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Economic and environmental effects of revised metabolizable protein and amino acid recommendations on Canadian dairy farms

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ABSTRACT

The objective of this research was to evaluate the potential economic and environmental effects of the formulation model used to balance dairy rations for metabolizable protein (MP) or 3 essential AA (EAA: His, Lys, and Met) in 3 regions of Canada with different farming systems. The Maritimes, Central Canada, and the Prairies reference dairy farms averaged 63, 71, 144 mature cows per herd and 135, 95, 255 ha of land, respectively. Using N-CyCLES, a whole-farm linear program model, dairy rations were balanced for (1) MP, based on National Research Council (NRC) requirements (MP_2001); (2) MP plus Lys and Met, based on NRC (AA_2001); (3) MP (MP_Rev); or (4) for His, Lys, and Met (AA_Rev), both based on a revised factorial approach revisiting both supply and requirements of MP and EAA. Energy was balanced to meet requirements based on NRC (2001). Assuming the requirements were met within each approach, it was considered that milk yield and composition were not affected by the type of formulation. Given the assumptions of the study, when compared with MP_2001 formulation, balancing dairy rations using the AA_Rev approach reduced calculated farm N balance by 3.8%, on average from 12.71 to 12.24 g/kg of fat- and protein-corrected milk; it also enhanced farm net income by 4.5%, from 19.00 to 19.70 $CAN/100 kg of fat- and protein-corrected milk, by reducing inclusion of protein concentrate in dairy rations. Calculated animal N efficiency was on average 4.3% higher with AA_Rev than with MP_2001 for mid-lactation cows. This gain in N efficiency would result in a reduction in N_2O emission by manure, contributing to a partial decrease of total greenhouse gas emission by 1.7%, through a reduction of N excreted in manure. With the AA_2001 formulation, farm N balance was 1% higher than with MP_2001 formulation while reducing farm net income by 6.4%, due to the need to purchase rumen-protected AA, with no effect on total greenhouse gas emission. Both MP formulations lead to fairly similar outputs. The AA_Rev formulation also indicated that His might be a co-limiting AA with Met in dairy rations balanced with ingredients usually included in Canadian dairy rations. Given the assumptions of the study, balancing dairy rations for 3 EAA (His, Lys, and Met) rather than MP, has some potential positive effects on Canadian dairy farms by increasing net incomes through a reduction of crude protein supply, leading to a decreased environmental effect.

Key words: N balance, greenhouse gas, whole-farm model, linear programing

INTRODUCTION

Amino acid supply is crucial to support protein synthesis. However, any excess represents an unnecessary cost of dairy rations and, additionally, has negative effects on the environment, due to its associated N content. Indeed, manure N may be volatilized in ammonia causing smog and water acidification, in nitrous oxide a strong greenhouse gas (**GHG**), or may run off as nitrite or nitrate contributing to water pollution (NRC, 2003). Protein content, degradability, and digestibility have significant effects on N excretion, influencing types of excretion (i.e., fecal vs. urinary, and the quantity excreted; Castillo et al., 2001; Agle et al., 2010). Whole-farm N balance can be used as an indicator of on-farm N excess and nutrient efficiency: a high value indicates that N importations are higher than exportations plus N recycled within the farm, which can lead to increased volatilization losses and leaching (Cela et al., 2014; Pellerin et al., 2017a).

Improving precision feeding through a better match between supply and requirement of MP and AA may provide an opportunity to decrease farm N balance. Updates of predictions of protein and AA supplies have been recently proposed. First, the true net supply of MP and AA should be the sum of digested RUP and

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microbial protein (**MCP**) and should not include a contribution from duodenal endogenous CP flow (Lapierre et al., 2016). For MCP, White et al. (2016) proposed estimations of rumen outflow based on feed composition, whereas Sok et al. (2017) proposed an AA profile from a deep literature review. Correction factors to acknowledge for incomplete recovery of AA with 24-h protein hydrolysis have also been proposed (Lapierre et al., 2019). Second, on the requirement aspect, Lapierre et al. (2016) published a review on the main export proteins in dairy cows, their AA composition, and the efficiency of utilization of MP and EAA. They presented averaged combined efficiencies of utilization of MP and individual EAA that could be used as a basis for recommendations for milk protein yield, metabolic fecal protein, scurf and urinary endogenous losses. Pregnancy requirements and heifer growth requirements for MP have also been reviewed in Nutrient Requirements of Beef Cattle from National Academies of Sciences, Engineering and Medicine (NASEM, 2016). The accumulated knowledge on protein and AA metabolism and nutrition cited above, combined with a variable efficiency of utilization, should have progressed enough to use a factorial approach to determine EAA requirements rather than the proportional approach proposed by NRC (2001). Indeed, Fadul-Pacheco et al. (2017) showed that in commercial dairy farms, high N efficient herds had a negative calculated MP balance, but did not have lower milk production than herds with a lower efficiency and positive MP balance: this could indicate the limitations of a fixed efficiency of utilization of MP, currently used in most of the North American dairy ration formulations.

The application of the updated estimations of supply and requirement mentioned above may have significant effects on dairy farm economics and nutrient balances. Indeed, an AA factorial formulation for dairy rations with a variable efficiency of utilization could reduce the amount of CP fed to the cows but still meet EAA requirements. Consequently, this would reduce both feeding costs and N excretion, i.e., pollution on farm, while maintaining cows' performance. Although milk production in Canada is under supply management, and milk prices are relatively stable, feed costs and feed availability vary widely across regions. This is due to geographical status, including climate, soil structure, and fertility, as well as overall farm management. The global production context could alter the effects of the update of formulation models.

Therefore, the main objective of this research was to evaluate the potential economic and environmental effects of an update of MP and AA supply and recommendations on Canadian dairy farms using a modeling and simulation approach. We hypothesized that moving from balancing dairy rations for MP including or not a proportional recommendation for Lys and Met (NRC, 2001) to an updated factorial approach balancing for MP or His, Lys, and Met can improve the net income and reduce the environmental effects of dairy farms; the effects of this update, however, might differ depending on the reference farm situation.

MATERIALS AND METHODS

Simulation Model Used

Farm simulations were conducted using N-CyCLES (Nutrient cycling: crops, livestock, environment, and soil), as described by Pellerin et al. (2017a). The N-CyCLES model is a whole-dairy-farm linear program model based on National Research Council nutritional requirements (NRC, 2001; Pellerin et al., 2017b). It integrates TMR formulation for 5 groups, including 2 groups of lactating cows (early: ≤152 DIM, mid-late: >152 DIM), one group of dry cows, and 2 groups of growing heifers (0–11 mo, 12 mo to calving), as well as manure management, crop production, and fertilization. The optimization objective of this whole-farm model can be set either to maximize farm net income (**FNI**), or to minimize farm N or P balance. In the current study, FNI was maximized. The variables in the optimizer are feed ingredients of the TMR and rotations to produce crops. Simulations were done using Opensolver 2.7.1, because of its known stability and reliability during optimization (Mason, 2012). All monetary values are in Canadian dollars; the average exchange rate used was US$0.97 for 2010 to 2014 (Bank of Canada, 2017). For comparison purposes, most results are reported in relation to the production of fat- and protein-corrected milk (**FPCM**), according to International Dairy Federation (2015) calculations as described below:

$$FPCM = milk \times (0.1226 \times Fat + 0.0766 \times TP + 0.2534), \quad [1]$$

where $FPCM$ = fat- and protein-corrected milk, kg; $milk$ = milk production, kg; Fat = fat content of milk, %; and TP = true protein content of milk, %.

