OPTIMAL HOUSING AND MANURE MANAGEMENT STRATEGIES TO FAVOR PRODUCTIVE AND ENVIRONMENT-FRIENDLY DAIRY FARMS IN QUÉBEC, CANADA: PART II. GREENHOUSE GAS MITIGATION METHODS

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

ABSTRACT. *Several strategies are available for mitigating greenhouse gas (GHG) emissions associated with dairy manure management in barns, storage units, and fields. For instance, incorporation of manure into the soil, solid-liquid separation, composting, enclosed manure storage, and anaerobic digestion have been identified as good options. However, these strategies are not widely adopted in Canada because clear information on their effectiveness to abate the whole-farm GHG footprint is lacking. Better information on the most cost-effective options for reducing on-farm GHG emissions would assist decision making for dairy producers and foster adoption of the most promising approaches on Canadian dairies. In this context, whole-farm modeling provides a tool for evaluating different GHG abatement strategies. An Excel-based linear optimization model (N-CyCLES) was used to assess the economics and the nutrient and GHG footprints of two representative dairy farms in Québec, Canada. The farms were located in regions with contrasting climates (southwestern and eastern Québec). The model was developed to optimize feeding, cropping, and manure handling as a single unit of management, considering the aforementioned mitigation options. Greenhouse gas emissions from the different simulated milk production systems reached 1.27 to 1.85 kg* CO_2e *kg*$^{-1}$ *of corrected milk, allowing GHG reductions of up to 25% compared to the base system described in Part I. Solid-liquid separation had the greatest GHG mitigation potential, followed by the digester-like strategy involving a tight cover for gas burning. However, both options implied a decrease in farm net income. Manure incorporation into the soil and composting were associated with high investment relative to their GHG abatement potential. The most cost-effective option was using a loose cover on the manure storage unit. This approach lessened the manure volume and ammonia-N volatilization, thereby reducing fertilizer and manure spreading costs, increasing crop sales and profit, and enhancing the whole-farm N and GHG footprints. Consequently, covering the manure tanks appears to be an economically viable practice for Québec dairy farms.*

Keywords. *Anaerobic digestion, Composting, Dairy cow, Farm net income, Greenhouse gas emission, Incorporation, Nutrient footprint, Solid-liquid separation, Storage cover, Whole-farm model.*

Climate change has become an important concern, as we are experiencing generally warmer and more variable weather (Ouranos, 2015). There is strong evidence that climate change is due to increasing levels of greenhouse gases (GHG) in the atmosphere, particularly carbon dioxide (CO_2) released by the burning of fossil fuels, but also methane (CH_4) and nitrous oxide (N_2O). The global livestock sector contributes a significant share to these anthropogenic GHG emissions (Rojas-Downing et al., 2017). Enteric fermentation from ruminants and storage of livestock effluents are important agricultural sources of CH_4. Nitrification and denitrification processes in cropland soil following addition of manure and, to a lesser extent, aerobic storage of effluents (solid manure) are the main sources of N_2O on farms (Chadwick et al., 2011).

Milk production is the main livestock sector in the province of Québec, Canada, with CAD$2.25 billion in cash receipts (MAPAQ, 2016). It respectively contributes for 36.4% and 3.4% of the province's agriculture-related (7.6 Mt CO_2e year^{-1}) and total (82.1 Mt CO_2e year^{-1}) GHG emissions (FPLQ, 2012; MELCC, 2016; Quantis et al., 2012). As a result, dairy farms are one of the Québec's main

---

Submitted for peer review in December 2018 as manuscript number PAFS 13272; 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, Quebec 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.

Vol. 62(4): 973-984 ISSN 2151-0032 https://doi.org/10.13031/trans.13272

emitting sectors, after transportation (33.8 %), industry (23.6%), residential/commercial/institutional (8.5%), and waste management (4.9%) (MELCC, 2016). Based on a life cycle analysis of Canadian milk production (Quantis et al., 2012), manure and soil management are the largest contributors to GHG emissions (47% of whole-farm emission), followed by enteric fermentation (46%) and on-farm energy use and transportation (7%). Promising alternatives to reduce GHG emissions from manure and soil, and to reduce the environmental footprint of dairy farms, have been described (Hou et al., 2017; Jayasundara et al., 2016; Montes et al., 2013). Among other strategies, those studies cited solid-liquid separation, composting, manure storage covers, and anaerobic digestion, which 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. Sub-surface incorporation can significantly reduce ammonia emissions following land application, implying that a smaller quantity of manure is required to meet crop nitrogen requirements, which reduces the potential for N_2O production. On the other hand, manure incorporation can increase N_2O emissions from soils by increasing the amount of N available, especially with banding and injection (Chantigny et al., 2010), and the net effect on the whole-farm GHG balance remains unclear.

However, these strategies are not widely used (Gerber et al., 2013). Any management change must maintain or improve production and be economically viable to be affordable (Rotz et al., 2016). Presently, mitigation measures generally represent an additional cost for producers, who are not aware of the potential economic and environmental benefits from a whole-farm perspective. For instance, improving management of nutrients by decreasing losses from manure or by reducing fertilizer purchases could represent net monetary gains (Misselbrook and Powell, 2005; Petersen et al., 2007). To assess the overall cost-effectiveness of mitigation strategies, farm-scale modeling can be a useful tool (Rotz, 2017). Moreover, using the Integrated Farm System Model (IFSM), Rotz et al. (2016) demonstrated that strategies such as enclosed storage, anaerobic digestion, and manure incorporation increased the net annual return of a representative dairy farm in New York State by US$7 to US$21 per cow with 18% to 20% GHG reduction.

The model N-CyCLES (Nutrient Cycling: Crops, Livestock, Environment, and Soils), an Excel-based linear program, is a unique research and education decision-making tool that allows analysis of the economic implications and alternative management options for reducing the whole-farm balance of nutrients or GHG emissions under Québec's conditions. It assumes that feeding, cropping, fertilizer use, and manure allocation is a single unit of management rather than four separate and loosely associated areas of decision-making (Wattiaux, 2018). N-CyCLES has been used by different researchers over the years (Moreno Prado, 2015; Pellerin et al., 2017) to provide estimates of farm net income (FNI) and GHG emissions when resources are allocated to reduce nitrogen (N) and phosphorus (P) footprints and the four aforementioned areas are optimized. Information on the most profitable options for different production systems for reducing on-farm GHG emissions would support decision-making by dairy producers and favor adoption of the most profitable options. The objectives of this study were to: (1) evaluate the FNI and GHG, N, and P footprints for representative dairy farms in two regions with contrasting climates (southwestern and eastern Québec) as influenced by implementation of five mitigation options related to manure handling (incorporation into soil, solid-liquid separation, composting, and enclosed storage with or without biogas production) under different production scenarios involving combinations of tie-stall or free-stall housing and solid or liquid manure management, and (2) compare results with the standard scenarios evaluated in Part I (Fournel et al., 2019a).

MATERIALS AND METHODS

MODEL DESCRIPTION

N-CyCLES 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 N, P, or GHG emissions. Farm net income was calculated as the difference between income and expenses. Whole-farm N and P footprints were calculated by the difference between farm-gate imports (purchased feeds and fertilizers, atmospheric N deposition, and biological N fixation) and exports (milk, animals, and crops sold). N-CyCLES also evaluated GHG emissions based on estimation methods used by Canada's National GHG Inventory, which complies with the 2006 methodological guidance by the Intergovernmental Panel on Climate Change (IPCC). 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 management systems, bedding options, and soil types were used to add precision to the model estimation.

