Whole-Herd Optimization with the Cornell Net Carbohydrate and Protein System. III. Application of an Optimization Model to Evaluate Alternatives to Reduce Nitrogen and Phosphorus Mass Balance

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ABSTRACT

The objectives of this paper were to use a linear programming model previously described to evaluate different alternatives for reducing excess nutrients that may influence water quality on a case study farm (300 lactating cows on 430 ha of cropland growing alfalfa, grass, and corn). Several alternatives perceived to influence farm nutrient balance were evaluated for their potential to reduce N and P mass balance. Dividing lactating cow diets into three groups according to their level of milk production versus a one-group total mixed ration decreased mass balance (tonne/yr) from 51.7 to 44.7 for N, from 6.7 to 6.1 for P and from 16.2 to 14.8 for K with little influence on return over feed costs. Increasing forage quality (lower neutral detergent fiber and higher crude protein) did not improve N balance because of the increased N fixation from the air to the soil, but it increased returns over feed costs by $31,385. Improving yields to the maximum potential for the farm reduced mass balance by 29, 51, and 100% for N, P, and K, respectively, and increased returns over feed costs by $70,579. Changing the crop hectare proportions to more corn and less alfalfa reduced N and K balances by 19 and 29%, respectively, and increased returns over feed costs $39,383. Increasing annual milk production 10% by increasing milk production per head 10% compared with increasing animal numbers at the current average milk production per cow until total milk increased 10% gave $34,132 more return over feed costs with less N, P, and K retained on the farm.

(**Key words:** linear programming, mass nutrient balance, Cornell Net Carbohydrate and Protein System, optimization)

Abbreviation key: CNCPS = Cornell Net Carbohydrate and Protein System; **CS** = corn silage; **DAFOSYM** = *Dairy Forage System Model;* **eNDF** = effective NDF; **GH** = grouping cows and changing hectares; **GHa** = grass hay a; **GHA** = grouping cows and changing hectares; **GHb** = grass hay b; **GHM** = grouping cows and hectare increases; **GQ** = grouping and improved forage quality; **GQYH** = grouping cows, increasing yield and forage quality; **GY** = grouping and increasing yield; **HMSC** = high moisture shell corn; **ME** = metabolizable energy; **MMLa** = alfalfa silage; **MMLb** alfalfa silage; **MP** = metabolizable protein; **NEDHI** = Northeast Dairy Herd Improvement; **O** = original.

INTRODUCTION

In the United States and Europe, increasing public attention has focused on animal agricultural production systems as a major nonpoint source of pollution affecting the quality of streams and groundwater resources (13, 20, 23, 26). The two nutrients from animal production systems most frequently considered are N and P because of their impact on water quality and eutrophication. Much research related to nutrient management has been conducted to reduce N and P pollution. Nutrient management is a complex issue because interrelationships among manure management, soil conservation, crop production, animal nutrition, and economic consequences must be considered. Because agricultural scientists have traditionally specialized in one field (e.g., crop or soil or animals), it has been difficult for a single-discipline researcher to understand the overall economic and environmental consequences of management decisions at the whole farm level. Therefore, much of the previous nutrient management research related to dairy farm operations has focused on altering the impact of specific farm components such as manure management (23), crop production (14), or animal nutrition (20) to improve nutrient utilization efficiency of the whole farm and reduce nutrient losses.

On dairy farms, feed N and P are the source of 60 to 80% of the total nutrients imported across the farm boundary (10, 11). Animals are the most important nutrient consumers and producers on a dairy farm. Increases in the efficiency with which animals utilize nu-

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trients may have the greatest possibilities for changing mass nutrient balances (4, 8, 17). Pell (16) and Klausner et al. (12) reported that manure nutrient excretion could be reduced up to 30 to 40% through optimization of nutritional management. Kohn et al. (13) proposed a model to analyze the relative importance of altering each component (manure management, soil, crop, and animal nutrition) of dairy farm nutrient management on N reduction and concluded that optimizing the feeding strategy played the most important role in reducing N balance.

Nutrient management should focus on maximizing utilization of farm-raised feeds, and purchased feeds should be used only as needed to support animals' nutrient requirements to meet the farm's production goal (5, 11, 16, 20, 22). However, the ability to modify crop rotation plans to provide a mix of homegrown feeds that better match herd requirements while minimizing excess nutrients in the ration, as well as to best match environmental and financial goals has been hampered by lack of sufficient tools. For this reason, we have developed an optimization model (24) to provide decision support in designing a whole farm nutrient management plan.