Updates for the Revised Recommendations

To begin, N-CyCLES was adapted to include a life cycle process to add the effect of GHG values from imported farm input (i.e., fertilizer, feedstuff, pesticide). Then, N-CyCLES was modified to include 4 protein or AA formulation approaches. To estimate the requirements, the first approach solely fulfilled the MP recommendations of the National Research Council (NRC, 2001; **MP_2001**). The second approach **(AA_2001)** added to MP_2001 a constraint to meet the Lys (6.95% of MP) and Met (2.38% of MP) recommendations from Whitehouse et al. (2010). For the third approach **(MP_Rev),** MP requirements covering milk, metabolic fecal protein, scurf, and endogenous urinary losses were estimated according to Lapierre et al. (2016), assuming an efficiency of 0.67 for the 3 former protein exportations, and an efficiency of 1 for endogenous urinary losses. For growth and gestation, requirements were those of NASEM (2016), Nutrient Requirements of Beef Cattle. For the fourth approach (**AA_Rev**), first, His, Lys, and Met exportation and accretion were calculated as the product of true protein exportation or accretion as in MP_Rev and the AA profile of each type of protein (Lapierre et al., 2016), which included a correction for incomplete recovery of AA from 24-h protein hydrolysis. Then, using the studies reported in Appendix Table A1, equations predicting efficiencies were developed based on the ratio of AA:energy supply, as suggested by Lapierre et al. (2020), except that NE_L was used instead of DE as the energy supply. These equations predicting efficiencies of utilization of His, Lys, and Met are reported in the Appendix. Then, for each exported EAA in each lactation group of each region, a recommended His, Lys, and Met supply was determined at the threshold supply where calculated efficiency (sum of EAA exported divided by EAA supply) was equal to the efficiency predicted by the equation. The energy supply meeting requirement (NRC, 2001) was used for the prediction of the efficiencies. This approach had to be used for AA_Rev due to limitations of linear programming and the nonlinearity of efficiency. The average optimal efficiencies of utilization of the EAA were 0.83 for His, 0.73 for Lys, and 0.77 for Met.

To estimate supplies for MP_2001 and AA_2001, predicted MP supply and EAA digestible flows from NRC (2001) were used. For the MP_Rev and AA_Rev, estimations of MCP duodenal flow for cows was adapted from Roman-Garcia et al. (2016) equation estimating MCP from DMI and starch intake (Equation 2).

$$MCP = (-18.3 + 10.8 \times DMI + 5.31 \times starch - 0.0839 \times starch^2) \times 6.25. \quad [2]$$

This equation needed to be linearized due to optimization restriction of linear programming; however, due to the difference in the type of rations fed to lactating versus dry cows, 2 equations were required to reach linearization¸ one for lactating (Equation 3) and one for dry cow (Equation 4), these 2 categories of cows being in different segments of the relationship.

$$MCP_{lactating} = 0.05152 \times DMI + 0.01077 \times starch \quad [3]$$

$$MCP_{dry} = 0.0375 \times DMI + 0.1547 \times starch \quad [4]$$

These equations were developed using inputs and outputs of Equation 2 and deriving a first-degree multivariate regression to these data with DMI and starch content as independent variables, using a lm function from stat package in R version 3.4.0 (https://cloud.r-project.org/). The DMI and starch values used to develop the linear equations and verify their accuracy were a sequence of DMI within the minimal and maximal values from our database for DMI (between 19.5 and 25.5 kg/d and 11.7 and 14.3 kg/d for lactating and dry cows, respectively), with different starch concentrations (between 20 and 32% of DM and 15 and 22% of DM, for lactating and dry cows, respectively). Within these values, the estimates obtained with the linear equations had R^2 of 0.988 (SE = 0.0009) and 0.991 (SE = 0.0017), with the original estimations from Equation 2, for the lactating and dry cows, respectively. The transfer of MCP duodenal flow to MP supply assumed 80% of true protein in MCP and 80% intestinal digestibility (NRC, 2001). For growing dairy heifers, MCP duodenal flow was estimated from NASEM (2016), due to uncertainty of the application of Roman-Garcia et al. (2016) equations at this physiological stage. The MCP AA profile used was as proposed by Sok et al. (2017), which includes protozoa and bacteria contribution. To be on the same basis as AA requirements, feed ingredient AA composition from Table 15 in NRC (2001) was also corrected to acknowledge for incomplete recovery of AA with 24-h hydrolysis of proteins (Lapierre et al., 2019). The MP_Rev supply summed the revised MCP supply and RUP estimated from NRC (2001) and did not include the MP supply from endogenous duodenal flow, as suggested by Lapierre et al. (2016).

Selection of the Three Canadian Regions

Three regions representing different Canadian agricultural systems were selected to compare the effect of the proposed recommendations. Those 3 regions correspond to the Maritimes (latitude 48°N; longitude 68°W), Central Canada (latitude 45°N; longitude 73°W), and the Prairies (latitude 52°N; longitude 113°W; International Civil Aviation Agency, 2002). For the current simulations, 2 types of soil, referred to as land units,

Table 1. Productivity and economic inputs for the reference farm of each region

Variable	The Maritimes	Central Canada	The Prairies
Farm productivity			
Breed	Holstein	Holstein	Holstein
Mature cows, heads	63	71	144
Mature BW, kg	656	656	682
Calving interval, mo	13.8	13.7	14.0
Culling rate, %	33.0	34.0	40.4
Age at first calving, mo	25.3	25.3	27.0
Milk production, kg/cow per year	8,608	9,102	9,198
Milk fat, kg/hL	4.13	4.13	3.89
Milk CP, kg/hL	3.35	3.39	3.29
Milk other solids, kg/hL	5.66	5.72	5.69
FPCM,[1] kg/yr	513,696	614,296	1,213,288
Farm economics input[2]			
Net milk price, $/100 kg of milk	77.47	77.94	77.19
Other incomes,[3] $/100 kg of milk	7.35	10.31	3.20
Variable costs,[3] $/100 kg of milk	9.13	8.62	7.96
Labor, $/yr	52,645	54,322	156,670
Taxes and insurances, $/yr	30,291	30,797	17,602
Depreciation, $/yr	71,524	70,910	111,291
Interest, $/yr	30,193	40,558	15,981
Other cost, $/yr	16,657	21,569	1,688

[1]FPCM = fat- and protein-corrected milk, calculated from International Dairy Federation (2015).

[2]All monetary values are in Canadian dollars; the average exchange rate used was US$0.97 for 2010 to 2014 (Bank of Canada, 2017).

[3]Excluding crop costs and incomes.

were used in each region: a mid-rich soil land unit (**LUrich**) and mid-poor soil land unit (**LUpoor**).

Origin of Farm Data. The Maritimes and Central Canada economic and productivity data originated from les Groupes Conseils Agricoles du Québec via their website (GCAQ, 2016), using the means of the years 2010 to 2014, inclusively. Inputs into the model for these 2 regions are presented in Table 1. The most commonly used feed ingredients in both regions from Lactanet (Dairy Production Centre of Expertise, Québec and Atlantic Provinces, Sainte-Anne-de-Bellevue, QC, Canada); registered farms were included as possible choices into the N-CyCLES model. Nutrient composition of feed ingredients and their prices were the average of the analyses for the producers of the same area registered to DHI service from Lactanet, from 2010 to 2014. The chemical compositions of these feed ingredients are shown in Appendix Table A2.

Data for the Prairies originated from values published by Alberta Agriculture and Forestry Ministry (Alberta Milk, 2016; Ministry of Agriculture and Forestry, 2016). Average values from years 2010 to 2014 were collected for economics and yields of cereal crops. When feed ingredient prices were not available on these sites, e.g., for minerals, they were estimated from Eastern region prices. Due to the lack of data on the chemical composition of feed ingredients for this region, values from NRC (2001) tables were used and validated by a local expert (V. S. Baron, Agriculture and Agri-food Canada, Lacombe, Canada; personal communication). The utilization of reference values instead of average regional values for the Prairies may affect absolute results, but, as all approaches within a region have the same feed ingredients, we expect that comparisons of the different approaches to be relevant to the Prairies reality.

Crop Selection. Crops and rotations proposed in N-CyCLES were chosen to reproduce what is done by an average producer for each region, following climate restrictions. For the Maritimes and Central Canada, crop selection and appropriate fertilization follow the recommendations from Centre de Références en Agriculture et Agroalimentaire du Québec (CRAAQ; 2010), whereas for the Prairies, crop nutrient requirements were confirmed by a local expert agronomist (V. S. Baron, personal communication). Crop yields used were 2010–2014 averages from La Finanacière Agricole du Québec (FADQ, 2016) for the Maritimes and Central Canada, whereas those of the Prairies were from the Ministry of Agriculture and Forestry databases (Ministry of Agriculture and Forestry, 2016). Cost of production of crops in the Maritimes and Central Canada were adapted from annual crop budgets published by Beauregard (2016). For the Prairies, they were from the Ministry of Agriculture and Forestry (Ministry of Agriculture and Forestry, 2016). The selected rotations and their nutrient requirements and costs are detailed in Appendix Table A3.