Cycling of nutrients within the farm was described by input-output relationships of animal groups in the herd and by input-output relationships of land units, which are defined as groups of fields with distinct characteristics that influence nutrient management plans. To meet a specific goal, the optimization algorithm in the model took into account 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 N and P recommendations of the crops. The model was parameterized with National Research Council algorithms (NRC, 2001) for the nutritional requirements of each feeding group (early and mid-late lactation, dry cows, heifers <1 year old, and heifers ≥1 year old) and regional nutrient management planning rules for nutrient application in the fields. Available feeds included nine crop-derived homegrown feeds and seventeen purchased feeds (table A1 in Part I). Sources of crop nutrients included five commercial fertilizers (table A1 in Part I) and two on-farm manure types (solid and liquid). The total mass and volume of manure were calculated by summing the amounts of excreted manure for each animal group (ASABE, 2005;

Nennich et al., 2005), bedding, used and dilution water, and rain accumulation in the storage unit (Godbout et al., 2013, 2017). Cost of manure spreading was based on the total quantity to spread, transport distance, and mode of application, as described by a review of recent studies (see Part I). Cropland was subdivided in two land units. Up to five crop rotations can be allocated to each land unit.

An overview of N-CyCLES and more details on the economic inputs, optimized variables, feeds and diets, manure and fertilizer, crops and rotations, and model outcomes is presented in Part I (Fournel et al., 2019a) and by Pellerin et al. (2017). The model used year as the unit of time and assumed that the production system was essentially at steady-state. Model outcomes were 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 (IDF, 2015) methodology, and thus milk and meat were allocated based on the physical method, and crops were allocated based on the economic method. The monetary unit was Canadian dollars (CAD$).

REPRESENTATIVE FARMS

Dairy production in the province of Québec is characterized by human-scale, family-run farms (PLQ, 2018) using tie-stall housing (93%; CDIC, 2016) and solid manure management (44%; Quantis et al., 2012) in high proportion for their lactating animals. However, the recent consolidation of Québec farms, which has led to an increase in the average herd size (49 to 65 milking cows per farm from 2005 to 2017; AGÉCO, 2018), is expected to drive a shift toward free-stall housing with liquid manure systems in the near future (Valacta, 2015).

Two regional cases were developed to describe representatives farms 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 could include either tie-stall housing with a milk line system or free-stall housing with an automated milking system. These regions were selected due to their high density of dairy farms and the ability (or not) to grow corn grain due to their contrasting climates. The average 2010-2014 farm characteristics and economic inputs for each region were from the Agritel database (GCAQ, 2016).

Productivity and economic inputs for both representative farms are summarized in table 1 of Part I (Fournel et al., 2019a). Briefly, both barns 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, based on farm milk composition, which has been stable and equivalent for both regions because of the quota system implemented in Canada, was representative of the 2010-2014 period and set at \$0.74 kg^{-1} of FPCM (approx. \$77.6 hL^{-1}). Other sources of fixed income, including mainly 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.

Table 1. Summary of farm simulations by region, housing type, and manure management considering incorporation of manure into soil.[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
Economics (\$ kg^{-1} FPCM)								
Income	0.95 (0)	0.95 (0)	0.95 (0)	0.95 (0)	0.86 (0)	0.86 (0)	0.86 (0)	0.86 (0)
Expenses	0.63 (+2)	0.63 (+2)	0.63 (+1)	0.63 (+2)	0.67 (+1)	0.69 (+2)	0.67 (+1)	0.68 (+2)
Net income	0.32 (-3)	0.32 (-3)	0.32 (-3)	0.32 (-3)	0.18 (-5)	0.17 (-7)	0.18 (-5)	0.18 (-7)
N footprint (g kg^{-1} FPCM)								
Imports	27.87 (-2)	22.90 (-5)	28.26 (-2)	23.28 (-4)	22.31 (-3)	19.82 (0)	22.75 (-3)	19.82 (-1)
Exports	11.75 (0)	11.78 (0)	11.75 (0)	11.78 (0)	7.99 (0)	8.56 (+1)	7.99 (0)	8.56 (+3)
Balance	16.13 (-3)	11.12 (-9)	16.51 (-3)	11.50 (-8)	14.32 (-5)	11.26 (-2)	14.75 (-4)	11.26 (-4)
Balance on land basis (kg ha^{-1})	117.69 (-3)	81.15 (-9)	120.52 (-3)	83.95 (-8)	72.10 (-5)	56.70 (-2)	74.29 (-4)	56.70 (-4)
P footprint (g kg^{-1} FPCM)								
Imports	2.71 (0)	2.48 (-1)	2.71 (0)	2.48 (+1)	3.16 (0)	2.76 (+1)	3.16 (0)	2.76 (+2)
Exports	1.92 (0)	1.93 (-1)	1.92 (0)	1.93 (0)	1.28 (0)	1.33 (+1)	1.28 (0)	1.33 (+2)
Balance	0.79 (0)	0.55 (-1)	0.79 (0)	0.55 (+4)	1.88 (0)	1.43 (+1)	1.88 (0)	1.43 (+1)
Balance on land basis (kg ha^{-1})	5.76 (0)	3.98 (-1)	5.76 (0)	3.98 (+4)	9.45 (0)	7.19 (+1)	9.45 (0)	7.19 (+1)
GHG production (kg CO_2e kg^{-1} FPCM)								
CO_2	0.40 (-4)	0.26 (-13)	0.41 (-3)	0.27 (-9)	0.29 (-7)	0.26 (+1)	0.30 (-6)	0.26 (+2)
CH_4	0.92 (0)	1.19 (0)	0.91 (0)	1.17 (0)	0.94 (0)	1.22 (0)	0.93 (0)	1.20 (0)
N_2O	0.53 (-1)	0.30 (-7)	0.52 (-1)	0.30 (-5)	0.45 (-1)	0.21 (-5)	0.44 (-1)	0.21 (-5)
Total	1.85 (-1)	1.74 (-3)	1.84 (-1)	1.73 (-2)	1.68 (-2)	1.68 (-1)	1.68 (-1)	1.66 (0)
Allocation (kg CO_2e kg^{-1} FPCM)								
Milk	1.47 (-1)	1.38 (-3)	1.46 (-1)	1.37 (-2)	1.39 (-2)	1.39 (-1)	1.39 (-1)	1.37 (-1)
Animal	0.24 (-1)	0.22 (-3)	0.24 (-1)	0.22 (-2)	0.25 (-2)	0.25 (-1)	0.25 (-1)	0.25 (-1)
Crops	0.14 (-1)	0.14 (-5)	0.14 (-1)	0.14 (-2)	0.04 (-2)	0.04 (+4)	0.04 (-1)	0.04 (+10)

[a] Numbers in parentheses indicate the difference (%) from the base scenario in Part I (Fournel et al., 2019a). FPCM = fat- and protein-corrected milk, N = nitrogen, P = phosphorus, GHG = greenhouse gas, CO_2 = carbon dioxide, CH_4 = methane, N_2O = nitrous oxide, and CO_2e = CO_2 equivalent units (a unit of CH_4 and a unit of N_2O are equivalent to 25 and 298 CO_2e units in global warming potential, respectively).

Calculated dry matter (DM) intake for cows in the early and mid-late lactation groups was, respectively, 25.0 and 23.1 kg d^{-1} in SWQ and 24.5 and 22.6 kg d^{-1} in EQ. Detailed consideration for dairy cow ration N and P are also presented in table 1 of Part I. The land base surface was 127 and 178 ha of cropland for SWQ and EQ, respectively, which was subdivided into two land units of equal size. 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 in 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. The crop rotations and the average cost of production of each rotation are presented in table A2 in Part I.

IMPLEMENTED MITIGATION STRATEGIES

The base system, as simulated in Part I for both representative farms using either tie-stall or free-stall housing and either solid or liquid manure management, included storing manure in an uncovered tank and broadcasting on the surface of cropland without incorporation. Cereal straw was used as bedding in all simulations. To demonstrate the evaluation of mitigation options in this part of the study, five other manure handling methods were simulated to illustrate their effects on farm profitability and environmental impact. Additional costs for purchasing equipment and operating each approach were assumed in the model by estimating the annual expense of each component according to its economic life (CRAAQ, 2015a).

The first option was incorporation of solid or liquid manure into the soil by tillage within 24 h of application. Because the practice and equipment are common, no supplemental machinery cost was assumed. Only an overcharge cost of \$1.87 per ton of incorporated manure was added to the standard \$2.35 per ton of manure spread to account for additional fuel used (Brown, 2011).

