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Determining Environmental Benefits and Economic Costs of Different Manure Handling Strategies in Quebec's Dairy Production using Farm Simulation

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ABSTRACT. *The recent consolidation of Quebec's dairy farms is such that the industry expects an increase in free-stall dairies under liquid manure management at the expense of tie-stall dairies under solid manure management. This transition could however have implications on greenhouse gases (GHG), so that dairy producers must consider strategies such as enclosed storage and manure incorporation for limiting their emissions to help control global warming. To assess the overall cost-effectiveness of different combinations of housing, manure management, and mitigation measures for a representative dairy farm in two regions with contrasted climate (Southwestern and Eastern Quebec), a farm-scale, optimization model (N-CyCLES) was used. Housing and manure management types did not significantly affect the farm net income (FNI) in both regions. Nevertheless, free-stall barns and solid manure management systems needed more N imports since they were respectively associated with greater N volatilization and slower release of elements into the soil. For these reasons, tie-stall barns and liquid manure systems generally had lower N balance and GHG production. A covered manure storage lessened manure volume and volatilization, which reduced fertilizer and manure spreading costs, increased crop sales and FNI, and enhanced N and GHG balances. Manure incorporation increased soil management costs, but reduced N and GHG footprints by decreasing use of N-based fertilizers and N_2O emissions caused by manure application. Consequently, the transition towards free-stall dairies with liquid systems seems advantageous from the economic and environmental point of views, and using covered manure storage would be economically viable to further reduce GHG emissions.*

Keywords. *Climate change, dairy cow, enclosed manure storage, farm-scale model, greenhouse gas emission, incorporation, manure management, mitigation, net income, nitrogen balance.*

Introduction

Dairy production in the province of Quebec, Canada, 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 Quebec 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 induce a shift towards free-stall housing with liquid manure systems in the near future by dairy stakeholders (Valacta, 2015). For practical and economic reasons, larger herds are generally associated with manure handling as slurry and free-stall barn systems (Jayasundara et al., 2014; Sheppard et al., 2011).

The projected transition may involve changes in greenhouse gas (GHG) emissions from Quebec dairy farms since 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 province's total GHG emissions (FPLQ, 2012; MDDELCC, 2016; Quantis et al., 2012), the upcoming conversion might affect the objective of Quebec's government to reduce provincial GHG emissions by 20%, in relation to 1990, for 2020 (MDDELCC, 2018). Global warming has become an important concern as we are experiencing generally warmer and more variable weather (Ouranos, 2015).

Consequently, dairy producers must implement strategies for limiting GHG emissions to help control global warming. Promising alternatives to reduce GHG emissions from animals and manure, and to reduce environmental footprint of dairy farms, have been targeted (Hristov et al., 2013; Jayasundara et al., 2016; Montes et al., 2013). However, the reported technologies and practices 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 reducing fertilizer purchases could represent net monetary gains (Misselbrook et al., 2005; Petersen et al., 2007).

To assess the overall cost-effectiveness of barn configurations and mitigation strategies, farm-scale modeling can be a useful tool (Rotz et al., 2016). The model N-CyCLES (nutrient cycling: crops, livestock, environment and soils), an Excel-based linear program, is one of the available tools providing estimates of farm net income (FNI) and GHG when resources are allocated to reduce nitrogen (N) and phosphorus (P) balances, and feeding, cropping, fertilizer use, and manure allocation are optimized under Quebec's conditions (Pellerin et al., 2017). The objectives of the present study was to evaluate FNI and N, P, and GHG balances for a representative dairy farm in two regions with contrasted climate (Southwestern and Eastern Quebec) according to different combinations of housing (tie- or free-stall), manure management (solid or liquid), and GHG mitigation measures (enclosed storage and manure incorporation).

Materials and Methods

Model Description

N-CyCLES (Figure 1) is a Microsoft Excel (Microsoft Corp., Redmond, WA, USA) based linear optimisation model, running with an open source add-in (Mason, 2011). It may be set to maximize FNI or to minimize N or P balances. Farm net income is calculated as the difference between incomes and expenses. Whole-farm N and P balances are calculated by 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 evaluates 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 literature, emission factors for specific housing categories, manure systems, 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.