Simulations

The 4 approaches of formulation were simulated for each region. Each simulation maximized FNI and met energy requirements based on NRC (2001) and MP or AA requirements according to one of the 4 approaches, as previously described, using DMI predicted by NRC (2001). Diets were all formulated as TMR. Although this manuscript presents only nutrition details for the lactating cows, dry cow and growing heifers' diets were optimized and considered for the reported whole-farm parameters, as they directly affect FNI and nutrient balance. Constraints applied on feed and nutrient requirement are described in Appendix Table A4. A sensitivity analysis was then performed (1) by reducing milk protein content by 5%, (2) by varying protein concentrate prices by 15%, and (3) by varying forage production costs by 15% below and above initial values. Another set of simulations was done excluding the use of blood meal in rations because of controversial usage of animal by-products in ruminant nutrition, as indicated by their banishment in European countries. Results are limited to the assumptions made on the original formulation models (NRC, 2001) and revised approaches; requirements are assumed to be met within each approach and therefore, milk production and composition are assumed not to be affected by the type of formulation.

RESULTS AND DISCUSSION

Nutritional Outputs

Early Lactation Groups. For early lactation cows, for all formulation approaches and regions, NE_L was either limiting or co-limiting with MP or AA (Table 2). Indeed, energy balance was always equal to zero (data not shown), whereas MP balance was also null with MP_2001. However, AA_2001, MP_Rev, and AA_Rev generated diets with positive MP balances, except in the Prairie where AA_2001 yielded a null MP balance and AA_Rev a slightly negative balance. This suggests that, at low-cost formulation, it is more difficult to fulfill energy than MP requirements at this stage of lactation. Indeed, ingredients selected to meet energy requirements also usually increased MP supply, which did not allow improvement of N efficiency with AA_2001 and MP_Rev when compared with MP_2001. Only AA_Rev formulation slightly increased N efficiency, but only by 0.2 and 0.1 percentage point in the Maritimes and in the Prairies, respectively, whereas in Central Canada, efficiency was even lower, decreasing from 28.8 to 28.5%.

In all regions, diets balanced using MP_2001 did not supply enough Lys and Met to meet their respective requirements, as estimated in AA_2001. In the Maritimes and in Central Canada, cows fed according to NRC_2001 were fed 20 and 21 g/d of Lys and 6 g/d of Met below AA_2001 requirements. In the Prairies, however, only 4 g/d of Lys and 8 g/d of Met were lacking with MP_2001 compared with AA_2001 requirements. The smaller difference in Lys in this region is probably due to the lower utilization of corn-based feed ingredients, mainly corn silage and corn distiller grain, which have low Lys concentration (NRC, 2001).

With both revised approaches, Lys was not estimated being limiting, as its balance was above 19 g/d in all regions. On the other hand, the supply of Met and His could be considered on the edge, as their balance was just slightly positive, varying by 3 to 4 g/d for both formulations. This approximately represents the 5% security margin used by the N-CyCLES model to balance rations.

Mid-Late Lactation Groups. Except in the Maritimes, for low-cost rations, energy was not considered limiting for the mid-late lactation cows. The higher proportion of forages, greater than 64% of the total DM in the ration (compared with less than 50% in the other regions), and their low energy content in this region, could explain this result. In Central Canada and in the Prairies, rations balanced to maximize FNI were feeding respectively 5 and 3% less energy when balanced with AA_Rev than with MP_2001, while still meeting requirements. This suggests that, in these 2 regions, to achieve MP supply, MP_Rev low-cost rations were supplying an excess of energy, which could be reduced concomitantly with MP supply using AA_Rev approach, without expected detrimental effect on performance. The lower nutrient density required in this group made it possible as opposed to the early lactation group.

Balancing rations using MP_2001 or AA_2001 did not alter the null estimated MP balance. With rations balanced with MP_2001 for mid-lactation cows, however, Met balance would be slightly negative in all regions, whereas Lys balance would be more negative in Central Canada. This important difference in Lys supply between regions is suspected to be mainly caused by a lower utilization of corn distiller grain in the latter region. On the other hand, in the 3 regions using the MP_Rev approach, MP balance was positive (around 80 g/d), whereas Lys would be fed from 21 to 30% above requirements and Met and His would be both overfed from 7 to 13%. Because energy was not limiting in these diets, balancing only for AA using AA_Rev decreased this balance to safety margins for His and Met, while still overfeeding Lys. This might indicate that Met and

Table 2. Simulated nutritional composition, MP and AA supply and balance, N efficiency, and cost for the rations of 2 lactation groups of cows by region and formulation approach[1]

	The Maritimes				Central Canada				The Prairies			
Item	MP_2001	AA_2001	MP_Rev	AA_Rev	MP_2001	AA_2001	MP_Rev	AA_Rev	MP_2001	AA_2001	MP_Rev	AA_Rev
Early lactation												
NE_L, Mcal/kg DM	1.59[2]	1.59[2]	1.59[2]	1.59[2]	1.61[2]	1.61[2]	1.61[2]	1.61[2]	1.59[2]	1.59[2]	1.59[2]	1.59[2]
CP, % DM	15.6	16.0	15.8	15.5	15.7	16.8	16.0	16.0	17.1	17.1	17.6	17.1
MP supply,[3] g/cow per d	2,174	2,236	2,244	2,201	2,289	2,451	2,382	2,384	2,267	2,267	2,336	2,208
MP balance,[3] g/cow per d	0	62	107	65	0	162	143	144	0	0	111	−16
Lys supply,[4] g/cow per d	142	168	161	157	150	184	165	165	165	170	183	174
Met supply g/cow per d	49	57	49	48	52	63	53	53	52	63	49	49
His supply, g/cow per d	46	48	58	56	52	64	53	55	61	60	63	59
Lys balance, g/cow per d	−20	4	21	20	−21	11	19	20	−4	0	24	22
Met balance, g/cow per d	−6	2	4	4	−6	4	4	4	−8	0	3	3
His balance, g/cow per d	—	—	4	4	—	—	3	3	—	—	3	3
N efficiency,[5] % of intake	28.0	27.5	27.8	28.2	28.8	27.2	28.5	28.5	25.9	25.9	25.2	26.0
Cost of ration, $/t DM	268	288	268	267	276	297	278	279	250	261	250	245
Mid-late lactation												
NE_L, Mcal/kg DM	1.46[2]	1.50	1.47	1.46[2]	1.62	1.56	1.64	1.54	1.59	1.60	1.60	1.56
CP, % DM	16.8	16.3	17.5	15.5	16.1	16.3	16.1	15.0	16.5	16.4	17.5	15.9
MP supply,[3] g/cow per d	1,935	1,935	2,019	1,762	2,032	2,032	2,102	1,919	2,016	2,016	2,086	1,797
MP balance,[3] g/cow per d	0	0	77	−177	0	0	81	−104	0	0	80	−215
Lys supply,[4] g/cow per d	141	144	159	138	133	152	150	143	147	151	163	140
Met supply g/cow per d	42	49	43	40	48	52	47	43	48	52	45	43
His supply, g/cow per d	42	42	54	42	45	54	50	45	53	53	56	43
Lys balance, g/cow per d	−3	0	28	23	−18	0	33	27	−4	0	38	28
Met balance, g/cow/d	−7	0	3	2	−4	0	6	3	−5	0	5	4
His balance, g/cow/d	—	—	4	2	—	—	6	3	—	—	8	4
N efficiency,[5] % of intake	23.5	24.1	22.8	25.7	25.4	25.2	25.7	27.6	24.0	24.1	23.0	25.4
Cost of ration, $/t of DM	203	213	205	189	214	221	220	208	189	198	194	178

[1]MP_2001 = NRC 2001 MP-based formulation; AA_2001 = NRC 2001 AA-based formulation; MP_Rev = Revised MP-based formulation; AA_Rev = Revised AA-based formulation: see text for detail.

[2]Equal to the lower requirement limits.

[3]These values exclude duodenal endogenous MP requirement and supply values, for comparison purposes, but these were considered in the calculation for NRC (2001) formulations.

[4]AA supplies and requirements were corrected to account for incomplete recovery of AA with 24-h hydrolysis of proteins (Lapierre et al., 2019); AA balance for MP_2001 and MP_Rev are estimated using requirements estimated their respective AA formulation.

[5]N efficiency = (N milk + N $accretion_{pregnancy}$ + N $accretion_{growth}$)/(CP of diet × DMI/6.25).

His could be both co-limiting AA in low protein rations in all 3 Canadian reference farms defined in the present study. Balancing for His, Lys, and Met rather than MP in the revised approach allowed a substantial decrease of diet CP, with AA_Rev proposing the lowest CP content of diets across regions. At these low protein levels, although His, Lys, and Met requirements were met, calculated MP balances were negative (between 104 to 214 g/d/cow). However, this estimated MP deficit should not have a negative effect on milk and milk protein yields, as demonstrated by Lee et al. (2012a) when a MP-deficient diet was supplemented with His, Lys and Met. This reduction in CP and MP supply for AA_Rev formulation for mid-late cows translated into an improvement of 1.4 to 2.2 percentage points in N efficiency compared with MP_2001.

