Optimizing productivity, herd structure, environmental performance, and profitability of dairy cattle herds

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ABSTRACT

This study used the Integrated Farm System Model to simulate the whole farm performance of a representative Wisconsin dairy farm and predict its economic and environmental outputs based on 25 yr of daily local weather data (1986 to 2010). The studied farm, located in southern Wisconsin, had 100 milking cows and 100 ha of cropland with no replacement heifers kept on the farm. Sensitivity analyses were conducted to test the effect of management strategies on energy-corrected milk production (ECM; 4.0% fat and 3.5% protein), net return to management, and greenhouse gas (GHG; including biogenic CO₂) emission. The management strategies included (1) target milk production, for which the model optimized available resources to attain, and (2) herd structure, represented by the percentage of first-lactation cows. Weather conditions affected the outputs by changing the farm quantity and the quality of produced feed resources. As expected, when target milk production increased, the ECM increased positively and linearly to a certain level, and then it increased nonlinearly at a decreasing rate, constrained by available feed nutrients. Thereafter, the ECM reached the maximum potential milk production and remained flat regardless of higher target milk production input. Greenhouse gas emissions decreased between 3.4 and 7.3% at different first-lactation cow percentages. As the first-lactation cow percent increased from 15 to 45% in 5% intervals, GHG increased between 9.4 and 11.3% at different levels of target milk production. A high percentage of first-lactation cows reduced the maximum potential milk production. Net return to management had a similar changing trend as ECM. As the target milk production increased from 9,979 to 11,793 kg, the net return to management increased between 31 and 46% at different first-lactation cow percentages. Results revealed a win-win situation when increasing milk production or improving herd structure, which

concurrently increased farm net return to management and decreased GHG emissions.

Key words: greenhouse gas emission, farm profitability, simulation model

INTRODUCTION

Agricultural greenhouse gases (GHG) constitute 8.1% of total United States GHG emissions (EPA, 2014). Livestock enteric fermentation and manure methane emission account for 34.4% of total anthropogenic CH₄ emission (EPA, 2014), and the dairy industry contributes 4% to global GHG emissions (FAO, 2010). Dairy farm GHG includes CO₂, CH₄, and N₂O from enteric fermentation, manure handling, crop production, and other processes (Rotz et al., 2010). Given these rates, dairy cattle farming faces a major challenge: to reduce GHG emissions while maintaining or increasing profitability. Crosson et al. (2011) reported that animal performance, including production and replacement decisions, influence the GHG from dairy farms. Increasing milk production through genetic and feeding improvement can decrease the per-kilogram of milk GHG (Rotz et al., 2010). Dutreuil et al. (2014) studied the economic effects of GHG-mitigation strategies, such as changing the grazing schedule, the forage ratio in diet, and manure-handling methods, and found that grazing cows in conventionally managed dairy farms would decrease GHG and increase net profit while keeping milk production constant. Likewise, Dutreuil et al. (2014) reported that increasing concentrate supplementation in grazing farms would decrease GHG emissions and increase milk production, which might increase the net profit depending on the increased amount. Additionally, adding an extra covered manure-storage facility decreased GHG emissions in conventional dairy farms because some GHG from manure was prevented from escaping to the atmosphere (Dutreuil et al., 2014). Garnsworthy et al. (2012) found that improving reproductive performance and replacement would reduce GHG emissions at the herd level by reducing the number of replacement animals, calving interval length, and increasing the average milk production.

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Due to the complex interaction of farm dynamic processes, whole farm systems need to be included in joint GHG emissions and economic studies (del Prado et al., 2010). The Integrated Farm System Model (IFSM; Rotz et al., 2013), which assesses the combined effect of the main dairy farm factors, is uniquely positioned to conduct this kind of study (Belflower et al., 2012; Stackhouse-Lawson et al., 2012; Dutreuil et al., 2014). The present study uses the IFSM to estimate the concurrent environmental and economic effects of 2 farm management strategies: (1) target milk production, the production goal for which the model optimizes feed allocation, and (2) the proportion of cows in first lactation, a proxy of reproduction and replacement management.

MATERIALS AND METHODS

The IFSM

The IFSM was used in our study to assess the economic and environmental output of a representative Wisconsin dairy farm. Farm performance was simulated using 25 yr of daily weather data for Madison, Wisconsin (1986–2010; Dane County Regional-Truax Field, WI; 43.13°N, 89.33°W, elevation = 259 m). The IFSM was applied to integrate crop growth, feed storage, machinery usage, and herd management to simulate farm performance with the available on-farm resources and purchased feed (Rotz et al., 2013). Daily weather data were used to estimate the annual farm-produced feed resources by simulating crop growth, tillage, and harvest. In addition, weather data were used in the manure-handling modules to estimate the manure ammonia emission as a function of temperature and wind speed. Weather data did not affect herd performance (Rotz et al., 2013). The IFSM simulates each year separately and does not consider carryover effects from one year to the next (i.e., it simulates 1 yr under historical yearly weather variability; Rotz et al., 2013).