For the second option, straw was replaced with recycled manure solids (RMS) as bedding material for farms with liquid manure management. To produce RMS on the farm, a solid-liquid separator (e.g., Xpress, GEA-Houle, Drummondville, Québec, Canada) and a drum composter (e.g., 400 Series, Brome Compost, Cowansville, Québec, Canada) at a cost of \$75,000 each were added to the farm scenarios. Both machines and the solid effluent before stall application were stored in a shed constructed at a cost of \$20,000. The liquid effluent was redirected to the liquid manure tank and applied to cropland as the original slurry would have been. Additional costs for electricity (\$0.02 m^{-3}) and workload (2 h $week^{-1}$) were considered. The costs and physico-chemical composition of the RMS and liquid fraction were based on Fournel et al. (2019b, 2019c).

The third option involved composting of solid manure in heaps. Supplemental costs (CRAAQ, 2015b) for tractor use and workload (5 h $week^{-1}$) associated with compost turning were added in the model. Compost was spread in the same way as solid manure.

The fourth option considered the installation of a rigid cover (e.g., wood or steel lid) on the solid or liquid manure storage unit at an approximate cost of \$50,000 (English and Fleming, 2006; FPPQ, 2007). The cover approach aimed at reducing the volume of manure by keeping precipitation out of the storage unit.

The remaining option considered in the model was an enclosed storage unit with treatment of the gas produced from the liquid manure. This digester-like approach including a tight floating plastic cover favoring anaerobic conditions aimed at degrading the biogas in a biofilter to convert the CH_4 to CO_2 to decrease the global warming potential. After processing, the digestate was stored in an uncovered manure storage unit until application. The initial cost of the cover and treatment system was \$110,000 (FPPQ, 2007; Leclerc and Groleau, 2014).

SIMULATIONS

For each strategy, the model was solved to maximize FNI and thus determine the whole-farm footprints of N, P, and GHGs. To understand the impact of each strategy, the percentage difference was calculated between the data in Part I for the base scenario without mitigation options and the data in this part for each scenario with a mitigation option.

RESULTS

MANURE INCORPORATION INTO SOIL

Manure incorporation into the soil (table 1) did not have a major impact on simulated total income when compared to the base system (\$0.95 and \$0.86 kg^{-1} of FPCM for SWQ and EQ, respectively), although EQ barns using liquid systems increased their crop revenues by 5% to 11%. This on-field practice benefitted all scenarios by decreasing fertilizer use by up to 68%. However, this reduction was not important in comparison with the 30% increase in manure handling costs due to the additional mechanical operation required for incorporating manure. In summary, the procedure involved an increase of expenses by \$0.01 kg^{-1} of FPCM, and thus a reduction of FNI by the same amount. Therefore, the simulated FNI dropped from \$0.33 and \$0.19 kg^{-1} in Part I to \$0.32 and \$0.18 kg^{-1} of FPCM for SWQ and EQ, respectively.

Manure incorporation improved N use by crops, thereby reducing the amount of imported fertilizers needed and thus N imports by 2% to 5% for most scenarios. For liquid systems in the EQ region, incorporation did not really affect fertilizer use but allowed a change in homegrown crops. The model replaced part of silage-based rotations in the base system with a barley-canola rotation to use more barley grain in animal diets (+3.87 to +8.38 g kg^{-1} of FPCM) and to sell more canola (+1.98 to +4.27 g kg^{-1} of FPCM). Therefore, the slight decrease (up to 1%) in N imports for EQ scenarios with liquid manure management is mainly attributed to a 3% to 6% reduction in legume N fixation. The enhanced sale of canola in EQ scenarios with liquid manure management also resulted in greater N exports than in the other scenarios. Overall, each system combination using manure incorporation improved the farm N footprint by 2% to 9% in comparison with scenarios without incorporation (base system).

In solid manure systems, incorporation of manure into the soil did not influence the calculated P imports, exports, and balance. However, these items varied in liquid systems according to region and housing system. In the SWQ tie-stall farm, less feeds were purchased (e.g., -3.39 g barley grain per kg of FPCM) and sold (e.g., -3.89 g corn grain per kg of FPCM), resulting in a 1% decrease in farm P footprint. On the contrary, the other three scenarios with liquid manure management imported and exported more feeds, resulting in global 1% to 4% increases in P footprint. The worst-case scenario (SWQ free-stall farm) was characterized by a supplemental purchase of dried corn distillers grain (+6.62 g kg^{-1} of FPCM).

While the calculated CH_4 emissions remained unchanged, the CO_2 and N_2O emissions were affected by manure incorporation by reducing the importation of fertilizers. More specifically, manure incorporation mainly decreased CO_2 emissions from fertilizer transport (0% to 68%) and from direct (0% to 68%) and indirect (volatilization; 2% to 17%) N_2O emissions caused by fertilizer application. Increases in GHG levels of up to 83% were also noted due to manure handling. Overall, manure incorporation reduced GHG emissions by 0.01 and 0.06 kg CO_2e kg^{-1} of FPCM (between 12.0 and 64.9 t CO_2e year^{-1}) in SWQ and EQ, respectively, representing reductions of 1% to 3% as compared to the base system. Milk and animal allocations were decreased in the same proportions.

SOLID-LIQUID SEPARATION

Using RMS (table 2) did not affect the calculated income ($0.95 and $0.86 kg^{-1} of FPCM in SWQ and EQ, respectively), although crop sales varied between 6% and 10% from the original values in Part I. However, the alternate bedding material involved several expense changes. The main effect (+$0.03 kg^{-1} of FPCM) appeared on fixed costs, which increased by 7% due to the addition of specialized equipment and infrastructure. Fertilizer cost was also increased (+$0.01 kg^{-1} of FPCM), more than doubling this budget item. This was the result of liquid manure in the RMS scenarios containing lower concentrations of nutrients following separation, involving additional imports of fertilizers to counterbalance crop needs. During the optimization process, the model made different rotation selections, which impacted spending on purchased feeds (-$0.01 kg^{-1} of FPCM). Because RMS represented a substantial fraction of the raw manure volume, manure spreading costs decreased by approximately 37% (-$0.02 kg^{-1} of FPCM) in each scenario. Overall, total expenses were the same, signifying that FNI remained unchanged.

Nitrogen flows for the RMS system diverged between the two Québec regions. In SWQ, maximizing FNI involved a 95% increase (+1.76 g kg^{-1} of FPCM) in imported N-based fertilizers (mostly calcium ammonium nitrate) to substitute a part of the silage-based rotations with rotations based on crops that can be sold. Consequently, the 5% to 9% increase in sales of homegrown corn grain, soybean, and wheat reduced legume N fixation by 3% (-0.16 g kg^{-1} of FPCM) and increased N exports (+0.41 g kg^{-1} of FPCM). All those changes affected purchases of feed ingredients, resulting in a 6% decrease for this N source (-0.98 g kg^{-1} of FPCM). In EQ, supplemental N to offset a lower quantity and less rich liquid manure was ensured by fertilizing products and legume fixation in similar proportions. Therefore, the RMS approach at the EQ farm involved production of 4% more alfalfa silage and 11% more mixed silage than the base system. Canola sales also decreased by 11%, reducing N exports by 0.23 g kg^{-1} of FPCM. Similar to SWQ, N imports from purchased feeds dropped by 9% (-1.10 g kg^{-1} of FPCM). In the end, the N footprint in SWQ increased by 2% (+0.21 g kg^{-1} of FPCM), while it remained stable in EQ.

