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Improving Dairy Farm Sustainability I: An Approach to Animal and Crop Nutrient Management Planning

S. D. Klausner,* D. G. Fox, C. N. Rasmussen, R. E. Pitt, T. P. Tylutki, P. E. Wright, L. E. Chase, and W. C. Stone

This two-part article reports on a process for integrating knowledge to develop and evaluate nutrient management plans for dairy farms. The focus is on accounting for and managing N, P, and K on a commercial farm. The case study farm was a well managed, progressive dairy farm located in central New York with 320 lactating cows (*Bos taurus*), 290 heifers, and 600 acres of crop land. This farm had the resources and management skills that are a model for dairy farming in the future. However, mass nutrient balances indicated that 60 to 72% of imported N, P, and K were in excess of nutrient exports from the farm; 60 to 80% of the imported nutrients were from purchased feeds. Evaluation and refinement of animal diets resulted in a reduction in crude protein content of the rations by 2 percentage points while supporting a 13% increase in milk production and a 34% decrease in total N excretion. Partial budgets projected that ration reformulation increased net farm income by $40 200. Implementation of a crop nutrient management plan was expected to decrease fertilizer purchases and application expenses by about $1350, but construction of a remote manure storage pond and custom spreading of manure resulted in a decrease of net farm income of $4000. The vast quantity of data required and the complexity of the analysis indicate that developing computerized decision aid tools will be necessary to apply the process to a large number of farms.

S.D. Klausner, Dep. of Soil, Crop, and Atmospheric Sciences, Emerson Hall; D.G. Fox, C.N. Rasmussen, T.P. Tylutki, L.E. Chase, W.C. Stone, Dep. of Animal Sci.; R.E. Pitt, P.E. Wright, Dep. of Agric. and Biological Eng., Cornell Univ., Ithaca, NY 14853. Received 21 Jan. 1997. *Corresponding author (dgf4@cornell.edu).

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SUSTAINABILITY of dairy farming in the USA is dependent on both environmental and economic viability (Altieri, 1989; Neher, 1992; Fretz et al., 1993; Francis, 1995). In some cases, environmental and financial goals are in direct conflict. Analysis of the nutrient imports and exports on New York dairy farms show that nutrient imports are typi-

Abbreviations: CNCPS, Cornell Net Carbohydrate and Protein System; DHIA, Dairy Herd Improvement Association.

Table 1. Inputs and data sources for various procedures in nutrient management.

Procedure	Variables and inputs needed	Data source
Mass nutrient balance	Imports of N, P, and K in feed, fertilizer, livestock, and legume N fixation Exports of N, P, and K in milk, meat, calves and crops sold	Farm records, crop data
Manure composition and flows	Manure processing, handling, storage	Farm records, manure analysis
Ration formulation	Feed composition, feed intake Body weights and condition scores Environment (temperature, etc.)	Farm records, feed analysis, DHIA records
Crop nutrient management plan	Quantity of manure nutrients Fertilizer requirements and soil N, P, and K Crop uptake (corn, alfalfa, other) Crop rotation	Farm records, manure analysis, Manure analysis, farm records, soil tests Crop analysis and yields Farm records, cattle requirements
Partial budget analysis	Input/output prices, rations, crop yields, manure application rate and distribution, labor, capital inputs, machinery data	Farm records, literature
Nitrogen leaching†	Soil hydraulic conductivity Condition of soil surface due to rainfall, temperature, evaporation, nutrient additions Cropping pattern	Background modeling, soil tests/regression Experiment station records Farm records
Nutrient flows†	Animal inventories, rations, crop production Mass nutrient balances, N losses	Farm records, mass balance calculations LEACHN model

† Hutson et al., 1998.

cally three to eight times greater than exports (Klausner, 1993). These excess nutrients may build up in the soil, flow out in surface or ground waters, or (in the case of N) escape into the atmosphere. Nitrates in drinking water can harm animals and humans, run-off of P contributes to eutrophication of water bodies, and elevated K levels in soils and consequently feedstuffs may negatively affect animal productivity.