Although researchers have demonstrated that dietary manipulations of nutrients can reduce intake and excretion (5, 11, 22), systematic analysis has been limited by the extent to which the whole farm environmental impact could be influenced by feeding program and forage resource. The Dairy Forage System Model (**DAFOSYM**) was designed to evaluate alternative forage production systems for dairy farms (18). This model accounts for the effects of changes in crops given annual production and capital costs. Recently, a dairy herd submodel was added to DAFOSYM to simulate the long-term performance and economics of alternative dairy farm systems (18, 19). The nutrition submodel is based on that of the National Research Council (15) and, therefore, does not consider differences in feed content of carbohydrate and protein fractions.

The objectives of this paper were to use a whole-herd optimization model developed for the Cornell Net Carbohydrate and Protein System (**CNCPS**) model (24) on a case study farm to 1) evaluate the economic and environmental impacts of feeding a high producing cow ration as a one-group TMR to all lactating cows; 2) evaluate the economic and environmental impacts of an increase in forage NDF and decrease in forage CP; 3) predict the economic and environmental impact of an increase in forage yield; and 4) evaluate the economic and environmental impact of increasing milk production.

MATERIALS AND METHODS

Case Study Farm

The case study dairy used was the Cornell Teaching and Research Farm described by Wang et al. (25). The description of herd groups, current rations, and feed analysis from this farm were described in Tedeschi et al. (21) and Wang et al. (24). These data are the required inputs and feed analyses for the CNCPS to calculate animal requirements and feed biological values. Feed analyses required for the CNCPS were from farm records of feed analyses determinations performed at the Northeast Dairy Herd Improvement (**NEDHI**) laboratory in Ithaca, New York. Prices of homegrown feeds reflect costs of production.

The **MMLb** and **GHb** used represent the high quality (mean of NDF-1 standard deviation and mean of CP+1 standard deviation, respectively) legume silage and grass hay in the Northeast area in the NEDHI database from May 1, 1997, to April 30, 1998. The MMLb and GHb were used to evaluate the impact of increasing forage quality. Table 1 lists the mean and standard deviations of NDF and CP of legume silage and grass hay from the NEDHI database.

Kaiser and Combs (8) and Glenn (7) stated that forages containing more protein generally are lower in fiber and have greater energy content. However, it cannot be assumed that each percentage change in NDF results in the same proportional change in CP. For our evaluation of the impact of a change in forage quality, we used an increase of one standard deviation in CP content coupled with the decrease of one standard deviation in NDF content because that was the field analytical data that was available in the NEDHI database.

According to farm records, the average yield of corn silage (**CS**), alfalfa silage (**MMLa**), grass hay (**GHa**), and high moisture shell corn (**HMSC**) was 6.9, 4.7, 5, and 3 tonne/ha (DM basis), respectively, in 1996. Total farm crop production for CS, MMLa, GHa, and HMSC were 1346, 874, 120, and 75 tonne from 195, 186, 24, and 25 ha for CS, MMLa, GH, and HMSC, respectively. The annual milk production for the year 1996 was 3888 tonne.

Alternatives Evaluated

Original (O). Diets from October 1996 were used to calculate the base mass nutrient balance. One TMR was used for all lactating cows.

Grouping (G). In this alternative, lactating cows were divided into three groups according to their levels of milk production to evaluate the environmental and economic consequence. Crop yield (tonne/ha), forage

Table 1. Northeast Dairy Herd Improvement mean and standard deviation (SD) of NDF and CP of legume silage and grass hay.

	NDF			CP		
	Mean	SD	N	Mean	SD	N
Legume silage	49.3	7.9	10,268	18.3	3.3	10,233
Grass hay	59.6	7.8	2320	13.5	3.5	2328

quality, and crop hectares were the same as the 1996 farm record.

Grouping and improved quality (GQ). To evaluate how improved quality can influence mass balance and return over feed costs, we replaced the forage MMLa and GHa with the previously described high quality MMLb and GHb from the NEDHI database.

Grouping and increasing yield (GY). We increased average crop yield to the potential for the farm (50% increase over the current yields) for the whole farm in this alternative with 7.1, 10.4, 7.5, and 4.5 tonne being used for alfalfa silage, corn silage, grass hay, and high moisture shell corn, respectively. These increased yields reflect the best yield record of each crop from the case study farm in 1996, since all fields have a similar yield potential. The excess forage production was assumed to be sold off farm.

Grouping and changing hectares (GH). This alternative modified cropland use to provide a mix of farm-raised feeds that best match herd requirements while minimizing excess nutrients in the ration. Minimum and maximum of crop hectares were set at 0 and 430 ha, respectively, for the model to find the best combination of crop hectares.

Grouping, increasing yield, quality, and changing hectares (GQYH). This alternative summed up the contribution of the above alternatives to estimate the maximum reduction in nutrient balances.