The herd-management module inside the IFSM optimizes feed allocation by maximizing the milk production and minimizing purchased feed cost. The herd module prioritizes on-farm feed use, supplementing with purchase feed as needed.

Farm Characteristics

The representative dairy farm had 100 large milking Holstein cows (including dry cows) and 100 ha of rented cropland (43 ha of alfalfa and 57 ha of corn). The cow's average mature weight was 759 kg. The farm's topography was gently sloping. The farm soil type was medium

clay loam with a soil phosphorus level of 30 to 50 mg/kg.

Alfalfa was planted and planned to have a 3-yr stand life. A yield adjustment of 90% was set to mimic the field conditions in Wisconsin. The yield adjustment factor is used to give some relative control over the simulation process to adjust the model prediction; the shorter the growth period is, the lower the adjustment factor (Rotz et al., 2013). The farm applied 20% of the total available cattle manure to the alfalfa land. A population of 11,300 plants/ha was used on the corn crop. The relative maturity index was 110 d. The grain yield adjustment was 85% and the silage yield adjustment was 100% (no adjustment). The remaining 80% of the available manure was applied to the cornfields, along with 20 kg/ha of nitrate fertilizer.

The on-farm machinery included one 47-hp (35 kW) tractor, one 87-hp (65 kW) tractor, and one 108-hp (80 kW) tractor. The 47-hp tractor was used for mowing, raking, drill seeding, and miscellaneous transporting. The 87-hp tractor was used for baling, feed mixing, silo filling, field cultivation, row crop planting, round bale loading, and pumping manure. The 108-hp tractor was used for forage chopping, manure handling, plowing, and disking. Grain harvest was custom hired. All the following tillage and planting operations were conducted only on suitable days with an upper layer soil moisture content allowing machine tractability. Alfalfa seeding started as early as April 25 and corn was planted on or after May 5. The following earliest operation dates were input, but the actual dates varied depending on weather, soil, or crop moisture conditions. Alfalfa had 4 cuttings per year: the earliest harvesting times fell around May 28, July 1, August 17, and October 15, as weather permitted. Corn was harvested for silage after September 1, for high-moisture grain after October 1, and for dried grain after October 21. The high-quality forage was stored in a 281-t of DM bunker silo, grain crop silage was stored in a similarly sized bunker, and the high-moisture grain was stored in a stave silo with 259 t of DM capacity.

The farm used a flat barn parlor and straw-bedded freestalls with natural ventilation. Cows were bred and calved year round. A loader and a mixer wagon were used to feed grain and silage. The cows were fed a low-forage diet, which maintained the minimum amount of dietary fiber (relative forage-to-grain ratio in the diet of 0.57, 0.68, and 0.80 for early, middle, and late lactation cows, respectively). Hay was provided in a self-fed hay feeder. The manure was collected and hauled using a scraper and slurry pump and then applied to the field within 2 d. Milk price was set at \$0.40 per kg, slaughter price at \$1.21 per kg, replacement heifer at \$1,500 per

Table 1. On-farm feed produced¹

Feed category (t of DM)	Mean $\pm$ SD	Median	Minimum	Maximum
High-quality hay	43.50 $\pm$ 28.03	54.7	0	79.50
Low-quality hay	14.50 $\pm$ 23.27	0	0	76.40
High-quality silage	247.60 $\pm$ 43.50	251.80	143.6	311.3
Grain crop silage	243.80 $\pm$ 1.87	243.7	241.1	250.2
High-moisture grain	173.60 $\pm$ 58.22	176.40	69.30	239.10
Dry grain	14.50 $\pm$ 26.93	0	0	104.00
Forage	295.80 $\pm$ 52.22	306.80	150.60	365.50

¹Results from simulations performed with the Integrated Farm System Model (Rotz et al., 2013) for 25 yr of daily weather data for south-central Wisconsin.

animal, and the calf price at \$150 per animal. The cost of purchasing replacement animals was the product of replacement heifer price times the number of first-lactation cows. The cost of purchasing replacement animals was a fixed value across target milk production levels.

Annual per-cow fixed expenses were \$372, including \$110 for veterinary and medicine costs, \$65 for semen and breeding costs, \$150 for animal and milking supply costs, \$12 for animal insurance, \$10 for animal hauling costs, and \$25 for DHIA registration costs.