The P footprint in the RMS scenarios especially varied according to soil P concentration. In SWQ where soils are P-

Table 2. Summary of farm simulations by region and housing type considering liquid systems using solid-liquid separation to produce recycled manure solids for bedding.[a]

	Southwestern Québec		Eastern Québec	
	Tie-Stall Housing	Free-Stall Housing	Tie-Stall Housing	Free-Stall Housing
Economics ($ kg^{-1} FPCM)				
Income	0.95 (0)	0.95 (+1)	0.86 (0)	0.86 (0)
Expenses	0.62 (+1)	0.62 (+1)	0.67 (0)	0.67 (0)
Net income	0.33 (-1)	0.33 (-1)	0.19 (-1)	0.19 (-2)
N footprint (g kg^{-1} FPCM)				
Imports	24.52 (+2)	25.08 (+3)	19.71 (-1)	19.74 (-2)
Exports	12.19 (+3)	12.23 (+4)	8.16 (-3)	8.11 (-2)
Balance	12.33 (+1)	12.84 (+3)	11.55 (+1)	11.63 (-1)
Balance on a land basis (kg ha^{-1})	89.99 (+1)	93.73 (+3)	58.16 (+1)	58.55 (-1)
P footprint (g kg^{-1} FPCM)				
Imports	2.58 (+3)	2.54 (+4)	3.16 (+15)	3.15 (+16)
Exports	2.00 (+3)	2.00 (+4)	1.30 (-2)	1.29 (-1)
Balance	0.58 (+5)	0.53 (+2)	1.86 (+31)	1.86 (+32)
Balance on a land basis (kg ha^{-1})	4.21 (+5)	3.89 (+2)	9.37 (+31)	9.35 (+32)
GHG production (kg CO_2e kg^{-1} FPCM)				
CO_2	0.33 (+12)	0.35 (+16)	0.25 (-3)	0.25 (-2)
CH_4	0.80 (-32)	0.79 (-32)	0.82 (-33)	0.81 (-32)
N_2O	0.29 (-9)	0.29 (-6)	0.21 (-5)	0.21 (-5)
Total	1.43 (-21)	1.43 (-20)	1.27 (-25)	1.27 (-24)
Allocation (kg CO_2e kg^{-1} FPCM)				
Milk	1.12 (-21)	1.13 (-20)	1.05 (-25)	1.05 (-24)
Animal	0.18 (-21)	0.18 (-20)	0.19 (-25)	0.19 (-24)
Crops	0.12 (-16)	0.12 (-13)	0.03 (-32)	0.03 (-29)

[a] Numbers in parentheses indicate the difference (%) from the base scenario in Part I (Fournel et al., 2019a). FPCM = fat- and protein-corrected milk, N = nitrogen, P = phosphorus, GHG = greenhouse gas, CO_2 = carbon dioxide, CH_4 = methane, N_2O = nitrous oxide, and CO_2e = CO_2 equivalent units (a unit of CH_4 and a unit of N_2O are equivalent to 25 and 298 CO_2e units in global warming potential, respectively).

rich, application of P-based fertilizers was limited to 0.12 g kg^{-1} of FPCM. In EQ where soils are less restricted in P, the same activity corresponded to a total of 1.59 g kg^{-1} of FPCM. This large range of values explained much of the gap in balance results because variations in P through purchased feeds and crops sold were minor. Actually, the 2% to 5% increase in P for the SWQ farm (+0.02 g kg^{-1} of FPCM) was marginal in comparison with the 32% increase associated with the EQ farm (+0.45 g kg^{-1} of FPCM).

On-farm production of RMS also had repercussions on calculated GHG emissions. The increased fertilizer use caused higher releases of CO_2 and N_2O (+72% to 99%) through transport and application (+0.01 and +0.07 kg CO_2e kg^{-1} of FPCM in EQ and SWQ, respectively). Changes in rotations required between 12% and 18% more fuel consumption by tractors for different mechanical operations (+0.01 kg CO_2e kg^{-1} of FPCM). All those detrimental effects were offset by benefits in the cow ration composition and manure management chain. New combinations of homegrown crops allowed reduction in GHG production associated with imported feeds (-0.02 kg CO_2e kg^{-1} of FPCM) and enteric fermentation (-0.04 kg CO_2e kg^{-1} of FPCM). Liquid manure in the RMS scenarios contained less organic matter and N, which reduced CH_4 emissions from the storage unit and direct and indirect N_2O emissions from manure application (-0.37 kg CO_2e kg^{-1} of FPCM). Therefore, GHG reductions with RMS as bedding reached 20% and 24% (-0.36 and -0.41 kg CO_2e kg^{-1} of FPCM) in SWQ and EQ, respectively.

Composting in Heaps

Composting solid manure in heaps (table 3) increased the calculated fixed costs due to supplemental handling charges (+\$0.01 kg^{-1} of FPCM), which negatively affected FNI by 4% to 7% (-\$0.01 kg^{-1} of FPCM). This technique involving frequent turnings produced higher volatile losses during the process in comparison with the base scenario in which manure was stored immobile. This situation especially impacted the need for fertilizers in each farm scenario (+65% to +94%) to counterbalance the lower nutrient concentrations in manure. If this increased fertilizer use did not affect economic outcomes, it negatively influenced N (+9% to +12%) and P (+15% to +23%) footprints. In both cases, increases in fertilizer amounts represented 1.17 to 1.41 g N kg^{-1} and 0.12 to 0.21 g P kg^{-1} of FPCM, respectively.

Imported fertilizers influenced the calculated GHG emissions because they were responsible for an increase in CO_2 and N_2O from transport and application of approximately 0.04 kg CO_2e kg^{-1} of FPCM. An extra 0.02 kg CO_2e kg^{-1} of FPCM was also attributed to fuel consumption during compost turning. In return, solid manure composting reduced GHG associated with manure management and application (-0.14 kg CO_2 kg^{-1} of FPCM) through decreases in CH_4 (-13% of CH_4) and N_2O (-102%) at the processing and spreading stages. Overall, composting involved a 4% decrease in total GHG emissions and a 4% decrease in milk allocation.

Cover on Manure Storage Unit

Installation of a rigid cover on the manure storage (table 4) was economically beneficial due to substantial reductions in manure volume and N volatilization. While fixed costs increased by 1% for each scenario, fertilizer and manure spreading costs decreased by 19% and 29% for farms with solid manure management systems and by 4% and 15% for farms with liquid manure management systems for SWQ and EQ, respectively. In addition, better preservation of manure N generally allowed farms with liquid manure management to increase rotations including grain corn and wheat (in SWQ) or canola (in EQ) at the expense of silage-based rotations, with the aim of increasing crop sales by 2%. As a re-

Table 3. Summary of farm simulations by region and housing type considering solid systems including manure composting in heaps.[a]

	Southwestern Québec		Eastern Québec	
	Tie-Stall Housing	Free-Stall Housing	Tie-Stall Housing	Free-Stall Housing
Economics (\$ kg^{-1} FPCM)				
Income	0.95 (0)	0.95 (0)	0.86 (0)	0.86 (0)
Expenses	0.63 (+2)	0.63 (+2)	0.68 (+2)	0.68 (+2)
Net income	0.32 (-4)	0.32 (-4)	0.18 (-7)	0.18 (-7)
N footprint (g kg^{-1} FPCM)				
Imports	29.64 (+5)	29.90 (+5)	24.41 (+7)	24.70 (+7)
Exports	11.75 (0)	11.75 (0)	7.99 (0)	7.99 (0)
Balance	17.89 (+10)	18.15 (+9)	16.41 (+12)	16.70 (+11)
Balance on a land basis (kg ha^{-1})	130.58 (+10)	132.50 (+9)	82.63 (+12)	84.10 (+11)
P footprint (g kg^{-1} FPCM)				
Imports	2.83 (+5)	2.83 (+5)	3.37 (+8)	3.37 (+8)
Exports	1.92 (0)	1.92 (0)	1.28 (0)	1.28 (0)
Balance	0.91 (+22)	0.91 (+23)	2.09 (+15)	2.09 (+15)
Balance on a land basis (kg ha^{-1})	6.66 (+22)	6.66 (+23)	10.52 (+15)	10.52 (+15)
GHG production (kg CO_2e kg^{-1} FPCM)				
CO_2	0.47 (+18)	0.48 (+17)	0.37 (+22)	0.38 (+21)
CH_4	0.84 (-6)	0.84 (-6)	0.86 (-6)	0.86 (-6)
N_2O	0.48 (-17)	0.47 (-16)	0.41(-21)	0.40 (-20)
Total	1.79 (-4)	1.79 (-4)	1.64 (-4)	1.64 (-4)
Allocation (kg CO_2e kg^{-1} FPCM)				
Milk	1.42 (-4)	1.42 (-4)	1.36 (-4)	1.36 (-4)
Animal	0.23 (-4)	0.23 (-4)	0.25 (-4)	0.25 (-4)
Crop	0.14 (-4)	0.14 (-4)	0.03 (-3)	0.03 (-3)

[a] Numbers in parentheses indicate the difference (%) from the base scenario in Part I (Fournel et al., 2019a). FPCM = fat- and protein-corrected milk, N = nitrogen, P = phosphorus, GHG = greenhouse gas, CO_2 = carbon dioxide, CH_4 = methane, N_2O = nitrous oxide, and CO_2e = CO_2 equivalent units (a unit of CH_4 and a unit of N_2O are equivalent to 25 and 298 CO_2e units in global warming potential, respectively).