Overall Changes in Feed Ingredients. One major effect of AA_2001 compared with MP_2001 is the need to include rumen-protected AA in rations, necessary to meet the recommended Lys and Met proportion of MP. Also, optimization resulted in a 5% decrease in perennial crops in the diets in the Maritimes when formulating with AA_2001 and AA_Rev, compared with MP_2001 and MP_Rev (data not shown). This forage was replaced mostly by barley grain with AA_2001 formulation. With AA_Rev formulation, there was also a partial substitution of blood meal and expelled soybean meal by canola meal and barley grain. The change in perennial crops for barley is assumed to enhance MCP production because of its higher rumen digestible nutrient content.

For simulations in Central Canada farms, formulating on an AA basis resulted in diets containing fairly similar ingredients for cows in early lactation compared with diets formulated with MP-based models. However, for mid-late groups, when formulating on an AA basis compared with MP formulation, all corn distiller grains were replaced with perennial forages, blood meal, and canola meal. The low content in Lys of corn distiller grains, although having a good MP supply potential, could explain this shift for both AA-based models. The high energy content of corn distiller grains could explain why it was still the main protein concentrate for early lactation cows, as it is relatively inexpensive for its nutrient content.

For simulations for farms in the Prairies, MP_2001, AA_2001, and MP_Rev diets were very similar, whereas AA_Rev substituted 4% of barley silage for alfalfa silage and barley grain for early lactation cows. Those changes did not affect CP content of the diet. For mid-late groups, the main change occurred within AA_Rev, where blood meal and canola meal were replaced by legume silage and wheat distiller grain, reducing CP supply. With AA_Rev, MCP represented a higher proportion of total MP supply, compared with the other formulation approaches. The main feed component selection and changes during optimization can be partly explained by simple mathematical process work. Within each region, utilization of a multivariate maximum likelihood approach, as described by St-Pierre and Glamocic (2000), seems to be a good predictor of the main feed used in diets by their breakeven point prices from feed components. With 4 components, RUP, RDP, energy, and NDF, feeds with the highest residuals were the main components of diets. In the present study, forages were included in the feed available for selection by considering their on-farm cost of production. However, constraints related to the formulation approach may force the utilization of more expensive feeds to meet requirements, such as rumen-protected fat to supply energy in early lactation cows, or when maximum limits were reached, as it happened with distiller grains in all regions.

Crop and Rotation Outputs

To understand the selections made during the optimization process, it is also important to keep in mind that harvest on the farm can have 2 purposes in the current simulations: feeding the herd and producing cash crops. The farm climate, crop yields, animal unit per land surface, and feed prices are the main factors influencing the fate of the crops, either being kept on farm and fed to the animal or sold (Cela et al., 2014; Pellerin et al., 2017a). Reasons explaining farm situation differences can be multiple. For example, in Central Canada, growing crops for sale is a common practice, and it is the only region to grow corn grain and soybeans. In the Prairies, the average farm is bigger than in Eastern regions and grows cereal grain and cereal silage more often. In the Maritimes, the colder climate makes it impossible to grow corn grain and limits corn silage yields. Therefore, in this region, which tends to be more autonomous on feed, farms are usually more centered around forages and also grow and feed barley grain, which minimizes purchased feeds.

In the Maritimes, MP_2001 resulted in a production of 145 t DM of barley and 51 t DM of canola grown, and 347, 233, and 536 t DM of legume, mixed, and corn silage, respectively (Table 3). The AA_2001 formulation model favored production of mixed silage with a 5% enhancement in production, reducing by 1 to 4% barley, canola, and corn silage productions. Compared with MP_2001, the MP_Rev and AA_Rev formulations followed the same pattern but with stronger effects, as total legume and grass silage production increased by 12 and 9%, respectively, with a reduction in barley by 6 and 3%, canola by 10 and 6%, and corn silage by

Table 3. Predicted total crop yields (t of DM) by region and formulation approach[1]

Item	MP_2001	AA_2001	MP_Rev	AA_Rev
The Maritimes				
Barley grain	145	143	136	141
Canola	51	49	46	48
Legume silage	347	350	358	353
Mixed silage	233	244	260	254
Corn silage	536	521	517	506
Central Canada				
Corn grain	419	381	388	380
Soybean	60	55	56	55
Legume silage	121	131	129	132
Mixed silage	152	165	162	166
Corn silage	485	526	518	527
Wheat	12	13	13	13
The Prairies				
Corn silage	450	449	449	461
Legume silage	268	267	267	280
Barley silage	24	24	24	32
Barley grain	266	268	267	250
Pea	74	75	75	69

[1]MP_2001 = NRC (2001) MP-based formulation; AA_2001 = NRC (2001) AA-based formulation; MP_Rev = revised MP-based formulation; AA_Rev = revised AA-based formulation; see text for details.

4 and 6%, respectively. These changes in production happened through a reattribution of total land surface from one crop to another. These selections reduced the N purchased by producing and feeding more forage N sources, but also resulted in selling fewer feed ingredients (i.e., canola and barley). Rotation selection seemed to be mainly linked to the best global or possible forage margin. This appeared to favor rotation 4, producing mainly corn silage and grass silage in LUrich, and rotation 2, producing barley grain and canola with grass silage in the poor land unit (Appendix Table A3). Reducing production of barley and canola reduced the total crop sold, thus reducing crop incomes. For this region, under this scenario, all forages and most barley were used on the farm, whereas all canola produced was sold.

In Central Canada, with the MP_2001 approach, 2 commercial crops (corn grain and soybean) took an important place, with 419 and 60 t DM, respectively. Because rotation 2 had the best global margin, it was selected when forage requirements were met (Appendix Table A3). Corn and soybean land surface was reduced by 7 to 10% with AA_2001, MP_rev, and AA_Rev (Table 3). This change resulted in an increased total forage production of 7 to 9% in all 3 simulations, with 121, 152, and 485 t DM of legume, mixed, and corn silage with MP_2001 simulation. Forages were mainly grown on the rotations with the best forage production cost margins in both land units. The soil P deposition is regulated in Eastern Canada, possibly influencing Central Canada and the Maritimes' P management (Gouvernement du Québec, 2019). This could also have contributed to this crop selection due to the higher ratio of the number of cows per ha observed in Central Canada. This is supported by the absence of purchased P fertilizer with all formulations of this region. The limitation in P deposition may have resulted in selection of crops exporting large amount of P, such as corn grain and corn silage. This could also have influenced the ration formulation by selecting low phosphorus-containing feed ingredients to lower phosphorus excretion. However, these hypotheses could not be validated. Across all formulations, most corn grain was sold, and all soybean was sold.

In the Prairies, corn silage was the main crop grown with an average of 449 t DM for MP_2001, AA_2001, and MP_Rev. The AA_Rev suggested growing 2.7% more corn silage. Legume silage followed the same pattern with 267 t DM produced for all models except for AA_Rev, which produced 5% more. In counterpart, barley and pea production would be reduced by 6 and 7%, respectively. A low variability in crop production occurred through the 4 types of formulation for this region. All barley produced was used on the farm, and pea was entirely sold in all simulations.

Economic Outputs

Within region, the AA_2001 formulation had the lowest calculated FNI, mainly caused by the highest purchase of feed ingredients (Table 4). More specifically, the FNI was 3 to 10% lower than MP_2001, with a 6 to 9% augmentation in purchased feedstuffs, with the largest difference in the Maritimes. This was mostly caused by the necessity to use rumen-protected AA, which are expensive feed ingredients, to reach the target proportions of Lys and Met as a percentage of MP. Those changes were reflected in ration costs (Table 2). Although our initial hypothesis assumes no change in milk protein yield with the different types of formulation, an enhancement of milk protein production might be expected when AA are balanced (Patton, 2010; Robinson, 2010; Zanton et al., 2014). We calculated that the cows in the Maritimes, Central Canada, and the Prairies would need to increase their milk protein yield by 35, 40, and 51 g/d, respectively, to compensate for economic losses associated with the purchase of rumen-protected AA with AA_2001, assuming no change in milk fat production. An enhanced milk protein production would also affect total N balance by exporting more N in milk and reducing N in manure.