Increasing annual milk production 10% by increasing milk production per cow 10%, while changing grouping and hectares (GHM). This alternative evaluated the impact of increasing milk production per cow 10% (from herd average of 10,755 kg to 11,830 kg) to achieve a 10% annual milk production increase on the farm. The three-group TMR feeding for lactating cows and modifying hectares was used for this alternative.

Increasing annual milk production 10% by increasing animal numbers at the current milk production level until milk production increased 10%, while changing grouping and hectares (GHA). This alternative evaluated the impact of increasing animal numbers (from 690 to 760, including replacement animals) to increase annual milk production 10% on the farm. The three-group TMR feeding program for lactating cows and modifying hectares was used for this evaluation.

Setting Constraints in the Optimization Model

The structure and procedure for using this whole farm optimization model was described by Wang et al. (24). The following describes the constraints set for evaluating the alternatives.

Animal nutrient requirements constraints. Table 2 lists the nutrient requirement constraints set for each group of animals. The minimum and maximum values for nutrient requirements for each group were suggested by dairy consultants (Larry Chase and Winfield Burhans, personal communication) who are familiar with the CNCPS system (6). The same constraints were used for each alternative. In the rebalancing process, we determined DMI for each group using the actual DMI from farm records (October 1996). Metabolizable energy (**ME**) and metabolizable protein (**MP**) were set as close to the requirement as possible, except for dry cows. We set it at higher than 120% of requirement for the late dry groups to reach levels recommended by the NRC (15). Effective NDF (**eNDF**) was set at a value greater than 20% of DMI to maintain the rumen pH value at more than 6.2. The rumen N and peptide balance were no lower than the requirement to insure adequacy to meet the bacterial requirement. However, a maximum value was set at 40% above requirement to prevent excess N excretion. The Ca and P were set within a range to satisfy the biological requirement and prevent excess excretion.

Transition heifers were not included in the rebalancing process because of their small contribution to forage use.

Cropland, nutrient excretion, and economic constraints. Feed production is determined by yield (tonne/yr) and cropland (ha). Crop yields and hectares are input variables in the optimization model. In evaluating the alternatives, we fixed cropland hectares at 186, 195, 24, and 25 ha for alfalfa, corn silage, grass hay, and HMSC, respectively, for the alternatives of O, G, GQ, and GY. For the alternatives of GH, GQYH, GHM, GHA, the minimum and maximum values of cropland were set at 0 and 430, respectively, to find the best combination of forage production to match animal requirements. We assumed 20 and 24% of DM was lost during storage, processing, and feeding for haylage and corn silage, respectively. To account for feed refusal, 6.5% of DMI was added to the feed requirement.

The whole farm optimization model can be constrained to the nutrient excretion and economic outcome within a range. In evaluating the alternatives, we compared the impact of alternatives on the whole farm N and P mass balance rather than nutrient excretion, so that the nutrient excretion constraints could be set at a wide range (0 and 100 tonne for minimum and maximum values, respectively). We also set a wide range (0 to one million) for economic outcome (return over feed cost) because our objective function is the maximum value of return over feed cost. We assume differences in returns over feed costs likely reflect differences in profits because the alternatives evaluated would have little impact on animal facilities, feed storage, machinery, and labor on this farm.

Objective Function

We set the objective function for maximum profit to determine the impact of various alternatives on mass nutrient (N, P) balance and returns over feed costs.

Assumptions

The example presented here considered the farm to be in steady state within a year, which means, among other things, that the herd size remained unchanged and the effect of variation in temperature on DMI was ignored. Normally, in winter the animals consume more DM than in summer. We can further divide the simulation period into months or seasons to account for this. In this model, we assumed the fertilizer application rate of a crop is the same; however, the fertilizer application rate was field specific and influenced by manure application and crop rotation history. The cost for fertilizer is ignored in this paper because of its small contribution to the expense of this case study farm (less than 1%).

Orts exported to other farm units (beef and sheep) were estimated by the farm manager to be 6.5% of DMI; the manure from these units is spread on land not included in this study. Meat sold off the farm was assumed to be proportionally the same in each alternative. We also assumed this farm carried no feed inventory (purchased and homegrown) to the next calendar year, and all surplus feed was sold.

RESULTS AND DISCUSSION

The original rations fed to each group were as presented by Wang et al. (24). Table 3 summarizes changes in feed allocation to lactating and nonlactating cattle as alternatives evaluated changed. Table 4 summarizes annual totals for farm raised and purchased feeds for each alternative. Tables 5 to 7 show the mass balance and returns over feed costs for each alternative. Figures 1 and 2 summarize the mass balance and return over feed costs with the various alternatives. These results demonstrate how this model can be used to identify alternative feeding strategies that minimize mass nutrient balances and maximize returns over feed costs. The alternatives indicate that changing diet grouping strategy, improving forage quality, increasing crop yield, and changing crop acres each contribute to the reduction of mass balance while increasing the returns over feed costs.