To some extent, an excess of nutrients is unavoidable due to inefficiencies in plant and animal metabolism, but losses can be minimized by developing crop and animal nutrient management plans that increase nutrient use efficiency (Lanyon and Beegle, 1989; Bacon et al. 1990, Hildebrand, 1990; Tamminga, 1992; Dou et al., 1996). The ability to develop such plans is limited more by the failure to integrate existing knowledge than by the lack of scientific information available to farmers and scientists.

This paper describes an approach taken by a multidisciplinary group of faculty, staff, students, extension agents, and cooperating farmers to develop a process of nutrient management planning and evaluation on a commercial, case-study dairy farm. This article describes the process of: (i) evaluation of the overall nutrient status of the farm; (ii) development of nutrient management plans for animal nutrition, crop growth, and soil fertility to maximize nutrient cycling and minimize losses; and (iii) evaluation of the impact on net farm income. The companion article (Hutson et al., 1997) describes the projected impact of excess nutrients on environmental quality.

The primary emphasis of this paper is the development of a process and the evaluation of strategies to reduce nutrient loading on dairy farms. The case study dairy farm was a well managed and profitable farm and considered to be a model for the future of dairy farming in New York State. The data presented are specific to the case study farm at the time of the research, but the process and lessons learned from the approach are applicable to other farms.

PROCEDURES

The farm, located in Central New York, had 290 heifers, 320 mature cows, and 604 acres of cropland growing primarily corn (*Zea mays* L.) and alfalfa (*Medicago sativa* L.) in a 4-yr/4-yr rotation. The soils on the farm were well drained to moderately well drained with slopes generally less than 6%. The rolling herd average milk production was 26 000 lb/yr. The only products sold off the farm were milk, calves, and cull cows. Table 1 summarizes the procedures, variables, inputs, and sources of data for the study.

Evaluation of Overall Farm Nutrient Status

A mass nutrient balance, a gross accounting of nutrients that cross the farm boundary, was done to evaluate the overall farm nutrient status. Farm imports and exports of nutrients in feeds, fertilizers, cattle, milk, and N fixation were determined from farm records, legume acreage, and percentage legume in the stand. Atmospheric N input, through symbiotic N fixation by alfalfa, was estimated to be 40% of the legume N content at harvest (Heichel et al., 1981, 1984). Nutrient composition of purchased feeds was obtained from the suppliers, and forage analyses of farm-produced feeds and milk analysis were performed by the Northeast Dairy Herd Improvement Association (DHIA, Ithaca, NY). Nutrient composition of purchased and sold cattle was estimated from Nour and Thonney (1988).

Nutrient Management Planning

Ration Reformulation. Changes in the rations for all cow groups were implemented over 12 mo to balance more closely the supply and requirement of dietary protein and energy. Cattle nutrient use was analyzed using the Cornell Net Carbohydrate and Protein System (CNCPS) as described by Fox et al. (1995). The model predicted animal performance, feed energy values, site of digestion and use of dietary protein, ruminal microbial growth efficiency, and the extent to which animal energy and protein requirements were deficient or in excess. Ration ingredients, dry matter intake, body condition scores, body weights, hair depth, and barn ambient temperatures were determined within 2 d of the monthly DHIA sampling for a period of 9 mo. Feeds were analyzed monthly by DHIA for concentrations of dry

Table 2. Product prices and input costs.