Table 2. Twenty-five year ECM production and per-cow milk income over feed cost results at different target milk production with 35% first-lactation cows

Year ¹	Target milk production		
	9,979 kg/cow per year ²	11,793 kg/cow per year ³	
	Milk income over feed cost (\$/cow)	ECM production (kg/cow)	Milk income over feed cost (\$/cow)
1986	2,656.67	9,998	2,904.98
1987	2,186.03	9,898	2,404.01
1988	1,914.36	10,048	2,174.16
1989	2,259.18	9,998	2,507.04
1990	2,534.18	9,849	2,735.85
1991	2,509.71	9,948	2,743.80
1992	2,330.98	9,998	2,582.96
1993	2,404.90	9,898	2,635.12
1994	2,615.45	9,998	2,875.77
1995	2,256.93	9,948	2,493.04
1996	2,174.48	9,849	2,378.54
1997	2,248.14	9,799	2,434.17
1998	2,613.78	9,998	2,863.16
1999	2,626.22	9,998	2,888.52
2000	2,440.01	9,849	2,641.31
2001	2,487.02	9,898	2,704.03
2002	2,084.11	9,948	2,323.72
2003	2,095.84	9,849	2,299.45
2004	2,519.76	9,849	2,722.33
2005	2,136.85	10,048	2,405.06
2006	2,471.72	9,998	2,720.89
2007	2,209.00	9,998	2,459.24
2008	2,319.46	9,998	2,570.96
2009	2,161.25	9,849	2,363.82
2010	2,635.08	9,849	2,837.44
Mean	2,355.64	9,934	2,586.77
SD	207.78	75.40	209.54
Median	2,330.98	9,948	2,582.96
Min	1,914.36	9,799	2,174.16
Max	2,656.67	10,048	2,904.98

¹Each year comprised a different daily weather data set of maximum and minimum temperature, solar radiation, and rainfall, collected in Dane County Regional-Truax Field, Wisconsin; 43.13°N, 89.33°W, elevation = 259 m.

²Target milk production level was lower than the maximum potential milk production with 35% first-lactation cows. Therefore, the ECM was 9,212 kg/cow per year through all 25 yr.

³Target milk production level exceeded the maximum potential milk production with 35% first-lactation cows.

Net Return to Management

The model calculated the farm net return to management by subtracting the cost of production from the sum of all income sources. The cost of production included equipment, facilities, energy, labor, custom operation, land rental, purchased feed and bedding, animal purchase and livestock expenses, milk hauling and marketing cost, property tax, and the cost of seed, fertilizer, and chemicals used on the cropland. The revenues stemmed from milk sales, extra animal sales, and extra feed and crop sales (Rotz et al., 2013).

Sensitivity Analyses

Sensitivity analyses were conducted on the target milk production, first-lactation cow percent, and their interactions to test their effect on environmental and economic outputs. Our study evaluated 2 key user-input variables of the IFSM: target milk production and

first-lactation cow percent. Target milk production was varied to estimate the maximum potential milk production, which represented the biological production limitation. The model optimizes the allocation of on-farm and purchased resources to maximize the actual milk production to approach the target milk production. This maximum potential milk production represented the maximum biological milk production that the herd could actually attain due to the individual cow rumen size limitation and available feed fiber contents and digestibility. As the farm can always purchase feed, the rumen volume determines the biological maximum milk production. Thus, increasing the target milk production in the input estimated the cows' maximum capacity for producing milk. First-lactation cow percent represented the herd structure that was closely associated with reproductive efficiency and replacement decisions. Target milk production was increased from 9,979 to 11,793 kg/cow per year by an interval of 227 kg; the first-lactation cow percentage was increased from 15 to

Figure 1. Relationship between target milk production (kg/cow per year) and ECM production obtained (kg/cow per year) for different herd structure (represented by varying first-lactation cow percent from 15 to 45%).

Table 3. Cost and revenues (mean $\pm$ SD, \$/cow) of a representative Wisconsin farm (100 cows, including dry cows, and 100 ha of land) at target milk production of 9,979 kg/cow per year¹ with different herd structures represented by varying first-lactation cow percent²