Dividing lactating cow diets into three groups according to their level of milk production decreased mass balance 7.0, 0.6, and 1.4 tonne/yr for N, P, and K, respectively (Table 5). This approximates a 14, 9, and 9% reduction for N, P, and K, respectively, in comparison with the original scenario, which uses a one group TMR diet for all lactating cows. On many dairy farms, a one-group TMR is fed to all lactating cows for convenience. These rations are often formulated to meet the requirements of the high cow groups, resulting in excess nutri-

Table 2. Minimum and maximum values (% of requirements) used in the optimization model.[1]

Group	DMI[2]	ME	MP	eNDF	RUMN	RUMPEP	Ca	P
HiC	99/101	100/110	100/110	20/50	100/130	100/115	100/150	100/120
MedC	99/101	100/110	100/110	20/50	100/130	100/115	100/150	100/120
LowC	99/101	100/110	100/110	20/50	100/130	100/110	100/150	100/120
FarD	97/100	120/140	120/140	20/50	100/140	95/110	100/150	100/150
ClzD	98/101	120/140	120/140	20/50	100/140	95/110	100/150	100/150
OpnH	100/105	100/113	100/110	20/50	100/140	100/120	100/150	100/120
BrdH	95/98	100/130	100/130	20/50	100/140	100/120	100/150	100/120

[1] HiC: High cow; MedC: medium cow; LowC: low cow; FarD: far-off dry cow; ClzD: close-up dry cow; OpnH: open heifer; BrdH: bred heifer. ME: metabolizable energy; MP: metabolizable protein; eNDF: effective NDF; RUMN: rumen nitrogen balance; RUMPEP: rumen peptide balance.

Table 3. Feed allocation (tonne/yr) to lactating and nonlactating cow groups in original and rebalanced alternatives.[1]

	O		G		GQ		GY		GH		GQYH		GHM		GHA	
Ingred.[2]	Lac[3]	Non[3]	Lac	Non	Lac	Non	Lac	Non	Lac	Non	Lac	Non	Lac	Non	Lac	Non
MMLb	0	0	. . .	. . .	267	433	. . .	. . .	. . .	306	168	371	. . .	. . .	. . .	. . .
MMLa	433	182	70	630	. . .	12	15	537	11	551	. . .	12	8	255	16	243
CS	663	530	872	151	616	406	1126	415	1189	. . .	761	613	1159	616	1234	630
GHa	0	256	108	12	. . .	. . .	118	62	70	. . .	. . .	. . .	94	13	25	4
GHb	0	0	. . .	. . .	120	. . .	. . .	. . .	. . .	. . .	552	62	. . .	. . .	. . .	. . .
HMSC	614	167	623	176	627	46	531	120	516	150	639	28	664	144	600	160
WCS	197	2	145	118	224	152	. . .	22	9	163	. . .	87	. . .	162	109	207
SHUL	98	0	228	113	241	147	199	. . .	188	20	. . .	. . .	167	. . .	214	53
SBM	246	85	215	. . .	110	. . .	304	39	300	2	237	23	320	. . .	282	. . .
SOY+	112	8	77	6	133	6	42	8	52	7	. . .	5	73	8	87	6
MVII	0	17	. . .	17	. . .	17	. . .	17	. . .	17	. . .	17	. . .	17	. . .	18
LIME	23	1	27	. . .	28	2	29	. . .	28	2	28	2	30	. . .	31	. . .
CASUL	10	1	36	3	36	5	34	5	36	8	36	7	36	9	39	13
DICAP	14	1	14	. . .	12	. . .	15	1	14	. . .	20	. . .	16	. . .	14	. . .

[1] O: Original diets; G: three groups of lactating cows; GQ: increasing forage quality and grouping lactating cows; GY: after increasing forage yield and grouping lactating cows; GH: after changing crop hectares and grouping lactating cows; GQYH: after increasing forage quality, yield and grouping lactating cows; GHM: increasing annual milk production by 10%, changing crop hectares and grouping lactating cows; GHA: increasing 10% animal numbers, changing crop hectares and grouping lactating cows.

[2] MMMLb: alfalfa silage; MMLa: alfalfa silage; CS: corn silage; GHb: grass hay; GHa: grass hay; HMSC: high moisture shell corn; WCS: whole cottonseed; SHUL: soy hull; SBM: soybean meal; SOY+: roasted soy; MVII: grain mix; LIME: lime stone; CASUL: calcium sulfate; DICAP: dicalcium phosphate.

[3] Lac: lactating cow groups, Non: non-lactating cow groups.

ents fed to other groups. This alternative requires dividing the herd into groups according to requirements, which requires more facilities and labor. More detailed financial analysis on labor and facility costs are required to evaluate the net profit from using this strategy.

