11.8	16.9	14.5
Energy use, MJ/kg FPCM	2.00	2.60	2.58	2.69
Reactive N footprint, g N/ha	65.7	61.7	82.8	45.4
Reactive N footprint, g N/kg FPCM	2.54	1.53	1.42	0.94
Carbon footprint, Mg CO2e/ha	4.24	5.21	8.36	5.34
Carbon footprint, kg CO2e/kg FPCM	1.46	1.15	1.28	0.99
Milk price, $/kg	0.81	0.61	0.40	0.40
Production cost, $/ha	1478	2523	2303	1678
Production cost, $/kg FPCM	0.51	0.56	0.35	0.31
Net return to management & labor, $/ha	855	324	670	529
Net return to management & labor, $/kg FPCM	0.29	0.07	0.10	0.10

* Results from an analysis representing all dairy farms in Pennsylvania (Rotz et al., 2020).

blue water use was least for the all-grass farm (Table 7). It was slightly greater than the other production systems though, when expressed per unit of milk produced. Greenhouse gas emissions varied from a low for the all-grass system to the highest with the confinement system (Table 7). Expressed per unit of milk, the greatest GHG intesity came from the all-grass system with the lowest from the grass with grain system.

Simulated production costs were lowest for the all-grass production system with similar costs for the other two systems (Table 7). Expressed per unit of milk produced, total production cost was much less for the confinement operation. Considering the greater milk price, the all-grass system provided the largest net return to management and labor, particularly when expressed per unit of milk produced.

3.4. Comparison to Pennsylvania dairy production

The final comparison was to results found in the previous study representing all dairy farms in Pennsylvania (Rotz et al., 2020). In general, feed production and use on Pennsylvania dairy farms was similar to that simulated for the confinement fed dairy production system. Over all farms, total feed consumption of the herd (including heifers) was 25.4 kg DM/cow per day with a feed efficiency of 0.94 kg FPCM/kg DM. These values were similar to those predicted for the confinement production system of our current study (Table 6), which helped verify or support our analysis.

Nutrient losses from the production systems in the current study were generally greater than those found across all Pennsylvania farms. Through less efficient fertilizer use, less efficient protein feeding, and lower milk production, greater nitrogen losses per unit of land area or per unit of milk were found on grass-based dairies (Table 7). The greatest difference was for nitrate leaching, which was primarily due to the greater leaching of nitrogen from urine deposits of grazing animals in the grass-based systems. The nitrogen applied to the small area of a urine spot is in great excess of plant growth requirement leading to greater leaching, volatilization, nitrification and denitrification emissions (Rotz, 2004). Accumulation of soil phosphorus per unit of farmland on grass-based systems was similar to that of Pennsylvania dairies (Table 7). When expressed per unit of milk produced, accumulation was greater on the relatively low milk producing grass-based farms. For this particular metric though, accumulation over the farm area is the more important measure with potential impacts at regional and watershed scales.

Life cycle fossil energy use in milk production was greater over all Pennsylvania farms than that used in grass-based operations whether expressed per unit of land or milk produced (Table 7). This greater energy use was due to greater use of machinery operations for tillage, planting, harvesting and feeding of annual crops. Greenhouse gas emissions per unit of farmland were similar between grass-based and all Pennsylvania farms. With the intensity expressed per unit of FPCM produced though, the greater milk production per cow over all Pennsylvania farms (Table 7, last column) created a lower intensity for the milk produced through confinement and semi-confinement production systems (Rotz et al., 2020).

Cost of production and net return data for all Pennsylvania dairy farms came from farm records obtained through a farm survey (Holly et al., 2019). Since the costs come from different sources and methodologies, their comparison is only general. Cost of production and net return for the simulated confinement production system were similar to those reported for Pennsylvania dairy farms, which helped verify our simulated systems. Production cost per hectare for Pennsylvania farms fell between those predicted by the model for the two grass-based systems (Table 7). When expressed per unit of milk produced, reported costs were much less for the Pennsylvania farms. Due to the greater milk price received though, the grass-based farms were more profitable per unit of land or per unit of milk produced (Table 7).

3.5. Other considerations

Simulation of the farms provides information on the performance, environmental impacts and economics of production systems. Environmental impacts of importance in dairy production depend upon the desired goal. Losses of nutrients per unit of land are important to consider when the goal is to reduce the impact on watersheds or other local areas. For long-term sustainability of food production, the goal becomes producing food with the least environmental harm and use of available land and resources. Thus, the impact per unit of milk produced becomes most important.