To meet a specific goal, the optimization algorithm in the model takes 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 crop N and P recommendations. The model was parameterized with National Research Council (NRC, 2001) for the nutritional requirements of each feeding group (early and mid-late lactation, dry cows, heifers <1 yr old, and heifers ≥1 yr old) and local nutrient management planning rules for nutrients' application in the fields. Available feeds include nine crop-derived homegrown feeds and seventeen purchased feeds. Sources of crop nutrients included five commercial fertilizers and two on-farm manure types (solid and liquid). Cropland is sub-divided in two land units with different nutrient availability. Up to five crop rotations can be allocated to each land unit.

More details on economic inputs, optimized variables, feeds and diets, manure and fertilizer, crops and rotations, model outcomes can be found in Pellerin et al. (2017). The model uses the year as unit of time and assumes that the production system is essentially at a steady state. Model outcomes are assessed on a per kilogram of fat- and protein-corrected milk (FPCM; IDF, 2015). Monetary unit is in Canadian dollars (CAD).

Representative Farms

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

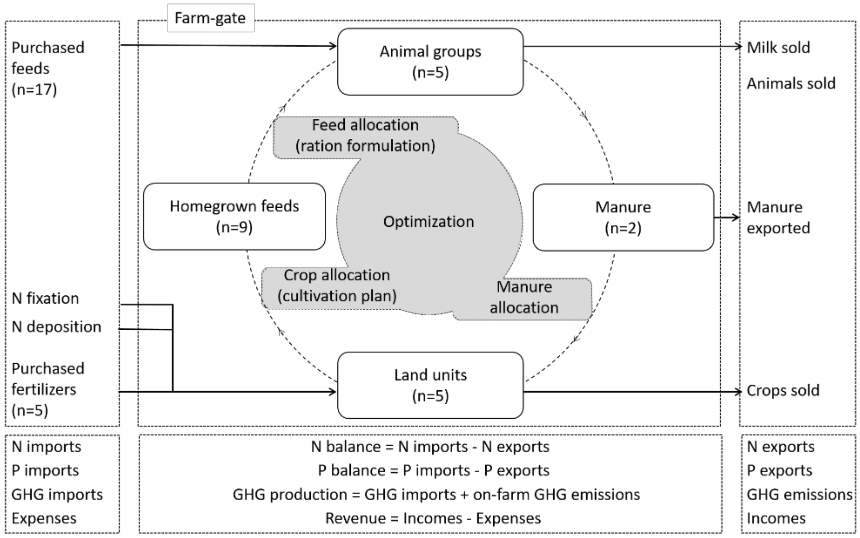

Figure 1. Overview of N-CyCLES (nutrient cycling: crops, livestock, environment, and soils) describing the N, P, and GHG imports and exports (solid lines) to establish balance across the boundary of the livestock-crop component of a farm (dotted line), the resources whose allocations are subject to simultaneous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

Both barns contain 95 mature Holstein cows, weighing approximately 670 kg. Calving interval and age at first calving average 14 and 25 months, respectively. Cow culling rate for SWQ and EQ farms is 31.2% and 34.0%, respectively. Milk production in SWQ and EQ is 10,107 and 9,756 kg cow^{-1} yr^{-1}, respectively. Milk fat, crude protein, and other solids contents are similar between regions at around 4.09%, 3.39%, and 5.72%, respectively. Average FPCM sold per farm, assuming 5% milk waste, is 926,914 and 896,233 kg yr^{-1} for SWQ and EQ, respectively. Milk price, which has been stable in Quebec because of the quota system, is representative of the 2010–2014 period and set at 0.74 \$ kg^{-1} of FPCM. Other incomes including mainly livestock sales represent 0.13 and 0.10 \$ kg^{-1} of FPCM for SWQ and EQ farms, respectively. Variables (breeding, health, supplies, etc.) and fixed (labor, taxes, insurances, depreciation, interest, etc.) costs account for 0.06 and 0.07 \$ kg^{-1} of FPCM, and 243,925 and 278,282 \$ yr^{-1} in SWQ and EQ, respectively. Dry matter (DM) intake for cows in early lactation group and in mid-late lactation group is 25.0 and 23.1 kg d^{-1} in SWQ, and 24.5 and 22.6 kg d^{-1} in EQ. The land base is 127 and 178 ha of cropland subdivided in two land units of equal size for SWQ and EQ, respectively. Because of reported associative patterns between soil P test and distance from manure storage, the two land units (MH-08 and LM-32) were set at medium-high and low-medium soil P concentrations with hauling distances of 0.8 and 3.2 km, respectively, in both regions. Soil type is clay and loam in SWQ and EQ, respectively.