Item	Cost, dollars
Purchased feeds, $/ton as fed	
Animal protein, 95 % DM	425
Protein mix, 90 % DM	236
Whole cottonseed, 90 % DM	200
Tallow, 98 % DM	750
Corn meal, 90 % DM	100
Soy plus, 90 % DM	240
ProPeak, 90 % DM	395
Soybean Oil Meal 48% CP, 88 % DM	206
Mineral Mix,99 % DM	338
Fertilizers, $/ton	
Anhydrous ammonia 82-0-0	350
Urea, 46% N	180
Potash 0-0-60	138
0-40-15 with boron	244
10-34-0	218
11-22-22	210
0-10-40	177
8-40-14	248
10-20-20	198
16-8-8	186
0-25-25	248
15-10-10	170
20-10-10	192
Diesel fuel, $/gal	0.809
Electricity, $/kW-h	0.13
Labor, $/h	11.50
Tractor 150 HP 4 WD repair and maintenance, $/h	3.51
Tractor 150 HP fuel, $/h	6.11
Tractor 80 HP 2 WD repair and maintenance, $/h	1.84
Tractor 80 HP fuel, $/h	3.25
Box manure spreader repair and maintenance, $/h	3.20
Anhydrous ammonia applicator repair and maintenance, $/h	0.76
Corn planter 6 row repair and maintenance, $/h	9.82
Truck mounted manure tank/spreader 3,850 gal	
Repairs and maintenance, $/h	10.00
Truck/tank fuel, $/hour	5.06

matter, NDF, crude protein, soluble protein, and acid detergent insoluble N. DHIA and farm milk sales records were used to monitor milk production. For details concerning CNCPS inputs on this farm, see Stone et al. (1992).

Crop Nutrient Management Planning. Recommendations for fertilizer and manure applications were made for each field considering the total amount of manure produced, the nutrient requirement of the crop rotation, soil type, and the risk of runoff and erosion. Soil samples were taken in the spring from the plow layer (0 to 10 in.) of each production field and analyzed for pH, P, K, Ca, Mg, Fe, Al, Mn, and Zn. Acreage, soil type, and crop rotation were recorded for each field. The quantity of manure collected was estimated from the volume of the manure spreaders and the number of loads removed each month. Representative samples of manure from each handling system were analyzed on a periodic basis until reasonably consistent results were obtained. Manure was analyzed by DHIA for dry matter, total N, organic N, ammoniacal N, and total P and K. Crop nutrient requirements were based on Cooperative Extension recommendations (Cornell, 1993).

Economic Evaluation of Nutrient Management Plans

Partial budgets were developed to estimate the expected impacts of ration reformulation and crop nutrient management on net farm income. Net farm income was the total return to the farm operators and other unpaid family members for their labor, management, and equity capital (Kay, 1986). Because the case study farm was a working farm with many conditions changing simultaneously, the baseline was considered to be current farm practices in an average future year before implementation of changes.

The costs and benefits of ration reformulation included changes in the costs of purchased feeds, acreages of farm-produced feeds, and consulting fees. Product prices and input costs used are shown in Table 2. The labor cost included direct labor expenses, workman's compensation, unemployment insurance, and employee benefits. Machinery repair and maintenance costs and fuel and lubricant costs were calculated using standard engineering formulas (ASAE, 1993). Costs and benefits of crop nutrient management included changes in fertilizer use and construction of a manure storage pond to improve the use of manure nutrients.

Table 3. Whole-farm mass nutrient balance.

	N		P		K	
	tons/ yr	% of imports	tons/ yr	% of imports	tons/ yr	% of imports
Imports						
Purchased feeds	43.8	61	8.4	81	12.3	63
Fertilizers	13.5	19	2.0	19	7.3	37
N fixation	14.6	20	0			0
Purchased animals	0.1		0.03		0.01	
Total	72.0		10.4		19.6	
Exports						
Milk	18.6		3.8		5.6	
Animals	1.9		0.5		0.1	
Total	20.5		4.3		5.7	
Net excess	51.5	72	6.1	59	13.9	71

Table 4. Manure nutrients produced, total crop nutrient requirements, manure nutrients available per tillable land area, and animal density.†

Nutrient	Manure nutrient production	Total crop nutrient requirement	Surplus nutrients	Manure nutrients per tillable land area
	tons/yr			lb/acre per yr
Total N	55.3	16.8	38.5	185
P_2O_5	24.2	6.3	17.9	81
K_2O	41.6	7.3	34.3	139

† Animal density was 1.1 animal units per acre, where 1 animal unit = 1000 lb body mass.