The two grass-based dairy production systems offered lower environmental impacts than the traditional confinement dairy for most of the metrics considered when expressed per unit of farmland. In central and eastern Pennsylvania, there is great interest in reducing nutrient losses to the Chesapeake Bay, and in the western part of the state, there is concern for impacts on Lake Erie. Nutrient losses in these watersheds are contributing to eutrophication of these large and important waterbodies (Boesch et al., 2001; Kleinman et al., 2019). Thus, priority in environmental sustainability assessment in this region has been given to reducing nutrient losses per unit of land. With less loss per unit of land, fewer nutrients should enter the waterbodies. From this perspective, grass-based dairy systems provide a benefit by reducing nitrogen and phosphorous losses from farms and potentially reducing pollution to downstream surface waters.

Energy use and GHG emissions have impacts far beyond a local watershed, so it is important to view these environmental indicators from a global perspective. From this perspective, all-grass dairies can provide more milk per unit of fossil energy used. Because more intensive systems using grain feeding can generate lower GHG emissions per unit of FPCM, these farming systems may translate to lower total emissions when aggregated across a global or regional supply chain. With a growing world population and limited land and other resources, grain-supplemented dairy systems with lower GHG emissions per kg FPCM may, therefore, have climate mitigation advantages compared to more extensive grass systems.

This study is one the first whole-farm environmental analyses of all-grass dairy farms in the U.S. and adds new data to the growing literature of LCA's of milk production systems. A recent meta-analysis of LCA's comparing confinement and mixed grass and grain dairies in Europe found that grass-based dairies showed slightly lower carbon footprints per kg FPCM than confinement farms on average, with considerable variation across studies (Lorenz et al., 2019). This meta-analysis showed that within a particular management system type (i.e. confinement or grass-based), increases in animal milk yield were correlated with lower emissions per kg FPCM. To this point, we found similar relationship between milk production and carbon footprint across our sample of grass-based dairies. The large variation in milk yield among farms along with other management differences indicates opportunities to improve the median production and environmental performance of grass-based dairies.

When assessing GHG emissions from grass-based systems, carbon sequestration is often noted as an important benefit for perennial grassland. When cropland or other land depleted in soil organic matter is converted to perennial grassland, considerable amounts of carbon can be sequestered or stored in the soil through the accumulation of organic matter. Depending upon soil properties and initial conditions, this accumulation of organic matter can continue for 20 or more years (Franzluebbers, 2005). The rate of accumulation decreases with time until the soil reaches a long-term balance where carbon emissions equal that added through plant and manure residue. During this transition period, soil accumulation of carbon can potentially offset a substantial portion of the carbon footprint of the milk produced in grass-based systems. Reported rates of carbon sequestration following the conversion of cropland to perennial grassland vary widely. Long-term average rates in temperate regions often fall in the range of 0.5 to 1.0 Mg C/ha per year over a 15 to 20 year transition period (Franzluebbers, 2005; Spangler et al., 2011; Kaempf et al., 2016). Following this period, little additional sequestration can be expected (Skinner, 2008). Applied to these farms, this range gives a potential carbon offset of 0.6 to 1.3 kg CO_2e/kg FPCM for the all-grass production system and 0.4 to 0.8 kg CO_2e/kg FPCM for the grass with grain system. This indicates that these systems can have a much lower carbon footprint than confinement systems during this transition period. Beyond this period though, grass-based systems lose this benefit. Management transitions in annual cropping systems, such as cover cropping or no-tillage, can also result in carbon sequestration, but at lower rates of 0.14 to 0.17 Mg C/ha per year with shorter transition periods (West and Marland, 2002).

4. Conclusions

For many metrics considered, grass-based grazing dairy production systems with or without supplemental grain feeding had less environmental impact on a per unit of farmland basis, but greater impact per unit of milk produced than a more traditional confinement feeding system. As exceptions to these general trends, we found that soil P accumulation was greater on grass-based dairies while energy use was lowest on all-grass dairies, on both a per unit land and per unit of milk basis. Production costs were lower for the all-grass dairies than those supplemented with grain. With a greater milk price, the all-grass dairy production system provided greater profitability per unit of land use and per unit of milk produced compared to the other production systems of similar size. These findings suggest that grass-based systems can be a viable strategy for sustaining family-scale dairies and for managing water quality in local watersheds. From the perspective of global supply chains, confinement systems may provide smaller nutrient losses and aggregate carbon footprints by producing more food per unit of impact.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank the eight dairy producers who collaborated on this project by opening their farms for visits and providing the data and information needed to support this analysis and comparison of production systems. Funding for this work was partially provided through a NIFA Beginning Farmer and Rancher Development Program grant (# 2017-70017-26849) and the USDA-ARS project 8078-11130-003-00D. USDA is an equal opportunity provider and employer.

