OPTIMAL HOUSING AND MANURE MANAGEMENT STRATEGIES TO FAVOR PRODUCTIVE AND ENVIRONMENT-FRIENDLY DAIRY FARMS IN QUÉBEC, CANADA: PART I. REPRESENTATIVE FARM SIMULATIONS

S. Fournel, É. Charbonneau, S. Binggeli, J.-M. Dion,
D. Pellerin, M. H. Chantigny, S. Godbout

ABSTRACT. *Tie-stall housing (93%) and solid manure management (44%) are used on many dairy farms in the province of Québec, Canada. However, this could change in the near future because the rise in average herd size and the popularity of milking robots are such that the industry expects an increase in free-stall dairies managing manure with liquid systems. This shift could affect the carbon (C), nitrogen (N), and phosphorus (P) footprints of Québec's dairy production. In this context, whole-farm modeling (N-CyCLES), considering all the production cycle, provides a tool for evaluating the economics and environmental impacts of standard housing and manure management systems (Part I) in combination with different mitigation approaches (Part II). Two representative dairy farms in southwestern Québec (SWQ; 45.3° N, 73.2° W) and eastern Québec (EQ; 48.45° N, 68.1° W) were simulated considering four scenarios involving combinations of tie-stall or free-stall housing and solid or liquid manure management. Maximum farm net income (FNI) was \$0.33 and \$0.18 kg*$^{-1}$ *of fat- and protein-corrected milk (FPCM) for the SWQ and EQ farms, respectively, with N and P footprints of 12.22 to 16.99 g N kg*$^{-1}$ *and 0.52 to 0.79 g P kg*$^{-1}$ *of FPCM in SWQ, and 11.48 to 15.39 g N kg*$^{-1}$ *and 1.41 to 1.88 g P kg*$^{-1}$ *of FPCM in EQ. Greenhouse gas (GHG) emissions reached 1.78 to 1.87 kg* CO_2e *kg*$^{-1}$ *and 1.67 to 1.71 kg* CO_2e *kg*$^{-1}$ *of FPCM in SWQ and EQ, respectively. The SWQ farm was associated with greater production of cash crops but also greater imports of fertilizers and purchased feeds, which negatively affected the N footprint and GHG emissions. Housing and manure management types did not influence FNI. Free-stall dairies were associated with greater N surpluses. Nevertheless, they emitted slightly less GHG than tie-stall dairies. Dairy farms under liquid manure management imported less fertilizers and produced less GHG despite greater* CH_4 *emissions. As a result, the current transition toward free-stall barns and liquid manure systems in Québec seems advantageous from an environmental standpoint without compromising economic profitability.*

Keywords. *Climate change, Dairy cow, Farm net income, Free stall, Greenhouse gas emission, Manure handling, Mitigation, Nutrient footprint, Tie stall, Whole-farm model.*

Dairy production in the province of Québec, Canada, is characterized by family-run farms (PLQ, 2018) using tie-stall housing (93%; CDIC, 2016) and solid manure management (44%; Quantis et al., 2012) in a large proportion. However, the recent consolidation of Québec farms has led to an increase in the average herd size (from 49 to 65 milking cows per farm from 2005 to 2017; AGÉCO, 2018), which is expected to induce a shift toward free-stall housing with liquid manure systems in the near future (Valacta, 2015) for practical and economic reasons (Jayasundara and Wagner-Riddle, 2014; Sheppard et al., 2011). Furthermore, new animal welfare regulations (Villettaz Robichaud et al., 2018) and the difficulty to recruit qualified workers, along with technological advancements in automated milking systems (Valacta, 2015), are prompting Québec dairy producers to rethink the way they operate.

The projected transition may involve changes in greenhouse gas (GHG) emissions from Québec dairy farms because the anaerobic nature of liquid manure systems increases the potential for methane (CH_4) release, while solid manure systems are substantial contributors of nitrous oxide (N_2O) through nitrification and denitrification processes (Chadwick et al., 2011; Gerber et al., 2013; Jayasundara et al., 2016). With dairy production contributing 3.4% of the

Submitted for peer review in December 2018 as manuscript number PAFS 13271; approved for publication as a Research Article by the Plant, Animal, & Facility Systems Community of ASABE in May 2019.

The authors are **Sébastien Fournel,** Postdoctoral Fellow, **Édith Charbonneau,** Full Professor, **Simon Binggeli,** Graduate Student, **Jean-Michel-Dion,** Undergraduate Student, and **Doris Pellerin,** Full Professor, Département des sciences animales, Université Laval, Québec City, Québec, Canada; **Martin H. Chantigny,** Research Scientist, Québec Research and Development Centre, Agriculture and Agri-Food Canada, Québec City, Québec, Canada; **Stéphane Godbout,** Research Scientist, Research and Development Institute in Agri-Environment, Québec City, Québec, Canada. **Corresponding author:** Sébastien Fournel, 2425 rue de l'Agriculture, Pavillon Paul-Comtois, Québec City, QC, Canada G1V 0A6; phone: 418-656-2131, ext. 408139; e-mail: sebastien.fournel@fsaa.ulaval.ca.

  ISSN 2151-0032 https://doi.org/10.13031/trans.13271

province's total GHG emissions (FPLQ, 2012; MDDELCC, 2016; Quantis et al., 2012), the upcoming conversion to liquid manure systems might affect the objective of Québec's government to reduce provincial GHG emissions by 20% below those of 1990 by 2020 (MDDELCC, 2018). Global warming has become an important concern, as we are generally experiencing warmer and more variable weather. It is expected that annual temperatures will rise by approximately 2°C to 4°C for the 2041-2070 period depending on location in the province. In addition, all areas in the province of Québec can expect an increase in annual precipitation. Rapid climate change poses risk to the well-being of society and sustainable development (Ouranos, 2015).

Consequently, dairy producers must implement strategies for limiting GHG emissions to help control global warming. Before evaluating alternatives in manure management and bedding materials for mitigating GHG emissions and reducing the environmental impact of dairy farms (discussed in Part II), the overall effect of a change in barn configuration needs to be addressed. To date, much research has focused on quantifying emissions from various sources within the agricultural production system with the aim of establishing emission factors; for example, Jayasundara et al. (2016) reviewed CH_4 and N_2O emissions from tie-stall or free-stall barns with solid or liquid systems in Canadian dairy farms. However, this source-level approach does not reflect the net impact of any management strategy on the animal-barn-storage-field continuum (AAFC, 2014). Some mitigation measures aimed at reducing emissions from livestock housing and manure tanks will result in potentially greater losses at the manure spreading level, reducing the overall effectiveness of such measures. Therefore, a whole-farm perspective is important, and indirect impacts on emissions from other sources and emissions of other pollutants should be considered (Petersen et al., 2007).

Farm-scale modeling provides a method for assessing the environmental footprint of different housing and manure handling systems (Rotz et al., 2016). The model N-CyCLES (Nutrient Cycling: Crops, Livestock, Environment, and Soils), an Excel-based linear program, is one of the tools developed to optimize feeding, cropping, fertilizer use, and manure allocation as a single unit of management under Québec conditions (Pellerin et al., 2017). Because any management change must maintain or improve production and be economically viable to preserve sustainable production, N-CyCLES also provides estimates of farm net income (FNI) when resources are allocated to reduce nitrogen (N) and phosphorus (P) footprints while optimizing the four aforementioned areas. The objective of this study was to compare FNI, N and P footprints, and GHG emissions while optimizing FNI under four scenarios involving combinations of tie-stall or free-stall housing with solid or liquid manure management for two dairy farms under contrasting climates (southwestern and eastern Québec).

Materials and Methods

Model Description

N-CyCLES (fig. 1) is a Microsoft Excel (Microsoft Corp., Redmond, Wash.) based linear optimization model (Wattiaux, 2018), running with an open-source add-in (Mason, 2011). It may be set to maximize FNI or to minimize the N or P footprint or GHG emissions. Farm net income is calculated as the difference between income and expenses. Whole-farm N and P footprints are calculated by the difference between farm-gate imports and exports. Sources of imports accounted for include purchased feeds and fertilizers and, in the case of N, atmospheric deposition and biological N fixation. Sources of exports accounted for include milk, animals, and crops sold. N-CyCLES also evaluates GHG production based on estimation methods, equations, activity data, emission factors, and agricultural parameters used by Canada's National GHG Inventory, which complies with the

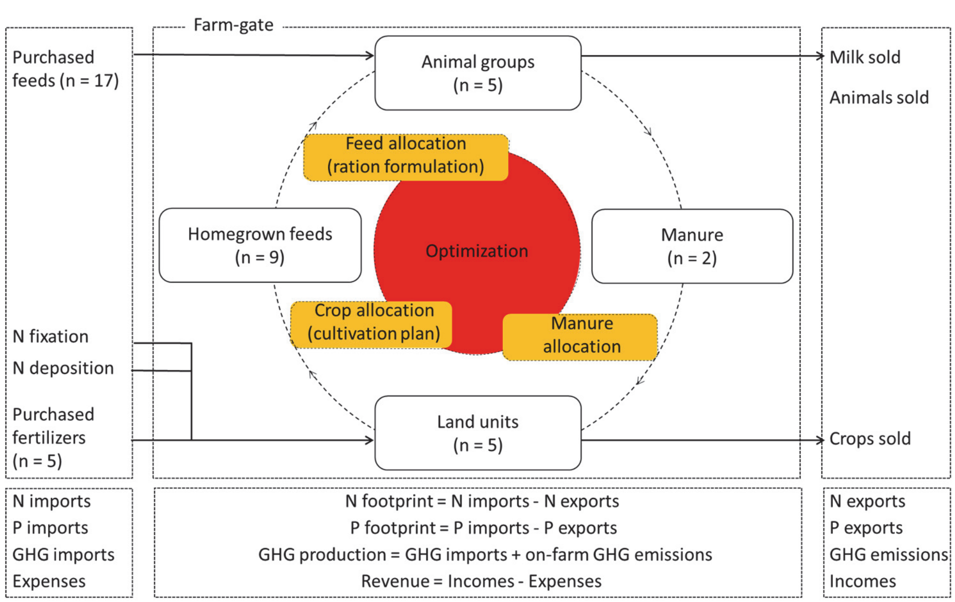

Figure 1. Overview of N-CyCLES model describing the N, P, and GHG imports and exports (solid lines) to establish footprints across the boundary of the livestock-crop component of a farm (dotted outline), the resources whose allocations are subject to simultaneous optimization (shaded area), and the cycling of nutrients within the boundary (dashed line) (adapted from Pellerin et al., 2017).