In the GQ alternative (Table 6), the purchased feed N was reduced by 1.7 tonne/yr and return over feed costs increased by 4% because less N from off farm resources was required, but N balance was not improved because of increased N fixation. In Klausner et al. (12), when forage NDF was reduced by one standard deviation, the ME balance was increased by 3 Mcal/d in lactating cows. Lower NDF in the forage results in a higher concentration of NFC, which are fermented rapidly in the rumen. Thus, the model would predict an increase in ruminal microbial growth, resulting in higher MP from bacteria. Reduction in NDF also reduced effective NDF, which is the portion of NDF that stimulates rumination, saliva production, and rumen motility, all of which promote normal ruminal pH. This alternative illustrates the importance of being able to account for plant and animal interactions in improving whole farm nutrient balances. Maturity at harvest affects the energy, fiber, water, and protein content of the feeds. The chemical and physical composition of the silage affects rumen function and animal efficiency. For example, harvesting alfalfa at an immature stage increases the energy value and total protein content. However, the degradable protein intake may be increased because of the lower cell wall content of the forage and likely higher water content of the forage at ensiling. Also the effectiveness of the fiber in maintaining an optimum pH in the rumen for maximum fiber digestion may be decreased.

Increasing the forage yield by 50% (GY alternative, Table 6), resulted in a predicted increase in return over feed costs by 11% ($664,279 vs. $734,858) and a predicted decrease in N, P and K mass balance by 12.8, 3.1 and 14.8 tonne/yr, respectively, which is an approximate 29, 50, and 100% reduction for N, P, and K, respectively, in comparison with the G alternative. In this alternative, 500 tonne (DM) of excess alfalfa silage (shown as a minus value for purchased feed) is sold off farm, exporting 14, 1.7, and 12 tonne of N, P, and K, respectively. However, N fixation increased 7.1 tonne because of the increased yield. Less purchased feed reduces nutrient imports by 20.6, 3.1, and 15.6 tonne for N, P, and K, respectively. The reduction in purchased feed is in part due to increased ME, and yield of bacterial protein, due to increased NFC because of the increased use of CS, which decreased the requirement for purchased energy.

By substituting hectares of corn silage for alfalfa silage (GH alternative, Tables 4 and 6), there is a 8.3 and 4.5 tonne/yr reduction in N and K mass balance, respectively. This is a reduction of approximately 20 and 30% for N and K, respectively, in comparison to the G strategy. P increases 1 tonne because of the increasing P fertilizer required for more corn hectares. Returns over feed costs from this alternative also increased 6% ($664,279 vs. $703,662). The reduction in

Table 4. Herd feed required and farm raised feeds (tonne/yr) and hectares from each alternative.[1]

	Alternatives							
Ingred.[2]	O	G	GQ	GY	GH	GQYH	GHM	GHA
MMLb	. . .	. . .	699	. . .	. . .	642	. . .	. . .
MMLa	614	699	12	552	263	12	252	327
CS	1193	1023	1023	1541	1285	537	1193	1102
GHa	257	120	. . .	180	575	. . .	677	664
GHb	. . .	. . .	120	. . .	. . .	1329	. . .	. . .
HMSC	781	799	683	645	803	751	954	932
WCS	199	261	374	14	156	70	157	179
SHUL	98	342	386	209	127	. . .	70	351
SBM	330	207	97	348	313	192	324	303
SOY+	120	92	148	50	7	5	28	6
MVII	17	17	17	17	17	17	17	17
LIME	23	28	28	30	29	29	31	30
CASUL	12	39	42	39	47	42	41	51
DICAP	15	14	13	16	18	14	20	22
	tonne/yr (ha)							
Farm raised feed								
MMLb	. . .	. . .	874 (186)	. . .	. . .	748 (105)	. . .	. . .
MMLa	874 (186)	874 (186)	. . .	1321 (186)	395 (84)	. . .	328 (70)	323 (69)
CS	1346 (195)	1346 (195)	1346 (195)	2048 (195)	2291 (332)	1810 (174)	2335 (338)	2452 (355)
GHa	120 (24)	120 (24)	. . .	180 (24)	70 (14)	. . .	108 (22)	30 (6)
GHb	. . .	. . .	120 (24)	. . .	. . .	615 (82)	. . .	. . .
HMSC	75 (25)	75 (25)	75 (25)	113 (25)	. . .	311 (69)	. . .	. . .

[1] DM basis; spoilage during harvest and processing is assumed to be 20, 24% for MMLa and CS, respectively; excess forage production was sold off farm.