Breakdown cost or revenue category (\$/cow)	First-lactation cow percent (%)						
	15	20	25	30	35	40	45
Equipment cost	546.88 $\pm$ 4.90	546.85 $\pm$ 4.89	546.83 $\pm$ 4.89	546.80 $\pm$ 4.88	546.77 $\pm$ 4.87	546.74 $\pm$ 4.86	546.71 $\pm$ 4.86
Facilities cost	615.62 $\pm$ 3.12	615.61 $\pm$ 3.12	615.61 $\pm$ 3.12	615.61 $\pm$ 3.12	615.61 $\pm$ 3.13	615.61 $\pm$ 3.13	615.60 $\pm$ 3.13
Energy cost	157.28 $\pm$ 3.56	157.27 $\pm$ 3.56	157.25 $\pm$ 3.55	157.23 $\pm$ 3.54	157.21 $\pm$ 3.54	157.19 $\pm$ 3.53	157.17 $\pm$ 3.52
Labor cost	524.85 $\pm$ 4.69	524.82 $\pm$ 4.68	524.79 $\pm$ 4.67	524.76 $\pm$ 4.66	524.72 $\pm$ 4.65	524.68 $\pm$ 4.65	524.64 $\pm$ 4.64
Custom operation cost	25.38 $\pm$ 3.62	25.38 $\pm$ 3.62	25.37 $\pm$ 3.62	25.37 $\pm$ 3.61	25.36 $\pm$ 3.61	25.36 $\pm$ 3.60	25.36 $\pm$ 3.60
Seed, fertilizer, and chemical cost	321.07 $\pm$ 0	321.07 $\pm$ 0	321.07 $\pm$ 0	321.07 $\pm$ 0	321.07 $\pm$ 0	321.07 $\pm$ 0	321.07 $\pm$ 0
Land rental cost	321.11 $\pm$ 0	321.11 $\pm$ 0	321.11 $\pm$ 0	321.11 $\pm$ 0	321.11 $\pm$ 0	321.11 $\pm$ 0	321.11 $\pm$ 0
Net purchased feed and bedding cost	213.91 $\pm$ 221.57	214.11 $\pm$ 221.39	214.32 $\pm$ 221.20	214.61 $\pm$ 221.09	214.80 $\pm$ 220.86	215.14 $\pm$ 220.71	215.47 $\pm$ 220.39
Replacement heifer purchase cost	225.00 $\pm$ 0	300.00 $\pm$ 0	375.00 $\pm$ 0	450.00 $\pm$ 0	525.00 $\pm$ 0	600.00 $\pm$ 0	675.00 $\pm$ 0
Livestock expenses	372.00 $\pm$ 0	372.00 $\pm$ 0	372.00 $\pm$ 0	372.00 $\pm$ 0	372.00 $\pm$ 0	372.00 $\pm$ 0	372.00 $\pm$ 0
Milk hauling and marketing fees	219.99 $\pm$ 0	219.99 $\pm$ 0	219.99 $\pm$ 0	219.99 $\pm$ 0	219.99 $\pm$ 0	219.99 $\pm$ 0	219.99 $\pm$ 0
Property tax total cost	41.62 $\pm$ 0	41.62 $\pm$ 0	41.62 $\pm$ 0	41.62 $\pm$ 0	41.62 $\pm$ 0	41.62 $\pm$ 0	41.62 $\pm$ 0
	3,584.71	3,659.83	3,734.96	3,810.17	3,885.26	3,960.51	4,035.74
Income from milk sales	4,025.98 $\pm$ 0	4,025.98 $\pm$ 0	4,025.98 $\pm$ 0	4,025.98 $\pm$ 0	4,025.98 $\pm$ 0	4,025.98 $\pm$ 0	4,025.98 $\pm$ 0
Income from animal sales	230.57 $\pm$ 0	275.66 $\pm$ 0	320.74 $\pm$ 0	365.83 $\pm$ 0	410.92 $\pm$ 0	456.00 $\pm$ 0	501.09 $\pm$ 0
Return to management and unpaid factors	671.86 $\pm$ 204.83	641.81 $\pm$ 204.68	611.77 $\pm$ 204.52	581.66 $\pm$ 204.44	551.64 $\pm$ 204.24	521.48 $\pm$ 204.11	491.33 $\pm$ 203.82

¹This target production level was lower than the maximum potential milk production for all first-lactation cow percent levels; therefore, this level of production was reached in all cases.

²Results from simulations performed with the Integrated Farm System Model (Rotz et al., 2013) using 25 yr of daily weather data for south-central Wisconsin.

Table 4. Cost and revenues (mean $\pm$ SD, \$/cow) of a representative Wisconsin farm (100 cows, including dry cows, and 100 ha of land) at a target milk production of 11,793 kg/cow per year^{1,2} with different herd structures represented by varying first-lactation cow percent³