2006 methodological guidance by the Intergovernmental Panel on Climate Change (IPCC, 2006). When available in the literature (Dollé et al., 2017; Dollé and Robin, 2006; Jayasundara et al., 2016; Montes et al., 2013; Pattey et al., 2005; Rodhe et al., 2015; Tate, 2000; VanderZaag et al., 2014), emission factors for specific housing categories, manure systems, bedding options, and soil types are used to add precision to the model estimation. Carbon dioxide (CO_2), CH_4, and N_2O emissions are tracked from crop, animal, and manure sources and sinks to predict net GHG emission in CO_2 equivalent (CO_2e) units. A unit of CH_4 is equivalent to 25 CO_2e units in global warming potential, whereas a unit of N_2O is equivalent to 298 CO_2e units (ECCC, 2019).

Cycling of nutrients within the farm is described by the input-output relationships of animal groups in the herd and by the input-output relationships of land units, which are defined as groups of fields with distinct characteristics that influence nutrient management plans. In N-CyCLES, manure nutrient outputs from the herd may serve as inputs to the crops, and feed nutrient outputs from the crops may serve as nutrient inputs for the herd. The model accommodates combinations of on-farm and off-farm nutrient resources to meet both animal and crop requirements. In the model, ration formulation, crop rotations, purchase of feeds and fertilizers, and allocation of manure N and P to the land are considered as a single integrated unit of management. In other words, to meet a specific goal, the optimization algorithm considers simultaneously the allocation of homegrown and purchased feeds to meet herd nutritional requirements, the allocation of land to crops grown in rotations, and the allocation of manure and purchased fertilizers to meet crop N and P requirements.

The model was parameterized with National Research Council algorithms (NRC, 2001) for the nutritional requirements and supplies of each feeding group and with local nutrient management planning rules for nutrient application in the fields (CRAAQ, 2010). Dietary guidelines are described for five animal groups, including two lactating groups (early and mid-late lactation) and three nonlactating groups (dry cows, heifers <1 year old, and heifers ≥1 year old). Available feeds include nine crop-derived homegrown feeds and seventeen purchased feeds (table A1 in the Appendix). Sources of crop nutrients (N, P, and K) include five commercial fertilizers (table A1) and two on-farm manure types (solid and liquid). For each animal group, the amount of manure excreted was calculated according to ASABE Standard D384.2 (ASABE, 2005) and Nennich et al. (2005). Nutrient excretions in manure are obtained by subtracting the amounts in animal products (milk and body weight gain) from dietary consumption. Total on-farm production of nutrients is calculated as manure excretion plus mineral nutrients in feed refusals. The total mass and volume of manure were calculated by adding to the amount of excreted manure the sum of bedding, used water, dilution water, and rain accumulation in the storage unit given by Godbout et al. (2017, 2013). The cost of manure spreading is user-defined and is based on the total amount to spread, transport distance, and mode of application, as described by recent studies (Brown, 2011; Daugherty et al., 2001; Gray et al., 2014; Hadrich et al., 2010; Harrigan, 2011; Howland and Karszes, 2014; Leibold and Olsen, 2007). Cropland is subdivided into two land units. The first land unit included fields with the greatest soil P, K, and organic matter concentrations, while the second land unit included fields with the lowest soil P, K, and organic matter concentrations. Up to five crop rotations can be allocated to each land unit.

More details on the economic inputs, optimized variables, feeds and diets, manure and fertilizer, crops and rotations, and model outcomes are provided by Pellerin et al. (2017). The model uses year as the unit of time and assumes that the production system is essentially at steady-state. Model outcomes are assessed per kilogram of fat- and protein-corrected milk (FPCM) based on a standard milk with 4% fat and 3.3% true protein content (IDF, 2015). Allocation of GHG emissions between co-products was assessed using the International Dairy Federation methodology (IDF, 2015); thus, milk and meat were allocated based on the physical method, and crops were allocated based on the economic method. The monetary unit is Canadian dollars (CAD).

Representative Farms

Two regional cases were developed to describe a representative farm in southwestern Québec (SWQ; 45.3° N, 73.2° W) and in eastern Québec (EQ; 48.45° N, 68.1° W) with a sufficient number of cows so that the barns can include either tie-stall housing with a milk line system or free-stall housing with an automated milking system. Those two locations were selected due to their high density of dairy farms and the possibility (SWQ) or not (EQ) of growing grain corn due to contrasting climates. Average 2010-2014 farm characteristics and economic inputs for each region were obtained from the Agritel Web Database (GCAQ, 2016).

The productivity and economic values for both representative farms are summarized in table 1. Both farms contained 95 mature Holstein cows, each weighing approximately 670 kg. The calving interval and age at first calving averaged 14 and 25 months, respectively. The cow culling rate for the SWQ and EQ farms was 31.2% and 34.0%, respectively. Milk performance in SWQ and EQ was 10,107 and 9,756 kg cow^{-1} $year^{-1}$, respectively. Milk fat, crude protein, and other solids contents were similar between regions at about 4.09%, 3.39%, and 5.72%, respectively. Average FPCM sold per farm, assuming 5% milk waste, was 926,914 and 896,233 kg $year^{-1}$ for SWQ and EQ, respectively. Milk price, which has been stable in Québec because of the quota system, was representative of the 2010-2014 period and was set at \$0.74 kg^{-1} of FPCM (approx. \$77.6 hL^{-1}). Other sources of income, including livestock sales, represented \$8.59 and \$6.47 hL^{-1} for SWQ and EQ, respectively. Variable costs (breeding, health, supplies, etc.) and fixed costs (labor, taxes, insurances, depreciation, interest, etc.) respectively accounted for \$6.75 hL^{-1} and \$243,925 $year^{-1}$ in SWQ and \$7.50 hL^{-1} and \$278,282 $year^{-1}$ in EQ.

Dry matter (DM) intake per cow in the early and mid-late lactation groups was calculated as, respectively, 25.0 and 23.1 kg d^{-1} in SWQ and 24.5 and 22.6 kg d^{-1} in EQ. The allowable range of rumen-degraded protein (RDP) was 10.2% to 12.1%. The maximum available P was set at 50% above the minimum; thus, the allowable range of available P (die-

Table 1. Description of representative farms included in N-CyCLES for southwestern Québec (SWQ) and eastern Québec (EQ).

	SWQ	EQ
Productivity		
Cow species	Holstein	Holstein
Mature cows (head)	95	95
Mature body weight (kg cow^{-1})	673	667
Calving interval (months)	14.0	13.9
Age at first calving (months)	25.0	25.1
Culling rate (%)	31.2	34.0
Milk production (kg year^{-1})	10,107	9,756
Milk fat (%)	4.08	4.10
Milk crude protein (%)	3.39	3.38
Milk other solids (%)	5.72	5.72
FPCM sold (kg year^{-1})[a]	926,914	896,233
Economic input		
Net milk price ($ hL^{-1})	77.52	77.63
Other income ($ hL^{-1})[b]	8.59	6.47
Variable costs ($ hL^{-1})[b]	6.75	7.50
Labor ($ year^{-1})	80,100	91,732
Taxes and insurances ($ year^{-1})	39,037	48,389
Depreciation ($ year^{-1})	61,673	69,013
Interest ($ year^{-1})	35,215	42,664
Other cost ($ year^{-1})	27,900	26,484
Feeding		
Early lactation cows		
Dry matter intake per cow (kg d^{-1})	25.0	24.5
Allowable range in RDP (%)[c]	10.5 to 12.1	10.4 to 12.0
Available P in ration (%)	0.27	0.25
Mid-late lactation cows		
Dry matter intake per cow (kg d^{-1})	23.1	22.6
Allowable range in RDP (%)[c]	10.2 to 11.7	10.1 to 11.6
Available P in ration (%)	0.36	0.33
Land		
Soil type	Clay	Loam
Cropland (ha)	127	178

[a] FPCM = fat- and protein-corrected milk.
[b] Excludes income and costs associated with crops.
[c] RDP = rumen-degraded protein.

tary DM basis) in both regions for the early and mid-late lactation groups was about 0.26% to 0.35%, respectively. Detailed ration N and P are presented in table 1, while feed ingredients and prices are listed in table A1 in the Appendix.

The land surfaces were 127 and 178 ha of cropland for SWQ and EQ, respectively, which was subdivided in two land units of equal size (table 1). Because of reported associative patterns between soil P test and distance from the manure storage, the two land units (MH-08 and LM-32) were set at medium-high and low-medium concentrations of soil P with hauling distances of 0.8 and 3.2 km, respectively. The soil types in SWQ and EQ were considered clay and loam, respectively, because those are the prevailing soil types in the respective regions. A description of the crop rotations and the average cost of production for each rotation are presented in table A2 in the Appendix. Regional differences in cropping practices were reflected in part by the production of corn grain and wheat in SWQ, while EQ can grow barley and canola. The allowable manure and fertilizer applications in each land unit were set to comply with regional policies and regulations. Fertilizer names and prices are listed in table A1 in the Appendix.

SIMULATIONS

Four scenarios for lactating and dry cows were simulated for each representative farm: (1) tie-stall housing with solid manure management, (2) tie-stall housing with liquid manure management, (3) free-stall housing with solid manure management, and (4) free-stall housing with liquid manure management. The housing system for both groups of heifers (pen) was fixed and never changed through the simulations. Heifer manure was managed in the same way as lactating and dry cow manure. Cereal straw was used as bedding across all simulations.