Table 4. Summary of farm simulations by region, housing type, and manure management considering a loose cover on manure storage unit.[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
Economics ($ kg^{-1} FPCM)								
Income	0.95 (0)	0.95 (0)	0.95 (0)	0.95 (0)	0.86 (0)	0.86 (0)	0.86 (0)	0.86 (0)
Expenses	0.61 (-1)	0.62 (0)	0.61 (-1)	0.61 (0)	0.66 (-1)	0.67 (0)	0.66 (-1)	0.67 (0)
Net income	0.34 (+3)	0.33 (+1)	0.34 (+2)	0.33 (+1)	0.20 (+4)	0.19 (+1)	0.20 (+4)	0.19 (+1)
N footprint (g kg^{-1} FPCM)								
Imports	27.38 (-4)	23.85 (-1)	27.80 (-3)	24.17 (-1)	21.87 (-5)	19.82 (0)	22.33 (-4)	19.97 (0)
Exports	11.75 (0)	11.82 (0)	11.75 (0)	11.82 (0)	7.99 (0)	8.52 (+1)	7.99 (0)	8.38 (+1)
Balance	15.63 (-6)	12.03 (-2)	16.05 (-6)	12.35 (-1)	13.87 (-8)	11.30 (-2)	14.34 (-7)	11.59 (-1)
Balance on a land basis (kg ha^{-1})	114.07(-6)	87.79 (-2)	117.14 (-6)	90.16 (-1)	69.85 (-8)	56.90 (-2)	72.20 (-7)	58.38 (-1)
P footprint (g kg^{-1} FPCM)								
Imports	2.71 (0)	2.50 (0)	2.71 (0)	2.50 (+2)	3.16 (0)	2.75 (0)	3.16 (0)	2.73 (0)
Exports	1.92 (0)	1.95 (0)	1.92 (0)	1.95 (+1)	1.28 (0)	1.33 (+1)	1.28 (0)	1.32 (+1)
Balance	0.79 (0)	0.55 (0)	0.79 (0)	0.55 (+5)	1.88 (0)	1.42 (0)	1.88 (0)	1.41 (0)
Balance on a land basis (kg ha^{-1})	5.76 (0)	4.02 (0)	5.76 (0)	4.02 (+5)	9.45 (0)	7.16 (0)	9.45 (0)	7.11 (0)
GHG production (kg CO_2e kg^{-1} FPCM)								
CO_2	0.39 (-7)	0.29 (-2)	0.40 (-7)	0.30 (+1)	0.28 (-11)	0.26 (0)	0.29 (-10)	0.25 (0)
CH_4	0.86 (-7)	1.04 (-12)	0.85 (-7)	1.03 (-12)	0.88 (-7)	1.07 (-12)	0.87 (-7)	1.05 (-12)
N_2O	0.31 (-41)	0.31 (-2)	0.32 (-40)	0.31 (0)	0.23 (-50)	0.21 (-4)	0.23 (-50)	0.22 (-4)
Total	1.56 (-17)	1.65 (-9)	1.57 (-16)	1.64 (-8)	1.38 (-19)	1.54 (-9)	1.39 (-18)	1.52 (-9)
Allocation (kg CO_2e kg^{-1} FPCM)								
Milk	1.24 (-17)	1.30 (-9)	1.24 (-16)	1.30 (-8)	1.14 (-19)	1.27 (-9)	1.15 (-18)	1.26 (-9)
Animal	0.20 (-17)	0.21(-9)	0.20 (-16)	0.21 (-8)	0.21 (-19)	0.23 (-9)	0.21 (-18)	0.23 (-9)
Crops	0.12 (-17)	0.13 (-9)	0.12 (-16)	0.13 (-6)	0.03 (-19)	0.03 (-6)	0.03 (-18)	0.04 (-6)

[a] Numbers in parentheses indicate the difference (%) from the base scenario in Part I (Fournel et al., 2019a). FPCM = fat- and protein-corrected milk, N = nitrogen; P = phosphorus, GHG = greenhouse gas, CO_2 = carbon dioxide, CH_4 = methane, N_2O = nitrous oxide, and CO_2e = CO_2 equivalent units (a unit of CH_4 and a unit of N_2O are equivalent to 25 and 298 CO_2e units in global warming potential, respectively).

sult, covering the manure storage enhanced calculated FNI by 1% to 4%.

Covering manure storage also improved farm N use efficiency. In scenarios where N imports were reduced in comparison with the base system, purchases of calcium ammonium nitrate were decreased by 25% to 94%. In the other two scenarios, higher canola sales involved a 2% increase in N exports. Consequently, the N footprint for each scenario was reduced by 0.22 to 1.95 g kg^{-1} of FPCM. Changes in the P footprint were essentially important for SWQ using a free-stall barn with liquid manure management. This case was characterized by higher purchases of corn distillers grain (+6.62 g kg^{-1} of FPCM) and barley (+4.96 g kg^{-1} of FPCM) to compensate for greater sales of corn grain (+7.78 g kg^{-1} of FPCM) and wheat (+2.46 g kg^{-1} of FPCM). As a result, P imports as well as the P balance increased with this scenario. Other simulation scenarios did not considerably influence the P footprint.

Covering the manure storage reduced GHG emissions mainly because it reduced the amount of precipitation entering the storage unit and thus reduced the manure disturbance. This decreased N_2O emissions from the nitrification-denitrification process occurring within solid manure heaps and decreased CH_4 emissions from liquid manure. Thus, covering the manure storage decreased manure-associated emissions of N_2O in solid systems and emissions of CH_4 in liquid systems by 82% and 26%, respectively. Important reduction in purchased N-based fertilizers also contributed to decrease CO_2 and N_2O emissions related to fertilizer transport and application in both systems (0% to 82%). Overall, covering the manure storage reduced GHG emissions by 0.34 and 0.18 kg CO_2e kg^{-1} of FPCM for solid and liquid manure management, respectively. This decrease had repercussions on milk, animal, and crop allocations, which were also reduced by up to 19%.

DIGESTION WITH GAS TREATMENT

Simulation of the strategy involving manure digestion and treatment of the produced biogas (table 5) had no major impact on income, despite a rise in crop revenues by 5% to 10%. Expenses were mainly affected by the purchase of a tight cover on the manure storage and a treatment system because fixed costs increased by 4%. However, reductions in fertilizer costs (up to 21%) and manure spreading costs (15%) partly alleviated the economic burden of the additional equipment. Overall, expenses only increased by 1% to 2% (+$0.01 kg^{-1} of FPCM). The FNI of the SWQ and EQ farms therefore decreased by 1% and 4%, respectively, to reach $0.33 and $0.18 kg^{-1} of FPCM.

Because the digested manure in the simulation emitted less N into the atmosphere, the SWQ and EQ fields were less dependent on N-based fertilizers (0 to -0.36 g kg^{-1} of FPCM) and legume N fixation (-0.07 to -0.33 g kg^{-1} of FPCM). However, corn grain, soybean, and canola replaced part of the alfalfa and mixed silage production, which caused changes in N fluxes through purchased feeds (+0.09 to +0.43 g kg^{-1} of FPCM) and sold crops (+0.12 to +0.44 g kg^{-1} of FPCM). In the end, the N footprint was reduced by 0.34 g kg^{-1} of FPCM in average. Similarly, the P footprint varied according to purchased ingredients and exported crops but in a smaller proportion.