Manure Management Systems and Mitigation Methods

In the model, manure management can be accomplished using solid or liquid systems. Solid manure management involves that manure is stored in an appropriate storage unit as a stack without a liquid part before being applied in the field with a traditional box spreader. Liquid manure management system involves that manure is stored in an appropriate, bottom-loaded storage unit before being applied in the field with a liquid tank with spray bar misting. Both methods use cereal straw as bedding.

Basically, N-CyCLES considers that manure storage is uncovered and manure is not incorporated into soil. However, enclosed storage and manure incorporation are GHG mitigation options that are available as model features. When these strategies are selected, additional costs for equipment and operation are applied. They correspond to the annual expenses of each new component according to its economic life (CRAAQ, 2015).

The enclosed storage case comprises the installation of a rigid cover (e.g., wood or steel lids) on the solid or liquid manure storage unit at an approximate cost of $50,000 (English et al., 2006; FPPQ, 2007). The manure incorporation case involves that solid or liquid manure is incorporated into the soil by tillage within 24 h of application. Since the practice and equipment are common on Quebec farms, no supplemental machinery cost is assumed. Only an overcharge cost of $1.87 per ton of incorporated manure is added to the standard $2.35 per ton of manure spread (Brown, 2011).

Simulations

Four simulation scenarios were considered for each regional case: (1) tie-stall housing with solid manure management systems; (2) tie-stall housing with liquid manure management systems; (3) free-stall housing with solid manure management systems; and (4) free-stall housing with liquid manure management systems. They were performed according to a specific case of mitigation measures: (A) uncovered manure storage and no manure incorporation; (B) covered manure storage and no manure incorporation; (C) uncovered manure storage and manure incorporation; and (D) covered manure storage and manure incorporation.

Simulation scenarios involved only changes in housing and manure management types for lactating and dry cows. Housing and manure management for both groups of heifers (pens with sufficient bedding) were set *a priori* and never modified during simulations. For each simulation, the model was solved to maximize FNI and determine whole-farm balances in N, P, and GHG.

Results and Discussion

Case A

Table 1 presents the output summary from N-CyCLES simulations for each representative farm using either tie- or free-stall housing under either solid or liquid manure management with uncovered manure storage and no manure incorporation. Incomes represented 0.95 and 0.86 $ kg^{-1} of FPCM in SWQ and EQ, respectively. Since gains from milk sold were equivalent for both regions (0.74 $ kg^{-1} of FPCM), the difference in incomes 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). By contrast, the EQ farm only sell its production of canola representing approximately 36 g kg^{-1} of FPCM. Expenses were slightly 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 depending on simulation scenarios. In comparison with liquid systems (7225 g kg^{-1} of FPCM on average), solid systems handled a lower quantity of manure (5714 g kg^{-1} of FPCM on average), reducing transportation costs by 0.01 $ kg^{-1} of FPCM. This advantage was alleviated (approximately 0.01 $ kg^{-1} of FPCM) by the property of solid manure to release elements into the soil more slowly than liquid manure (CRAAQ, 2010), requiring more applications of urea ammonium nitrate and diammonium phosphate. Overall, manure management, as well as housing, did not influence FNI. Only the region had an impact on farm profit, whereas the SWQ farm, due to greater incomes and lower expenses, had a greater FNI (0.33 $ kg^{-1} of FPCM) than the EQ farm (0.19 $ kg^{-1} of FPCM).