Solid manure management implied that manure was stored in an appropriate, uncovered storage unit as a stack without a liquid part before being applied in the field with a traditional box spreader. Liquid manure management implied that manure was stored in an appropriate, uncovered, and bottom-loaded storage unit before being applied in the field with a spreader tank equipped with drop hoses attached to splash plates. Manure solids in liquid systems formed a crust on the storage surface, reducing gaseous emissions. The model considers that the majority of both manure types is spread during the growing season (April to September), taking into account that 20.4% (solid manure) and 10.8% (liquid manure) of the annual manure volume is spread after October 1 (Sheppard et al., 2011). Manure treatment or incorporation into the soil were not considered. Tillage, planting, and harvesting operations remained the same across all simulations.

For each scenario, the model was solved to maximize FNI and thus determined the whole-farm footprints for N, P, and GHG. A sensitivity analysis was also conducted to assess the effect of variability in feed (±35%) and fertilizer (±25%) prices on key model outcomes.

RESULTS

FARM NET INCOME

Table 2 presents economic data from the N-CyCLES simulations when FNI was maximized for each representative farm using either tie-stall or free-stall housing with solid or liquid manure management. Income represented $0.95 and $0.86 kg^{-1} of FPCM in SWQ and EQ, respectively. Because the gains from milk sold were equivalent for both regions ($0.74 kg^{-1} of FPCM), the difference in income originated from animal and crop sales, which were greater in SWQ ($0.20 kg^{-1} of FPCM) than in EQ ($0.12 kg^{-1} of FPCM). These results are especially associated with the possibility for the SWQ farm to grow valuable crops, such as grain corn, soybean, and wheat, and thus to sell a major part of the production (approximately 183, 46, and 9 g kg^{-1} of FPCM, respectively; table 3). By contrast, the EQ farm mainly uses its crop production to feed the herd and sells only its production of canola, representing approximately 36 g kg^{-1} of FPCM (table 3).

Expenses were lower in SWQ ($0.62 kg^{-1} of FPCM) than in EQ ($0.67 kg^{-1} of FPCM). The difference between both ranges can be mainly attributed to an additional $0.05 kg^{-1} of FPCM in fixed costs for the EQ farm, as other expenses (variable costs, feeds, and soil amendment costs) were similar for both regions. However, fertilizer and manure spreading costs differed according to manure management. In comparison with liquid systems (7225 g kg^{-1} of FPCM on average; table 3), a lower quantity of manure was handled with solid

Table 2. Economic output summary of farm simulations ($ kg^{-1} of FPCM) by region, housing type, and manure management.[a]

	Southwestern Québec				Eastern Québec			
	Tie-Stall Housing		Free-Stall Housing		Tie-Stall Housing		Free-Stall Housing	
	Solid Manure	Liquid Manure	Solid Manure	Liquid Manure	Solid Manure	Liquid Manure	Solid Manure	Liquid Manure
Income	0.95	0.95	0.95	0.95	0.86	0.86	0.86	0.86
Milk	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
Animals	0.13	0.13	0.13	0.13	0.10	0.10	0.10	0.10
Crops	0.07	0.08	0.07	0.07	0.02	0.02	0.02	0.02
Expenses	0.62	0.62	0.62	0.62	0.67	0.67	0.66	0.67
Fixed and variable costs	0.33	0.33	0.33	0.33	0.38	0.38	0.38	0.38
Homegrown feeds	0.09	0.09	0.09	0.09	0.10	0.09	0.10	0.10
Purchased feeds	0.15	0.15	0.15	0.15	0.14	0.14	0.14	0.14
Fertilizer costs	0.01	0.00	0.02	0.00	0.01	0.00	0.01	0.00
Manure spreading costs	0.04	0.05	0.03	0.04	0.04	0.05	0.04	0.05
Net income	0.33	0.33	0.33	0.33	0.19	0.19	0.19	0.19

[a] FPCM = fat- and protein-corrected milk.

Table 3. Crop, feed, and fertilizer outputs in farm simulations by region, housing type, and manure management.

	Southwestern Québec				Eastern Québec			
	Tie-Stall Housing		Free-Stall Housing		Tie-Stall Housing		Free-Stall Housing	
	Solid Manure	Liquid Manure	Solid Manure	Liquid Manure	Solid Manure	Liquid Manure	Solid Manure	Liquid Manure
Homegrown crops (g kg^{-1} of FPCM)[a]								
Used feed								
Corn silage	382.43	382.43	382.43	382.43	335.94	342.79	335.94	342.79
Alfalfa silage	118.48	99.79	118.48	112.28	228.52	214.19	228.52	218.89
Grass-legume mixture	115.37	125.63	115.37	118.14	168.21	139.81	168.21	148.37
Hay	0.00	8.66	0.00	2.35	-	-	-	-
Corn grain	147.30	137.23	147.30	145.97	-	-	-	-
Barley grain	-	-	-	-	99.56	113.31	99.56	108.80
Sold feed								
Soybean	46.98	44.24	46.98	46.41	-	-	-	-
Corn grain	179.58	189.96	179.58	182.19	-	-	-	-
Wheat grain	7.84	11.37	7.84	8.91	-	-	-	-
Canola	-	-	-	-	33.56	40.58	33.56	38.28
Purchased feed (g kg^{-1} of FPCM)[a]								
Hay	98.33	98.37	98.33	98.14	62.38	77.57	62.38	74.54
Corn grain	0.00	0.00	0.00	0.00	30.13	13.79	30.13	13.79
Barley grain	33.81	41.05	33.81	36.08	39.64	52.66	39.64	45.21
Wheat grain	0.00	0.00	0.00	0.00	46.64	60.45	46.64	60.45
Fats and oils (calcium soaps)	9.37	9.37	9.37	9.37	9.30	9.71	9.30	9.71
Canola meal	65.62	62.53	65.62	65.96	24.98	20.45	24.98	22.48
Soybean meal (expellers)	0.00	0.00	0.00	0.00	40.97	41.18	40.97	41.27
Soybean meal (solvent)	41.58	41.58	41.58	41.58	0.00	0.00	0.00	0.00
Dried corn gluten meal	0.48	0.00	0.48	0.48	0.00	0.00	0.00	0.00
Dried distillers grain with solubles (corn)	78.61	85.24	78.61	78.61	34.59	34.59	34.59	34.59
Straw feed	10.43	10.43	10.43	10.43	15.26	15.26	15.26	15.26
Straw bedding (g kg^{-1} of FPCM)[a]								
Produced	5.53	8.02	5.53	6.28	41.21	46.67	41.21	44.88
Purchased	114.84	112.35	114.84	114.09	84.89	79.42	84.89	81.22
Fertilizer (g kg^{-1} of FPCM)[a]								
Produced manure	5756.40	7260.41	5527.61	6968.26	5903.03	7486.69	5668.01	7185.09
Purchased soil amendments								
Calcium ammonium nitrate (27-0-0)	21.37	6.50	22.67	7.29	6.94	0.00	8.38	0.00
Diammonium phosphate (18-46-0)	1.34	0.00	1.34	0.00	7.46	0.00	7.46	0.00
Monoammonium phosphate (11-52-0)	0.00	0.00	0.00	0.00	0.00	4.56	0.00	4.52

[a] FPCM = fat- and protein-corrected milk.

systems (5714 g kg^{-1} of FPCM on average; table 3), thus reducing transport costs by $0.01 kg^{-1} of FPCM. This advantage was nullified by the propensity of solid manure to release nutrients into the soil more slowly than liquid manure (CRAAQ, 2010), resulting in greater need for calcium ammonium nitrate and diammonium phosphate (approx. $0.01 kg^{-1} of FPCM; table 3). Overall, housing and manure management did not influence FNI, whereas location had an impact. The warmer climate for the SWQ farm resulted in greater income, lower expenses, and greater FNI ($0.33 kg^{-1} of FPCM) than the colder climate for the EQ farm ($0.19 kg^{-1} of FPCM).

Nutrient Mass Balances

Table 4 lists the imports, exports, and balances in N and P under optimized FNI in N-CyCLES for each of the four farm scenarios in SWQ and EQ. Total N imports for the SWQ farm (24.0 to 28.7 g kg^{-1} of FPCM) exceeded those of the EQ farm (19.9 to 23.4 g kg^{-1} of FPCM). For each barn configuration, the difference was primarily attributed to the greater amount of purchased feeds (hay and meals of distillers' corn, soybean, and canola) and calcium ammonium nitrate by the SWQ farm (table 3). Actually, in SWQ, it was more profitable to grow (and sell) valuable but N-demanding

Table 4. Summary of N and P footprints from farm simulations (g kg^{-1} of FPCM) by region, housing type, and manure management.[a]

	Southwestern Québec				Eastern Québec			
	Tie-Stall Housing		Free-Stall Housing		Tie-Stall Housing		Free-Stall Housing	
	Solid Manure	Liquid Manure	Solid Manure	Liquid Manure	Solid Manure	Liquid Manure	Solid Manure	Liquid Manure
N footprint								
Imports	28.38	24.04	28.73	24.31	23.00	19.91	23.38	20.06
Purchased feeds	16.28	16.44	16.28	16.33	11.72	12.00	11.72	11.95
Purchased fertilizers	6.01	1.75	6.36	1.97	3.22	0.50	3.61	0.50
Legume N fixation	5.27	5.02	5.27	5.19	6.87	6.22	6.87	6.42
Atmospheric deposition	0.82	0.82	0.82	0.82	1.19	1.19	1.19	1.19
Exports	11.75	11.82	11.75	11.78	7.99	8.43	7.99	8.29
Milk	5.23	5.23	5.23	5.23	5.20	5.20	5.20	5.20
Animals	0.62	0.62	0.62	0.62	0.68	0.68	0.68	0.68
Crops	5.90	5.97	5.90	5.93	2.11	2.55	2.11	2.40
Balance	16.63	12.22	16.99	12.53	15.00	11.48	15.39	11.77
Balance on a land basis (kg ha^{-1})	121.41	89.20	123.97	91.44	75.53	57.79	77.49	59.25
P footprint								
Imports	2.71	2.50	2.71	2.45	3.16	2.74	3.16	2.72
Purchased feeds	2.44	2.50	2.44	2.45	1.66	1.70	1.66	1.69
Purchased fertilizers	0.27	0.00	0.27	0.00	1.50	1.04	1.50	1.03
Exports	1.92	1.95	1.92	1.93	1.28	1.32	1.28	1.31
Milk	0.89	0.89	0.89	0.89	0.88	0.88	0.88	0.88
Animals	0.18	0.18	0.18	0.18	0.20	0.20	0.20	0.20
Crops	0.85	0.88	0.85	0.86	0.20	0.24	0.20	0.23
Balance	0.79	0.55	0.79	0.52	1.88	1.42	1.88	1.41
Balance on a land basis (kg ha^{-1})	5.76	4.02	5.76	3.82	9.45	7.13	9.45	7.09

[a] FPCM = fat- and protein-corrected milk.

crops and purchase greater quantities of feed sub-products with high nutritional value at a lower price. In addition, compared to the SWQ farm, more N was added to the soil through legume fixation (+1.40 g kg^{-1} of FPCM on average) at the EQ farm because this farm produced silage-based rotations on a greater proportion of its land base (table A3 in the Appendix). The important sales of corn grain and soybean by the SWQ farm (table 3) led to higher N exports (+3.60 g kg^{-1} of FPCM on average) than for the EQ farm. Nitrogen left both farms through sold milk and animal sales in similar proportions. The N footprint in EQ was 6% to 10% (35% to 38% on a land basis) lower than that of SWQ depending on the housing type and manure management. Thus, many farm characteristics that affect the N footprint, such as soil type, historical accumulation of N, and animal density per hectare, are different between EQ and SWQ.

