Feeding strategies and manure management for cost-effective mitigation of greenhouse gas emissions from dairy farms in Wisconsin

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ABSTRACT

Greenhouse gas (GHG) emissions from dairy farms are a major concern. Our objectives were to assess the effect of mitigation strategies on GHG emissions and net return to management on 3 distinct farm production systems of Wisconsin. A survey was conducted on 27 conventional farms, 30 grazing farms, and 69 organic farms. The data collected were used to characterize 3 feeding systems scaled to the average farm (85 cows and 127 ha). The Integrated Farm System Model was used to simulate the economic and environmental impacts of altering feeding and manure management in those 3 farms. Results showed that incorporation of grazing practices for lactating cows in the conventional farm led to a 27.6% decrease in total GHG emissions [−0.16 kg of CO₂ equivalents (CO₂eq)/kg of energy corrected milk (ECM)] and a 29.3% increase in net return to management (+\$7,005/yr) when milk production was assumed constant. For the grazing and organic farms, decreasing the forage-to-concentrate ratio in the diet decreased GHG emissions when milk production was increased by 5 or 10%. The 5% increase in milk production was not sufficient to maintain the net return; however, the 10% increase in milk production increased net return in the organic farm but not on the grazing farm. A 13.7% decrease in GHG emissions (−0.08 kg of CO₂eq/kg of ECM) was observed on the conventional farm when incorporating manure the day of application and adding a 12-mo covered storage unit. However, those same changes led to a 6.1% (+0.04 kg of CO₂eq/kg of ECM) and a 6.9% (+0.06 kg of CO₂eq/kg of ECM) increase in GHG emissions in the grazing and the organic farms, respectively. For the 3 farms, manure management changes led to a decrease in net return to management. Simulation results suggested that the same feeding and manure management mitigation strategies led to different outcomes depending on the farm system, and furthermore, effective mitigation

strategies were used to reduce GHG emissions while maintaining profitability within each farm.

Key words: Integrated Farm System Model, environmental stewardship, feeding system, environmental and economic sustainability

INTRODUCTION

Greenhouse gas (GHG) emissions need to be reduced to limit undesirable outcomes of climate change (IPCC, 1994), such as the rise in sea level, extensive species losses, and economic losses due to extreme weather. Livestock operations are one of the largest sources of agricultural GHG emissions (EPA, 2009), and milk production is considered to be responsible for 4% of global anthropogenic emissions of GHG (FAO, 2010). An important challenge for a state such as Wisconsin, which ranks second in the United States with 14% of national milk production (USDA/NASS, 2013), is to reduce emissions of GHG while remaining economically competitive.

The 3 main GHG are carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), and their emissions are usually expressed on a CO₂-equivalent (CO₂eq) basis to represent their global-warming potential in the atmosphere. Methane and N₂O have global-warming potentials 25 and 298 times of that of CO₂, respectively (IPCC, 2007). Sources of CO₂ on the dairy farm include plant respiration, animal respiration, and microbial respiration in the soil and manure. Carbon dioxide can also be assimilated on the farm via carbon fixation (Rotz et al., 2011a). Methane sources include enteric fermentation, manure storage, field application of manure, and feces deposited on pasture or on the barn floor (Rotz et al., 2011a). Sources of N₂O on the farm include soil and manure through the processes of nitrification and denitrification (Rotz et al., 2011a). In total, enteric fermentation, feed production, and manure management typically account for 35, 32, and 26% of GHG at the farm scale, respectively. The rest of the emissions come from fuel and electricity consumption (Thoma et al., 2013).

Many reviews have looked at strategies to reduce GHG emissions from dairy farms (Cottle et al., 2011;

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Rafiu et al., 2012). However, these reviews did not include the economics of the mitigation strategies, did not differentiate type of dairy-farm system, and limited the boundaries of the system at either the cow, housing, manure storage, or field level. Moreover, none of aforementioned studies included the 3 GHG. Yet, the decrease in GHG emissions in one area of the farm may not necessarily lead to a reduction in GHG emissions for the whole farm or the CO₂eq per kilogram of milk produced on the farm. Furthermore, the effects of a mitigation strategy may depend upon the farm system. Hence, it is critical to study the farm as a whole when evaluating mitigation strategies.

Simulation is a powerful tool to integrate, in a single study, the effect of management practices on both GHG emissions and economic outcomes within a whole farm system framework. In this study, 2 areas of management were targeted for mitigation strategies. First, feeding management was selected because of its effect on enteric CH₄ emission (Aguerre et al., 2011), and it is often the single-most important cost in milk production on dairy farms (Eckard et al., 2010). Furthermore, changes in this area can easily be made with readily observable effects. The second area targeted was manure management because manure is a major source of GHG emissions on dairy farms (Sommer et al., 2000; Chadwick et al., 2011; Thoma et al., 2013). The Integrated Farm System Model (IFSM) has been used to define and study management strategies in different farm systems (Rotz et al., 2007; Belflower et al., 2012; Stackhouse-Lawson et al., 2012), and it is a useful tool to assess simultaneously the combined effect of feeding and manure management strategies on GHG emissions and profitability. The objectives of this work were (1) to compare Wisconsin organic, grazing, and conventional farms in terms of simulated GHG emissions and economics using survey data and the IFSM, and (2) to assess the potential effect of different feeding and manure management strategies on simulated GHG emissions and net return to management of those 3 farm systems.

MATERIALS AND METHODS

IFSM

The IFSM is a simulation model that integrates the major biological and physical processes of a dairy farm and assesses economic performances given a set of management practices (Rotz et al., 2011a). Crop production, feed and manure management, and environmental impact were simulated on a daily time step over 25 yr of daily weather conditions including minimum and maximum temperature, precipitation, and solar radiation as

recorded in Madison, Wisconsin. To avoid the possible confounding effect of soil type, medium clay loam was used as a default for all simulations conducted in this study.