Total N imports by the SWQ dairy (24.0–28.7 g kg^{-1} of FPCM) exceeded those of the EQ dairy (19.9–23.4 g kg^{-1} of FPCM). For each barn configuration, the difference was primarily attributed to the greater amount of purchased feeds (corn, soybean, and canola meals) and urea by the SWQ farm. Actually, in SWQ, the dairy bought huge quantities of sub-products because land was largely used to grow (and sell) valuable, but N-demanding crops. Nevertheless, compared to SWQ dairy, more N was added to soil through legume fixation (+1.40 g kg^{-1} of FPCM on average) and atmospheric deposition (+0.37 g kg^{-1} of FPCM on average) in EQ dairy since this farm produced silage-based rotations on a greater proportion of its land base. The important sales of corn grain and soybean by the SWQ farm also led to higher N exports (+3.60 g kg^{-1} of FPCM on average) than in the EQ farm. Nitrogen left both farms through sold milk and animals sales in similar proportions. The N balance in EQ was 6% to 10% lower than that of SWQ depending on housing type and manure management. Globally, free-stall housing increased net N footprint by approximately 0.33 g kg^{-1} of FPCM, in comparison with tie-stall housing, because greater soiled surfaces in free-stall barn increase N loss through volatilization of ammonia. Farms using free-stall housing thus need to purchase more urea ammonium nitrate and/or to grow more legume crops to compensate for these N losses. In regard to manure management, liquid systems reduced N balance 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. As described before, nutrients in solid manure are released more slowly into the soil and are thus less available to crops than in liquid manure.

Total P imports were higher in EQ (2.72–3.16 g kg^{-1} of FPCM) than in SWQ (2.45–2.71 g kg^{-1} of FPCM). While P imports in SWQ dairy were almost exclusively attributed to purchased feeds, because fertilizer contribution was negligible (P-rich soil), purchased feeds and fertilizers contributed almost equally to P imports on EQ dairy. The important utilization of phosphates in EQ can be explained by the use of a 5-yr barley-canola-alfalfa rotation, which is P-demanding, on 100% of 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 the SWQ dairy. Therefore, the SWQ farm had a more environment-friendly balance regarding P, with levels 2.5-fold lower than those expected in EQ. Housing type did not influence P footprint. However, as was found with N, imports of fertilizer-derived P were 0.27–0.47 g kg^{-1} of FPCM greater with solid than liquid manure management, resulting in similar balance differences.

Table 1. Output summary of farm simulations by region, housing type, and manure management considering uncovered manure storage and no manure incorporation.

	Southwestern Quebec				Eastern Quebec			
	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} of FPCM[a])								
Incomes	0.95	0.95	0.95	0.95	0.86	0.86	0.86	0.86
Expenses	0.62	0.62	0.62	0.62	0.67	0.67	0.66	0.67
Net income	0.33	0.33	0.33	0.33	0.19	0.19	0.19	0.19
N[b] footprint (g kg^{-1} of FPCM[a])								
Imports	28.38	24.04	28.73	24.31	23.00	19.91	23.38	20.06
Exports	11.75	11.82	11.75	11.78	7.99	8.43	7.99	8.29
Balance	16.63	12.22	16.99	12.53	15.00	11.48	15.39	11.77
P[b] footprint (g kg^{-1} of FPCM[a])								
Imports	2.71	2.50	2.71	2.45	3.16	2.74	3.16	2.72
Exports	1.92	1.95	1.92	1.93	1.28	1.32	1.28	1.31
Balance	0.79	0.55	0.79	0.52	1.88	1.42	1.88	1.41
GHG[c] production (kg CO_2e[d] kg^{-1} of FPCM[a])								
CO_2	0.42	0.30	0.43	0.30	0.31	0.25	0.32	0.25
CH_4	0.92	1.19	0.91	1.16	0.94	1.22	0.93	1.20
N_2O	0.53	0.32	0.52	0.31	0.45	0.22	0.45	0.22
Total	1.87	1.80	1.86	1.78	1.71	1.69	1.70	1.67
Allocation (kg CO_2e[d] kg^{-1} of FPCM[a])								
Milk	1.48	1.43	1.48	1.41	1.41	1.40	1.41	1.38
Animal	0.24	0.23	0.24	0.23	0.26	0.25	0.26	0.25
Crops	0.15	0.14	0.14	0.14	0.04	0.04	0.04	0.04

[a] FPCM = fat- and protein-corrected milk.
[b] Nutrients: N = nitrogen; P = phosphorus.
[c] Greenhouse gases (GHG): CO_2 = carbon dioxide; CH_4 = methane; N_2O = nitrous oxide.
[d] CO_2e = CO_2 equivalent units (a unit of CH_4 and N_2O are equivalent to 25 and 298 CO_2e units in global warming potential, respectively).