References

Belflower, J.B., Bernard, J.K., Gattie, D.K., Hancock, D.W., Risse, L.M., Rotz, C.A., 2012. A case study of the potential environmental impacts of different dairy production systems in Georgia. Agric. Syst. 108, 84–93.
Benbrook, C.M., Davis, D.R., Heins, B.J., Latif, M.A., Leifert, C., Peterman, L., Butler, G., Faergeman, O., Abel-Caines, S., Baranski, M., 2018. Enhancing the fatty acid profile of milk through forage-based rations, with nutrition modeling of diet outcomes. Food Sci. Nutr. 2018 (6), 681–700.
Bergman, M.A., Richert, R.M., Cicconi-Hogan, K.M., Gamroth, M.J., Schukken, Y.H., Stiglbauer, K.E., Ruegg, P.L., 2014. Comparison of selected animal observations and management practices used to assess welfare of calves and adult dairy cows on organic and conventional dairy farms. J. Dairy Sci. 97, 4269–4280.
Boesch, D.F., Brinsfield, R.B., Magnien, R.E., 2001. Chesapeake Bay eutrophication: scientific understanding, ecosystem restoration and challenges for agriculture. J. Environ. Qual. 30, 303–320.
Bonifacio, H.F., Rotz, C.A., Leytem, A.B., Waldrip, H.M., Todd, R.W., 2015. Process-based modeling of ammonia and nitrous oxide emissions from open lot beef and dairy facilities. Trans. ASABE 58 (3), 827–846.
Cardoso, C.S., Hötzel, M.J., Weary, D.M., Robbins, J.A., von Keyserlingk, M.A.G., 2016. Imagining the ideal dairy farm. J. Dairy Sci. 99, 1663–1671.
Franzluebbers, A.J., 2005. Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA. Soil Till. Res. 83, 120–147.
Gerdes, S., 2019. Grass-Fed Dairy Sector Small, but Growing Rapidly: Organic and Grass-Fed Dairy Products Offer Higher Levels of Healthy Omega-3s. Dairy Foods. https://www.dairyfoods.com/articles/93994-grass-fed-dairy-sector-small-but-growing-rapidly, Accessed date: 15 January 2020.
Holly, M.A., Gunn, K.M., Rotz, C.A., Kleinman, P.J.A., 2019. Management characteristics of Pennsylvania dairy farms. Appl. Anim. Sci. 35, 325–338.
IDF, 2015. A common carbon footprint approach for dairy. In: Bulletin 479/2015.

International Dairy Federation, Brussels, Belgium. https://www.fil-idf.org/wp-content/uploads/2016/09/Bulletin479-2015_A-common-carbon-footprint-approach-for-the-dairy-sector.CAT.pdf, Accessed date: 19 July 2019.

IPCC, 2006. Guidelines for National Greenhouse Inventories. vol. 4: Agriculture, forestry and other land use International Panel on Climate Change. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html, Accessed date: 19 July 2019.

Jego, G., Rotz, C.A., Belanger, G., Tremblay, G.F., Charbonneau, E., Pellerin, D., 2015. Simulating forage crop production in a northern climate with the Integrated Farm System Model. Can. J. Plant Sci. 95, 745–757.

Kaempf, I., Hoelzel, N., Stoerrle, M., Broll, G., Kiehl, K., 2016. Potential of temperate agricultural soils for carbon sequestration: a meta-analysis of land-use effects. Sci. Total Environ. 566, 428–435.

Kim, D., Stoddart, N., Rotz, C.A., Veltman, K., Chase, L., Cooper, J., Ingraham, P., Izaurralde, R.C., Jones, C.D., Gaillard, R., Aguirre-Villegas, H.A., Larson, R.A., Ruark, M., Salas, W., Jolliet, O., Thoma, G.J., 2019. Analysis of beneficial management practices to mitigate environmental impacts in dairy production systems around the Great Lakes. Agric. Syst. 176, 1–12.