The AA_Rev showed the best results in all 3 regions, with the Maritimes benefit being the most important in terms of FNI. Compared with MP_2001, gains of FNI within a region varied between 0 to 9% (Table 4).

Table 4. Economic output summary of simulations by region and formulation approach[1]

Output[2]	The Maritimes				Central Canada				The Prairies			
	MP_2001	AA_2001	MP_Rev	AA_Rev	MP_2001	AA_2001	MP_Rev	AA_Rev	MP_2001	AA_2001	MP_Rev	AA_Rev
Net income,[3] $/100 kg of FPCM	11.0	9.9	11.3	12.0	22.6	21.3	22.4	22.6	23.4	22.6	23.7	24.4
Purchased feeds, $/100 kg of FPCM	9.9	10.8	9.6	8.5	18.0	19.1	16.2	15.4	11.5	12.4	11.6	10.5
Homegrown feeds, $/100 kg of FPCM	12.6	12.5	12.7	12.6	10.3	10.4	10.4	10.3	12.1	12.1	11.9	11.9
Fertilizers + manure, $/100 kg of FPCM	1.8	2.0	1.7	1.8	1.6	1.5	1.5	1.5	1.0	1.0	1.0	1.1
Fixed cost, $/100 kg of FPCM	47.8	47.8	47.8	47.8	43.6	43.6	43.6	43.6	32.8	32.8	32.8	32.8
Crop incomes, $/100 kg of FPCM	3.0	2.8	2.9	2.5	12.9	12.6	10.9	10.3	2.1	2.2	2.2	2.0
Milk + animal incomes, $/100 kg of FPCM	80.3	80.3	80.3	80.3	83.2	83.2	83.2	83.2	78.6	78.6	78.6	78.6
Global IOFC,[4] $/cow per day	13.23	12.92	13.20	13.40	13.90	13.58	13.81	14.09	14.65	14.43	14.59	14.85

[1]MP_2001 = NRC (2001) MP-based formulation; AA_2001 = NRC (2001) AA-based formulation; MP_Rev = revised MP-based formulation; AA_Rev = revised AA-based formulation; see text for details.

[2]All monetary values are in Canadian dollars; the average exchange rate used was US$0.97 for 2010 to 2014 (Bank of Canada, 2017).

[3]FPCM = fat- and protein-corrected milk, calculated according to International Dairy Federation (2015).

[4]IOFC = income over feed cost.

Most of this modification in FNI was caused by a reduction in purchased feedstuffs, ranging from 9 to 14% for AA_Rev formulation in comparison to MP_2001. Compared with MP_2001 in Central Canada, MP_Rev and AA_Rev resulted in lower crop incomes of 15 and 20% respectively, but also in lower purchased feedstuff costs, showing a shift in feedstuff origin. In these 2 formulations, more of the corn grain grown on the farm was directly used in rations, which implied less corn grain was sold, reducing crop incomes. Both MP-based formulations had similar results in economic output of all 3 regions. In addition, the possibility to formulate below MP requirements in AA_Rev made it possible to buy less expensive feedstuffs, reducing global feed cost. Although in the Maritimes and Central Canada, early lactation AA_Rev cow ration costs were almost identical across all models, mid-late lactation rations costs were $13 and $6/t DM less expensive than MP_2001, respectively. In the Prairies, however, early lactation rations cost $6/t DM less and mid-late, $12/t less, compared with MP_2001 as shown in Table 2.

Producers do not always take into account possible incomes from crops sold or how they can benefit from them. In the current optimization study, in Central Canada, crop income represented, on average, 12% of total income. From GCAQ (2016) farm group analysis, in Central Canada global region, crop incomes averaged 25% of total income. Such large difference indicates the importance of considering crop management when maximum profit is the objective.

The income over feed cost estimated in the Maritimes region varied between $12.92 and $13.40/cow per day for lactating cows. It varied between $13.58 to $14.09/cow per day in Central Canada and between $14.43 to $14.85/cow per day in the Prairies (Table 4). Within regions, they have the same behavior as FNI. In comparison, in the province of Québec and the Maritimes, commercial farms had an average income over feed cost of $12.16/cow per day during the 2010–2014 period (Valacta, 2017), indicating that our results are in plausible ranges of optimal management for Central Canada and the Maritimes.

Environmental Outputs

One important aspect of the N-CyCLES optimization program is to simulate the effect of different scenarios on farm nutrient balance. In the present study, the best results among simulations in all 3 regions for the N balance were usually observed with AA_ Rev (Table 5). The decreases in N balance varied between 0 and 7%, depending on the region, when compared with MP_2001 formulation originally being 11.98, 12.82, and 13.32 g of N/g of FPCM, for the Maritimes, Central

Canada, and the Prairies, respectively. In contrast, N balances obtained with AA_2001 in the Maritimes and Central Canada were 1.3 and 2.0% higher, and with MP_Rev in the Prairies it increased by 11%, compared with their respective MP_2001 formulation. The main change was in the feed N purchased parameter (Table 5). Compared with MP_2001, across regions, AA_Rev reduced feed N purchased parameter by 2 to 16%. Furthermore, it also decreased cash crops sold, resulting in less feed N exported and ranging within a region from 5 to 18% compared with MP_2001. Nitrogenous fertilizers and atmospheric deposition had little effect on N balance. Overall, the farm N efficiency (N output:N input) was more influenced by the region through parameters prevailing in each reference region than by the formulation within region: it ranged from 42.7 to 44.2%, 52.6 to 54.5% ,and from 37.6 to 40.0% in the Maritimes, Central Canada, and the Prairies, respectively, depending on the nutritional approach used. The high proportion of crops sold in Central Canada explained these differences in N efficiency from the other 2 regions. These results in Central Canada are similar to those obtained in a previous optimization conducted by Pellerin et al. (2017a) for the province of Québec, whereas the Maritimes and the Prairies results are comparable to those from studies conducted in New York with a median of 35% (Cela et al., 2014). When excluding N atmospheric deposition, N balance varied from 0.65 to 2.21 g/kg FPCM in the Maritimes, from 5.53 to 6.47 in Central Canada and from 5.36 to 6.86 in the Prairies, with AA_Rev being the lowest in all regions.

For total GHG emissions, AA_Rev was from 0 to 4% lower than MP_2001 (Table 5). In the Maritimes and Central Canada, the reduction in purchased feedstuff with AA_Rev translated in a reduction in indirect emissions of 12 and 27%, respectively, when compared with MP_2001. However, in the Prairies, even if there was a reduction in purchased feedstuff, emissions were 4.5% higher, mostly because of the substitution of canola meal with wheat distiller grain, which was cheaper but emits 3.5 times more GHG during its production process (Brander and Wylie, 2011; Agriculture and Agri-Food Canada, 1999). Total methane emissions varied at most by 0.5% through all models. The gain in N efficiency of AA_Rev formulation translated to a 0.7 to 3.2% reduction in nitrous oxide emissions due to the lower N excretion in manure.

In their study in Eastern Canada, Mc Geough et al. (2012) established a global effect of milk production on GHG of 0.92 kg of CO_2 Eq/kg of FPCM, which is an average of 27% lower than the value obtained in the present study. The main difference resides in the fact that a fixed enteric methane emission factor of 6.5% of gross energy supply for lactating cows was used in the present study, whereas a 5.5% of gross energy methane emission factor was selected in their study. They also considered that crops were not fertilized with nitrogenous fertilizers, whereas they were the main fertilizer sources in this study, and imported a non-negligible amount of CO_2 Eq. They also considered that all feeds consumed on the farm, except minerals, were produced on farm, thus excluding all imported feed that were considered in our study. Those 2 factors combined resulted in approximately 0.15, 0.26, and 0.19 kg of CO_2 Eq/kg of FPCM in the Maritimes, Central Canada, and the Prairies, respectively. A versatile or a multivariate emission factor would be strongly suggested as Tier 3 of IPCC (2006) recommended. Such emission factors should consider the effect of variation in diet composition on methane emission (Moraes et al., 2014). This would enable more representative interpretation of the effect of diet changes on GHG emissions.