The production of CO_2 in SWQ (0.30–0.43 kg CO_2e kg^{-1} of FPCM) was generally greater than in EQ (0.25–0.32 kg CO_2e kg^{-1} of FPCM) because the greater fuel consumption by EQ farm, due to a larger land base, had much smaller impact on GHG emissions than the greater amounts of feeds and fertilizers imported by SWQ farm. Emission of CH_4 was very comparable between farms (approximately 1.06 kg CO_2e kg^{-1} of FPCM) since both dairies had a similar number of cows and produced a similar quantity of manure. Results for N_2O generation varied according to soil type in each region, which influenced plant N uptake. Consequently, N_2O levels from amendment application and crop residue decomposition in SWQ characterized by clayey soils (approximately 0.12 kg CO_2e kg^{-1} of FPCM) were slightly higher than in EQ characterized by loamy soils (approximately 0.05 CO_2e kg^{-1} of FPCM). Overall, GHG emissions from the SWQ farm was greater (1.78–1.87 kg CO_2e kg^{-1} of FPCM) than from the EQ farm (1.67–1.71 kg CO_2e kg^{-1} of FPCM), mainly because of intensive production of cash crops on soils favorable to N_2O emission. The lower and upper limits of GHG ranges correspond to levels obtained when farm utilized liquid and solid systems, respectively. Since 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 importation and application of fertilizers (–0.13 kg CO_2e kg^{-1} of FPCM on average). Housing system slightly affected GHG emissions. Methane 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. The calculation of each co-product contribution to GHGs revealed that milk alone accounted for 79% to 83% of dairies carbon footprint. GHGs 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.

Case B

Table 2 shows the output summary from N-CyCLES simulations for each dairy farm using either tie- or free-stall housing under either solid or liquid manure management with covered manure storage and no manure incorporation. Numbers in parentheses in this table indicate the difference in percentage with the reference case A (Table 1).

The installation of a rigid cover on the manure storage 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%, respectively, in farms managing manure with solid systems, and by 4% and 15% in farms managing manure with liquid systems. In addition, better preservation of manure N generally allowed farms under 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 result, covering the manure storage system enhanced FNI by 1% to 4%.

Table 2. Output summary[a] of farm simulations by region, housing type, and manure management considering covered manure storage and no manure incorporation.

	Southwestern Quebec				Eastern Quebec			
	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} of FPCM[b])								
Incomes	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[c] footprint (g kg^{-1} of FPCM[b])								
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)
P[c] footprint (g kg^{-1} of FPCM[b])								
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)
GHG[d] production (kg CO_2e[e] kg^{-1} of FPCM[b])								
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[e] kg^{-1} of FPCM[b])								
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 (%) with the base case.
[b] FPCM = fat- and protein-corrected milk.
[c] Nutrients: N = nitrogen; P = phosphorus.
[d] Greenhouse gases (GHG): CO_2 = carbon dioxide; CH_4 = methane; N_2O = nitrous oxide.
[e] CO_2e = CO_2 equivalent units (a unit of CH_4 and N_2O are equivalent to 25 and 298 CO_2e units in global warming potential, respectively).

Covering manure storage also improved N use efficiency. In scenarios where N imports were reduced in comparison with the reference case A, purchases of urea ammonium nitrate were decreased by 25% to 94%. In the other two scenarios, higher canola sales involved a 2% increase in N exports. Consequently, N balance for each scenario was reduced by 0.22 to 1.95 g kg^{-1} of FPCM. Changes in P footprint were more important for the SWQ farm using a free-stall barn under 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 P footprint.

Covering manure storage reduced GHG emissions mainly because it reduced the amount of precipitation entering the storage unit. This decreased N_2O emissions from the nitrification-denitrification process occurring within solid manure heap, and CH_4 emissions from liquid manure. Thus, covering manure decreased manure-associated emissions of N_2O in solid systems and 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 (0–82%). Globally, covering manure storage reduced GHG emissions by 0.34 and 0.18 kg CO_2e kg^{-1} of FPCM under solid and liquid manure management, respectively. This decrease had repercussions on milk, animal, and crops allocations, which were also reduced by up to 21%.