Simulation of GHG Emissions. Total GHG emissions are assessed at the whole-farm level including sources and sinks of CO₂, CH₄, and N₂O. Main sources and sinks of CO₂ include plant and soil respiration, plant fixation, animal respiration, manure storage, barn-floor manure, and fuel combustion (Rotz et al., 2011a). Carbon dioxide emitted by plant and soil respiration is assessed using functions from DAYCENT (2007), which are incorporated in the IFSM. Carbon dioxide emitted by animal respiration is a function of total DMI (Kirchgeßner et al., 1991). Emissions of CO₂ from the barn floor are calculated based on ambient temperature and manure-covered area using the following equation: $E_{CO_2} = \max(0.0, 0.0065 + 0.0192t) \times A_{barn}$, where E_{CO_2} = daily rate of CO₂ emission from barn floor, kg of CO₂/d; t = ambient temperature in the barn, °C; and A_{barn} = floor area covered by manure, m².

A coefficient of 2.637 kg of CO₂/L is used to calculate emission from fuel combustion. For uncovered and covered manure storages, average emission rates of 0.04 kg of CO₂/m³ per day and 0.008 kg of CO₂/m³ per day are used, respectively. Main sources of CH₄ emission include enteric fermentation, barn floor, manure storage, field application, and feces deposited on pasture. An equation developed by Mills et al. (2003) is used to assess CH₄ emission from enteric fermentation based on dietary composition, management practices, and animal type and size. The model from Sommer et al. (2004) based on volatile solids (organic compounds of animal or plant origin), temperature, and storage time is used to calculate emission from manure storage. Methane emission from the barn floor is a function of ambient temperature. For bedded-pack barns, an adaptation of the tier-2 approach of IPCC (2006) is used to account for higher emission rates compared with a daily-cleaned barn floor. Methane emission from the field is accounted for up to 11 d after manure application and is a function of the concentration of volatile fatty acids in the soil. A factor of 0.086 g of CH₄/kg of feces is used to evaluate CH₄ emission from manure deposited on pasture. Main sources of N₂O include barn floor and manure storage. The emission of N₂O occurring during the nitrification-denitrification process is modeled using functions from DAYCENT (2007), which are incorporated in the IFSM model. Nitrous oxide emitted from barn floors is calculated based on the tier-2 approach of the IPCC (2006) for bedded pack and dry lot. Emission of N₂O is set to zero for facilities where manure is removed on a daily basis. For an uncovered slurry-storage tank where

a natural crust forms, N_2O emission is a function of the exposed surface area. When no natural crust forms, N_2O emission is set to zero.

Whole-farm GHG emissions are divided into 7 categories. Emissions from housing facilities include CH_4 emitted from the barn floor, CO_2 from animal respiration, and enteric CH_4 when animals are housed indoors. Emissions from manure storage include CO_2 , CH_4 , and N_2O . Emissions from feed production include CH_4 emitted from field-applied manure and cropland emission of N_2O . Emission from grazing includes enteric CH_4 of grazing cows and CO_2 from animal respiration for the time spent grazing. Net biogenic CO_2 includes emission and assimilation of CO_2 from the crops, as well as carbon sequestration (Rotz et al., 2011a). Emission from fuel combustion includes CO_2 from the engines needed for feeding, handling of manure, and establishing and harvesting of crops. Finally, secondary sources include emissions of all 3 gases during manufacture of fuel, electricity, machinery, fertilizers, pesticides, and plastic used in production of feed and for maintenance of animals imported to the farm.

Simulation of Economic Performance. The economic analysis of the IFSM includes a whole-farm budget in which the total cost of production is compared with revenues to predict annual net return (Rotz et al., 2011a). Annual fixed costs include costs for equipment, facilities, and land. Annual variable costs include costs of labor (feeding, milking, animal handling, and field work), resources (fuel and repairs), and products (fertilizers, seeds, chemicals, feed supplements). Total revenue includes revenue from milk sales, animal sales, and feed sales. The economic parameters do not vary across years. The economic analysis does not include tax implications or other governmental subsidies.

Wisconsin Farm Survey

An interdisciplinary and comprehensive survey instrument was developed to collect information on Wisconsin dairy-farm systems. Data were collected on farm structure, labor, herd management, feeding, cropping, and economics for the year 2010. Farms were selected from Wisconsin's official lists of certified milk producers and organic milk producers as well as a list of graziers compiled by extension agents of the University of Wisconsin. Further details on sampling and survey protocol can be found in Hardie et al. (2014). For this study, farms were classified in 1 of 3 feeding systems: organic, grazing, and conventional. Organic farms were those that had received USDA certification. Grazing farms were those not certified organic but for which at least 30% of the estimated DMI of lactating cows during the grazing season was from grazed pasture.

Conventional farms were defined as nonorganic and nongrazing, which included farms that typically grow crops and harvest forages for indoor feeding and housing for most of the year.

Farms Simulated and Management Scenarios

Survey data collected on 27 conventional farms, 30 grazing farms, and 69 organic farms were used to characterize 3 farm management systems. To remove the possible confounding effect due to difference in farm size, data were scaled to the average surveyed farm for land area (127 ha, out of which 79 ha were owned and 48 ha were rented) and number of cows ($n = 85$). In our sample, conventional farms were larger (125 cows on 162 ha), grazing farms were intermediate (89 cows on 121 ha), and organic farms were smaller (68 cows on 119 ha).

The main characteristics of the 3 production systems included in the study are found in Table 1, and values of some key economic parameters used in the simulations are presented in Table 2. Costs of seeds and chemicals come from survey results. When data were not available from surveys, estimates from previous studies were used, such as in the case of some economic parameters for feed prices (Rotz et al., 2007; Rotz et al. 2008) or veterinary and breeding costs (Kriegl, 2007).