RESULTS

Overall Nutrient Status

The mass nutrient balance (Table 3) showed that nutrient imports exceeded exports, with net excess rates of 72, 59, and 71% for N, P, and K, respectively. Between 60 and 80% of the imported nutrients were from purchased feeds. These results are similar to mass nutrient balances for other Northeast dairy farms (Bacon et al., 1990; Klausner, 1993; Dou et al., 1996).

Soil test levels were high to very high on crop land for P (18 to 56 lb/acre) and K (132 to 260 lb/acre). Table 4 shows that supplemental nutrient requirements of the crop rotation were minimal owing to the residual N supply from crop residue (alfalfa) and the high P and K soil test levels. The quantity of nutrients contained in manure exceeded crop

Table 5. Average fertilizer and manure application rates from the crop nutrient management plan.

Land use	N	P_2O_5	K_2O	Manure Total	Manure Per area
	lb/acre			gal	gal/acre
Triticale-peas/alfalfa	40	20	20	0	0
Alfalfa, established	0	8	30	140 000	700
Corn†	38	22	21	2 370 000	8,200
Grass	160	0	0	0‡	0
Idle land	0	0	0	2 000	12 000
All crops§	23.4	15.0	21.8	3 120	5200

† Manure was not applied to first-year corn following alfalfa.
‡ No manure was applied to grass because of need for low-K grass hay for dry cows.
§ Average application rates of N, P_2O_5, K_2O, and manure; sum of total manure applied to all crop land.

Table 6. Quantity and analysis of manure collected.

Manure source	Weight or volume produced per year	Total N	NH_4 N	Organic N	P_2O_5	K_2O
		Analysis, lb/ton or lb/1000 gal (Quantity, tons/yr)				
Bedded pack	652 tons	14 (4.6)	2 (0.7)	12 (3.9)	18 (5.9)	14 (4.6)
Lactating cows	2 100 000 gal	35 (36.8)	15 (15.7)	20 (21.0)	12 (12.6)	19 (20.0)
Heifers	360 000 gal	50 (9.0)	21 (3.8)	29 (5.2)	22 (4.0)	58 (10.4)
Dry cows	288 000 gal	34 (4.9)	18 (2.6)	16 (2.3)	12 (1.7)	46 (6.6)

requirements (Table 4). Because nutrients in manure are not as readily available nor can they be timed or placed as efficiently as fertilizer, an apparent surplus of manure nutrients may not be sufficient to meet crop requirements. For example, on the case study farm, ammonia volatilization and partial decomposition of organic N resulted in a N deficit despite an apparent surplus of total N in manure.

Crop Nutrient Management Planning

The crop nutrient management plan specified manure and fertilizer application rates for each field. Table 5 shows the average manure and fertilizer applications for each crop. The results of each step in the crop nutrient management plan are outlined below (also see Klausner, 1995). The quantity of manure collected annually and nutrient composition of the manure are given in Table 6. Multiplying the quantity of manure by its respective nutrient concentration (Table 6) and summing over manure sources gave the amount of nutrients collected annually (Table 4). The crop rotation and crop to be grown on each field were used to prioritize fields on the basis of nutrient requirements. Fields with steep slopes, frequent flooding, or close proximity to neighbors were ranked as a low priority for manure spreading.

The N, P, and K crop requirement for each field was based on the soil tests and an estimate of residual N from crop residues (alfalfa) and the previous 2 yr of manure applications using the decay series of Klausner et al. (1994). Net nutrient requirement was calculated as the total requirement minus starter fertilizer application, and minus residual manure N availability when formulating the N recommendation. For this farm, allocation decisions were based on the requirement for N because it was considered most limiting for crop production. Implications of this assumption are discussed later.

Table 7. Analysis of the base ration and reformulated ration for early lactation cows using the CNCPS.