Case C

Table 3 lists the output summary from N-CyCLES simulations for each representative farm using either tie- or free-stall housing under either solid or liquid manure management with an uncovered manure storage and manure incorporation. Numbers in parentheses in this table indicate the difference in percentage with the reference case A (Table 1).

Manure incorporation to soil did not significantly influence total incomes when compared to reference case A (0.95 and 0.86 $ kg^{-1} of FPCM in 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%. This reduction was however 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, simulated FNI dropped to 0.32 and 0.18 $ kg^{-1} of FPCM in SWQ and EQ, respectively.

Table 3. Output summary[a] of farm simulations by region, housing type, and manure management considering uncovered manure storage and manure incorporation.

	Southwestern Quebec				Eastern Quebec			
	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} of FPCM[b])								
Incomes	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[c] footprint (g kg^{-1} of FPCM[b])								
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)
P[c] footprint (g kg^{-1} of FPCM[b])								
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)
GHG[d] production (kg CO_2e[e] kg^{-1} of FPCM[b])								
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[e] kg^{-1} of FPCM[b])								
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 (%) with the base case.
[b] FPCM = fat- and protein-corrected milk.
[c] Nutrients: N = nitrogen; P = phosphorus.
[d] Greenhouse gases (GHG): CO_2 = carbon dioxide; CH_4 = methane; N_2O = nitrous oxide.
[e] CO_2e = CO_2 equivalent units (a unit of CH_4 and N_2O are equivalent to 25 and 298 CO_2e units in global warming potential, respectively).

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

In solid manure systems, incorporation of manure to soil did not influence 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 balance. On the contrary, the other three scenarios under liquid manure management imported more feeds, resulting in a global 1–4% increase in P balance. The worst scenario (SWQ free-stall farm) was characterized by a supplemental purchase of dried corn distillers grain (+6.62 g kg^{-1} of FPCM).

While CH_4 emissions remained unchanged, 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 (0–68%) and direct (0–68%) and indirect (volatilization; 2–17%) N_2O emissions caused by fertilizer application. Increases in GHG levels up to 83% were also noted due to manure handling. Globally, 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 yr^{-1}), representing reduction of 1% to 3% as compared to reference case A. The GHG allocated to milk and animal were decreased in the same proportions.

Case D

Table 4 exposes the output summary from N-CyCLES simulations for each farm type using either tie- or free-stall housing under either solid or liquid manure management with a covered manure storage and manure incorporation. Numbers in parentheses in this table indicate the difference in percentage with the reference case A (Table 1).

Implementation of both GHG mitigation strategies influenced FNI in two different ways depending on manure management. In solid systems, FNI was increased in comparison with results from the reference case A because of the positive impact of the cover, as in case B. However, the inclusion of manure incorporation practice lessened FNI. In liquid systems, the expenses associated with both alleviation practices decreased FNI by 2–5% as compared to reference case A.

The combination of manure cover and incorporation generally induced higher reductions in N and GHG footprints than each practice taken alone. In most scenarios, individual results can be summed so that decreases in footprints reached 2–13% for N and 9–21% for GHG. Milk allocation hence dropped to 1.12–1.26 kg CO_2e kg^{-1} of FPCM. For P balance, cases B to D were similar.

Conclusion

The location of the SWQ farm provided a financial advantage (e.g., warmer climate) over the EQ farm because thermal corn units were sufficient to grow grain corn, soybean, and wheat, allowing supplementary incomes from sales. However, greater production of cash crops on the SWQ dairy implied: (i) greater imports of N-based fertilizers to meet recommended applications rates for optimal plant growth; and (ii) greater amounts of purchased feeds, thereby increasing CO_2 emissions associated with their transport. The SWQ farm, which is characterized by clayey, P-rich soils, produced more N_2O than EQ farm following application of N-based fertilizers and manure, but had a better P balance due to restricted use of P-based fertilizers in SWQ.

Housing type and manure management did not significantly influence FNI. However, free-stall barns and solid manure systems needed more N inputs from fertilizers or legume fixation since they were respectively associated with greater N volatilization and lower availability of nutrients to crops. For these reasons, tie-stall barns and liquid manure systems had lower N balance. Liquid systems also decreased net GHG production on the farm.