Conventional Farm. The standardized conventional farm (baseline: scenario 0C, Table 3) consisted of 47.4 ha of alfalfa, 42.6 ha of corn, 22.4 ha of perennial grass, 12.2 ha of oats, and 2.4 ha of soybean. All crop operations, except grain harvest, were completed by on-farm labor. Alfalfa was established for 3 yr with oats as a cover crop and was harvested 3 times a year, with the first and third cuts preserved as silage and the second cut as hay. Oat was harvested as grain before the first cut of alfalfa. Grass was established for 10 yr with a seeding rate of 10% white clover and 90% orchardgrass. One cut of hay was harvested from these 22 ha in the spring before older heifers and dry cows were allowed to graze it for the rest of the growing season.

The herd consisted of 85 large Holstein cows producing 9,820 L of ECM/cow per year, 36% of which were first-lactation animals. The cows were milked twice daily in a double 8 parlor and housed in a naturally ventilated freestall barn. All heifers were housed in a bedded pack barn and included 35 less than 1 yr old and 40 greater than 1 yr old (Table 1).

Manure was collected using a scraper with a slurry pump and stored in a 6-mo storage pit. Eighty percent of the manure collected was applied to the cornfields. The remaining 20% of manure was applied to the alfalfa fields.

Three sets of simulations were conducted for the conventional farm (Table 3, Figure 1). In the first 2

Table 1. Mean (and SD) of the main characteristics of the 3 farm types

Item	Conventional	Grazing	Organic
Farms surveyed (no.)	27	30	69
Land base (ha)	127 (118.9)	127 (118.9)	127 (118.9)
Alfalfa (ha)	47.4 (25.47)	37.7 (24.43)	45.5 (26.11)
Grass (ha)	22.4 (21.19)	61.9 (36.56)	43.1 (38.44)
Corn (ha)	42.6 (29.66)	16.3 (11.65)	16.8 (14.01)
Oats (ha)	12.2 (7.77)	5.0 (4.88)	16.0 (8.07)
Soybean (ha)	2.4 (4.49)	6.1 (10.59)	3.6 (4.93)
Young heifers (<1 yr old)	35 (12.3)	34 (12.3)	33 (15.3)
Old heifers (>1 yr old)	40 (11.8)	36 (12.5)	40 (14.3)
Cows (no.)	85 (107.8)	85 (107.8)	85 (107.8)
First-lactation cows (%)	36 (11.4)	30 (12.9)	31 (11.0)
Milk production (L of ECM/cow per year)	9,820 (2,138.5)	7,256 (1,694.9)	6,159 (1,874.9)
Milk price (\$/100 L)	35.99 (2.051)	37.52 (2.911)	56.20 (7.641)
Grazing strategy	Older heifers and dry cows	All weaned animals during the grazing season	All weaned animals during the grazing season
Housing facilities	Freestall barn, naturally ventilated	Tie stall barn	Tie stall barn
Manure storage	Top-loaded lined earthen basin	No storage (daily haul)	No storage (daily haul)

scenarios (scenario A and B), lactating cows grazed during the grazing season. As a result, the labor needed for managing grazing animals was increased from 2 to 6 h/wk. The effect of grazing on GHG emission was assessed using the same milk production (scenario A) or a 5% decrease in milk production (scenario B) as reported in Vibart et al. (2008). The second set of simulation scenarios focused on manure management (scenario C). The manure in this scenario was incorporated in the soil the same day it was applied. At the same time, the 6-mo storage pit was replaced with a 12-mo sealed covered storage tank to limit GHG emissions. The efficiency of the collector and flare is assumed to be 99%. The third set of simulation scenarios (scenarios AC and BC) looked at the combinations of the first 2 sets of simulations.

Grazing Farm. The standardized grazing farm (baseline: scenario 0G, Table 4) consisted of 61.9 ha of grass, 37.7 ha of alfalfa, 16.3 ha of corn, 6.1 ha of soybean, and 5 ha of oats. All crop operations, except grain harvest, were completed by on-farm labor. Alfalfa was established for 3 yr with oats as a cover crop and was harvested 3 times per year, with the first and third cuts preserved as silage and the second cut as hay. Grass was established for 5 yr with 45% white clover and 55% orchardgrass. Two cuts of hay were harvested from these 62 ha. The first cut was done before the beginning of the grazing season and the second cut happened in the fall. All weaned animals were grazed.

The herd consisted of 85 large Holstein cows producing 7,256 L of ECM/cow per year, 30% of which were first-lactation animals. The cows were milked twice

Table 2. Key economic parameters used for the simulation of the conventional, grazing, and organic farms

Item	Conventional	Grazing	Organic
Diesel fuel price (\$/L)	0.68	0.68	0.68
Electricity price (\$/kWh)	0.11	0.11	0.11
Labor wage (\$/h)	11.24	11.24	11.24
Land rental charge (\$/ha per yr)	214.99	214.99	214.99
Fertilizer prices			
Nitrogen (\$/kg)	1.100	1.100	Not applicable
Phosphate (\$/kg)	1.199	1.199	Not applicable
Potash (\$/kg)	1.001	1.001	Not applicable
Seeds (from survey data)			
Corn (\$/ha)	160	140	210
1st-yr alfalfa (\$/ha)	175	105	215
Oats (\$/ha)	70	70	85
Soybean (\$/ha)	230	250	295
Chemicals (from survey data)			
Corn (\$/ha)	138	50	0
1st-yr alfalfa (\$/ha)	147	78	0
Oats (\$/ha)	95	40	0
Soybean (\$/ha)	88	27	0

Table 3. A comparison of annual production, economic effects, and greenhouse gas emissions for various management changes simulated on the conventional farm¹