	Base	Reformulated
Diet dry matter, lb/d		
Corn silage	12.7	11.5
Alfalfa silage	5.3	10.0
High moisture ear corn	10.9	12.7
Heat-treated soybean meal		2.5
Soybean meal	10.4	2.5
Whole cottonseed	5.6	5.9
Protein mix	1.0	2.1
Corn grain	4.6	5.3
Tallow	0.5	
Minerals	0.7	1.9
Total dry matter intake, lb/d	51.7	54.4
Predicted dry matter intake, lb/d	51.7	54.7
Diet crude protein, % dry matter	20.2	18.3
Actual milk production, lb/d	95.7	102.6
Energy-allowable milk production, lb/d	95.7	99.7
Metabolizable energy balance, Mcal/d	1.0	−1.5
Metabolizable protein balance, lb/d	0.21	0.21
Metabolizable protein from bacteria, lb/d	2.77	2.99
Metabolizable protein from feed, lb/d	3.42	3.56
Bacterial N balance, lb/d	0.46	0.30
Peptide balance, lb/d	0.27	−0.10
Urea cost, Mcal/d	2.27	1.27
Days to condition-score change	380	272
Effective NDF supplied, lb/d	10.7	10.8
Effective NDF required, lb/d	10.3	10.9
Predicted ruminal pH	6.25	6.44
Predicted plasma urea N, mg%	16.4	13.0
Limiting amino acid	MET†	MET†
Limiting amino acid, % req.	94	96

† MET = methionine.

Dividing the net nutrient requirement by the fertilizer replacement value of manure (Klausner et al., 1994; Klausner, 1995) gave a recommended manure application rate for each field. Because of the long time delay between application and incorporation, it was assumed that all of the ammoniacal N was lost by volatilization (Lauer et al., 1976). Based on mineralization rates of organic N, it was estimated that 7, 10, and 5.5 lb N would be equivalent to fertilizer N per 1000 gal of liquid manure produced by the lactating cows, heifers, and dry cows, respectively, with 4 lb N/ton from the bedded pack.

There was insufficient manure on the case farm to meet the N requirements for all fields. Because N was the priority nutrient, the acreages of the highest N-requiring crop (two or more years of continuous corn) were summed and divided into the quantity of manure collected. This gave a base rate of 10 000 and 12 000 gal/acre for the second and third-or-more years of continuous corn, respectively, based on lactating-cow manure. For other manure sources, the rate of application was adjusted for the available N (e.g., an adjusted rate from the dry cow barn on second-year corn was 10 000 × (7/5.5) = 12 700 gal/acre). The supplemental fertilizer requirement for each field was the difference between the net N, P, and K requirement and the quantity applied in manure. Pre-sidedress nitrate soil test for corn (Magdoff et al., 1984; Klausner et al., 1993) was used to verify the need for additional fertilizer N on all corn fields.

Table 5 gives the average manure and fertilizer applications for each crop. Over 75% of the manure was allocated to corn with a small amount of manure applied to older stands of alfalfa.

Table 8. Impact of proposed alternatives on annual net farm income (NFI).

Management alternative	Items that add to NFI	Items that reduce NFI	Change in NFI
Ration reformulation	Milk production increase Net decrease in purchased feed costs	Nutritional consultant Feedstuff analysis Net increase in direct cost of farm produced feeds	$40 198
Crop nutrient management plan (NMP)	Decrease commercial fertilizer purchase and application cost		$ 1 350
NMP with remote manure storage	Net value of crops produced on land set aside for manure application Decrease commercial fertilizer purchase and application cost	Manure storage pond, road and pump depreciation, interest and insurance Repairs, fuel, and labor associated with loading, agitating and unloading storage. Repairs, fuel and labor associated with spreading additional volume due to precipitation.	$ 2 315
NMP with remote manure storage and manure spreading done by custom operator	Net value of crops produced on land set aside for manure application Decrease commercial fertilizer purchase and application cost	Manure storage pond, road and pump depreciation, interest and insurance Repairs, fuel, and labor associated with loading, agitating and unloading storage. Repairs, fuel and labor associated with spreading additional volume due to precipitation Custom operator charges	–$4 043

Animal Nutrient Management

Table 7 shows a base ration for early lactation mature cows and the ration reformulated with the CNCPS. The reformulated ration used a greater quantity of farm-produced feeds and was lower in protein. Farm produced corn silage, alfalfa silage, and high-moisture ear corn increased from 56 to 63% of ration dry matter. Crude protein content decreased by about 2 percentage points.