Covering manure storage lessened manure volume and N volatilization, thereby reducing fertilizer and manure spreading costs, increasing crop sales and FNI, and enhancing N and GHG balances. Manure incorporation increased soil management costs, but reduced N and GHG footprints by decreasing use of N-based fertilizers and indirect N_2O emissions following manure application. The implementation of both mitigation methods summed their advantages.

Consequently, the current transition towards free-stall barns and liquid manure management in the province of Québec seems advantageous from the economic and environmental standpoints. To further reduce GHG emissions, covering manure storage appears as an economically viable practice. Manure incorporation would also allow GHG mitigation, but at a certain cost.

Table 4. Output summary[a] of farm simulations by region, housing type, and manure management considering covered manure storage and manure incorporation.

	Southwestern Quebec				Eastern Quebec			
	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} of FPCM[b])								
Incomes	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	0.62 (0)	0.62 (+1)	0.62 (0)	0.62 (+1)	0.66 (0)	0.68 (+2)	0.66 (0)	0.68 (+2)
Net income	0.33 (+1)	0.32 (–2)	0.33 (+1)	0.33 (–2)	0.19 (+1)	0.18 (–5)	0.19 (+1)	0.18 (–5)
N[c] footprint (g kg^{-1} of FPCM[b])								
Imports	26.77 (–6)	22.66 (–6)	27.23 (–5)	23.21 (–5)	21.05 (–8)	19.82 (0)	21.57 (–8)	19.82 (–1)
Exports	11.75 (0)	11.78 (0)	11.75 (0)	11.82 (0)	7.99 (0)	8.56 (+1)	7.99 (0)	8.56 (+3)
Balance	15.02 (–10)	10.88 (–11)	15.48 (–9)	11.39 (–9)	13.05 (–13)	11.26 (–2)	13.58 (–12)	11.26 (–4)
P[c] footprint (g kg^{-1} of FPCM[b])								
Imports	2.71 (0)	2.48 (–1)	2.71 (0)	2.50 (+2)	3.16 (0)	2.76 (+1)	3.16 (0)	2.76 (+2)
Exports	1.92 (0)	1.93 (–1)	1.92 (0)	1.95 (+1)	1.28 (0)	1.33 (+1)	1.28 (0)	1.33 (+2)
Balance	0.79 (0)	0.55 (–1)	0.79 (0)	0.55 (+5)	1.88 (0)	1.43 (+1)	1.88 (0)	1.43 (+1)
GHG[d] production (kg CO_2e[e] kg^{-1} of FPCM[b])								
CO_2	0.37 (–12)	0.25 (–15)	0.38 (–11)	0.27 (–9)	0.26 (–18)	0.26 (+1)	0.27 (–17)	0.26 (+2)
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)	0.29 (–10)	0.31 (–40)	0.29 (–6)	0.22 (–51)	0.20 (–8)	0.23 (–50)	0.20 (–9)
Total	1.54 (–18)	1.58 (–12)	1.54 (–17)	1.59 (–10)	1.35 (–21)	1.53 (–10)	1.36 (–20)	1.51 (–9)
Allocation (kg CO_2e[e] kg^{-1} of FPCM[b])								
Milk	1.22 (–18)	1.25 (–12)	1.23 (–17)	1.26 (–11)	1.12 (–21)	1.26 (–10)	1.13 (–20)	1.25 (–10)
Animal	0.20 (–18)	0.20 (–12)	0.20 (–17)	0.20 (–11)	0.20 (–21)	0.23 (–10)	0.21 (–20)	0.23 (–10)
Crops	0.12 (–13)	0.13 (–13)	0.12 (–17)	0.13 (–8)	0.03 (–21)	0.04 (–5)	0.03 (–20)	0.04 (0)

[a] Numbers in parentheses indicate the difference (%) with the base case.
[b] FPCM = fat- and protein-corrected milk.
[c] Nutrients: N = nitrogen; P = phosphorus.
[d] Greenhouse gases (GHG): CO_2 = carbon dioxide; CH_4 = methane; N_2O = nitrous oxide.
[e] CO_2e = CO_2 equivalent units (a unit of CH_4 and N_2O are equivalent to 25 and 298 CO_2e units in global warming potential, respectively).

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