Item	0C	A ²	B ²	C ²	AC ²	BC ²
Annual milk production (kg of ECM/cow)	9,735	0	-406	0	0	-406
Feed production and use						
Hay and silage production (t of DM)	332	0	0	0	0	0
Corn and oats production (t of DM)	443	-3	-4	0	-5	-5
Grazed forage consumed (t of DM)	94	36	35	1	37	36
Forage sold (t of DM)	236	33	40	2	34	41
Grain purchased (t of DM)	187	-2	-10	0	-1	-9
Soybean purchased (t of DM)	19	1	0	0	2	0
Mineral purchased (t of DM)	6	0	0	0	0	0
Costs of production and net return						
Total feed costs (\$)	182,124	994	-1,795	116	1,425	-1,349
Total income (\$)	357,151	3,668	-7,979	177	3,865	-7,780
Net return to management (\$)	23,895	7,005	-802	-3,536	3,180	-4,641
Variation (SD) in net return across years (\$)	18,355	-477	1,724	-51	-803	-1,973
Net return to management (\$/1,000 kg of ECM)	28.9	8.4	0.2	-4.3	3.8	-4.6
Greenhouse gas emission (CO ₂ equivalent)						
Housing facility (kg/kg of ECM)	0.46	-0.20	-0.21	0.00	-0.20	-0.21
Manure storage (kg/kg of ECM)	0.15	-0.10	-0.10	-0.08	-0.13	-0.13
Feed production (kg/kg of ECM)	0.13	-0.01	-0.01	-0.01	-0.01	-0.01
Grazing (kg/kg of ECM)	0.05	0.13	0.14	0.00	0.13	0.14
Net biogenic CO ₂ (kg/kg of ECM)	-0.34	0.02	0.03	0.01	0.02	0.03
Fuel combustion (kg/kg of ECM)	0.04	0.00	-0.01	0.00	0.00	-0.01
Secondary sources (kg/kg of ECM)	0.17	-0.01	-0.02	0.00	-0.01	-0.02
Net emission (kg/cow per d)	15.36	-4.09	-4.39	-1.95	-4.79	-5.08
Net emission (kg/kg of ECM)	0.58	-0.16	-0.15	-0.08	-0.18	-0.18
Net emission (kg/yr)	476,623	-126,959	-136,289	-60,550	-148,829	-157,555

¹0C: initial conventional farm with 85 cows, producing 9,820 L of ECM/cow per year on 127 ha, no grazing, top-loaded lined earthen basin for manure storage; A: grazing was offered to the lactating cows with no decrease in milk production; B: grazing was offered to the lactating cows with a 5% decrease in milk production; C: manure management changes included incorporation of manure the same day of application, and a 12-mo covered tank storage was used to reduce emission from manure storage; AC: combination of scenarios A and C; BC: combination of scenarios B and C.

²Values are expressed as difference from the baseline scenario 0C.

daily using a pipeline system and housed in a tie stall barn. All heifers were housed in a bedded pack barn and included 34 less than 1 yr old and 36 greater than 1 yr old (Table 1).

Manure was collected using gutter cleaners and hauled daily (i.e., no manure storage on the farm). Fifty percent of the manure collected was applied to the cornfields, 20% on grassland, 20% on alfalfa, and 10% on oats.

Three sets of simulations were conducted on the grazing farm (Table 4, Figure 1). In the first 2 scenarios (scenario D and E), the forage-to-concentrate ratio was set from high to low. A high forage-to-concentrate ratio consisted of 83, 90, and 93% forage in the diet for the early-, mid-, and late-lactation cows, respectively. A low forage-to-concentrate ratio consisted of 57, 68, and 80% forage in the diet for the early-, mid-, and late-lactation cows, respectively (Rotz et al., 2011a). As a result, milk production was increased by 5% (scenario D) as reported in Aguerre et al. (2011). A 10% increase was also simulated (scenario E) to follow results of Sterk et al. (2011). The second set of simulations focused on manure management (scenario F). Manure was incorporated the day of field application and a 12-

mo sealed covered storage tank was used to limit GHG emissions. The efficiency of the collector and flare is assumed to be 99%. The third set of simulations (scenario DF and EF) looked at the combinations of the first 2 simulations.

Organic Farm. The standardized organic farm (baseline: scenario 0O, Table 5) consisted of 45.5 ha of alfalfa, 43.1 ha of grass, 16.8 ha of corn, 16 ha of oats, and 3.6 ha of soybean. Two hectares were not available for crop production because of the organic regulation for buffer zones between organic and conventional land (Rotz et al., 2007; USDA Agricultural Marketing Service, 2013). Yields reported on the survey were used as targets for simulated yields. Farmers reported an average yield of 12.1, 13.8, 3.8, and 2.25 t of DM/ha for alfalfa, corn silage, oats, and soybean, respectively, in 2010. All crop operations except grain harvest were completed by on-farm labor. Alfalfa was established for 3 yr with oats as a cover crop and was harvested 3 times a year, with the first and third cuts preserved as silage and the second cut as hay. Grass was established for 5 yr with 35% white clover and 65% orchardgrass. Two cuts of hay were harvested from these 43 ha. The first cut was done before the beginning of the grazing

Figure 1. Scenarios simulated on the conventional, grazing, and organic farms.

season and the second cut happened in the fall. All weaned animals were grazed.

The herd consisted of 85 large Holstein cows producing 6,159 L of ECM/cow per year, 31% of which were first-lactation animals. The cows were milked twice daily using a pipeline system and housed in a tie stall barn. All heifers were housed in a bedded-pack barn and included 33 less than 1 yr old and 40 greater than 1 yr old.

Manure was collected using gutter cleaners and hauled daily (i.e., no manure storage on the farm). Fifty percent of the manure collected was applied on cornfields, 20% on grassland, 20% on oats, and 10% on alfalfa.

The same 3 sets of simulations used for the grazing farm were used for the organic farm (scenario G, H, I, GI, and HI, Table 5, Figure 1).

RESULTS

Comparison of Feeding and Manure Management Systems

Results of the different sets of simulations conducted on the conventional, grazing, and organic farms are presented as deviation from the baseline scenario (Tables 3, 4, and 5).