Overall, free-stall housing increased the N footprint by approximately 0.33 g kg^{-1} of FPCM, in comparison with tie-stall housing, because greater soiled surfaces in free-stall barns increase N loss through volatilization of ammonia. Farms using free-stall housing thus need to purchase more calcium ammonium nitrate and/or to grow more legume crops (table 3) to compensate for these N losses. Regarding manure management, liquid systems reduced the N footprint by approximately 4.00 g kg^{-1} of FPCM relatively to solid systems because the quantity of fertilizers used was 3-fold lower with liquid systems (table 3). As mentioned before, the nutrients in solid manure are released more slowly into the soil and are thus less available to crops than the nutrients in liquid manure.

Total P imports were higher in EQ (2.72 to 3.16 g kg^{-1} of FPCM) than in SWQ (2.45 to 2.71 g kg^{-1} of FPCM). While P imports for the SWQ farm were almost exclusively attributed to purchased feeds because fertilizer contribution was negligible (P-rich soils originating from historic over-fertilization; Beaudet et al., 2004), purchased feeds and fertilizers contributed almost equally to P imports for the EQ farm. The important use of phosphates in EQ (table 3) can be explained by the use of a five-year barley-canola-alfalfa rotation, which is P-demanding (table A2 in the Appendix), on 100% of the fields in land unit LM-32. The difference in P exports (0.63 g kg^{-1} of FPCM on average) between the farms was associated with the greater quantity of crops sold by SWQ (table 3). Therefore, the SWQ farm had a P footprint 2.5-fold lower than that of EQ. Housing type did not influence the P footprint. However, as previously found with N, imports of fertilizer-derived P were 0.27 to 0.47 g kg^{-1} of FPCM greater with solid than with liquid manure management.

Greenhouse Gas Emissions

Table 5 shows the CO_2, CH_4, and N_2O emissions from various sources and the carbon footprints associated with milk, animals, and crops sold. Although fuel consumption by the EQ farm was greater than that of the SWQ farm, because of a larger land base, the impact on GHG emissions was outcompeted by the greater amounts of feeds and fertilizers imported by the SWQ farm. As a result, the total production of CO_2 in SWQ (0.30 to 0.43 kg CO_2e kg^{-1} of FPCM) was generally greater than in EQ (0.25 to 0.32 kg CO_2e kg^{-1} of FPCM). Emission of CH_4 was comparable between the farms (approx. 1.06 kg CO_2e kg^{-1} of FPCM) because both dairies had a similar number of cows (table 1) and produced a similar quantity of manure (table 3). Results for N_2O generation varied according to soil type in each region (table 1), which influenced plant N uptake. Consequently, the N_2O levels from amendment application and crop residue decomposition in SWQ (approx. 0.12 kg CO_2e kg^{-1} of FPCM), which was characterized by clayey soils, were slightly higher than in EQ (approx. 0.05 CO_2e kg^{-1} of FPCM), which was characterized by loamy soils. Overall, GHG emissions from the SWQ farm were greater (1.78 to 1.87 kg CO_2e kg^{-1}

Table 5. Summary of GHG production and carbon footprint of milk, animals, and crops from farm simulations (kg CO_2e kg^{-1} of FPCM) by region, housing type, and manure management.[a]

	Southwestern Québec				Eastern Québec			
	Tie-Stall Housing		Free-Stall Housing		Tie-Stall Housing		Free-Stall Housing	
	Solid Manure	Liquid Manure	Solid Manure	Liquid Manure	Solid Manure	Liquid Manure	Solid Manure	Liquid Manure
CO_2	0.42	0.30	0.43	0.30	0.31	0.25	0.32	0.25
Imported feeds	0.18	0.18	0.18	0.18	0.14	0.15	0.14	0.15
Imported fertilizers	0.18	0.05	0.19	0.06	0.08	0.02	0.10	0.02
Crop residue decomposition	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03
Fuel consumption	0.04	0.04	0.04	0.04	0.06	0.06	0.06	0.06
CH_4	0.92	1.19	0.91	1.16	0.94	1.22	0.93	1.20
Enteric fermentation	0.63	0.63	0.63	0.63	0.64	0.64	0.64	0.64
Manure management	0.29	0.56	0.28	0.54	0.30	0.58	0.29	0.55
N_2O	0.53	0.32	0.52	0.31	0.45	0.22	0.45	0.22
Manure management	0.26	0.06	0.25	0.06	0.26	0.06	0.26	0.06
Manure application	0.03	0.07	0.02	0.07	0.01	0.03	0.01	0.03
Fertilizer application	0.05	0.01	0.05	0.02	0.03	0.00	0.03	0.00
Crop residue decomposition	0.04	0.05	0.04	0.04	0.02	0.02	0.02	0.02
Indirect volatilization	0.10	0.07	0.10	0.08	0.09	0.07	0.10	0.07
Indirect leaching and runoff	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04
GHG	1.87	1.80	1.86	1.78	1.71	1.69	1.70	1.67
Milk allocation	1.48	1.43	1.48	1.41	1.41	1.40	1.41	1.38
Animal allocation	0.24	0.23	0.24	0.23	0.26	0.25	0.26	0.25
Crop allocation	0.15	0.14	0.14	0.14	0.04	0.04	0.04	0.04

[a] FPCM = fat- and protein-corrected milk.

of FPCM) than from the EQ farm (1.67 to 1.71 kg CO_2e kg^{-1} of FPCM), mainly because of intensive production of cash crops on soils favorable to N_2O emission and because of feed and fertilizers imported on the farm.

The lower and upper limits of the GHG ranges correspond to levels obtained when the farms used liquid and solid systems, respectively. Because the beneficial effect of liquid manure on N_2O emissions due to better crop N use after manure application (-0.22 kg CO_2e kg^{-1} of FPCM on average) was offset by greater CH_4 emissions from manure stored under anaerobic conditions (+0.26 kg CO_2e kg^{-1} of FPCM on average), the main advantage of liquid manure management regarding GHG emissions came from reduced use of fertilizers (-0.13 kg CO_2e kg^{-1} of FPCM on average). Housing system slightly affected GHG emissions, and CH_4 emissions due to manure management were 0.01 to 0.03 kg CO_2e kg^{-1} of FPCM less for free-stall barns than for tie-stall barns. Calculation of the economic contribution of each on-farm coproduct to GHG revealed that milk alone accounted for 79% to 83% of the farm's carbon footprint. GHG associated with animal allocation (14%) did not vary substantially among scenarios, while crop allocation contributed 8% and 2% of farm GHG emissions in SWQ and EQ, respectively.

SENSITIVITY ANALYSIS

Positive or negative changes in feed or fertilizer prices (table 6) had minor effects (<5% variation) on N and P footprints and total and milk-derived GHG for all scenarios. However, variations for the SWQ farm reached 2% to 5% on more occasions than for the EQ farm due to greater flexibility in crop sales, which affected the nutrient and GHG footprints. Regarding FNI, fluctuations in fertilizer prices had

Table 6. Effect of variation (%) in feed and fertilizer prices on farm net income, nitrogen (N) and phosphorus (P) footprints, and total and milk-allocated greenhouse gas (GHG) emissions.

		Southwestern Québec				Eastern Québec			
		Tie-Stall Housing		Free-Stall Housing		Tie-Stall Housing		Free-Stall Housing	
		Solid Manure	Liquid Manure	Solid Manure	Liquid Manure	Solid Manure	Liquid Manure	Solid Manure	Liquid Manure
Feed prices +35%	Net income	-7	-7	-7	-7	-21	-21	-21	-21
	N footprint	+2	0	+2	+2	0	0	0	0
	P footprint	-3	-3	-3	+1	0	-1	0	-2
	GHG	+2	0	+2	+1	0	-1	0	-1
	Milk allocation	-2	-3	-2	-2	0	-2	0	-1
Fertilizer prices +25%	Net income	-1	0	-1	0	-1	-1	-2	-1
	N footprint	0	-1	0	0	0	0	0	0
	P footprint	+3	0	+3	+3	0	0	0	0
	GHG	0	-1	0	0	0	0	0	0
	Milk allocation	0	-1	0	0	0	0	0	0
Fertilizer prices -25%	Net income	+1	0	+1	0	+1	+1	+2	0
	N footprint	+2	0	+2	+2	0	-2	0	-4
	P footprint	-2	-3	-2	+1	0	+1	0	+1
	GHG	+2	0	+2	+1	0	0	0	0
	Milk allocation	+1	0	+1	+1	0	0	0	0
Feed prices -35%	Net income	+7	+7	+7	+7	+21	+21	+21	+21
	N footprint	0	-1	0	0	0	-1	0	-1
	P footprint	+5	-1	+5	+4	0	+1	0	+1
	GHG	0	-1	0	0	0	0	0	0
	Milk allocation	+3	+2	+3	+3	+1	+1	+1	+1

little influence (<2% variation), while modifications to feed prices resulted in variations of \$0.02 and \$0.04 kg^{-1} of FPCM in SWQ and EQ, respectively. For each scenario, both farms sold more or less crops to adjust to lower or higher expenses in feed ingredients. However, the effect was greater in EQ (±21%) than in SWQ (±7%) because the same variation on both farms had a different impact because their FNI values were dissimilar (table 2).