Sensitivity Analysis

Sensitivity analysis was conducted to determine if altering a few main farm components would affect the general conclusions, by comparing the results of the 4 approaches within a specific alternative context, and not against their respective initial simulation values. As described previously, sensitivity analysis was conducted by removing blood meal from choices of feed, reducing milk CP content by 5%, varying protein concentrate prices or forage production cost by 15% from the initial scenario in all regions. Within region, the sensitivity analysis indicated that farm FNI showed a similar behavior as observed in the initial simulations when the studied factors varied. For example, across all different sensitivity analysis scenarios, AA_Rev have the best FNI, ranging from 100 to 111% of MP_2001 value, as observed in the initial simulations (Table 6). With AA_2001 reaching 84 to 97% of MP_2001 FNI values, results are also similar to initial simulations. The MP_Rev approach, as with the initial simulations, usually yielded slightly greater FNI than MP_2001. However, as N balance was not optimized nor constrained in our simulations, it was more susceptible to variations than FNI. Using the AA_2001 or MP_Rev approach either slightly increased or decreased the farm N balance, from 98 to 104% of their MP_2001 values, depending on the context except in the Prairies whereas MP_Rev consistently raised the N balance compared with MP_2001. However, in all scenarios of the sensitivity analysis, AA_Rev decreased N balance from 90 to 97% of MP_2001 values. As Pellerin et al. (2017a) had shown, applying a constraint on N balance to a lower target would inevitably reduce FNI. However, to

Table 5. Simulated farm N and P balances and greenhouse gas emissions by region and formulation approach[1]

	The Maritimes				Central Canada				The Prairies			
Item	MP_2001	AA_2001	MP_Rev	AA_Rev	MP_2001	AA_2001	MP_Rev	AA_Rev	MP_2001	AA_2001	MP_Rev	AA_Rev
N balance,[2] g/kg of FPCM	11.98	12.14	12.3	11.13	12.82	13.07	12.89	12.28	13.32	13.29	14.75	13.32
Feed N purchased, g/kg of FPCM	8.83	8.72	9.21	7.42	18.41	18.64	17.36	16.16	13.89	14.01	15.546	13.63
Fertilizer N purchased, g/kg of FPCM	2.10	2.68	1.62	2.03	3.37	2.85	3.05	3.00	0.25	0.26	0.19	0.31
Atmospheric N deposition, g/kg of FPCM	10.33	9.92	10.63	10.49	6.40	6.60	6.60	6.75	7.95	7.89	7.89	7.90
Milk and meat N exported, g/kg of FPCM	5.88	5.88	5.88	5.88	5.90	5.90	5.90	5.90	6.09	6.09	6.09	6.09
Feed N exported, g/kg of FPCM	3.40	3.30	3.29	2.93	9.47	9.12	8.81	7.73	2.68	2.78	2.78	2.56
Farm N efficiency, %	43.7	43.1	42.7	44.2	54.5	53.5	54.5	52.6	39.7	40.0	37.6	39.6
P balance, g/kg of FPCM	1.70	1.71	1.68	1.70	0.41	0.08	0.32	0.09	0.84	0.83	0.89	0.82
Feed P purchased, g/kg of FPCM	1.20	1.14	1.21	1.13	3.00	2.63	2.69	2.39	1.81	1.80	2.00	1.64
Fertilizer P purchased, g/kg of FPCM	1.99	2.01	1.97	1.97	0.00	0.00	0.00	0.00	0.52	0.53	0.38	0.65
Milk and meat P exported, g/kg of FPCM	1.12	1.12	1.12	1.12	1.11	1.11	1.11	1.11	1.19	1.19	1.19	1.19
Feed P exported, g/kg of FPCM	0.37	0.32	0.37	0.28	1.48	1.44	1.25	1.18	0.29	0.31	0.31	0.28
Greenhouse gases, CO_2eq[3]/kg of FPCM	1.59	1.62	1.58	1.57	1.69	1.67	1.66	1.62	1.50	1.51	1.50	1.50
Methane, CO_2eq/kg of FPCM	1.05	1.05	1.06	1.05	0.97	0.98	0.98	0.98	1.03	1.03	1.03	1.03
N_2O linked to manure CO_2 eq/kg of FPCM	0.22	0.22	0.23	0.22	0.22	0.23	0.22	0.22	0.22	0.21	0.22	0.21
N_2O mineral fertilizer, CO_2 eq/kg of FPCM	0.02	0.03	0.02	0.02	0.03	0.03	0.03	0.03	0.00	0.00	0.00	0.00
N_2O field other, CO_2eq/kg of FPCM	0.03	0.03	0.03	0.03	0.07	0.07	0.07	0.06	0.04	0.04	0.04	0.04
CO_2 fuel, CO_2eq/kg of FPCM	0.08	0.08	0.08	0.08	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
CO_2eq import feeds, CO_2 eq/kg of FPCM	0.08	0.10	0.08	0.08	0.21	0.20	0.20	0.17	0.13	0.14	0.13	0.13
CO_2eq crop input, CO_2eq/kg of FPCM	0.10	0.12	0.08	0.08	0.13	0.11	0.12	0.12	0.04	0.04	0.04	0.04
Milk allocation GHG, CO_2eq/kg of FPCM	1.27	1.30	1.26	1.26	1.21	1.21	1.23	1.20	1.16	1.17	1.16	1.16
Meat allocation GHG, CO_2eq/kg of FPCM	0.26	0.27	0.26	0.26	0.24	0.24	0.24	0.24	0.30	0.30	0.30	0.30
Crop allocation GHG, CO_2eq/kg of FPCM	0.06	0.05	0.05	0.05	0.23	0.22	0.19	0.18	0.04	0.04	0.04	0.04

[1]MP_2001 = NRC (2001) MP-based formulation; AA_2001 = NRC (2001) AA-based formulation; MP_Rev = revised MP-based formulation; AA_Rev = revised AA-based formulation; see text for details.

[2]FPCM = fat- and protein-corrected milk, calculated according to International Dairy Federation (2015).

[3]CO_2eq = kg of CO_2 equivalent.

Table 6. Effects of a reduction of CP content of milk, a variation in protein concentrate and forages prices, and the exclusion of blood meal[1]

	The Maritimes				Central Canada				The Prairies			
Item[2]	MP_2001	AA_2001	MP_Rev	AA_Rev	MP_2001	AA_2001	MP_Rev	AA_Rev	MP_2001	AA_2001	MP_Rev	AA_Rev
Milk CP: −5%												
Net income, $/100 kg of FPCM	10.4	9.2	10.7	11.3	21.8	20.6	21.8	22.0	23.6	22.8	24.0	24.7
N balance, kg/FPCM	11.84	12.33	12.44	11.17	12.62	13.01	12.67	12.52	13.22	13.21	14.54	12.72
Animal N efficiency, %	24.6	24.4	24.0	25.8	26.5	25.4	26.7	26.7	24.3	24.3	23.5	25.6
Protein concentrates price: +15%												
Net income, $/100 kg of FPCM	10.8	9.5	11.1	11.9	22.0	20.6	21.8	22.2	23.1	22.2	23.4	24.6
N balance, kg/FPCM	11.88	11.93	11.65	11.14	12.82	13.06	12.41	11.51	13.25	13.04	13.96	12.19
Animal N efficiency, %	25.9	26.2	25.9	26.8	26.9	26.0	27.7	28.8	24.9	24.9	24.8	26.9
Protein concentrate prices: −15%												
Net income $/100 kg of FPCM	11.4	10.4	11.8	12.2	23.3	22.0	23.1	23.3	23.9	23.0	24.2	24.9
N balance, kg/FPCM	12.31	12.19	12.67	11.53	13.71	13.44	13.34	12.63	13.09	13.31	14.26	12.83
Animal N efficiency, %	24.8	24.9	24.5	26.3	25.3	25.4	26.1	27.5	25.1	24.9	24.4	26.2
Forages production costs: +15%												
Net income $/100 kg FPCM	9.6	8.5	9.9	10.7	21.5	20.2	22	22.3	22.1	21.3	22.4	23.2
N BALANCE, kg/FPCM	12.39	12.52	12.51	11.16	12.84	13.06	12.86	12.37	13.50	13.53	14.53	12.29
Animal N efficiency, %	25.4	25.2	25.4	26.8	26.9	26.0	27.1	28	24.8	24.8	24.2	26.9
Forages production costs: −15%												
Net income, $/100 kg of FPCM	12.5	11.4	12.8	13.4	23.6	22.3	23.5	23.8	24.8	24.0	25.1	26.1
N balance, kg/FPCM	11.90	12.17	11.97	11.06	12.72	13.05	12.74	12.07	13.26	13.29	14.06	12.44
Animal N efficiency, %	25.3	24.9	25.2	26.8	26.9	25.9	27.0	28.0	24.9	24.9	24.8	26.8
Blood meal exclusion												
Net income, $/100 kg of FPCM	10.8	9.1	11.1	11.7	22.5	20.7	22.5	22.7	23.1	21.9	23.5	24.3
N Balance, kg/FPCM	11.66	11.59	11.52	11.41	12.80	13.35	12.82	12.33	13.09	13.08	13.97	12.71
Animal N efficiency, %	25.6	25.6	25.7	26.3	26.9	26.1	27.0	28.0	25.1	25.1	24.7	26.1

[1]MP_2001 = NRC (2001) MP-based formulation; AA_2001 = NRC (2001) AA-based formulation; MP_Rev = revised MP-based formulation; AA_Rev = revised AA-based formulation; see text for details.