Cost of Production and Net Return. The 3 farms produced enough forage on 127 ha to feed 85 cows and their replacements (Figure 2). Because of higher forage yields, the conventional farm sold more forage than the grazing or organic farms (236, 192, and 94 t/yr for the conventional, grazing, and organic farm, respectively). However, higher milk production per cow in the conventional farms compared with grazing and organic farms was associated with higher purchases of grain (187, 104, and 107 t/yr for the conventional, grazing, and organic farms, respectively) and higher purchases of soybean (19, 12, and 4 t/yr of soybean for the conventional, grazing, and organic farm, respectively).

The organic farms had an income from milk sales similar to the conventional farms (\$294,179/yr and \$297,834/yr, respectively) but an intermediate feed cost (\$149,744/yr) compared with the conventional and grazing farms (Figure 3). Thus, the organic farm had the highest net return to management (\$59,120/yr) compared with \$23,895/yr for the conventional farm and \$14,439/yr for the grazing farm. In addition, the variation in net return across years was the smallest for the organic farms (Tables 3, 4, and 5). Thus, the conventional farms ranked second for net return because the income from the high-producing cows was insufficient to compensate for the high feed cost (\$182,124/yr). Even though the grazing farms had the lowest feed

Table 4. A comparison of annual production, economic effects, and greenhouse gas emissions for various management changes simulated on the grazing farm¹

Item	0G	D ²	E ²	F ²	DF ²	EF ²
Annual milk production (kg of ECM/cow)	7,256	362	725	0	362	725
Feed production and use						
Hay and silage production (t of DM)	314	0	0	0	0	0
Corn and oats production (t of DM)	196	0	0	0	0	0
Grazed forage consumed (t of DM)	385	-121	-118	0	-122	-118
Forage sold (t of DM)	192	92	88	1	92	88
Grain purchased (t of DM)	104	168	176	1	168	176
Soybean sold (t of DM)	12	-3	-3	0	-3	-3
Mineral purchased (t of DM)	5	0	0	0	0	0
Costs of production and net return						
Total feed costs (\$)	134,133	34,797	36,670	242	34,994	36,871
Total income (\$)	288,603	21,560	32,627	95	21,614	32,681
Net return to management (\$)	14,439	-12,846	-4,683	-3,565	-16,407	-8,247
Variation (SD) in net return across years (\$)	9,810	-1,768	-1,715	-48	-1,814	-1,760
Net return to management (\$/1,000 kg of ECM)	23.4	-20.9	-9.0	-5.8	-26.4	-14.3
Greenhouse gas emission (CO ₂ equivalent)						
Housing facility (kg/kg of ECM)	0.44	-0.11	-0.10	0.00	-0.11	-0.10
Manure storage (kg/kg of ECM)	0.00	0.00	0.00	0.06	0.05	0.05
Feed production (kg/kg of ECM)	0.21	-0.05	-0.05	-0.01	-0.06	-0.06
Grazing (kg/kg of ECM)	0.34	-0.10	-0.10	0.00	-0.10	-0.10
Net biogenic CO ₂ (kg/kg of ECM)	-0.36	0.01	0.00	0.00	0.01	0.00
Fuel combustion (kg/kg of ECM)	0.04	-0.01	-0.01	0.00	-0.01	-0.01
Secondary sources (kg/kg of ECM)	0.09	0.11	0.12	0.00	0.11	0.12
Net emission (kg/cow per d)	13.07	-2.79	-2.63	0.79	-2.11	-1.94
Net emission (kg/kg of ECM)	0.66	-0.17	-0.18	0.04	-0.13	-0.15
Net emission (kg/yr)	405,565	-86,729	-81,796	24,506	-65,447	-60,282

¹0G: initial grazing farm with 85 cows, producing 7,256 L of ECM/cow per year on 127 ha, with a high forage:concentrate ratio and no manure storage; D: forage:concentrate ratio was defined as 57, 68, and 80% for the early-, mid-, and late-lactation cows, respectively, with a 5% increase in milk production; E: forage:concentrate ratio was defined as 57, 68, and 80% for the early-, mid-, and late-lactation cows, respectively, with a 10% increase in milk production; F: manure management changes included incorporation of manure the same day of application and the addition of a 12-mo covered tank storage; DF: combination of scenarios D and F; EF: combination of scenarios E and F.

²Values are expressed as difference from the baseline scenario 0G.

cost (\$134,133/yr), the lower milk production led to the lowest net return to management (\$14,439/yr).

GHG Emission. On a yearly basis, the conventional farms emitted the greatest amount of GHG (476,623 kg of CO₂eq/yr) and the grazing farms emitted the lowest amount of GHG (405,565 kg of CO₂eq/yr), whereas the organic farms had an intermediate level of emission (454,780 kg of CO₂eq/yr; Tables 3, 4, and 5). However, when GHG emission was expressed by kilograms of ECM produced, the emission from the conventional farms was the lowest (0.58 kg of CO₂eq/kg of ECM), followed by the grazing farms (0.66 kg of CO₂eq/kg of ECM) and the organic farms (0.74 kg of CO₂eq/kg of ECM). For the 3 farm systems, the major source of GHG emission was from the housing facilities (i.e., the barn floor, animal respiration, and enteric fermentation when animals were housed inside the barn). Other important sources of GHG emissions on the conventional farms included secondary sources (0.17 kg of CO₂eq/kg of ECM), manure storage (0.15 kg of CO₂eq/kg of ECM), and feed production (0.13 kg of CO₂eq/kg of ECM). For the grazing and organic farms, other important sources were feed production (0.21 and 0.27 kg of CO₂eq/kg of ECM, respectively)

and grazing animals (0.34 and 0.38 kg of CO₂eq/kg of ECM, respectively; Figure 4).