Kleinman, P.J.A., Fanelli, R.M., Hirsch, R.M., Buda, A.R., Easton, Z.M., Wainger, L.A., Brosch, C., Lowenfish, M., Collick, A.S., Shirmohammadi, A., Boomer, K., Hubbart, J.A., Bryant, R.B., Shenk, G.W., 2019. Phosphorus and the Chesapeake Bay: lingering issues and emerging concerns for agriculture. J. Environ. Qual. 48, 1191–1203.

LEAP, 2016. Environmental Performance of Large Ruminant Supply Chains: Guidelines for Assessment. Food and Agriculture Organization. http://www.fao.org/3/a-i6494e.pdf, Accessed date: 23 April 2018.

Leytem, A.B., Bjorneberg, D.L., Rotz, C.A., Moraes, L.E., Kebreab, E., Dungan, R.S., 2018. Ammonia emissions from dairy lagoons in the western U.S. Trans. ASABE 61, 1001–1015.

Lorenz, H., Reinsch, T., Hess, S., Taube, F., 2019. Is low-input dairy farming more climate friendly? A meta-analysis of the carbon footprints of different production systems. J. Cleaner Prod. 211, 161–170.

Müller-Lindenlauf, M., Deittert, C., Köpke, U., 2010. Assessment of environmental effects, animal welfare and milk quality among organic dairy farms. Livestock Sci. 128, 140–148.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, B., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and natural radiative forcing. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J. ... Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

NOAA, 2019. Land-Based Station Data. National Climatic Data Center. National Oceanic and Atmospheric Administration. https://www.ncdc.noaa.gov/data-access/land-based-station-data, Accessed date: 8 May 2019.

Rotz, C.A., 2004. Management to reduce nitrogen losses in animal production. J. Anim. Sci. 82 (E. Suppl), E119–E137.

Rotz, C.A., Mertens, D.R., Buckmaster, D.R., Allen, M.S., Harrison, J.H., 1999. A dairy herd model for use in whole farm simulations. J. Dairy Sci. 82, 2826–2840.

Rotz, C.A., Montes, F., Chianese, D.S., 2010. The carbon footprint of dairy production systems through partial life cycle assessment. J. Dairy Sci. 93 (3), 1266–1282.

Rotz, C.A., Montes, F., Hafner, S.D., Heber, A.J., Grant, R.H., 2014. Ammonia emission model for whole farm evaluation of dairy production systems. J. Environ. Qual. 43, 1143–1158.

Rotz, C.A., Corson, M.S., Chianese, D.S., Montes, F., Hafner, S.D., Bonifacio, H.F., Coiner, C.U., 2018. Integrated Farm System Model: Reference Manual. USDA Agricultural Research Service, University Park, Pennsylvania. https://www.ars.usda.gov/ARSUserFiles/80700500/Reference%20Manual.pdf, Accessed date: 5 April 2019.

Rotz, C.A., Stout, R.C., Holly, M.A., Kleinman, P.J.A., 2020. Regional environmental assessment of dairy farms. J. Dairy Sci. 103 (4) (in press).

Skinner, R.H., 2008. High biomass removal limits carbon sequestration potential of mature temperate pastures. J. Environ. Qual. 37, 1319–1326.

Spangler, L., Vance, G.F., Schuman, G.E., Derner, J.D., 2011. Rangeland Sequestration Potential Assessment. U.S. Department of Energy. https://www.bigskyco2.org/sites/default/files/pdf/BSCSP_Rangeland_Study_Final_Report_2011.pdf, Accessed date: 7 November 2019.

USDA-ARS, 2018. Integrated Farm System Model, Version 4.4. Agricultural Research Service, University Park, PA. https://www.ars.usda.gov/northeast-area/up-pa/pswmru/docs/integrated-farm-system-model/, Accessed date: 13 August 2019.

USDA-NASS, 2019. Quick Stats 2.0. National Agricultural Statistics Service, Washington, DC. http://quickstats.nass.usda.gov, Accessed date: 19 February 2019.

USDA-NRCS, 2019. Web Soil Survey. Natural Resource and Conservation Service, USDA. http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx, Accessed date: 16 March 2018.

Veltman, K., Rotz, C.A., Chase, L., Cooper, J., Ingraham, P., Izaurralde, R.C., Jones, C.D., Gaillard, R., Larsson, R.A., Ruark, M., Salas, W., Thoma, G., Jolliet, O., 2018. A quantitative assessment of beneficial management practices to reduce carbon and reactive nitrogen footprints and phosphorus losses of dairy farms in the Great Lakes region of the United States. Agric. Syst. 166, 10–25.

West, T.O., Marland, G., 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agric. Ecosyst. Environ. 91, 217–232.