[2] MMLb: alfalfa silage; MMLa: alfalfa silage; CS: corn silage; GHb: grass hay; GHa: grass hay; HMSC: high moisture shell corn; WCS: whole cottonseed; SHUL: soy hull; SBM: soybean meal; SOY+: roasted soy; MVII: grain mix; LIME: lime stone; CASUL: calcium sulfate; DICAP: dicalcium phosphate; ME:(Mcal/d); MP:(Kg/d); ME%req: ME/requirement; MP%req:MP/requirement; RumN%:N supply/N requirement in rumen; Pep%:peptide supply/peptide requirement in rumen; BMP%:% of metabolizable protein from bacteria; N exec:total N excretion (g/d); P exec:total P excretion (g/d).

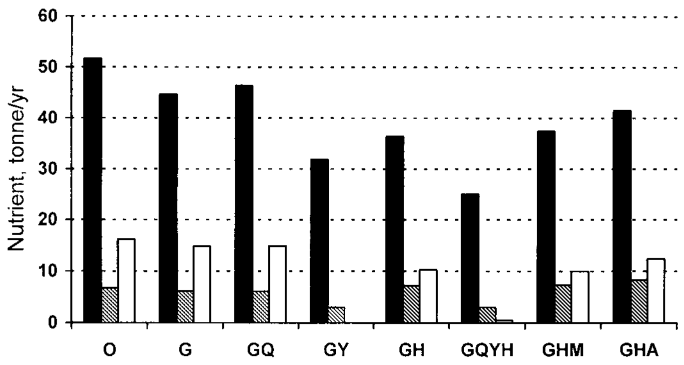

Figure 1. Mass balance of various alternatives. Black = N, diagonal = P, and white = K. O = Original, G = grouping, GQ = grouping and improved quality; GY grouping and increasing yield; GH = grouping and changing hectares; GQYH = grouping, increasing yield, quality; GHM = grouping and hectare increases; GHA = grouping lactating cows, changing crop hectares, and increasing animal number.

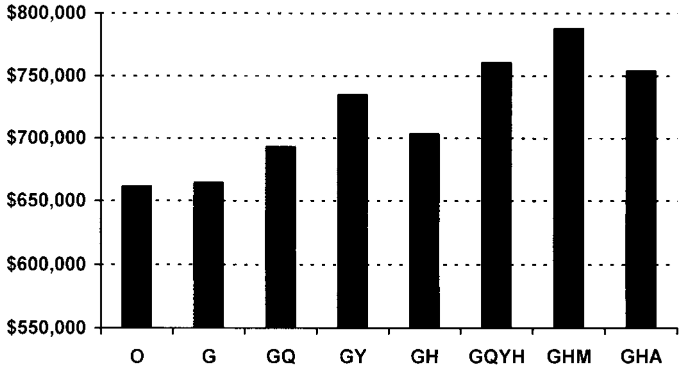

Figure 2. Profits of various alternatives. Bar = profits. Original, G = grouping, GQ = grouping and improved quality; GY = grouping and increasing yield; GH = grouping and changing hectares; GQYH = grouping, increasing yield, quality; GHM = grouping and hectare increases; GHA = grouping lactating cows, changing crop hectares, and increasing animal number.

Table 5. Mass nutrient balance for original diet O and alternative G.[1]

	O			G		
Milk[2]	3888			3872		
Profits	661,202			664,279		
	N	P	K	N	P	K
	(tonne/yr)					
Nfix	15.1	. . .	. . .	15.1	. . .	. . .
Fert	4.2	5.7	5.4	4.2	5.7	5.4
Feeds	60.9	6.8	20.4	53.4	6.2	18.9
Total imports	80.2	12.5	25.7	72.7	11.8	24.2
Milk	19.0	3.9	5.8	19.0	3.9	5.8
Meat[3]	3.1	0.9	0.2	3.1	0.9	0.2
Feeds	6.4	1.0	3.5	5.9	0.9	3.4
Total exports	29.5	5.7	9.4	28.0	5.7	9.4
Rem	51.7	6.7	16.2	44.7	6.1	14.8
%Rem	64.5	54.0	63.0	61.5	51.7	61.1

[1] O: original diet; G: three groups of lactating cows.

[2] Unit: tonne/yr, Milk price = $30.8 per 100 kg; Profit = return over feed costs; Nfix = N fixation; Fert = fertilizer; Rem = remaining; %Rem = % remaining.

[3] Total: 121 tonne, N:2.53%, P:0.72%, K:0.19% (as reported by Klausner (10)).

N balance was attributed primarily to the reduction of N fixation from 15.1 to 6.8 tonne (G vs. GH), though fertilizer N increased from 4.2 to 5.2 tonne to support the higher N requirement of corn hectares. Purchased N was also reduced 1.4 tonne due to a higher bacterial protein production from the increasing use of CS, which has a higher proportion of NFC, which increases microbial growth. Therefore, less N from purchased feeds is required. From an environmental point of view, grass and corn may therefore be superior to alfalfa (1, 2, 3).