Assessment of Strategies to Reduce GHG Emissions for Conventional Farms

Scenarios A and B. Scenarios A and B explored the change in feeding management strategies allowing for grazing of lactating cows with no change in milk production (scenario A) or with a drop in milk production (scenario B). Assuming milk production remained unchanged at 9,735 kg/cow per year and given the way pastures were managed in the baseline scenario, grazing lactating cows increased net return to management (+\$7,005/yr) and decreased GHG emission by 27.6% (-0.16 kg of CO₂eq/kg of ECM, scenario A, Table 3). For the baseline scenario, only one cut of hay was harvested out of the pastures and only dry cows and heifers were grazing. This management did not allow the conventional system to take full advantage of the pastures. By having the lactating cows grazing, pastures were used more efficiently, so that more feed was obtained from the pastures and less preserved forage was needed during the grazing season. Consequently, sales of for-

Figure 2. Feed production and use on simulated conventional (C), grazing (G), and organic (O) feeding systems of Wisconsin dairy farms.

Table 5. A comparison of annual production, economic effects, and greenhouse gas emissions for various management changes simulated on the organic farm¹

Item	00	G ²	H ²	I ²	GI ²	HI ²
Annual milk production (kg of ECM/cow)	6,159	308	615	0	308	615
Feed production and use						
Hay and silage production (t of DM)	347	0	0	0	0	0
Corn and oats production (t of DM)	160	0	0	0	0	0
Grazed forage consumed (t of DM)	268	-61	-59	-1	-61	-60
Forage sold (t of DM)	94	150	145	1	150	146
Grain purchased (t of DM)	107	157	164	1	158	165
Soybean sold (t of DM)	4	-2	-2	0	-1	0
Mineral purchased (t of DM)	5	0	0	0	0	0
Costs of production and net return						
Total feed costs (\$)	149,744	49,788	52,369	403	49,861	52,465
Total income (\$)	350,185	39,429	53,253	130	39,526	53,322
Net return to management (\$)	59,120	-9,766	605	-4,855	-14,793	-4,403
Variation (SD) in net return across years (\$)	14,498	-2,991	-2,941	98	140	161
Net return to management (\$/1,000 kg of ECM)	112.9	-23.1	-9.2	-9.2	-32.3	-17.9
Greenhouse gas emission (CO ₂ equivalent)						
Housing facility (kg/kg of ECM)	0.52	-0.13	-0.12	0.00	-0.13	-0.12
Manure storage (kg/kg of ECM)	0.00	0.00	0.00	0.07	0.06	0.05
Feed production (kg/kg of ECM)	0.27	-0.08	-0.08	-0.01	-0.09	-0.08
Grazing (kg/kg of ECM)	0.38	-0.11	-0.10	0.00	-0.11	-0.10
Net biogenic CO ₂ (kg/kg of ECM)	-0.38	0.01	0.00	0.00	0.01	0.00
Fuel combustion (kg/kg of ECM)	0.06	-0.02	-0.02	0.00	-0.02	-0.01
Secondary sources (kg/kg of ECM)	0.12	0.12	0.12	0.00	0.12	0.12
Net emission (kg/cow per d)	14.66	-3.30	-3.15	0.99	-2.47	-2.31
Net emission (kg/kg of ECM)	0.87	-0.23	-0.25	0.06	-0.18	-0.20
Net emission (kg/yr)	454,780	-102,405	-97,632	30,728	-76,632	-71,615

¹00: initial organic farm with 85 cows, producing 6,159 L of milk/cow per year on 127 ha, with a high forage:concentrate ratio and no manure storage; G: forage:concentrate ratio was defined as 57, 68, and 80% for the early-, mid-, and late-lactation cows, respectively, with a 5% increase in milk production; H: forage:concentrate ratio was defined as 57, 68, and 80% for the early-, mid-, and late-lactation cows, respectively, with a 10% increase in milk production; I: manure management changes included incorporation of manure the same day of application and the addition of a 12-mo covered tank storage; GI: combination of scenarios G and I; HI: combination of scenarios H and I.

²Values are expressed as difference from the baseline scenario 00.

Figure 3. Feed costs and income on simulated conventional, grazing, and organic feeding systems of Wisconsin dairy farms.

age increased by 33 t/yr and income from feed sales increased by \$3,684/yr (not shown) in scenario A compared with the baseline scenario. Net return to management also increased because of a decrease of \$3,856/yr (not shown) in total manure management cost. The time spent grazing decreased the amount of manure that needed to be stored and handled, reducing the cost of manure management. The decrease in GHG emission was possible for the same reasons. Because cows were spending time outdoors, GHG emission included in the “housing facilities” and “manure storage” categories decreased (-0.20 kg of $\text{CO}_2\text{eq/kg}$ of ECM and -0.10 kg of $\text{CO}_2\text{eq/kg}$ of ECM, respectively) and emission from grazing animals increased ($+0.13$ kg of $\text{CO}_2\text{eq/kg}$ of ECM), resulting in a net reduction in GHG emission when grazing substituted for confinement feeding during part of the year. When milk production was decreased by 5% (scenario B, Table 3), GHG emissions decreased by 26% (-0.15 kg of $\text{CO}_2\text{eq/kg}$ of ECM). However, the increase in income from forage sales was compensated by the decrease in milk production, and

the net return to management remained unchanged compared with the baseline scenario (\$23,093/yr). Because total net return to management remained unchanged for scenario B and milk production decreased by 5%, then the net return to management per 1,000 kg of ECM was slightly better for scenario B compared with the baseline scenario (\$29.1/1,000 kg of ECM vs. \$28.9/1,000 kg of ECM, respectively).

Scenario C. Increasing manure storage capacity from 6 to 12 mo with a covered tank and incorporating manure the day of field application led to an increase in total manure cost of \$3,398/yr (not shown). The net return to management decreased by \$3,536, but GHG emissions decreased by 16% (-0.08 kg of $\text{CO}_2\text{eq/kg}$ of ECM, Table 3). The decrease in emissions from the manure storage and from the field during feed production contributed to this improvement (Table 3).