Digestion with gas treatment had several implications on GHG emissions for the simulated farms. The foremost effect was the 63% reduction in CH_4 production from the manure storage, which resulted in -0.35 kg CO_2e kg^{-1} of FPCM. In counterbalance, N_2O release from manure application more

Table 5. Summary of farm simulations by region, housing type, and manure management considering digested liquid manure and treatment of biogas.[a]

	Southwestern Québec		Eastern Québec	
	Tie-Stall Housing	Free-Stall Housing	Tie-Stall Housing	Free-Stall Housing
Economics (\$ kg^{-1} FPCM)				
Income	0.95 (+1)	0.95 (+1)	0.86 (0)	0.86 (0)
Expenses	0.63 (+2)	0.63 (+2)	0.68 (+1)	0.68 (+1)
Net income	0.33 (-1)	0.33 (-1)	0.18 (-4)	0.18 (-4)
N footprint (g kg^{-1} FPCM)				
Imports	23.93 (0)	24.28 (0)	19.82 (0)	19.82 (-1)
Exports	12.22 (+3)	12.22 (+4)	8.56 (+1)	8.52 (+3)
Balance	11.71 (-4)	12.06 (-4)	11.26 (-2)	11.30 (-4)
Balance on a land basis (kg ha^{-1})	85.46 (-4)	88.00 (-4)	56.70 (-2)	56.88 (-4)
P footprint (g kg^{-1} FPCM)				
Imports	2.55 (+2)	2.55 (+4)	2.76 (+1)	2.75 (+1)
Exports	2.01 (+3)	2.01 (+4)	1.33 (+1)	1.33 (+2)
Balance	0.54 (-1)	0.54 (+4)	1.43 (+1)	1.42 (+1)
Balance on a land basis (kg ha^{-1})	3.96 (-1)	3.96 (+4)	7.19 (+1)	7.16 (+1)
GHG production (kg CO_2e kg^{-1} FPCM)				
CO_2	0.29 (-3)	0.30 (+1)	0.26 (+1)	0.26 (+1)
CH_4	0.84 (-29)	0.83 (-29)	0.86 (-30)	0.85 (-29)
N_2O	0.39 (+21)	0.38 (+22)	0.25 (+11)	0.24 (+9)
Total	1.51 (-16)	1.51 (-15)	1.36 (-20)	1.35 (-19)
Allocation (kg CO_2e kg^{-1} FPCM)				
Milk	1.19 (-16)	1.19 (-15)	1.12 (-20)	1.11 (-20)
Animal	0.19 (-16)	0.19 (-15)	0.20 (-20)	0.20 (-20)
Crops	0.13 (-11)	0.13 (-7)	0.04 (-16)	0.03 (-12)

[a] Numbers in parentheses indicate the difference (%) from the base scenario in Part I (Fournel et al., 2019a). FPCM = fat- and protein-corrected milk, N = nitrogen, P = phosphorus, GHG = greenhouse gas, CO_2 = carbon dioxide, CH_4 = methane, N_2O = nitrous oxide, and CO_2e = CO_2 equivalent units (a unit of CH_4 and a unit of N_2O are equivalent to 25 and 298 CO_2e units in global warming potential, respectively).

than doubled in each scenario, for a global +0.03 to +0.08 kg CO_2e kg^{-1} of FPCM. The impact on CO_2 depended on the reduction level in imported fertilizers. Actually, CO_2 emissions increased in each scenario except for the SWQ farm using tie-stalls, where fertilizer use was decreased in the greatest proportion. In the end, total produced GHG emissions were reduced by 15% to 20%, allowing milk allocation to drop to 1.19 and 1.11 kg CO_2e kg^{-1} of FPCM for SWQ and EQ, respectively.

DISCUSSION

TOTAL GREENHOUSE GAS EMISSIONS

Greenhouse gas emissions from different milk production systems reached 1.27 to 1.85 kg CO_2e kg^{-1} of FPCM. This range of values was slightly greater than that reported (0.92 to 1.43 kg CO_2e kg^{-1} of FPCM) by recent life cycle assessments of nongrazing dairy systems (Arsenault et al., 2009; Flysjö et al., 2011; Hagemann et al., 2011; Kristensen et al., 2011; McGeough et al., 2012; Rotz et al., 2010).

However, these results must be compared with caution because of expected discrepancies among studies. Although the broad principles, as outlined by the IPCC (2006) methodology, may be common to all research studies, the specific methodologies and assumptions regarding production parameters, management practices, and sources used to calculate GHG intensity often vary greatly (McGeough et al., 2012). As explained in Part I (Fournel et al., 2019a), the algorithms and emissions factors used in this study to calculate farm gaseous emissions were based on studies conducted in Québec, may differ in other models using the general equations proposed by the IPCC (2006), and may not be applicable to other regions (Rotz, 2017). For instance, for a similar SWQ farm using tie-stalls and solid manure systems, McGeough et al. (2012) used the IPCC approach and found that manure-related CH_4 and N_2O contributed 0.07 to 0.08 kg CO_2e kg^{-1} of FPCM, well below the range of values for the uncovered scenarios in the present study (0.20 to 0.29 kg CO_2e kg^{-1} of FPCM). The general CH_4 and N_2O emission factors proposed by IPCC (2006) are lower than the specific field-measured factors used in the current study, which explains the 3 to 4 times greater values reported in this study. As a comparison, Owen and Silver (2015) stipulated that amended calculations can approximately double GHG intensity from the manure produced by dairy cattle.

GREENHOUSE GAS MITIGATION POTENTIAL

As shown in tables 1 to 5, alternative manure handling strategies can reduce GHG emissions by up to 25%. The mitigation potential of solid-liquid separation (19% to 25%) fell within the range of values reported by several studies for this approach (1% to 37%). Rotz et al. (2016) found a 1% GHG reduction while combining solid-liquid separation and tillage incorporation for a simulated large-scale dairy in Pennsylvania. Hou et al. (2017) simulated the implementation of slurry separation in Europe for 20% of all manure produced at the barn level and showed that it would decrease GHG emissions by 8% to 12%. Jayasundara et al. (2016) reported that solid-liquid separation may reduce GHG emissions by 20% to 37% as compared to untreated dairy manure.

Anaerobic digestion with gas treatment could reduce GHG emissions by 15% and 20%. Similarly, Rotz et al. (2016) showed that an enclosed storage with a flare to burn the gas produced could reduce GHG by 19%. As a comparison, these authors also simulated the on-farm use of the biogas for heating water or generating electricity and found no supplemental benefit in terms of GHG mitigation.

In the present study, a permanent wooden cover on the manure storage resulted in GHG reductions of 8% to 19%. Using similar equipment, Clemens et al. (2006) reported abatements of 12% and 14% during summer and winter, respectively. Other cover types (synthetic and straw) achieved GHG abatements between 1% and 26% (VanderZaag et al., 2009, 2010).

Composting solid manure in heaps had a modest GHG mitigation potential (4%). Hou et al. (2017) reported that composting in Europe would decrease GHG emissions by 7% relative to the reference, but they considered that only 20% of manure produced was processed. In other whole-farm evaluations, Amon et al. (2001) and Pattey et al. (2005) found that a composting system emitted, overall, 25% to 31% less GHG than a conventional solid manure handling system. Amon et al. (2001) reported that composting could reduce GHGs by 84% in summer but only by 10% in winter. Variable results for GHG mitigation by composting in winter were also observed by others; Ahn et al. (2011) indicated a 20% increase in GHG emissions, while Mulbry and Ahn (2014) indicated mitigation of GHG by 9% to 25%. Management practices, such as timing and frequency of turning, appeared to be critical for composting during winter because cold and wet conditions can adversely affect the performance of the composting process (Jayasundara et al., 2016). The fact that the present study used an annual emission factor without considering temperature can partially explain our relatively low GHG reductions as compared to Amon et al. (2001) and Pattey et al. (2005). Another explanation is that N-CyCLES includes emissions caused by increased purchase of fertilizers and fuel consumption by tractors for pile turning, offsetting an important portion of CH_4 and N_2O emissions, which were the only emissions changes considered by the other reported studies.