By changing grouping strategy, crop hectares, increasing forage quality, and yield (GQYH alternative, Table 6), N, P and K mass balance were reduced 26.6, 3.7, and 15.7 tonne/yr, respectively, which is a reduction of 52, 55, and 97% in comparison to the original alternative. Returns over feed costs were increased 13% ($670,927 vs. $760,864) if all these modifications were adopted.

Evaluation of these alternatives was made possible by the use of the whole farm optimization model de-

Table 6. Mass nutrient balance for alternatives G, GQ, GY, GH, and GQYH.[1]

	G			GQ			GY			GH			GQYH		
Milk[2]	3872			3872			3872			3872			3872		
Profits	664,279			692,913			734,858			703,662			760,864		
	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K
	(tonne/yr)														
Nfix	15.1	. . .	. . .	18.1	. . .	. . .	22.8	. . .	. . .	6.8	. . .	. . .	15.5	. . .	. . .
Fert	4.2	5.7	5.4	4.2	5.7	5.4	4.2	5.7	5.4	5.2	7.1	2.4	7.5	5.5	3.0
Feeds	53.4	6.2	18.9	52.3	6.2	19.4	32.8	3.1	3.3	52.0	5.8	17.1	30.0	3.3	7.7
Imports	72.7	11.8	24.2	74.6	11.8	24.8	59.8	8.7	8.7	64.0	12.9	19.6	52.9	8.8	10.8
Milk	19.0	3.9	5.8	19.0	3.9	5.8	19.0	3.9	5.8	19.0	3.9	5.8	19.0	3.9	5.8
Meat[3]	3.1	0.9	0.2	3.1	0.9	0.2	3.1	0.9	0.2	3.1	0.9	0.2	3.1	0.9	0.2
Feeds	5.9	0.9	3.4	6.1	0.9	3.8	5.8	0.9	3.5	5.5	0.9	3.3	5.8	1.0	4.2
Exports	28.0	5.7	9.4	28.2	5.7	9.9	27.9	5.7	9.5	27.6	5.7	9.3	28.0	5.8	10.2
Rem	44.7	6.1	14.8	46.4	6.1	14.9	31.9	3.0	0.0	36.4	7.2	10.3	25.0	3.0	0.5
%Rem	61.5	51.7	61.1	62.0	51.7	60.0	53.3	34.5	0.0	56.9	55.8	52.6	47.2	34.1	4.6

[1] G: three groups of lactating cows; GQ: increasing forage quality and grouping lactating cows; GY: after increasing forage yield and grouping lactating cows; GH: after changing crop hectares and grouping lactating cows; GQYH: after increasing forage quality, yield and grouping lactating cows.

[2] Unit: tonne/yr, Milk price = $30.8 per 100 kg; Profits = return over feed costs; Nfix = N fixation; Fert = fertilizer; Rem = remaining; %Rem = % remaining.

[3] Total: 121 tonne, N:2.53%, P:0.72%, K:0.19% (as reported by Klausner (11)).

scribed by Wang et al. (24). Operational research processes have been widely used in other industries to optimally utilize resources to achieve maximum returns over costs. This approach applies the same concepts to whole farm nutrient management. Each alternative has different homegrown feed resources to allocate. This model can allocate these resources across the different animal groups to support the expected milk production level with the most efficient use of nutrients, while maximizing return over feed costs. Relative to diets O, in the G alternative, most of the CS was allocated to lactating cow groups, and alfalfa silage was shifted to the nonlactating group because lactating cows require more energy (Table 4).

In the GQ alternative, because of the improved quality of MMLb (higher energy and protein), more MMLb could be allocated to satisfy requirements in lactating groups (267 vs. 70 tonne). Therefore, less CS was required in the lactating groups, which resulted in more CS being shifted from lactating to nonlactating groups.

In the GY alternative, because more CS is available from the increased yield, lactating groups were able to use more energy from CS (1126 vs. 872 tonne in G); therefore, less HMSC is required (531 vs. 623 tonne in G). Higher NFC from the increased CS in the diets resulted in more protein from bacteria in lactating groups, requiring more soybean meal to satisfy the peptide requirement but less heat-treated soy. In the GY alternative, there is about 500 tonne MMLa in excess, which can be exported off farm.

In the GH alternative, hectares grown for each crop was adjusted to better match the forage grown to the animal requirement to minimize nutrient excretion. More CS was used in both lactating and nonlactating groups (GH vs. G). Because of the increased hectares for CS (332 vs. 195 in G), there is more CS for nonlactating groups in the GH alternative. Knowing the optimum allocation of farm forage resources is crucial in designing a whole farm nutrient management plan because the importation of concentrates depends on the homegrown forage supply.