Scenarios AC and BC. These scenarios explored the combined effect of changes in feeding management and manure management. If milk production was maintained at the same level (9,735 kg/cow per year, scenario

Figure 4. Greenhouse gas emissions from simulated conventional, grazing, and organic feeding and manure management systems on Wisconsin dairy farms.

AC, Table 3), the adoption of grazing for the lactating cows and the changes in manure management led to an increase in net return to management (+\$3,180/yr) compared with the baseline scenario and a decrease in GHG emission of 31% (-0.18 kg of CO₂eq/kg of ECM). The change in net return was the result of the increase in income from feed sales, the decrease in total manure handling cost observed in the first scenario, and the increase in manure handling costs observed in the second scenario. The change in GHG emission was the result of a decrease in emission from the housing facilities and the manure storage compared with the baseline scenario. However, the overall decrease in GHG emission for scenario AC compared with the baseline scenario did not add up to the sum of the decreases observed in scenarios A and C. If milk production was reduced by 5% (9,329 kg of ECM/cow per year, scenario BC, Table

3), GHG emission decreased by 0.18 kg of CO₂eq/kg of ECM, but net return to management was also reduced by \$4,641/yr compared with the baseline scenario.

Assessment of Strategies to Reduce GHG Emissions for Grazing Farms

Scenarios D and E. Scenario D simulated on the grazing farm looked at the effect of changing the forage-to-concentrate ratio from high to low with a 5% increase in milk production. This strategy reduced GHG emission by 25.8% compared with the baseline scenario (-0.17 g of CO₂eq/kg of ECM), but also reduced substantially the net return to management ($-\$12,846$ /yr; Table 4). In that case, the income from the increase in milk production and the additional forage sold (+92 t/yr) did not cover the expenses needed to buy the

additional grain. Feed costs increased by \$34,797/yr compared with the baseline scenario. In regard to GHG emission, the increase of 0.11 kg of CO₂eq/kg of ECM from secondary sources due to the grain purchased was offset by the reduction in emission from housing facilities (−0.11 kg of CO₂eq/kg of ECM), grazing (−0.10 kg of CO₂eq/kg of ECM) and feed production (−0.05 kg of CO₂eq/kg of ECM). When milk production was increased by 10% (scenario E, Table 4), the effect of changing the forage-to-concentrate ratio was essentially the same on GHG emission and the decrease in net return was reduced (−\$4,683/yr) compared with the baseline scenario.

Scenario F. Scenario F simulated on the grazing farm looked at the effect of changing manure management. Adding a 12-mo covered tank and incorporating the manure the same day of application increased GHG emission (+0.04 kg of CO₂eq/kg of ECM) and decreased net return to management (−\$3,565/yr; Table 4). The reduction in net return was due to an increase in total manure cost of \$3,521/yr (not shown) over the baseline scenario. The reduction of GHG emission from feed production (−0.01 kg of CO₂eq/kg of ECM) possible with the incorporation of manure the same day of application did not compensate for the increase in GHG emission from the manure storage (+0.06 kg of CO₂eq/kg of ECM), leading to an overall increase of 0.04 kg of CO₂eq/kg of ECM.

Scenarios DF and EF. Scenarios DF and EF simulated on the grazing farm looked at the combination of scenarios D and E with scenario F. The change in net return was a cumulative combination of the results observed for the first 3 scenarios. When milk production increased by 5% (scenario DF, Table 4), net return decreased by \$16,407/yr compared with the baseline scenario because of an increase in feed cost from the grain purchased (+\$33,498/yr, not shown) and an increase in total manure costs (+\$3,521/yr, not shown). When milk production increased by 10% (scenario EF, Table 4), net return decreased by \$8,247/yr for the same reasons. The overall GHG emission was reduced by 0.13 kg of CO₂eq/kg of ECM and 0.15 kg of CO₂eq/kg of ECM for a 5 and 10% increase in milk production, respectively. The reduction in GHG emission compared with the baseline scenario was the result of the cumulative decrease observed in scenarios D and E and the increase observed in scenario F.

Assessment of Strategies to Reduce GHG Emissions for Organic Farms

Scenarios G and H. Scenarios G and H on the organic farms (Table 5) described results for the same sets of simulations as did scenarios D and E for the

grazing farms (Table 4). The results observed followed the same trend as described above for the grazing farm. With a 5% increase in milk production (scenario G, Table 5), changing the forage-to-concentrate ratio from high to low decreased the net return to management by \$9,766/yr and decreased the GHG emission by 0.23 kg of CO₂eq/kg of ECM. With a 10% increase in milk production (scenario H, Table 5), GHG emissions were reduced by 0.25 kg of CO₂eq/kg of ECM. On the organic farms, a 10% increase in milk production was sufficient to maintain net return compared with the baseline scenario (+\$605/yr) in spite of an increase in feed cost (+\$52,369/yr, Table 5).

Scenario I. Scenario I simulated on the organic farm focused on the effect of changing manure management. Adding a 12-mo covered tank and incorporating the manure the same day of application decreased net return to management by \$4,855/yr because of an increase in total manure handling cost, and GHG emissions were increased by 0.06 kg of CO₂eq/kg of ECM.

Scenarios GI and HI. Scenarios GI and HI simulated on the organic farm focused on the combination of scenarios G and H with scenario I. The results for scenarios GI and HI were a cumulative combination of the results from the first 3 scenarios. With a 5% increase in milk production and a change in manure management (scenario GI, Table 5), net return to management decreased by \$14,793/yr and GHG emissions decreased by 0.18 kg of CO₂eq/kg of milk compared with the baseline scenario. With a 10% increase in milk production and a change in manure management (scenario HI, Table 5), net return to management decreased by \$4,403/yr and GHG emission decreased by 0.20 kg of CO₂eq/kg of ECM.