Breakdown cost or revenue category (\$/cow)	First-lactation cow percent (%)						
	15	20	25	30	35	40	45
Equipment cost	552.11 $\pm$ 5.02	551.63 $\pm$ 4.95	551.15 $\pm$ 4.90	550.68 $\pm$ 4.88	550.23 $\pm$ 4.87	549.73 $\pm$ 4.83	549.27 $\pm$ 4.80
Facilities cost	615.84 $\pm$ 3.62	615.83 $\pm$ 3.59	615.79 $\pm$ 3.50	615.78 $\pm$ 3.48	615.76 $\pm$ 3.45	615.72 $\pm$ 3.38	615.70 $\pm$ 3.33
Energy cost	167.05 $\pm$ 3.69	166.21 $\pm$ 3.64	165.37 $\pm$ 3.56	164.53 $\pm$ 3.53	163.74 $\pm$ 3.59	162.84 $\pm$ 3.50	162.04 $\pm$ 3.47
Labor cost	531.35 $\pm$ 4.63	530.77 $\pm$ 4.56	530.19 $\pm$ 4.51	529.61 $\pm$ 4.51	529.05 $\pm$ 4.51	528.44 $\pm$ 4.47	527.87 $\pm$ 4.46
Custom operation cost	25.43 $\pm$ 3.66	25.42 $\pm$ 3.66	25.41 $\pm$ 3.65	25.40 $\pm$ 3.64	25.39 $\pm$ 3.63	25.39 $\pm$ 3.63	25.38 $\pm$ 3.62
Seed, fertilizer, and chemical cost	321.07 $\pm$ 0	321.07 $\pm$ 0	321.07 $\pm$ 0	321.07 $\pm$ 0	321.07 $\pm$ 0	321.07 $\pm$ 0	321.07 $\pm$ 0
Land rental cost	321.11 $\pm$ 0	321.11 $\pm$ 0	321.11 $\pm$ 0	321.11 $\pm$ 0	321.11 $\pm$ 0	321.11 $\pm$ 0	321.11 $\pm$ 0
Net purchased feed and bedding cost	329.85 $\pm$ 223.06	319.96 $\pm$ 223.39	310.66 $\pm$ 223.41	301.11 $\pm$ 223.40	292.18 $\pm$ 222.82	282.49 $\pm$ 222.74	273.46 $\pm$ 222.16
Replacement heifer purchase cost	225.00 $\pm$ 0	300.00 $\pm$ 0	375.00 $\pm$ 0	450.00 $\pm$ 0	525.00 $\pm$ 0	600.00 $\pm$ 0	675.00 $\pm$ 0
Livestock expenses	372.00 $\pm$ 0	372.00 $\pm$ 0	372.00 $\pm$ 0	372.00 $\pm$ 0	372.00 $\pm$ 0	372.00 $\pm$ 1.76	372.00 $\pm$ 1.76
Milk hauling and marketing fees	245.84 $\pm$ 1.69	243.64 $\pm$ 1.87	241.45 $\pm$ 1.68	239.28 $\pm$ 1.76	237.23 $\pm$ 1.76	234.95 $\pm$ 0	232.89 $\pm$ 0
Property tax	41.62 $\pm$ 0	41.62 $\pm$ 0	41.62 $\pm$ 0	41.62 $\pm$ 0	41.62 $\pm$ 0	41.62 $\pm$ 0	41.62 $\pm$ 0
Total cost	3,748.27	380.9.26	3,870.82	3,932.19	3,994.38	4,055.36	4,117.41
Income from milk sales	4,499.23 $\pm$ 30.98	4,458.85 $\pm$ 32.46	4,418.77 $\pm$ 30.79	4,379.10 $\pm$ 32.26	4,341.51 $\pm$ 32.27	4,299.93 $\pm$ 32.24	4,262.16 $\pm$ 32.21
Income from animal sales	230.57 $\pm$ 0	275.66 $\pm$ 0	320.74 $\pm$ 0	365.83 $\pm$ 0	410.92 $\pm$ 0	456.00 $\pm$ 0	501.09 $\pm$ 0
Return to management and unpaid factors	981.53 $\pm$ 209.84	925.24 $\pm$ 208.82	868.69 $\pm$ 206.13	812.73 $\pm$ 205.50	758.04 $\pm$ 205.75	700.56 $\pm$ 202.89	645.83 $\pm$ 202.57

¹This target production level exceeds the maximum potential milk production for all first-lactation cow percent levels; therefore, this production level was not reached in all cases.

²The ECM production for 15, 20, 25, 35, 40, and 45% first-lactation cow percent were 10,295, 10,203, 10,111, 10,020, 9,934, 9,839, and 9,753 kg/cow per year, respectively.

³Results from simulations performed with the Integrated Farm System Model (Rotz et al., 2013) using 25 yr of daily weather data for south-central Wisconsin.

45% by intervals of 5%. The lowest first-lactation cow percentage (15%) might not be realistic in commercial dairy farms; however, this extraordinary value was used to expand the sensitivity test range.

GHG Emissions

Greenhouse gas emission was expressed as CO₂ equivalents, including biogenic CO₂, per kilogram of ECM. Global-warming potentials of CH₄ and N₂O that are 25 and 298 times greater than CO₂, respectively, were used to calculate the CO₂ equivalents (Rotz et al., 2013). Biogenic CO₂ represents the net CO₂ assimilated from and released to the atmosphere, including assimilation in plant growth and animal body, and carbon sequestration (Stackhouse-Lawson et al., 2012; Dutreuil et al., 2014). Carbon sequestration occurs when depositing manure to cropland as fertilizer. It is a chemical process where partial manure carbon is fixed into soil carbon or plants. Therefore, including biogenic CO₂ reduces

the overall farm GHG emissions (Stackhouse-Lawson et al., 2012).

RESULTS AND DISCUSSION

Output Variation

Due to the separate calculation for each year and no carryover effects in the IFSM (Rotz et al., 2013), the large variation in the results at one given management level can be explained by the difference in each year's weather. These weather differences are primarily caused by variation in feed production, which affects the farm's overall outcomes.