[2]All monetary values are in Canadian dollars; the average exchange rate used was US$0.97 for 2010 to 2014 (Bank of Canada, 2017); FPCM = fat- and protein-corrected milk, calculated from International Dairy Federation (2015); animal N efficiency = (N milk + N accretion_pregnancy + N accretion_growth)/N intake, averages for lactating cows.

target the same N balance as observed for MP_2001, FNI difference may still be positive, as in the Pellerin et al. (2017a) study in which a reduction of 1 g of N/kg of FPCM led to a $0.02/kg of FPCM reduction. In general, within a region, animal N efficiency variation follows a proportionally inverse change to global farm N balance variation. This followed Spears et al. (2003) observations where, for farm growing crops, farm N balance and animal N efficiency are strongly negatively correlated. Altogether, these data indicate that when animals utilize protein more efficiently, the whole farm also becomes more efficient with N, resulting in a lower farm N balance. Across all sensitivity analysis simulations, AA_Rev showed for all regions an improvement of animal N efficiency of 3 to 8% compared with MP_2001 formulation. On the other hand, AA_2001 resulted in a lower N efficiency than MP_2001 in most of the simulations. The stability of the patterns of the responses indicates the robustness of the results from our initial simulations on FNI and N efficiency. It validates the potential use of AA_Rev formulation approach to have a beneficial effect on Canadian dairy farms, whereas AA_2001 maybe more limiting without consideration of milk or milk protein enhancement.

Domain of Validity and Limitations

The approach of whole-farm optimization, as opposed to optimizing only the diet, makes it possible to see the dynamic effect of changes, as a single-unit of decision. As a farm can grow a limited quantity of crops, resource management is important, even more so when animal density is elevated. With changes of requirement and supply estimations in simulations where FNI is maximized, diet optimization may involve a reallocation of some feed resources from one group of animals to another to meet nutrient requirements of all animal groups on the farm. By extension, crop production also changes. In addition, modifications to diets affect manure production and composition (Arndt et al., 2015), which will have an effect on inputs needed for fertilization.

As N-CyCLES is a requirement-based model, we must assume that as long as initial requirements are met, animals and crops will maintain productivity; thus, we assumed no response to diet or fertilizer changes. Assuming change in production when requirements are exceeded is an error often made in requirement-based models and should not be done (St-Pierre and Weiss, 2012). Furthermore, it will be important to validate that proposed requirements and diets for AA_rev can sustain milk production and composition set in our simulations. As explained before, linear programming optimization may also force the selection or modification of equations to meet linearity which may then reflect less accurately the biology. Finally, the interpretation of the analysis must be limited to the scenario situations and inputs. Nevertheless, the consistent conclusions across regions and models, and the different scenarios tested with the sensitivity analysis suggest that the reported trends are robust enough to be generalizable.

CONCLUSIONS

The current trend toward balancing dairy rations for individual EAA seems to be justified. Simulations to maximize income while balancing for His, Lys, and Met using a factorial approach positively affect the FNI predictions and decrease the environmental effect of dairy farming across different dairy regions in Canada with different management scenarios. Assuming no change in milk protein yield, formulation for 3 EAA (His, Lys, and Met) using a variable efficiency of utilization with a factorial approach of requirement and supply without balancing for MP has the potential to reduce GHG and N farm balance, with no negative and even a slight positive effect on FNI. This could also enhance animal N efficiency in opposition of having both MP and AA constraints as in the AA_2001 approach. However, more work is still needed to refine AA formulation model to meet requirements of all EAA, and also include potential interaction with energy supply, both in terms of type of energy and quantity. As this was a modeling and simulation approach, applications on commercial dairy farms should be undertaken to validate that diet optimization performs as predicted, and also to determine if gains in FNI are really obtainable.

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APPENDIX

Equations and studies used to develop the equations of the efficiency of utilization of His, Lys, and Met for the revised AA formulation approach:

$$His_{effi} = 2.001 - \frac{His_{supi}}{NE_L} \times 1.051 + \left(\frac{His_{supi}}{NE_L}\right)^2 \times 0.180 - DIM \times 0.00167 + DIM \times 5.78e^{-6},$$

$$Lys_{effi} = 1.983 - \frac{Lys_{supi}}{NE_L} \times 0.371 + \left(\frac{Lys_{supi}}{NE_L}\right)^2 \times 0.0246 - DIM \times 0.00147 + DIM \times 4.23e^{-6}, \text{ and}$$

$$Met_{effi} = 1.571 - \frac{Met_{supi}}{NE_L} \times 0.715 + \left(\frac{Met_{supi}}{NE_L}\right)^2 \times 0.1019 - DIM \times 0.00017,$$

where His_{effi}, Lys_{effi}, and Met_{effi} = His, Lys, and Met efficiency of utilization at AA supply i; His_{supi}, Lys_{supi}, and Met_{supi} = AA supply level i, g/d; NE_L = NE_L requirements, Mcal/d.

Table A1. Studies used to develop the equations of the efficiency of utilization of His, Lys, and Met for the revised AA formulation approach

Study
Agle et al. (2010)
Arriola Apelo et al. (2014)
Berthiaume et al. (2006)
Blouin et al. (2002)
Borucki Castro et al. (2008)
Boucher et al. (2007)
Brito and Broderick (2006)
Broderick et al. (2009)
Broderick et al. (2015)
Davidson et al. (2003)
Doepel et al. (2016)
Giallongo et al. (2015)
Giallongo et al. (2016)
Giallongo et al. (2017)
Halmemies-Beauchet-Filleau et al. (2014)
Korhonen et al. (2002)
Lee et al. (2012a)
Lee et al. (2012b)
Lee et al. (2015)
Leonardi et al. (2003)
Mjoun et al. (2010)
Noftsger and St-Pierre (2003)
Nursoy et al. (2018)
Olmos Colmenero and Broderick (2006)
Ordway et al. (2009)
Pereira et al. (2017)
Raggio et al. (2004)
Reynal and Broderick (2005)
Savari et al. (2018)
Socha et al. (2005)
Socha et al. (2008)
Vargas-Rodriguez et al. (2014)
Wang et al. (2010)

Table A2. Chemical composition of feed ingredients used in ration formulations for each region[1]