Discussion

Outcomes Analysis

The economic results for our simulated farms (table 2) are comparable to values reported by Pellerin et al. (2017) using N-CyCLES for a dairy farm located in southern Québec with a similar herd size and land base (87 cows and 142 ha) using tie-stall housing and liquid manure management (FNI = \$0.23 kg^{-1} of FPCM, with income and expenses accounting for \$0.84 and \$0.61 kg^{-1} of FPCM, respectively). By contrast, simulations with N-CyCLES for a non-grazed dairy operation in Wisconsin (Pellerin et al., 2017) and with IFSM (Integrated Farm System Model) for a non-grazed dairy operation in New York (Rotz et al., 2016) found lower FNI (\$0.03 to \$0.11 kg^{-1} of FPCM) with lower income (\$0.39 to \$0.51 kg^{-1} of FPCM) and lower expenses (\$0.36 to \$0.40 kg^{-1} of FPCM). This appears logical because American dairy production is characterized by lower milk prices (no quota system) and lower fixed and variable costs (slightly warmer climate) relative to Canadian dairy production.

The nutrient footprints (table 4) were also consistent with the literature. Pellerin et al. (2017) reported N and P footprints of 15.70 and 0.60 g kg^{-1} of FPCM, respectively, for the aforementioned dairy farm in southern Québec. These numbers fall within the ranges presented for the SWQ farm. However, some differences in nutrient imports and exports exist between the two studies due to variations in selected crop rotations. For instance, the farm modeled by Pellerin et al. (2017) produced barley and purchased wheat, while wheat was homegrown and barley was purchased on the SWQ farm. In other studies considering small to large free-stall dairy farms in the northeastern U.S. (Cela et al., 2014; Pellerin et al., 2017; Rotz et al., 1999, 2006, 2016; Soberon et al., 2015) and Denmark (Nielsen and Kristensen, 2005), the N and P footprints on a per hectare basis reached 85 to 277 kg N ha^{-1} and 0 to 16 kg P ha^{-1}. These ranges are comparable to the results shown in table 4.

The GHG levels before the allocation shown in table 5 were higher than those reported by previous “cradle to farm gate” life cycle analyses (0.92 to 1.45 kg CO_2e kg^{-1} of FPCM) for the average Canadian dairy farm (Quantis et al., 2012; Vergé et al., 2007, 2013), for single simulated farms in different Canadian provinces (Arsenault et al., 2009; Hagemann et al., 2011; Jayasundara and Wagner-Riddle, 2014; McGeough et al., 2012), and in the U.S. (Capper et al., 2009; Phetteplace et al., 2001; Rotz et al., 2010). All the Canadian studies used emission estimates based on models that generally followed the IPCC (2006) methodology and were adjusted to Canadian conditions. However, the IPCC (2006) provides very general CH_4 and N_2O emission factors for the manure produced by dairy cattle as influenced by average annual ambient temperature, region, and type of manure management (Rotz, 2017). As a result, CH_4 and N_2O emissions following the IPCC (2006) modeling approach underestimated field measurement means for most manure management practices (Owen and Silver, 2015). More specific estimations can be obtained by considering the individual components making up the production system (Rotz, 2017). The N-CyCLES model followed this path by adjusting some emission factors *a priori* for specific housing categories, manure systems, and soil types, which added precision to our simulation results. Therefore, modeling with revised emissions factors for manure-derived GHG increased the GHG intensity. In fact, total GHG emissions would have reached only 1.42 to 1.61 kg CO_2e kg^{-1} of FPCM if the generic IPPC approach was used. Similarly, Owen and Silver (2015) found that adapted calculations nearly doubled slurry CH_4 emissions for Europe and increased the N_2O emissions from solid manure piles and lagoons in the U.S. by the same order of magnitude. Differences in assumptions are also reflected in the GHG allocated to milk, which varied widely from 0.67 to 1.20 kg CO_2e kg^{-1} of FPCM in the aforementioned studies.

Farm Analysis

The location of the SWQ farm provided a financial advantage over the EQ farm because the climate conditions allowed production of grain corn, soybean, and wheat, providing supplementary income. Pellerin et al. (2017) also highlighted important sales of corn grain (357 g kg^{-1} of FPCM) and soybean (66 g kg^{-1} of FPCM), and thus high crop income (\$0.09 kg^{-1} of FPCM), for a similar dairy farm in southern Québec.

However, greater production of cash crops on the SWQ farm implied greater imports of N-based fertilizers to meet recommended applications rates for optimal plant growth, and greater amounts of purchased feeds, in comparison with the EQ farm. As explained by Powell et al. (2010), an increasing reliance on imported feed is accompanied with a decreasing land base on which to recycle manure N, which increases the N surplus and lowers the whole-farm N use efficiency. Consequently, the advantage of the EQ farm regarding N footprint came from using most of the land to grow legume crops that fixed atmospheric N and were used on-farm as feed ingredients. Regarding P, the SWQ farm had a better footprint than the EQ farm due to restricted use of P-based fertilizers in SWQ, due to P-rich soils originating from historic over-fertilization, which compensated for greater feed P imports.

Overall, our results are in line with other studies (Cela et al., 2014; Hristov et al., 2006; Soberon et al., 2015; Spears et al., 2003a, 2003b) suggesting that purchased feed and fertilizers were the most important factors that affected whole-farm N and P footprints. In Denmark, Nielsen and Kristensen (2005) also observed that N surplus on conventional dairy farms (corn-based and grass-legume rotations accounted for 29% and 22% of farmland, respectively) exceeded that of organic dairy farms (corn-based and grass-legume rotations accounted for 16% and 40% of farmland, respectively) by 43 kg ha^{-1} because of greater imports of concentrates and mineral fertilizers on the conventional farms.

Pellerin et al. (2017) revealed that: (1) the amounts of corn grain (-156 g kg^{-1} of FPCM) and soybean (-13 g kg^{-1} of FPCM) are decreased when FNI is maximized by partial (33%) reduction of the N footprint, and (2) purchased feeds contributed almost four times as much as purchased fertilizers to total P imports on dairy farms in southern Québec.

Purchased feeds and fertilizers can also influence GHG emissions (Rotz, 2017). In SWQ, greater purchases of feed ingredients and fertilizers were responsible for increased CO_2 and N_2O emissions associated with transformation and transport of inputs and fertilizer application.

Housing Analysis

Housing type did not influence FNI. However, it affected the N balance, as free-stall dairies needed greater N inputs from fertilizers or legume fixation to compensate for greater N volatilization inside the barn. Ammonia (NH_3) volatilization is generally the main pathway of loss for manure N (Montes et al., 2013). According to Monteny and Erisman (1998), NH_3 emissions from tie-stalls (5 to 27 g cow^{-1} d^{-1}) tend to be lower than from free-stalls (25 to 45 g cow^{-1} d^{-1}) because tie-stalls have a smaller surface area of soiled floors. The same reason was also given by Liu et al. (2017) to explain lower NH_3-N loss per unit of N intake for mechanically ventilated, tie-stall dairies than for naturally ventilated, free-stall dairies. Based on typical designs for cattle housing, the soiled areas considered for tie-stall and free-stalls are in fact 1.2 and 3.5 m^2 cow^{-1}, respectively (Rotz et al., 2014). Consequently, lower NH_3-N losses in the barn allowed tie-stall dairies to use less inorganic N fertilizers, which helped to improve the whole-farm N use efficiency (Powell et al., 2010).

Housing type also had a slight impact on GHG emissions due to the small difference between free-stall and tie-stall dairies regarding CH_4 emissions associated with manure management. In a similar study using IFSM, Rotz et al. (2014) found that a free-stall configuration produced less GHG (4668 kg CO_2e cow^{-1}) at the barn level (housing and animals) than a tie-stall configuration (6643 kg CO_2e cow^{-1}) for a representative dairy farm in Pennsylvania (100 cows and 100 ha). However, manure was scraped from the barn floors twice a day in the free-stall dairy, while manure was removed daily from gutters in the tie-stall dairy. Jayasundara et al. (2016) also stated that tie-stall dairies (25 to 75 g cow^{-1} d^{-1}) might emit more manure-related CH_4 than free-stall dairies (1 to 8 g cow^{-1} d^{-1}); in the reported tie-stall studies, manure was temporarily stored (usually for 2 to 3 weeks) in pits within the barn before moving to long-term storage, which may have caused higher emissions. Indeed, CH_4 emissions from manure are much greater for dairy barns where manure accumulates for prolonged periods of time compared with barns where manure is transferred daily to outdoor storage (Montes et al., 2013).

Manure Management Analysis

Manure management did not affect FNI, but solid manure systems were associated with a greater use of fertilizers because of lower availability of nutrients to crops (CRAAQ, 2010). For instance, when solid manure is applied to land, soil microorganisms may immobilize available N during the decomposition of bedding and undigested feed. If this process takes place during crop growth, an additional amount of N must be provided to support normal crop development (Fulhage and Pfost, 1993). In return, higher amounts of N in solid manure than in liquid manure are available in subsequent years (Brown, 2013). Nevertheless, this legacy effect is difficult to assess, so N-CyCLES does not account for such a possible long-term advantage of solid manure. In contrast, scenarios using liquid manure systems are associated with smaller use of fertilizers, reducing N and P footprints and GHG emissions associated with decreased import and application of fertilizers.