Table 1 shows the annual on-farm feed production, including high-quality hay, low-quality hay, high-quality silage, grain crop silage, high-moisture grain, dry grain, and forage. The farm-produced feed resources determine the total feed cost (Table 2). When the target milk production was attained, milk income over feed cost reflected changes in feed purchase cost because the

Figure 2. Relationship between ECM (kg/cow per year) and net return to management (\$) for different herd structure (represented by varying first-lactation cow percent from 15 to 45%).

Table 5. Net return to management (\$/cow; mean $\pm$ SD) of a representative Wisconsin farm (100 cows, including dry cows, and 100 ha of land) with different herd structures (represented by varying first-lactation cow percent) and target milk production¹

Item	First-lactation cow percent (%)							Decrease (%) ²
	15	20	25	30	35	40	45	
Target milk production (kg/cow per year)								
9,979	671.86 $\pm$ 204.83	641.81 $\pm$ 204.68	611.77 $\pm$ 204.52	581.66 $\pm$ 204.44	551.64 $\pm$ 204.24	521.48 $\pm$ 204.11	491.33 $\pm$ 203.82	36.74
10,206	732.04 $\pm$ 205.08	701.78 $\pm$ 204.89	671.61 $\pm$ 204.59	641.59 $\pm$ 204.41	611.53 $\pm$ 204.25	581.50 $\pm$ 204.07	551.44 $\pm$ 203.88	32.75
10,433	791.89 $\pm$ 205.78	761.75 $\pm$ 205.58	731.37 $\pm$ 205.07	701.31 $\pm$ 204.89	671.03 $\pm$ 204.42	641.22 $\pm$ 203.92	611.23 $\pm$ 203.81	29.56
10,659	851.99 $\pm$ 205.69	821.84 $\pm$ 205.56	791.64 $\pm$ 205.38	761.49 $\pm$ 205.19	730.59 $\pm$ 204.98	690.22 $\pm$ 205.20	647.37 $\pm$ 202.42	31.61
10,886	911.65 $\pm$ 206.14	881.47 $\pm$ 205.95	846.04 $\pm$ 206.25	808.53 $\pm$ 206.83	757.94 $\pm$ 204.92	700.40 $\pm$ 202.67	645.74 $\pm$ 202.19	41.18
11,113	965.79 $\pm$ 207.53	922.97 $\pm$ 210.24	868.52 $\pm$ 207.51	812.48 $\pm$ 205.11	758.44 $\pm$ 205.93	700.88 $\pm$ 202.70	645.10 $\pm$ 202.19	49.71
11,340	979.99 $\pm$ 207.71	926.00 $\pm$ 208.78	868.40 $\pm$ 207.19	812.92 $\pm$ 205.11	758.31 $\pm$ 206.32	700.72 $\pm$ 202.69	645.52 $\pm$ 202.19	51.81
11,567	980.44 $\pm$ 208.89	925.86 $\pm$ 209.54	868.25 $\pm$ 207.51	813.37 $\pm$ 204.36	758.16 $\pm$ 205.90	700.62 $\pm$ 202.70	645.93 $\pm$ 202.18	51.79
11,793	981.53 $\pm$ 209.84	925.24 $\pm$ 208.82	868.69 $\pm$ 206.13	812.73 $\pm$ 205.50	758.04 $\pm$ 205.75	700.56 $\pm$ 202.89	645.83 $\pm$ 202.57	51.98
Increase (%) ³	31.47	34.34	37.42	39.73	42.00	44.16	46.09	

¹Results from simulations performed with the Integrated Farm System Model (Rotz et al., 2013) using 25-yr of daily weather data for south-central Wisconsin.

²Decrease in net return to management when first-lactation cow percent increases from 15 to 45%.

³Increase in net return to management when the target milk production increases from 9,979 to 11,793 kg/cow per year.

milk income was fixed with constant production. The highest milk income over feed cost (\$2,656.67 per cow) was 38.8% greater than the lowest milk income over feed cost (\$1,914.36 per cow). This difference represented the yearly variation in quantity and quality of farm-produced feed as affected by weather.

Milk Production

As expected, the ECM (4.0% fat and 3.5% protein) increased linearly with the target milk production to a certain level, followed by the target milk production and ECM increasing nonlinearly at a decreasing rate. Thereafter, the ECM remained flat at the maximum potential milk production regardless of higher target milk production input (Figure 1). The increase of ECM showed similar trends at each level of first-lactation cow percentage. The more first-lactation cows in a herd, a lower per-cow milk production was reached. Hence, the turning point target milk production was lower when the percentage of first-lactation cows was high. Regardless of the herd structure, cows were able to produce as much as the target on lower target milk production because the target level was lower than the maximum potential milk production. Nonmature first-lactation cows that are still growing produce less milk, have a lower peak on their lactation curves, and show a greater milk persistency than their later lactation counterparts (Shanks et al., 1981). As a result, the greater the proportion of first-lactation cows, the lower the maximum potential milk production.