To increase the annual milk production by 10%, increasing the milk production per head by 10% (GHM alternative, Table 7) is superior to increasing animal numbers to increase milk production by 10% (GHA alternative, Table 7) from the perspectives of both mass nutrient balance and financial outcomes. In comparison to the strategy of increasing animal numbers, the increasing milk yield per cow strategy increased return over feed cost by $34,132 ($788,213 vs. $754,081) with 3.5, 1.0, and 2.4 tonne/yr less balance for N, P, and K, respectively (Table 7). This illustrates that increasing animal productivity is an environmentally sound strategy to improve dairy farm return over feed costs compared with increasing herd size. Annual farm milk production was almost the same in GHM and GHA. Increasing the milk production 10% (GHM vs. GH) resulted in an 11% higher return over feed costs ($788,213 vs. $703,662) with a similar N, P, and K mass balance.

These alternatives indicate considerable potential to reduce mass nutrient balance on dairy farms without adversely affecting milk production and return over feed costs. Previous work (13) has suggested that the

Table 7. Mass nutrient balance for alternatives G, GHM, and GHA.[1]

	G[1]			GHM[1]			GHA[1]		
Milk[2]	3872			4300			4256		
Profits	664,279			788,213			754,081		
	N	P	K	N	P	K	N	P	K
	(tonne/yr)								
Nfix	15.1	. . .	. . .	5.7	. . .	. . .	5.6	. . .	. . .
Fert	4.2	5.7	5.4	5.7	7.1	2.0	5.1	7.5	2.0
Feeds	53.4	6.2	18.9	56.1	6.3	17.9	60.9	7.0	20.5
Imports	72.7	11.8	24.2	67.4	13.4	20.0	71.5	14.5	22.5
Milk	19.0	3.9	5.8	21.1	4.3	6.5	20.9	4.3	6.4
Meat[3]	3.1	0.9	0.2	3.1	0.9	0.2	3.1	0.9	0.2
Feeds	5.9	0.9	3.4	5.8	1.0	3.3	6.1	1.0	3.5
Exports	28.0	5.7	9.4	30.0	6.2	10.0	30.1	6.2	10.1
Rem	44.7	6.1	14.8	37.4	7.3	10.0	41.5	8.3	12.4
%Rem	61.5	51.7	61.2	55.5	54.5	50.0	58.0	57.2	55.1

[1] G: three groups of lactating cows; GHM: increasing annual milk production by 10%, changing crop hectares and grouping lactating cows; GHA: increasing 10% animal numbers, changing crop hectares and grouping lactating cows.

[2] Unit: tonne/yr, Milk price = $30.8 per 100 kg; Profits = return over feed costs; Nfix = N fixation; Fert = fertilizer; Rem = remaining; %Rem = % remaining.

[3] Total: 121 tonne, N:2.53%, P:0.72%, K:0.19% (as reported by Klausner (11)).

application of several specific practices could reduce mass nutrient balance, but their analysis did not consider the full range of practices currently available for modification on dairy farms. Rotz et al. (19) reported that more efficient strategies for protein supplementation might increase farm profit and reduce N loss from the farm. The authors also stated that these benefits were higher for greater animal densities, higher milk production, and sandier soils (19).

The present analysis demonstrates the impact various animal and crop management practices can have on farm nutrient balances. To evaluate their effects on net farm profit, the returns over feed costs used to compare alternatives in this paper must be adjusted for differences in labor cost, machinery, and facilities needed to improve forage yield, quality, crop hectares and grouping strategy. However, we believe the relative differences between alternatives evaluated here in returns over feed cost likely reflect differences in farm net return over feed costs on this particular dairy farm.

APPLICATION

The optimization model developed has the potential to be used to allocate feeds produced on the farm for most efficient use of their nutrients and can be used to identify the economic and environmental impact of animal feeding and cropping strategies. This sensitivity analysis provides insight into the potential for altering mass balance of dairy farms and the most promising means to do so.

Evaluations of alternative feeding and cropping strategies on a dairy farm as they affect farm production decisions, return over feed costs, and nutrient losses can lead to a better understanding of optimal resource allocation and its effect on the environment. This study does not prove the approach presented in this paper will give the predicted results. It would be difficult to measure the impact of intervention for each of the alternatives evaluated. This study does demonstrate how the CNCPS model can be used to address the questions of optimal feeding strategies with alternatives frequently available on dairy farms in the Northeastern United States. The results from the model evaluations can be used as guidelines for making nutrient management decisions. We believe the sustainability, profitability, and environmental impact of each dairy farm will be affected by its operator's ability to integrate information about soils, crops, and animal resources to develop its own unique whole farm plan. This optimization model can be a useful tool for that purpose.

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