Based on a life cycle analysis of Canadian milk production (Quantis et al., 2012), on-farm use of commercial fertilizers (20%) is the most important GHG emission factor on dairy farms, after enteric fermentation (46%) and manure management (27%). Because the CH_4 emitted from the digestive tracts of ruminants did not differ among the simulation scenarios, variability in GHG emissions was predominantly linked to the choice of manure management type. As our results indicated, the anaerobic nature of liquid manure systems increases the potential for CH_4 production and decreases N_2O production, whereas solid manure systems can be substantial sources of N_2O and minor sources of CH_4. In this study, solid manure systems emitted 47% less CH_4 than liquid manure systems, whereas N_2O production with liquid systems was 4-fold less than with solid systems. These numbers are in line with Owen and Silver (2015) for Europe and with Jayasundara et al. (2016) for Canada, who concluded that CH_4 emissions were 13% to 40% lower from solid than from liquid dairy manure, whereas N_2O emissions were 4 to 20 times greater from solid than from liquid manure.

Promising alternatives to reduce GHG emissions from manure and soil, and to reduce the environmental footprint of dairy farms, have been targeted in the literature (Hou et al., 2017; Jayasundara et al., 2016; Montes et al., 2013). Among other strategies, solid-liquid separation, composting, manure storage covers, and anaerobic digestion showed important overall GHG decreases of 20% to 37%, 31% to 84% (during summer), 1% to 26%, and 23% to 53%, respectively. Incorporating manure into the soil can also indirectly decrease GHG emissions. However, these strategies are not widely used (Gerber et al., 2013), and Québec is no exception. An evaluation of their potential impacts on FNI, N and P balances, and GHG footprint is needed to verify if they can maintain or improve production and if they are economically viable and affordable by producers (Fournel et al., 2019).

Conclusion

Considering feeding, manure, and crop management as a single unit of management, the N-CyCLES model identified differences in key outcomes for representative, simulated dairy farms, using tie-stall or free-stall housing and solid or liquid manure management, in two regions with contrasting climates. A warmer climate was associated with a greater production of cash crops and lower expenses, but also greater imports of N-based fertilizers and purchased feeds, which negatively affected the farm N footprint and GHG emissions. Housing and manure management type did not influence FNI; however, they had some repercussions on the environment. Compared to tie-stall dairies, free-stall dairies had greater N losses at the barn, which had to be compensated by greater purchases of N-based fertilizers, resulting in greater N surplus. Nevertheless, free-stall dairies emitted slightly less GHG than tie-stall dairies, mainly because the manure was less concentrated in N and emitted less N_2O. Dairies with solid manure management were associated with low availability of nutrients and high N_2O emissions following manure application to the soil. As a result, they imported more fertilizers and altogether produced more GHG than dairies with liquid manure, despite greater CH_4 emissions from the liquid manure storage unit. Based on these results, the current transition toward free-stall barns and liquid manure systems in the province of Québec seems advantageous from an environmental standpoint without comprising economic profitability.

ACKNOWLEDGEMENTS

This project was completed under Part 4 of the 2013-2018 Prime-Vert program and received financial support from the Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (MAPAQ) via the Fonds Vert. This work was also supported by the Fonds de Recherche du Québec - Nature et Technologies (FRQNT), by Mitacs through the Mitacs Accelerate Program, and by Université Laval through student and postdoctoral scholarships.

REFERENCES

AAFC. (2014). Reducing methane emissions through livestock waste and manure applications. *Innov. Express, 5*(3), 3-4. Ottawa, ON, Canada: Agriculture and Agri-Food Canada.

AGÉCO. (2018). Nombre moyen de vaches laitières par ferme et par province au 1er juillet, Canada, 2005 à 2017. *Faits saillants laitiers québécois.* Retrieved from http://groupeageco.ca/fsl/

Arsenault, N., Tyedmers, P., & Fredeen, A. (2009). Comparing the environmental impacts of pasture-based and confinement-based dairy systems in Nova Scotia (Canada) using life cycle assessment. *Intl. J. Agric. Sustain., 7*(1), 19-41. https://doi.org/10.3763/ijas.2009.0356

ASABE. (2005). D384.2: Manure production and characteristics. St. Joseph, MI: ASABE.

Beaudet, P., Grenier, M., Giroux, M., & Girard, V. (2004). Description statistique des propriétés chimiques des sols minéraux du Québec. Québec City, QC, Canada: Ministere de l'Agriculture, des Pêcheries et de l'Alimentation du Québec. Retrieved from https://irda.blob.core.windows.net/media/1935/beaudet-et-al-2004_rapport_descrip_statistique_proprietes_chimiques_sols_minx_qc.pdf

Brown, C. (2011). Economic of manure management. Guelph, ON, Canada: Ontario Ministry of Agriculture, Food and Rural Affairs. Retrieved from http://fieldcropnews.com/2011/10/economic-of-manure-management/

Brown, C. (2013). *Available nutrients and value for manure from various livestock types* (Vol. AGDEX 538). Guelph, ON, Canada: Ontario Ministry of Agriculture, Food, and Rural Affairs.

Capper, J. L., Cady, R. A., & Bauman, D. E. (2009). The environmental impact of dairy production: 1944 compared with 2007. *J. Animal Sci., 87*(6), 2160-2167. https://doi.org/10.2527/jas.2009-1781

CDIC. (2016). Dairy barns by type in Canada. Ottawa, ON, Canada: Canadian Dairy Information Center. Retrieved from http://dairyinfo.gc.ca/index_e.php?s1=dff-fcil&s2=farm-ferme&s3=db-el

Cela, S., Ketterings, Q. M., Czymmek, K., Soberon, M., & Rasmussen, C. (2014). Characterization of nitrogen, phosphorus, and potassium mass balances of dairy farms in New York State. *J. Dairy Sci., 97*(12), 7614-7632. https://doi.org/10.3168/jds.2014-8467

Chadwick, D., Sommer, S., Thorman, R., Fangueiro, D., Cardenas, L., Amon, B., & Misselbrook, T. (2011). Manure management: Implications for greenhouse gas emissions. *Animal Feed Sci. Tech., 166-167*, 514-531. https://doi.org/10.1016/j.anifeedsci.2011.04.036

CRAAQ. (2010). *Guide de référence en fertilisation* (2nd ed.). Québec City, QC, Canada: Centre de référence en agriculture et agroalimentaire du Québec.

Daugherty, A. S., Burns, R. T., Cross, T. L., Raman, D. R., & Grandle, G. F. (2001). Liquid dairy waste transport and land application cost comparisons considering herd size, transport distance, and nitrogen versus phosphorus application rates. ASAE Paper No. 012263. St. Joseph, MI: ASAE.

Dollé, J.-B., & Robin, P. (2006). Émissions de gaz à effet de serre en bâtiment d'élevage bovin. *Fourrages, 186*, 205-214.

Dollé, J.-B., Chambaut, H., Delagarde, R., Edouard, N., Eugene, M., Foray, S., ... Manneville, V. (2017). Mesures d'atténuation des gaz à effet de serre en élevage bovin lait et viande. *Innov. Agronomiques, 55*, 301-315.

ECCC. (2019). Gatineau, QC, Canada: Global warming potentials. Environment and Climate Change Canada. Retrieved from https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/quantification-guidance/global-warming-potentials.html

Fournel, S., Charbonneau, E., Binggeli, S., Dion, J.-M., Pellerin, D., Chantigny, M. H., & Godbout, S. (2019). Optimal housing and manure management strategies to favor productive and environment-friendly dairy farms in Québec, Canada: Part II. Greenhouse gas mitigation methods. *Trans. ASABE, 62*(4), (in press). https://doi.org/10.13031/trans.13272

FPLQ. (2012). L'empreinte carbone du lait québécois. Longueuil, QC, Canada: Federation des producteurs de lait du Québec (FPLQ). Retrieved from http://lait.org/fichiers/RapportAnnuel/FPLQ-2012/carbone.pdf

Fulhage, C. D., & Pfost, D. L. (1993). Fertilizer nutrients in dairy manure. Colombia, MO: University of Missouri Extension. Retrieved from https://extension2.missouri.edu/wq307

GCAQ. (2016). Agritel. Longueuil, QC, Canada: Les Groupes conseils agricoles du Québec (GCAQ). Retrieved from http://agritel.gcaq.ca/

Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., ... Tempio, G. (2013). Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities. Rome, Italy: United Nations FAO.

Godbout, S., Brassard, P., & Palacios, J. (2017). Calcul du volume de fumier pour le dimensionnement des structures d'entreposage: Évaluation des volumes complémentaires. Québec City, QC, Canada: IRDA.

Godbout, S., Brassard, P., Pelletier, F., Grenier, M., Grenier, P., Belzile, L., ... Bilodeau, D. (2013). Étude des volumes de précipitation et d'évaporation pour le calcul des structures d'entreposage de fumier dans un contexte de changements climatiques. Québec City, QC, Canada: IRDA

Gray, C. W., Chen, L., de Haro-Mari, M. E., Chahine, M., &

Neibling, H. (2014). Costs of liquid-manure application systems. Moscow, ID: University of Idaho Extension. Retrieved from https://www.cals.uidaho.edu/edcomm/pdf/BUL/BUL888.pdf

Hadrich, J. C., Harrigan, T. M., & Wolf, C. A. (2010). Economic comparison of liquid manure transport and land application. *Appl. Eng. Agric., 26*(5), 743-758. https://doi.org/10.13031/2013.34939

Hagemann, M., Hemme, T., Ndambi, A., Alqaisi, O., & Sultana, M. N. (2011). Benchmarking of greenhouse gas emissions of bovine milk production systems for 38 countries. *Animal Feed Sci. Tech., 166-167*, 46-58. https://doi.org/10.1016/j.anifeedsci.2011.04.002

Harrigan, T. M. (2011). Time is money when hauling manure. East Lansing, MI: Michigan State University Extension. Retrieved from http://msue.anr.msu.edu/news/time_is_money_when_hauling_manure

Hou, Y., Velthof, G. L., Lesschen, J. P., Staritsky, I. G., & Oenema, O. (2017). Nutrient recovery and emissions of ammonia, nitrous oxide, and methane from animal manure in Europe: Effects of manure treatment technologies. *Environ. Sci. Tech., 51*(1), 375-383. https://doi.org/10.1021/acs.est.6b04524

Howland, B., & Karszes, J. (2014). The manure application cost study. Ithaca, NY: Cornell University, College of Agriculture and Life Sciences, Dyson School of Applied Economics and Management.