Net Return to Management

The cost of purchasing replacement heifers was the major difference across herd structures when target milk production was lower than the maximum potential milk production (Table 3). The per-cow replacement heifer cost increased 200% from \$225 at 15% first-lactation cows to \$675 at 45% first-lactation cows, which was the greatest change in total cost. Once the target milk production exceeded the maximum potential milk production of the high first-lactation cow percentage, the ECM of high first-lactation cow percentage stayed the same. Meanwhile the ECM kept increasing at a low first-lactation cow percentage with the same target milk production. As the target milk production increased, the high first-lactation cow percentage had less purchase cost of feed and bedding due to the stable ECM compared with the low one, which compensated for the replacement heifer purchase cost. Feed and bedding cost per cow was \$273.46 for 45% first-lactation cows and it was \$329.85 for 15% first-lactation cows (Table 4) at a 11,793 kg/cow per year target milk production.

Figure 3. Relationship between target milk production (kg/cow per year) and net return to management (\$/cow) with different herd structure (represented by varying first lactation cow percent from 15 to 45%).

Generally, the net return to management increased as the amount of first-lactation cows decreased, indicating that more first-lactation cows would result in

less farm profit. St-Pierre and Eastridge (2013) found a similar result, indicating that when the proportion of first-lactation cows increased with culling rate from

Table 6. Greenhouse gas emission including biogenic CO₂¹ (kg of equivalent CO₂/kg of ECM, mean ± SD) with different target milk production (kg/cow per year) and herd structure (represented by varying first-lactation cow percent)²

Item	First-lactation cow percent (%)							Increase (%) ³
	15	20	25	30	35	40	45	
Target milk production								
9,979	0.53 ± 0.04	0.55 ± 0.04	0.56 ± 0.04	0.57 ± 0.04	0.58 ± 0.04	0.58 ± 0.04	0.59 ± 0.04	11.32
10,206	0.53 ± 0.04	0.54 ± 0.04	0.55 ± 0.04	0.56 ± 0.04	0.57 ± 0.04	0.58 ± 0.04	0.58 ± 0.04	9.43 ⁴
10,433	0.52 ± 0.04	0.53 ± 0.04	0.54 ± 0.04	0.55 ± 0.04	0.56 ± 0.04	0.57 ± 0.04	0.58 ± 0.04	11.54
10,659	0.51 ± 0.04	0.52 ± 0.04	0.54 ± 0.04	0.55 ± 0.04	0.56 ± 0.04	0.57 ± 0.04	0.57 ± 0.04	11.76
10,886	0.51 ± 0.04	0.52 ± 0.04	0.53 ± 0.04	0.54 ± 0.04	0.55 ± 0.04	0.56 ± 0.04	0.57 ± 0.04	11.76
11,113	0.50 ± 0.04	0.51 ± 0.04	0.53 ± 0.04	0.54 ± 0.04	0.55 ± 0.04	0.56 ± 0.04	0.57 ± 0.04	14.00
Decrease (%) ⁵	5.66	7.27 ⁵	5.36	5.26	5.17	3.45	3.39	

¹Biogenic CO₂ represents the net CO₂ assimilated from and released to the atmosphere, including assimilation in plant growth and animal body and carbon sequestration (Stackhouse-Lawson et al., 2012; Dutreuil et al., 2014).

²Results from simulations performed with the Integrated Farm System Model (Rotz et al., 2013) using 25 yr of daily weather data for south-central Wisconsin.

³Increase in greenhouse gas emission when the first-lactation cow percent increases from 15 to 45%.

⁴Small absolute values and 2-decimal rounding as reported by the model cause this value to appear inconsistent. Nonetheless, it is clear that overall results still follow the general GHG emissions trend.

⁵Decrease in greenhouse gas emission when the target milk production increases from 9,979 to 11,113 kg/cow per year.

Figure 4. The effect of the interaction of target milk production and herd structure (represented by varying first-lactation cow percent from 15 to 45%) on greenhouse gas including biogenic CO₂ emission [kg of CO₂ equivalents (eq.) / kg of ECM]. Biogenic CO₂ represents the net CO₂ assimilated from and released to the atmosphere, including assimilation in plant growth and animal body, and carbon sequestration.

35 to 40%, income over feed cost decreased \$0.022 per kilogram of milk. A herd structure with more mature cows increases revenue from selling extra bred heifers, or decreases cost of purchasing replacement heifers. Moreover, the more mature the cows, the higher the feed efficiency as they are able to produce the same amount of milk with less feed intake (Connor et al., 2013).

The net return to management was strongly and positively related to ECM produced ($r = 0.88$) at each first-lactation cow percent level. At the same ECM production level, net return on management was lower with a greater proportion of first-lactation cows (Figure 2). A greater ECM led to a greater net return to management. As the target milk production increased from 9,979 to 11,793 kg, the net return to management increased between 31 and 46% as the proportion of first-lactation cows increased (Table 5). At a given proportion of first-lactation cows, greater target milk production generally led to a greater net return to management before exceeding the maximum potential milk production plateau. Regardless of increased input of target milk production, the farm net return plateaued after the target milk production reached the maximum potential production (Figure 3).