Manure incorporation had a slight influence on GHG emissions (0% to 3% reduction). Rotz et al. (2016) reported that direct injection of liquid digested manure resulted in a 1% increase in carbon footprint.

COST-EFFECTIVE MITIGATION METHODS

Selecting cost-effective mitigation strategies is challenging (table 6). The farm must normally gain some economic benefits, through reduced fertilizer use or energy produced on the farm, to offset the increased cost encountered with the change in management, through greater investment in equipment and facilities and increased labor and energy use (Rotz et al., 2016). The only option corresponding to this definition was covering the manure storage unit. With that option, the savings associated with reduced fertilizer purchase and manure volumes were high enough to counterbalance the increases in the fixed and variables costs. As a result, a covered manure storage contributed to a greater FNI while reducing the farm GHG footprint. In fact, the cover option ended with a positive cost-effectiveness, earning \$15 to \$27 t^{-1} of CO_2e mitigated.

With the solid-liquid separation, digestion with gas treatment, and composting options, the reductions in feed, fertilizer, and manure spreading expenses were insufficient to offset the additional equipment and workload expenses. Implementation of solid-liquid separation for GHG reduction was near the zero cost (\$6 to \$10 t^{-1} of CO_2e saved), similar to Rotz et al. (2016), who reported a small gain of \$0.5 t^{-1} of CO_2e saved when combining solid-liquid separation with slurry incorporation for a large-scale dairy in Pennsylvania. A positive cost-effectiveness would likely have been reached if N-CyCLES had considered increased milk production or a decreased cow culling rate due to perceived RMS benefits on cow welfare, such as longer lying times and fewer hock lesions (Leach et al., 2015). At this time, no relevant data are available to do so. The digestion with gas treatment option had a cost-effectiveness slightly greater than that of solid-liquid separation at \$17 to \$23 t^{-1} of CO_2e saved. Rotz et al. (2016) also reported that an enclosed storage with a flare to burn the biogas had a negative impact of \$42 cow^{-1} on the farm net return. Composting of solid manure allowed a small decrease in GHG emissions (\$59 to

Table 6. Variation in net return, greenhouse gas (GHG) reductions, and cost-effectiveness of mitigation strategies by region, housing type, and manure management considered by farm simulations.

	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
Manure incorporation into soil								
Net return (\$)	-8,857	-10,334	-8,539	-9,748	-8,442	-12,436	-8,148	-11,803
GHG reduction (t CO_2e saved)	17	57	16	40	24	8	22	7
Cost-effectiveness (\$ t^{-1} CO_2e saved)	-515	-182	-533	-244	-353	-1,630	-366	-1,669
Solid-liquid separation								
Net return (\$)	-	-2,106	-	-2,530	-	-2,420	-	-3,633
GHG reduction (t CO_2e saved)	-	350	-	318	-	376	-	358
Cost-effectiveness (\$ t^{-1} CO_2e saved)	-	-6	-	-8	-	-6	-	-10
Composting in heaps								
Net return (\$)	-12,119	-	-11,926	-	-12,525	-	-12,318	-
GHG reduction (t CO_2e saved)	70	-	68	-	60	-	59	-
Cost-effectiveness (\$ t^{-1} CO_2e saved)	-172	-	-175	-	-208	-	-210	-
Cover on manure storage unit								
Net return (\$)	7,707	2,761	7,159	2,679	7,613	2,323	7,064	2,023
GHG reduction (t CO_2e saved)	287	146	274	126	291	139	278	133
Cost-effectiveness (\$ t^{-1} CO_2e saved)	27	19	26	21	26	17	25	15
Digestion with gas treatment								
Net return (\$)	-	-4,434	-	-4,564	-	-6,468	-	-6,675
GHG reduction (t CO_2e saved)	-	267	-	245	-	300	-	290
Cost-effectiveness (\$ t^{-1} CO_2e saved)	-	-17	-	-19	-	-22	-	-23

\$70 t^{-1} of CO_2e), resulting in a high cost per ton of GHG mitigated (\$172 to \$210 t^{-1} of CO_2e saved).

Similar to composting, manure incorporation involved important expenses for low emission reductions. The cost-effectiveness of this practice was \$182 to \$1669 t^{-1} of CO_2e saved.

IMPACT ON NUTRIENT FOOTPRINTS

In addition to impacting GHG emissions, the options assessed in this study also influenced nutrient footprints. Although manure incorporation had the lowest cost-effectiveness for GHG mitigation, it was the best approach to improve the farm N footprint, with 2% to 9% reduction. Loose and tight covers also enhanced the N footprint (1% to 8% reduction). These options reduced the amount of fertilizer N needed to meet crop N requirements by greatly reducing ammonia (NH_3) emissions during manure storage and after field application (Montes et al., 2013).

Powell et al. (2011) investigated the NH_3 volatilization mitigating potential of three methods of dairy slurry application (surface broadcast, surface broadcast followed by partial incorporation using an aerator implement, and injection) and found that the total N loss was 27.1%, 23.3%, and 9.1%, respectively. With farm simulation, Rotz et al. (2016) noted that N volatilization through NH_3 decreased from 74.6 kg cow^{-1} without incorporation to a range between 30.3 and 54.7 kg cow^{-1} when manure was injected into the soil. Those authors also demonstrated that an enclosed manure storage emitted 46.0 kg NH_3-N cow^{-1}, compared to 50.9 kg NH_3-N cow^{-1} for an open storage. Therefore, manure incorporation and covered storage lessen the environmental problems associated with gaseous N emissions, such as the formation of fine particles in the atmosphere and re-deposition of NH_3 with rain (Bittman and Mikkelsen, 2009).

However, if manure incorporation and loose and tight covers improved the N footprint, they worsened the P footprint, in a majority of cases, by up to 5%. This antagonistic effect was also noted by Pellerin et al. (2017) in simulating a similar SWQ farm in N-CyCLES under a constraint of reducing the N footprint, which increased the P footprint. To our knowledge, few simulation tools are available to study systematically the interactions between N and P footprints. Exploration of such relationships is important because the literature has provided evidence of pollution swapping (i.e., an increase in one pollutant as a result of a taking action to reduce another pollutant; Stevens and Quinton, 2009).

In contrast, RMS and compost production involved nutrient reductions during the process (Ackerman et al., 2018; Brito et al., 2008; Fournel et al., 2019b), resulting in higher needs for N and P inputs at the farm level to compensate for the losses. Consequently, the N and P footprints were increased, especially for P in the EQ region, where there is no limitation on P on a larger land surface. Farms the EQ region should hence pay attention to P inputs, as the footprint can increase drastically (up to 32% with the RMS option).

CONCLUSION

A farm-scale optimization model was used to assess the overall cost-effectiveness of different GHG mitigation options for two representative dairy farms with contrasting climates. Manure incorporation, solid-liquid separation, pile composting, and enclosed storage with or without gas treatment can reduce GHG emissions by up to 25%. With the exception of pile composting, these options also improved the farm N footprint by reducing manure N losses through gaseous emissions. In the simulation conditions, only the enclosed storage approach resulted in a positive cost-effectiveness for GHG mitigation and enhancement of nutrient footprints. Covering the manure storage hence appears to be a simple and economically viable practice to implement on Québec's dairy farms.

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

Ackerman, J., Khafipour, E., & Cicek, N. (2018). Sustainable re-use of dairy cow manure as bedding and compost: Nutrients and self-heating potential. *Canadian Biosyst. Eng., 60*(1), 6.1-6.7. https://doi.org/10.7451/CBE.2018.60.6.1

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/

Ahn, H. K., Mulbry, W., White, J. W., & Kondrad, S. L. (2011). Pile mixing increases greenhouse gas emissions during composting of dairy manure. *Bioresour. Tech., 102*(3), 2904-2909. https://doi.org/10.1016/j.biortech.2010.10.142

Amon, B., Amon, T., Boxberger, J., & Alt, C. (2001). Emissions of NH_3, N_2O, and CH_4 from dairy cows housed in a farmyard manure tying stall (housing, manure storage, manure spreading). *Nutr. Cycl. Agroecosys., 60*(1), 103-113. https://doi.org/10.1023/a:1012649028772

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 (MAR2005): Manure production and characteristics. St. Joseph, MI: ASABE.