Item	DM, % feed	EE[2]	NDF	ADL	CP	NDIN	ADIN	Starch
The Maritimes								
Corn silage-35[3]	34.83	3.23	46.30	3.07	9.18	1.30	0.81	31.37
Alfalfa silage-83	38.67	3.02	45.68	7.14	18.57	3.28	1.60	1.94
Mix silage-74	41.67	3.14	51.52	6.22	16.05	3.51	1.39	2.12
Grass hay-52	85.34	2.52	58.68	4.83	11.88	3.90	1.13	1.48
Corn grain-27	87.67	4.25	9.48	1.02	9.79	0.70	0.30	68.89
Straw-120	90.60	1.72	72.40	8.80	7.28	0.00	0.80	1.70
Barley grain-08	88.83	2.21	20.80	2.09	12.71	1.80	0.51	54.44
Wheat grain-116	88.33	2.30	16.75	1.82	14.16	1.70	0.22	62.31
Canola meal-19	90.00	5.40	29.80	10.56	39.20	6.30	2.49	1.46
Calcium soaps fat-40	95.76	83.94	0.00	0.00	0.00	0.00	0.00	0.00
Soybean meal-104	88.00	9.09	29.70	0.70	53.41	14.99	1.06	1.65
Soybean meal-107	89.60	1.11	9.79	0.56	52.49	0.70	0.41	1.65
Corn gluten meal-25	86.67	2.50	11.64	1.74	62.54	3.60	3.08	15.30
Corn distillers-23	64.37	15.72	35.71	4.52	35.50	8.60	2.66	4.10
Central Canada								
Corn silage-35	35.00	3.07	42.59	2.74	7.88	1.32	0.80	31.37
Alfalfa silage-83	40.17	2.88	45.27	7.22	20.08	2.90	1.60	1.94
Mix silage-74	38.83	3.12	51.35	6.00	16.84	3.53	1.35	2.12
Grass hay-52	85.34	2.59	59.92	4.84	12.83	3.90	1.14	1.48
Corn grain-27	87.00	4.25	9.51	1.03	9.61	0.71	0.33	68.89
Straw-120	88.50	1.90	71.50	8.94	9.80	0.00	0.80	0.00
Wheat grain-116	88.00	3.11	25.75	2.80	15.14	1.70	0.20	62.31
Barley grain-08	91.00	2.20	20.80	2.09	12.16	1.80	0.52	54.44
Canola meal-19	89.50	4.36	29.96	10.56	40.76	6.30	2.40	1.46
Calcium soaps fat-40	96.48	84.36	0.00	0.00	0.00	0.00	0.00	0.00
Soybean meal-104	89.60	8.10	21.70	1.50	46.30	7.75	0.40	1.65
Soybean meal-107	89.50	1.10	9.80	0.50	53.80	0.70	0.40	1.65
Corn gluten meal-25	86.67	2.50	11.64	1.74	62.54	3.60	3.08	15.30
Corn distillers-23	68.50	15.15	32.30	3.55	29.65	7.78	3.58	4.10
The Prairies								
Corn silage-35	34.83	3.23	46.30	3.07	9.18	1.30	0.81	31.37
Alfalfa silage-83	45.27	2.88	45.27	7.22	20.08	2.90	1.60	1.94
Barley silage-10	35.50	3.50	56.30	5.60	12.00	1.60	0.90	6.30
Pea-34	87.28	1.86	13.67	1.06	23.91	4.44	4.38	48.00
Barley grain-08	88.00	2.20	20.80	1.90	12.40	1.80	0.50	54.44
Straw-120	88.50	1.90	71.50	8.94	5.00	0.00	0.80	0.00
Wheat grain-116	88.00	2.30	9.48	1.02	9.79	1.70	0.30	62.31
Grass hay-52	85.34	2.52	58.68	4.83	11.88	3.90	1.13	1.48
Legume-haylage-83	48.33	2.76	44.82	6.98	17.82	3.10	1.60	1.94
Wheat distillers-43	90.60	5.00	34.00	13.40	37.50	21.45	5.23	3.20
Canola meal-19	92.00	4.36	29.96	10.56	40.00	6.30	2.40	1.46
Calcium soaps fat-40	96.48	84.36	0.00	0.00	0.00	0.00	0.00	0.00
Soybean meal-104	88.00	9.09	29.70	0.70	53.41	14.99	1.06	1.65
Soybean meal-107	89.50	1.10	9.80	0.56	52.49	0.70	0.41	1.65
Corn gluten meal-25	86.67	2.50	11.64	1.74	62.54	3.60	3.08	15.30

Mineral	DM, % feed	Ca	P	Mg	Na	Cl	S
$CaCO_3$	98.00	38.90	0.00	0.05	0.06	0.00	0.00
$CaHPO_4$	97.00	22.00	19.00	0.59	0.05	0.00	1.14
MgO	98.00	0.00	0.00	56.20	0.00	0.00	0.00
$CaSO_4·2H_20$	97.00	23.28	0.00	0.00	0.00	0.00	18.62
NaCl	98.00	0.00	0.00	0.00	40.00	60.00	0.00
$MgSO_4·7H_20$	97.00	0.00	0.00	9.80	0.00	0.00	13.23

[1]% of DM, unless noted otherwise.

[2]Ether extract.

[3]Number represents feed ID in the NRC (2001) tables.

Table A3. Crops[1] used in rotation (R) for all land units (LU) for each region with their yields and requirements (rqt)

Year	1	2	3	4	5	6	7	Yield t/ha	N rqt kg/ha	P rqt, kg/ha	Cost $/ha	Margin $/ha[2]	Forage margin $/ha[2]
The Maritimes													
LUrich R1	BG+AS	AS	MS	MS				4.3	18.8	26.9	413.86	389.92	329.63
LUrich R2	BG	BG	CA					2.7	67.9	30.8	293.79	419.37	82.41
LUrich R3	CS	BG+AS	AS	MS	MS			5.9	28.8	27.5	457.40	530.55	482.32
LUrich R4	CS	CS	BG+AS	AS	MS			7.3	46.8	28.5	513.72	655.73	607.50
LUrich R5	BG+AS	AS	MS	MS	GH			4.2	33.3	27.3	368.89	410.73	362.50
LUpoor R1	BG	BG+AS	AS	MS	MS			4.1	37.0	43.3	385.88	383.40	288.43
LUpoor R2	BG	CA	BG+AS	AS	MS	MS		3.7	49.0	46.3	386.94	420.39	208.99
LUpoor R3	BG+AS	AS	MS	MS				4.3	30.6	40.6	413.86	389.92	329.63
LUpoor R4	BG+AS	AS	MS					4.4	27.5	42.5	439.20	387.49	307.11
LUpoor R5	BG+AS	AS	MS	MS	GH			4.2	46.5	39.8	368.89	410.73	362.50
Central Canada													
LUrich R1	CS	AS-I	AS	MS				8.7	38.4	29.3	576.24	848.18	848.18
LUrich R2	CG	CG	SB					6.4	97.5	21.6	623.68	1,281.79	0.00
LUrich R3	CG	CS	WG+AS	AS	MS	MS	GH	7.7	66.0	28.0	545.65	920.37	642.25
LUrich R4	WG+AS	AS	MS	MS				5.5	20.6	26.8	521.75	518.79	501.22
LUrich R5	CS	CS	WG+AS	AS	MS	MS		9.8	57.7	27.9	600.64	968.29	956.58
LUpoor R1	CS	AS-I	AS	MS				8.7	55.0	48.1	576.24	848.18	848.18
LUpoor R2	CG	CG	SB					6.4	115.0	38.3	623.68	1,281.79	0.00
LUpoor R3	CG	CS	WG+AS	AS	MS	MS	GH	7.7	83.5	42.6	545.65	920.37	642.25
LUpoor R4	WG+AS	AS	MS	MS				5.5	32.5	40.6	521.75	518.79	501.22
LUpoor R5	CS	CS	WG+AS	AS	MS	MS		9.7	75.0	43.7	600.64	968.29	956.58
The Prairies													
LUrich R1	CS	CS	BG+AS	AS	AS	AS		6.3	18.3	23.3	573.85	373.66	413.68
LUrich R2	CS	BG	BG+AS	AS	AS	AS		5.5	10.0	22.5	511.55	320.14	294.29
LUrich R3	BG	BG	PE					5.1	26.6	30.0	478.39	422.30	80.39
LUrich R4	CS	CS	PE	BG+AS	AS	AS	AS	5.8	18.5	25.7	569.43	353.91	354.58
LUrich R5	CS	BG	PE	BG+AS	AS	AS	AS	5.1	11.4	25.0	516.02	308.03	252.25
LUpoor R1	CS	BS	BG+AS	AS	AS	AS		5.79	24.17	47.50	494.65	573.29	613.31
LUpoor R2	CS	BG	BG+AS	AS	AS	AS		5.5	24.1	47.5	511.55	320.14	294.29
LUpoor R3	BG	BG	PE					5.1	43.3	43.3	478.39	422.30	80.39
LUpoor R4	CS	BS	PE	BG+AS	AS	AS	AS	5.33	23.5	47.8	501.54	525.02	525.69
LUpoor R5	CS	BG	PE	BG+AS	AS	AS	AS	5.1	23.5	47.8	516.02	308.03	252.25

[1]BG = barley grain, CS = corn silage, AS = alfalfa silage, MS = mixed silage, CA = canola, GH = grass hay, CG = corn grain, SB = soybean, WG = wheat grain, BS = barley silage, PE = field pea, AS-I = alfalfa silage pure implantation.

Table A4. Nutrient and feed minimal and maximal constraints used in the formulation of the lactating dairy rations

Item	Minimum	Maximum
Nutrient		
NDF, % DM	25	—
Forage NDF, % DM	19	—
NFC, % DM	—	42
RDP, % DM	9	12
Ether extract, % DM	—	6.5
Feed		
Corn silage, % DM	—	40
Corn grain, % DM	—	40
Wheat grain, % DM	—	20
Barley grain, % DM	—	20
Grass hay, % DM	—	10
Distiller grain, % DM	—	10
Rumen-protected fat, % DM	—	7