The interaction of target milk production and proportion of first-lactation cows affecting the net return to management is depicted in Figure 3. From the lowest target milk production, the net return to management increase was greater on the low first-lactation cow percent than in the high first-lactation cow percent. From the lowest to the greatest first-lactation cow percentages, the net return to management decreased nonlinearly as the target milk production increased. The decrease in net return to management increased as the target milk production increased up to 11,340 kg/cow per year (Table 5). The plateau that followed was because the cow attained the maximum potential milk production when the target milk production exceeded the biological limitation of the animal. The maximum net return to management was associated with the greatest target milk production and the lowest first-lactation cow percent. The minimum net return to management was associated with the lowest target milk production and the greatest first-lactation cow percent.

Results of the current study confirmed that milk sales are the dominating factor in total net return (Lehenbauer and Oltjen, 1998; MacDonald et al., 2007). The reduction in milk sales between low and high first-lactation cow percent had greater effect than

Figure 5. Linear regression correlation between greenhouse gas emission [kg of CO₂ equivalents (eq.)/kg of ECM] and net return to management (\$/cow) with different herd structure (represented by varying first-cow lactation percent).

the increase in animal sale revenue between the 2 levels. The first-lactation cow percentage was an indicator of herd replacement policy together with reproduction efficiency; with greater culling rate, more replacement heifers were needed to keep the herd size constant, which resulted in a greater first-lactation cow percentage. Furthermore, reproduction efficiency determined the number of available replacement cows on the farm and affected the replacement rate due to culling for reproduction failure. Replacement decisions affect farm profits (Olynk and Wolf, 2008; Kalantari and Cabrera, 2012). The IFSM determines the culling decision merely by the first-lactation cow percentage, which influenced the representative farm net profit at each target milk production. In reality, culling decisions are more complex based on milk production, animal health, reproductive performance, and market prices (Groenendaal et al., 2004; Kalantari and Cabrera, 2012).

GHG Including Biogenic CO₂

The relationship between GHG and target milk production by the first lactation cow percentage is shown in Figure 4. Carbon dioxide equivalent emission decreased with more milk production. As target milk production increased from 9,979 to 11,793 kg/cow per year, CO₂ equivalent emission including biogenic CO₂ decreased between 3.4 and 7.3% at different proportions of first-lactation cows. The results demonstrated that greater production would decrease GHG emissions per unit of produced milk (Beukes et al., 2010; Rotz et al., 2010). Elevating target milk production requires greater feed intake to meet the nutrient requirements. The higher target milk production indirectly increased total equivalent CO₂ emission; however, the greater ECM decreased the kilograms of CO₂ per kilograms of ECM (Rotz et al., 2010). In general, increasing milk production per cow is an efficient method to reduce GHG emissions while improving profitability.

A higher first-lactation cow percentage led to higher GHG emissions. As the proportion of first-lactation cows increased from 15 to 45%, CO₂ equivalent emissions increased between 9.4 and 11.3% at different target milk production levels (Table 6). A lower culling rate reduced the GHG per kilogram of ECM, demonstrating that better reproductive performance or a lower culling rate would decrease the GHG emissions (Beukes et al., 2010; O'Brien et al., 2011; Crosson et al., 2011). First-lactation cows have lower feed efficiency, as they require more feed to produce the same amount of milk, corresponding with more CH₄ emission and urinary-N partition (De Klein and Eckard, 2008; Beukes et al., 2010). The greater GHG per kilogram of

ECM on higher culling rates was due to the higher total GHG emission along with lower ECM per cow per year.

Herd structure and target milk production affect GHG emissions (Table 6, Figure 4), in agreement with Crosson et al. (2011), who indicated that animal performance influences the GHG emissions. The greatest GHG emissions per kilogram of ECM occurred with the lowest target milk production and highest culling rate; the lowest GHG occurred with the highest target milk production and lowest culling rate (Figure 4).

The data demonstrated a negative relationship between GHG and net return to management (Figure 5). Regardless of the first-lactation cow percent, higher CO₂ equivalent emissions were always associated with lower farm net return to management ($R^2 > 0.92$; Figure 5). As the first-lactation cow percentage increased, both CO₂ equivalent emissions and net return to management decreased at a given target milk production. This result suggests that reducing GHG by increasing herd average milk production or decreasing the first-lactation cow percentage would improve whole farm net return.

CONCLUSIONS

This study demonstrates that increased milk production per cow increases farm net profit and decreases the per-kilogram milk GHG emissions, a win-win situation. Also, a decreased percentage of first-lactation cows, a trait related to reproduction and replacement, increases average milk production, farm net profit, and decreases the per-kilogram milk GHG emissions. Therefore, lower GHG emissions are associated with increased milk production and decreased first-lactation cow percentages.

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