Bittman, S., & Mikkelsen, R. (2009). Ammonia emissions from agricultural operations: Livestock. *Better Crops, 93*(1), 28-31.

Brito, L. M., Coutinho, J., & Smith, S. R. (2008). Methods to improve the composting process of the solid fraction of dairy cattle slurry. *Bioresour. Tech., 99*(18), 8955-8960. http://dx.doi.org/10.1016/j.biortech.2008.05.005

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/

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

ferme&s3=db-el

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

Chantigny, M. H., Rochette, P., Angers, D. A., Bittman, S., Buckley, K., Massa, D., ... Gasser, M.-O. (2010). Soil nitrous oxide emissions following band-incorporation of fertilizer nitrogen and swine manure. *J. Environ. Qual., 39*(5), 1545-1553. https://doi.org/10.2134/jeq2009.0482

Clemens, J., Trimborn, M., Weiland, P., & Amon, B. (2006). Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. *Agric. Ecosys. Environ., 112*(2), 171-177. https://doi.org/10.1016/j.agee.2005.08.016

CRAAQ. (2015a). AGDEX 824/825a Loyer annuel - Fonds de terre, bâtiments, machinerie et équipements. Québec City, QC, Canada: Centre de référence en agriculture et agroalimentaire du Québec (CRAAQ).

CRAAQ. (2015b). AGDEX 740/825a Machinerie - Coûts d'utilisation et taux à forfait suggeres avec système d'autoguidage. Québec City, QC, Canada: Centre de références en agriculture et agroalimentaire du Québec (CRAAQ).

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'attenuation des gaz à effet de serre en élevage bovin lait et viande. *Innov. Agronomiques, 55*, 301-315.

English, S., & Fleming, R. (2006). Liquid manure storage covers. Guelph, ON, Canada: University of Guelph. Retrieved from https://www.ridgetownc.com/research/documents/fleming_liquid_manure_storage_covers.pdf

Flysjö, A., Henriksson, M., Cederberg, C., Ledgard, S., & Englund, J.-E. (2011). The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden. *Agric. Syst., 104*(6), 459-469. https://doi.org/10.1016/j.agsy.2011.03.003

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

Fournel, S., Godbout, S., Ruel, P., Fortin, A., Duquette-Lozeau, K., Létourneau, V., ... Pellerin, D. (2019b). Production of recycled manure solids for bedding in Canadian dairy farms: II. Composting methods. *J. Dairy Sci., 102*(2), 1847-1865. https://doi.org/10.3168/jds.2018-14967

Fournel, S., Godbout, S., Ruel, P., Fortin, A., Généreux, M., Côté, C., ... Pellerin, D. (2019c). Production of recycled manure solids for bedding in Canadian dairy farms: I. Solid-liquid separation. *J. Dairy Sci., 102*(2), 1832-1846. https://doi.org/10.3168/jds.2018-14966

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

FPPQ. (2007). Les couvertures sur les fosses à lisier. Longueuil, QC, Canada: Federation des producteurs de porcs du Québec (FPPQ). Retrieved from http://www.accesporcqc.ca/nsphp/portail/publications/pub_dl.php?dir=476&download=lescouverturessurlesfossesalisierjuin2007.pdf

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.

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

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

IDF. (2015). A common carbon footprint approach for the dairy sector: The IDF guide to standard life cycle assessment methodology. *Bull. Intl. Dairy Fed.*(479), 60.

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., Ranga Niroshan Appuhamy, J. A., 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

Kristensen, T., Mogensen, L., Knudsen, M. T., & Hermansen, J. E. (2011). Effect of production system and farming strategy on greenhouse gas emissions from commercial dairy farms in a life cycle approach. *Livestock Sci., 140*(1), 136-148. https://doi.org/10.1016/j.livsci.2011.03.002

Leach, K. A., Archer, S. C., Breen, J. E., Green, M. J., Ohnstad, I. C., Tuer, S., & Bradley, A. J. (2015). Recycling manure as cow bedding: Potential benefits and risks for U.K. dairy farms. *Vet. J., 206*(2), 123-130. http://dx.doi.org/10.1016/j.tvjl.2015.08.013

Leclerc, A., & Groleau, H. (2014). Traitement des biogaz provenant d'ouvrages de stockage de lisier de porc par biofiltration: Rapport final. Retrieved from https://www.mapaq.gouv.qc.ca/SiteCollectionDocuments/Agroenvironnement/1458_Rapport.pdf

MAPAQ. (2016). Production agricole. Québec City, QC, Canada: Ministere de l'Agriculture, des Pêcheries et de l'Alimentation du Québec. Retrieved from http://www.mapaq.gouv.qc.ca/fr/md/statistiques/Pages/production.aspx

Mason, A. J. (2011). OpenSolver: An open-source add-in to solve linear and integer progammes in Excel. In K. Diethard, H.-J. Lüthi, & K. Schmedders (Eds.), *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

MELCC. (2016). Inventaire québécois des émissions de gaz à effet de serre en 2016 et leur évolution depuis 1990. Québec City, QC, Canada: Ministère de l'environnement et de la lutte contre les changements climatiques (MELCC). Retrieved from http://www.mddelcc.gouv.qc.ca/changements/ges/2014/Inventaire1990-2014.pdf

Misselbrook, T. H., & Powell, J. M. (2005). Influence of bedding material on ammonia emissions from cattle excreta. *J. Dairy Sci., 88*(12), 4304-4312. https://doi.org/10.3168/jds.S0022-0302(05)73116-7

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

Moreno Prado, J. M. (2015). Impact potentiel des changements climatiques sur la durabilité technico-économique et agroenvironnementale des fermes laitières du Québec. MS thesis. Québec City, QC, Canada: Universite Laval.

Mulbry, W., & Ahn, H. (2014). Greenhouse gas emissions during composting of dairy manure: Influence of the timing of pile mixing on total emissions. *Biosyst. Eng., 126*, 117-122. https://doi.org/10.1016/j.biosystemseng.2014.08.003

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*, 3721-3733. https://doi.org/10.3168/jds.S0022-0302(05)73058-7

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. *Glob. 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 resultof 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

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., Jokela, W. E., & Misselbrook, T. H. (2011). Dairy slurry application method impacts ammonia emission and nitrate leaching in no-till corn silage. *J. Environ. Qual., 40*(2), 383-392. https://doi.org/10.2134/jeq2010.0082

Quantis; AGÉCO; CIRAIG. (2012). Environmental and socioeconomic life cycle assessment of Canadian milk. Ottawa, ON, Canada: 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. *Agr. Ecosys. Environ., 199*(supp. C), 358-368. https://doi.org/10.1016/j.agee.2014.10.004

Rojas-Downing, M. M., Nejadhashemi, A. P., Harrigan, T. M., & Woznicki, S. A. (2017). Climate change and livestock: Impacts, adaptation, and mitigation. *Clim. Risk Mgmt., 16*, 145-163. https://doi.org/10.1016/j.crm.2017.02.001

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., 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

Stevens, C. J., & Quinton, J. N. (2009). Policy implications of pollution swapping. *Physics Chem. Earth A/B/C, 34*(8-9), 589-594. https://doi.org/10.1016/j.pce.2008.01.001

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

VanderZaag, A. C., Gordon, R. J., Jamieson, R. C., Burton, D. L., & Stratton, G. W. (2009). Gas emissions from straw-covered liquid dairy manure during summer storage and autumn agitation. *Trans. ASABE, 52*(2), 599-608. https://doi.org/10.13031/2013.26832

VanderZaag, A. C., Gordon, R. J., Jamieson, R. C., Burton, D. L., & Stratton, G. W. (2010). Permeable synthetic covers for controlling emissions from liquid dairy manure. *Appl. Eng. Agric., 26*(2), 287-297. https://doi.org/10.13031/2013.29544

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