DISCUSSION

Comparison of Feeding and Manure Management Systems

Profitability. Previous studies have found that managed grazing can be more profitable than confinement feeding or mixed farms using extensive grazing (Hanson et al., 1998; Dartt et al., 1999; Winsten et al., 2000; Gillespie et al., 2009; Hanson et al., 2013). For instance, Hanson et al. (2013) reported a net profit of \$105.60 and \$54.44 per 1,000 kg of ECM for grazing and conventional farms, respectively. Similarly, Gillespie et al. (2009) reported a whole-farm net return of \$104.88 and \$81.11 per 1,000 kg of ECM for grazing and conventional farms, respectively. However, those studies are based on survey results and involved dairy-farm systems of different size, which are different to our study. Grazing herds from those studies were smaller in

number of cows and land area. Winsten et al. (2000) showed the importance of herd size and milk production per cow as major factors affecting profitability. They reported a \$10.03 increase in net farm income when milk production per cow per year increased by 1 kg and a \$292.14 increase in net return when herd size increase by one cow. This could explain the difference in results obtained with the simulation in this study, which was designed to focus on assessing the effect of management practice at the same farm size. This is supported by the finding of Foltz and Lang (2005), who showed that grazing systems are not more profitable than conventional systems when other factors are controlled. Moreover, because crop management was not the focus of this particular study, one of the assumptions was that all feeding systems had the same crop-related machinery and used the same crop-related practices (land preparation and planting). This assumption could have decreased profitability for grazing farms because they typically have less machinery compared with conventional farms. Hanson et al. (1998) reported lower machinery costs for grazing systems compared with conventional systems.

Organic premium for milk price confers an economic advantage to organic dairy farms, leading to higher profitability compared with conventional herds (McBride and Greene, 2009). In their study, herd size was 82 and 156 cows for organic and conventional farms, respectively. Rotz et al. (2007) found the same results using the IFSM for dairy farms in Pennsylvania. They showed that with the same land base and the same number of cows, organic farms had a higher net return to management per cow, in spite of lower milk production per cow, compared with grazing or confinement farms. The economic advantage was even more important when net return to management was expressed on a kilograms-of-ECM basis.

GHG Emission. Gerber et al. (2011) reported that increasing milk production reduced the amount of GHG emission per kilogram of milk. The simulations conducted for our study corroborate those results. Even though the conventional farm had the highest net emission of GHG per year, it had the lowest net emission of GHG per kilogram of milk because of a higher milk production compared with the other 2 feeding and manure management systems. Kristensen et al. (2011) also showed that organic farms emitted more GHG per kilogram of milk produced compared with the conventional farms for the same reason as described here.

Our study revealed that the main source of GHG emissions among the 3 feeding and manure management systems was enteric fermentation whether the animals were fed indoors or outdoors (grazing). Even though the exact amount of GHG emission derived from

enteric fermentation was not known from the simulation results, one can see that the 2 categories including enteric fermentation, housing facilities, and grazing are, together, the largest sources of emission on the farm for the 3 management systems. They represent 0.51, 0.78, and 0.90 kg of CO₂eq/kg of ECM on the conventional, grazing, and organic farm, respectively (Table 3, 4, and 5). Our observations agree with those from Thoma et al. (2013), who indicated that enteric fermentation, manure management, and feed production are the 3 main sources of GHG emissions for milk production.

The importance of other sources of GHG emissions differed among feeding and manure management systems, which means that the implementation of the same mitigation strategies is likely to yield different outcomes across farms.

For the farm types studied here, emissions included in the “feed production” category were high because most of the dairy farms relied heavily on on-farm production of forages for the herd. Secondary sources of GHG emissions associated with manufacture of inputs were of less importance on the organic and grazing farms compared with the conventional farms, as the former 2 rely more on on-farm resources.

Economic Versus Environmental Outcomes of Altering Feeding and Manure Management Practices

The simulations of mitigation strategies demonstrated that changes in management can reduce GHG emissions in all 3 farm systems studied. On the organic and conventional farms, in some cases, reduction in GHG emission may be achieved while maintaining or even improving profitability.

Changes in feeding strategies in each farm type were effective in reducing GHG emissions. Those strategies are easy to implement, their effect can be observed in the short term, and according to Vellinga et al. (2011), they are what farmers would be most inclined to do among all other mitigation strategies proposed. On conventional farms, based on the results from the simulations, the use of extensive grazing for the lactating cows seemed to be possible without decreasing milk production. This strategy should be possible to implement on actual farms because most of the conventional farms surveyed had some land in pasture. Future research should be done to compare pasture management when conventional farms transition to grazing of lactating cows. For the organic farm, increasing the amount of concentrates fed to the cows was also an effective way to decrease GHG emissions while maintaining profitability if milk yield was increased by 10%. One should note that those results are for 2010 prices. On the grazing farm, increasing the amount of concentrates

fed to the cows was effective at reducing GHG, but at the same time reduced profitability even when a 10% increase in milk production was simulated. Moreover, this strategy might be in contradiction with the way farmers want to operate their farms because graziers usually seek cost reduction and low input systems.

Changes in manure management led to contrasting results on GHG emissions among the types of farms. Greenhouse gas emissions were reduced on the conventional farms, but they were increased on the grazing and organic farms. In all cases, those strategies had a negative effect on net return to management because of an increase in total manure management costs. When looking at the simulation results, changes in manure management may be seen as not desirable. Although, this study focused on GHG emissions, changes in manure management could have additional beneficial effect on the environment by reducing ammonia emission, nitrate leaching, and phosphorus runoff (Rotz et al., 2011b). A more complete life-cycle assessment of the environmental impacts of mitigation strategies should be made before drawing final conclusions about the effect of those strategies on the environment and farm profitability.

CONCLUSIONS

Under the simulation conditions of this study, feeding management changes can be made to reduce GHG emissions on Wisconsin conventional, grazing, and organic dairy farms, and those changes can improve profitability in some cases. In contrast, changes in manure management to reduce GHG emission were possible, but these changes had a negative effect on profitability. However, the evaluation and the implementation of mitigation strategies should be based on farm characteristics, and data from site-specific farm conditions are needed before making any recommendations.

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