Hristov, A. N., Hazen, W., & Ellsworth, J. W. (2006). Efficiency of use of imported nitrogen, phosphorus, and potassium and potential for reducing phosphorus imports on Idaho dairy farms. *J. Dairy Sci., 89*(9), 3702-3712. https://doi.org/10.3168/jds.S0022-0302(06)72411-0

IDF. (2015). A common carbon footprint approach for the dairy sector: The IDF guide to standard life cycle assessment methodology. IDF Bulletin 479. Brussels, Belgium: International Dairy Federation.

IPCC. (2006). Chapter 10. Emissions from livestock and manure management. In *2006 IPCC guidelines for national greenhouse gas inventories. Vol. 4: Agriculture, forestry and other land use.* Geneva, Switzerland: Intergovernmental Panel on Climate Change.

Jayasundara, S., & Wagner-Riddle, C. (2014). Greenhouse gas emissions intensity of Ontario milk production in 2011 compared with 1991. *Canadian J. Animal Sci., 94*(1), 155-173. https://doi.org/10.4141/cjas2013-127

Jayasundara, S., Ranga Niroshan Appuhamy, J. A. D., Kebreab, E., & Wagner-Riddle, C. (2016). Methane and nitrous oxide emissions from Canadian dairy farms and mitigation options: An updated review. *Canadian J. Animal Sci., 96*, 306-331. https://doi.org/10.1139/cjas-2015-0111

Leibold, K., & Olsen, T. (2007). Value of manure nutrients. Ames, IA: Iowa State University Extension. Retrieved from https://www.extension.iastate.edu/agdm/livestock/html/b1-65.html

Liu, Z., Liu, Y., Murphy, J. P., & Maghirang, R. (2017). Ammonia and methane emission factors from cattle operations expressed as losses of dietary nutrients or energy. *Agriculture, 7*(16), 1-12. https://doi.org/10.3390/agriculture7030016

Mason, A. J. (2011). OpenSolver: An open source add-in to solve linear and integer progammes in Excel. In K. Diethard, H.-J. Lathi, & K. Schmedders (Ed.), *Proc. Intl. Conf. on Operations Research (OR 2011)* (pp. 401-406). Berlin, Germany: Springer. https://doi.org/10.1007/978-3-642-29210-1_64

McGeough, E. J., Little, S. M., Janzen, H. H., McAllister, T. A., McGinn, S. M., & Beauchemin, K. A. (2012). Life-cycle assessment of greenhouse gas emissions from dairy production in eastern Canada: A case study. *J. Dairy Sci., 95*(9), 5164-5175. http://dx.doi.org/10.3168/jds.2011-5229

MDDELCC. (2016). Inventaire québécois des émissions de gaz à effet de serre en 2014 et leur évolution depuis 1990. Québec City, QC, Canada: MDDELCC. Retrieved from http://www.mddelcc.gouv.qc.ca/changements/ges/2014/Inventaire1990-2014.pdf

MDDELCC. (2018). 2013-2020 Climate change action plan. Québec City, QC, Canada: MDDELCC. Retrieved from http://www.mddelcc.gouv.qc.ca/changementsclimatiques/plan-action-fonds-vert-en.asp

Monteny, G. J., & Erisman, J. W. (1998). Ammonia emission from dairy cow buildings: A review of measurement techniques, influencing factors, and possibilities for reduction. *Netherlands J. Agric. Sci., 46*, 225-247.

Montes, F., Meinen, R., Dell, C., Rotz, A., Hristov, A. N., Oh, J., ... Dijkstra, J. (2013). Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options. *J. Animal Sci., 91*(11), 5070-5094. https://doi.org/10.2527/jas.2013-6584

Nennich, T. D., Harrison, J. H., VanWieringen, L. M., Meyer, D., Heinrichs, A. J., Weiss, W. P., ... Block, E. (2005). Prediction of manure and nutrient excretion from dairy cattle. *J. Dairy Sci., 88*(10), 3721-3733. https://doi.org/10.3168/jds.S0022-0302(05)73058-7

Nielsen, A. H., & Kristensen, I. S. (2005). Nitrogen and phosphorus surpluses on Danish dairy and pig farms in relation to farm characteristics. *Livest. Sci., 96*(1), 97-107. https://doi.org/10.1016/j.livprodsci.2005.05.012

NRC. (2001). *Nutrient requirements of dairy cattle* (7th revised ed.). Washington, DC: National Research Council.

Ouranos. (2015). Synthesis on climate change knowledge in Québec. Montréal, QC, Canada: Ouranos. Retrieved from https://www.ouranos.ca/publication-scientifique/Synthesis_Summary.pdf

Owen, J. J., & Silver, W. L. (2015). Greenhouse gas emissions from dairy manure management: A review of field-based studies. *Global Change Biol., 21*(2), 550-565. https://doi.org/10.1111/gcb.12687

Pattey, E., Trzcinski, M. K., & Desjardins, R. L. (2005). Quantifying the reduction of greenhouse gas emissions as a result of composting dairy and beef cattle manure. *Nutr. Cycl. Agroecosys., 72*(2), 173-187. https://doi.org/10.1007/s10705-005-1268-5

Pellerin, D., Charbonneau, E., Fadul-Pacheco, L., Soucy, O., & Wattiaux, M. A. (2017). Economic effect of reducing nitrogen and phosphorus mass balance on Wisconsin and Québec dairy farms. *J. Dairy Sci., 100*(10), 8614-8629. https://doi.org/10.3168/jds.2016-11984

Petersen, S. O., Sommer, S. G., Beline, F., Burton, C., Dach, J., Dourmad, J. Y., ... Mihelic, R. (2007). Recycling of livestock manure in a whole-farm perspective. *Livestock Sci., 112*(3), 180-191. https://doi.org/10.1016/j.livsci.2007.09.001

Phetteplace, H. W., Johnson, D. E., & Seidl, A. F. (2001). Greenhouse gas emissions from simulated beef and dairy livestock systems in the United States. *Nutr. Cycl. Agroecosyst., 60*(1), 99-102. https://doi.org/10.1023/a:1012657230589

PLQ. (2018). On the farm. Longueuil, QC, Canada: Les Producteurs de lait du Québec. Retrieved from http://lait.org/en/the-farm-in-action/on-the-farm/

Powell, J. M., Gourley, C. J., Rotz, C. A., & Weaver, D. M. (2010). Nitrogen use efficiency: A potential performance indicator and policy tool for dairy farms. *Environ. Sci. Policy, 13*(3), 217-228. https://doi.org/10.1016/j.envsci.2010.03.007

Quantis, AGÉCO, & CIRAIG. (2012). Environmental and socioeconomic life cycle assessment of Canadian milk. Dairy Farmers of Canada. Retrieved from https://www.dairyresearch.ca/pdf/LCA-DFCFinalReport_e.pdf

Rodhe, L. K. K., Ascue, J., Willen, A., Persson, B. V., & Nordberg, A. (2015). Greenhouse gas emissions from storage and field application of anaerobically digested and non-digested cattle slurry. *Agric. Ecosys. Environ., 199*(supp. C), 358-368. https://doi.org/10.1016/j.agee.2014.10.004

Rotz, C. A. (2017). Modeling greenhouse gas emissions from dairy farms. *J. Dairy Sci., 101*(7), 6675-6690. https://doi.org/10.3168/jds.2017-13272

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. https://doi.org/10.3168/jds.2009-2162

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*(4), 1143-1158. http://dx.doi.org/10.2134/jeq2013.04.0121

Rotz, C. A., Oenema, J., & van Keulen, H. (2006). Whole farm management to reduce nutrient losses from dairy farms: A. Simulation study. *Appl. Eng. Agric., 22*(5), 773-784. https://doi.org/10.13031/2013.21992

Rotz, C. A., Satter, L. D., Mertens, D. R., & Muck, R. E. (1999). Feeding strategy, nitrogen cycling, and profitability of dairy farms. *J. Dairy Sci., 82*(12), 2841-2855. https://doi.org/10.3168/jds.S0022-0302(99)75542-6

Rotz, C. A., Skinner, R. H., Stoner, A. M., & Hayhoe, K. (2016). Evaluating greenhouse gas mitigation and climate change adaptation in dairy production using farm simulation. *Trans. ASABE, 59*(6), 1771-1781. https://doi.org/10.13031/trans.59.11594

Sheppard, S., Bittman, S., Swift, M., Beaulieu, M., & Sheppard, M. (2011). Ecoregion and farm size differences in dairy feed and manure nitrogen management: A survey. *Canadian J. Animal Sci., 91*(3), 459-473. https://doi.org/10.4141/cjas2010-004

Soberon, M. A., Cela, S., Ketterings, Q. M., Rasmussen, C. N., & Czymmek, K. J. (2015). Changes in nutrient mass balances over time and related drivers for 54 New York State dairy farms. *J. Dairy Sci., 98*(8), 5313-5329. https://doi.org/10.3168/jds.2014-9236

Spears, R. A., Kohn, R. A., & Young, A. J. (2003a). Whole-farm nitrogen balance on western dairy farms. *J. Dairy Sci., 86*(12), 4178-4186. http://dx.doi.org/10.3168/jds.S0022-0302(03)74033-8

Spears, R. A., Young, A. J., & Kohn, R. A. (2003b). Whole-farm phosphorus balance on western dairy farms. *J. Dairy Sci., 86*(2), 688-695. http://dx.doi.org/10.3168/jds.S0022-0302(03)73648-0

Tate III, R. L. (2000). *Soil microbiology* (2nd ed.). New York, NY: John Wiley and Sons.

Valacta. (2015). L'évolution de la production laitière québécoise. Sainte-Anne-de-Bellevue, QC, Canada: Valacta. Retrieved from http://www.valacta.com/FR/Nos-publications/Documents/EL2015_FINAL2.pdf

VanderZaag, A. C., Flesch, T. K., Desjardins, R. L., Balde, H., & Wright, T. (2014). Measuring methane emissions from two dairy farms: Seasonal and manure-management effects. *Agric. Forest Meteorol., 194*(supp. C), 259-267. https://doi.org/10.1016/j.agrformet.2014.02.003

Vergé, X. P. C., Dyer, J. A., Desjardins, R. L., & Worth, D. (2007). Greenhouse gas emissions from the Canadian dairy industry in 2001. *Agric. Syst., 94*(3), 683-693. https://doi.org/10.1016/j.agsy.2007.02.008

Vergé, X. P., Maxime, D., Dyer, J. A., Desjardins, R. L., Arcand, Y., & Vanderzaag, A. (2013). Carbon footprint of Canadian dairy products: Calculations and issues. *J. Dairy Sci., 96*(9), 6091-6104. https://doi.org/10.3168/jds.2013-6563

Villettaz Robichaud, M., Rushen, J., de Passille, A. M., Vasseur, E., Haley, D. B., & Pellerin, D. (2018). Is the profitability of Canadian tiestall farms associated with their performance on an animal welfare assessment? *J. Dairy Sci., 101*(3), 2359-2369. https://doi.org/10.3168/jds.2017-13316

Wattiaux, M. (2018). Introduction to N-CyCLES (Nutrient cycling: Crops, livestock, environment and soil). Madison, WI: University of Wisconsin. Retrieved from https://kb.wisc.edu/dairynutrient/page.php?id=60349

APPENDIX

Table A1. Names, codes, prices, and limits for feed ingredients and fertilizers included in N-CyCLES for southwestern Québec (SWQ) and eastern Québec (EQ).

	Name (Code)[a]	Price ($ t^{-1} of DM)[b]		Limit[c]
		SWQ	EQ	
Homegrown or sold feed	Corn silage (CoSi-35)	143.95	144.08	40
	Alfalfa silage (AlSi-83)	185.44	185.73	-
	Mixed silage (MxSi-74)	185.85	185.62	-
	Grass hay (GrHy-52)	185.83	185.70	10
	Canola (Can-18)	-	531.11	-
	Soybean seed, whole (SBw-108)	477.87	-	-
	Corn grain, ground (CoGr-27)	271.91	317.09	40
	Barley, grain and rolled (Barley-8)	-	225.46	20
	Wheat, grain and rolled (Wheat-116)	297.43	-	20
Purchased feed	Barley, grain and rolled (Barley-8)	232.53	-	-
	Wheat, grain and rolled (Wheat-116)	-	297.43	-
	Canola meal (Canola-19)	351.34	351.34	-
	Fats and oils, calcium soaps (FatCa-40)	1815.65	1952.72	7
	Soybean meal, expellers (SBMx-104)	708.15	718.45	-
	Soybean meal, solvent (SBM48-107)	600.13	608.86	-
	Corn gluten meal, dried (CGM-25)	970.74	974.74	-
	Corn distillers grain with solubles, dried (CoDi-23)	349.72	452.88	10
	Straw feed (Straw-120b)	120.69	120.22	-
	Beet pulp (Beet pulp-11)	558.52	558.52	-
	Calcium carbonate ($CaCO_3$)	271.00	359.00	-
	Dicalcium phosphate ($CaHPO_4$)	833.00	833.00	-
	Magnesium oxide (MgO)	805.00	816.00	-
	Calcium sulfate ($CaSO_4 \cdot 2H_2O$)	538.98	538.98	-
	Sodium chloride (NaCl)	333.00	382.00	3.5
	Magnesium sulfate heptahydrate ($MgSO_4 \cdot 7H_2O$)	606.60	606.60	-
	Blood meal ring (Blmearlr-14)	850.00	850.00	-
Purchased fertilizer	Calcium ammonium nitrate (27-0-0)	641.00	641.00	-
	Diammonium phosphate (18-46-0)	876.00	876.00	-
	Monoammonium phosphate (11-52-0)	895.00	895.00	-
	Triple super phosphate (0-46-0)	976.00	976.00	-
	Muriate of potash (0-0-60)	762.00	762.00	-

[a] When present, the number associated with a feed code indicates the feed entry number in the NRC (2001) feed composition tables.

[b] Median prices representative of the 2010-2014 period from the Valacta (Sainte-Anne-de-Bellevue, QC, Canada) database.

[c] Upper limit in ration dry matter (DM).

Table A2. Rotations, N-P-K recommendations, fuel consumption, and cost of production included in N-CyCLES for southwestern Québec (SWQ) and eastern Québec (EQ).[a]

	Rotation Year[c]							Recommended Fertilization ($kg\ ha^{-1}$)			Fuel Consumption ($L\ ha^{-1}$)	Cost[e] ($\$\ ha^{-1}$)
	1	2	3	4	5	6	7	N	P_2O_5	K_2O_5		
SWQ rotations												
Land unit MH-08[b]												
#1	Cs	As	As	Ms	-	-	-	38.44	29.38	63.13	106.14	576.24
#2	Cg	Cg	Sb	-	-	-	-	97.50	21.67	40.00	68.16	623.68
#3	Cg	Cs	As[d]	As	Ms	Ms	H	66.07	28.04	58.39	108.58	545.65
#4	As[d]	As	Ms	Ms	-	-	-	20.63	26.88	59.38	109.32	521.75
#5	Cs	Cs	As[d]	As	Ms	Ms	-	57.71	27.92	64.58	127.30	600.64
Land unit LM-32[b]												
#1	Cs	As	As	Ms	-	-	-	55.00	48.13	134.38	106.14	576.24
#2	W	Cg	Sb	-	-	-	-	91.67	41.67	68.63	58.46	542.37
#3	Cg	Cs	As[d]	As	Ms	Ms	H	83.57	42.68	120.89	108.58	545.65
#4	As[d]	As	Ms	Ms	-	-	-	32.50	40.63	133.13	109.32	521.75
#5	Cs	Cs	As[d]	As	Ms	Ms	-	75.00	43.75	137.08	127.30	600.64
EQ rotations												
Land unit MH-08[b]												
#1	As[d]	As	Ms	Ms	-	-	-	18.75	26.88	59.38	103.72	413.86
#2	B	B	Cn	-	-	-	-	67.92	30.83	32.50	74.03	293.79
#3	Cs	As[d]	As	Ms	Ms	-	-	28.75	27.50	62.50	115.84	457.40
#4	Cs	Cs	As[d]	As	Ms	-	-	46.75	28.50	65.50	129.09	513.72
#5	As[d]	As	Ms	Ms	H	-	-	33.25	27.25	56.75	99.16	368.89
Land unit LM-32[b]												
#1	B	As[d]	As	Ms	Ms	-	-	37.00	43.26	118.76	97.28	385.88
#2	B	Cn	As[d]	As	Ms	-	-	49.00	46.26	100.76	93.47	386.94
#3	As[d]	As	Ms	Ms	-	-	-	30.63	40.63	133.13	103.72	413.86
#4	As[d]	As	Ms	-	-	-	-	27.50	42.50	130.83	105.59	439.20
#5	As[d]	As	Ms	Ms	H	-	-	46.50	39.75	126.25	99.16	368.89

[a] Cs = corn silage, As = alfalfa silage, Ms = mixed alfalfa and grass silage, Cg = grain corn, Sb = soybean, H = grass hay, W = wheat, B = barley, and Cn = canola.

[b] MH-08 = land unit with medium-high concentrations in soil P at a hauling distance of 0.8 km; LM-32 = land unit with low-medium concentrations in soil P at a hauling distance of 3.2 km.

[c] Crop grown in each successive year of a rotation; for example, in the case of SWQ rotation 2 in land unit MH-08, the rotation requires three years for completion, including two years of corn grain followed by one year of soybean.

[d] Alfalfa silage established with wheat (SWQ) or barley (EQ).

[e] Rotation average excluding fertilization costs (purchased fertilizers and manure spreading costs) but including farm income stabilization insurance reimbursement for barley, corn grain, soybean, and wheat.

Table A3. Rotation and purchased feed additive outputs in farm simulations by region, housing type, and manure management.

	Southwestern Québec				Eastern Québec			
	Tie-Stall Housing		Free-Stall Housing		Tie-Stall Housing		Free-Stall Housing	
	Solid Manure	Liquid Manure	Solid Manure	Liquid Manure	Solid Manure	Liquid Manure	Solid Manure	Liquid Manure
Rotation (%)[a]								
Cs/As/As/Ms	16.70	0.00	16.70	11.47	-	-	-	-
Cg/Cg/Sb	43.96	41.40	43.96	43.43	-	-	-	-
Cg/Cs/W+As/As/Ms/Ms/H	0.00	11.06	0.00	3.01	-	-	-	-
Cs/Cs/W+As/As/Ms/Ms	39.33	47.54	39.33	42.09	-	-	-	-
B/B/Cn	-	-	-	-	0.00	6.27	0.00	4.22
Cs/B+As/As/Ms/Ms	-	-	-	-	18.20	3.62	18.20	7.83
Cs/Cs/B+As/As/Ms/Ms	-	-	-	-	31.80	40.11	31.80	37.95
B/Cn/B+As/As/Ms	-	-	-	-	50.00	50.00	50.00	50.00
Purchased feed additives ($g\ kg^{-1}$ of FPCM)[b]								
Calcium carbonate ($CaCO_3$)	2.51	2.52	2.51	2.54	0.93	1.02	0.93	0.96
Dicalcium phosphate ($CaHPO_4$)	0.16	0.16	0.16	0.16	0.00	0.00	0.00	0.00
Magnesium oxide (MgO)	0.04	0.04	0.04	0.04	0.05	0.07	0.05	0.06
Calcium sulfate ($CaSO_4 \cdot 2H_2O$)	0.68	0.89	0.68	0.68	0.91	1.20	0.91	1.07
Sodium chloride (NaCl)	4.40	4.38	4.40	4.41	4.34	4.38	4.34	4.37
Magnesium sulfate heptahydrate ($MgSO_4 \cdot 7H_2O$)	0.51	0.20	0.51	0.51	0.21	0.21	0.21	0.21

[a] Cs = corn silage, As = alfalfa silage, Ms = mixed alfalfa and grass silage, Cg = corn grain, Sb = soybean, W+As = first year alfalfa established with wheat (cover crop), H = grass hay, B = barley, Cn = canola, and B+As = first year alfalfa established with barley (cover crop).

[b] FPCM = fat- and protein-corrected milk.