A portion of feed protein is degraded in the rumen to peptides and ammonia that are required by ruminal bacteria. For the base diet, the positive balances of metabolizable protein, bacterial N, and peptides suggested an excess of rumen-degradable protein. The predicted plasma urea N of 16.4 mg% suggested there was excess urea in the blood associated with excreting the excess rumen ammonia. The energetic cost of this excretion ("urea cost") was predicted to be 2.2 Mcal/d; this was unusually high and increased the requirement for metabolizable energy.

Over the period of ration reformulation, milk production increased about 7% for this cow group. Dry matter intake was also higher, and while use of alfalfa and high moisture ear corn was increased, intake of purchased feeds was reduced. Also, a portion of the soybean [*Glycine max* (L.) Merr.] meal was replaced with heat treated soybean meal, whose protein is less ruminally degradable. The reduction in degradable protein resulted in a closer balance between supply and requirement for ammonia and peptides in the rumen that reduced plasma urea N, urea cost, and metabolizable energy requirement. Using a higher percentage of high moisture ear corn in the ration increased ruminally degraded carbohydrates, which in turn increased ruminal microbial protein production.

Milk production and excretion of total N, organic N, ammonia N, P, and K for the whole herd during the study are shown in Fig. 1. Cow numbers varied by less than 4% during this period. Excretion of total N decreased by 34% while milk production increased by 13%. Apparently, reductions in N excretion resulted both from reduced intake of protein and more efficient use of nutrients.

Economic Evaluation

Partial budget analyses projected that annual net farm income would increase from adopting the crop and animal nutrient management plans (Table 8). Complete analyses for

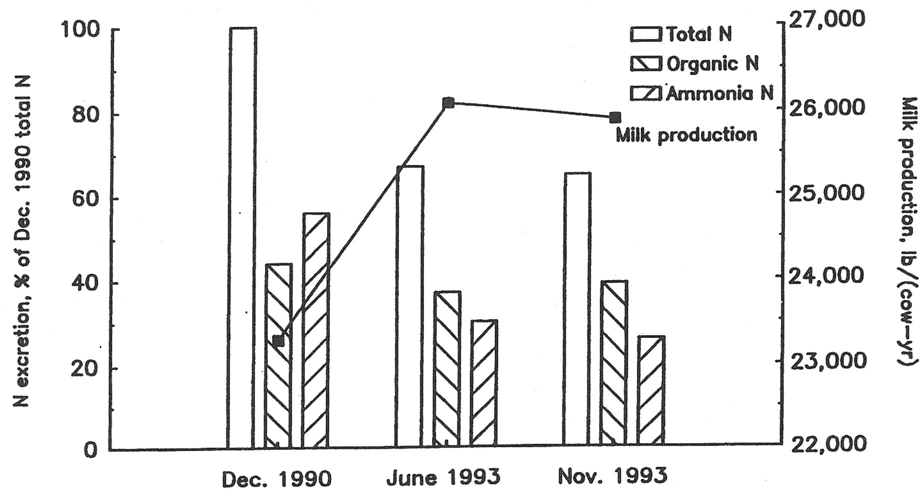

Fig. 1. Changes in milk production and excretion of total N; organic N; and ammonia N, P, and K at three sampling times during the study period (1 = December, 2 = June, 3 = November).

Table 9. Detail of economic analysis of ration reformulation.

Items that add to net farm income		Items that reduce net farm income	
Added income		Reduced income	
30% of increased milk production = 305 lb/cow per year × 320 cows × $0.12 /lb milk	$11 712	None	
Reduced costs		Added costs	
A. Reduced purchases of feed		A. Added purchases of feed	
1. Protein sources	43 742	1. Soybean Meal	$21 207
2. Cotton seed	27 592	2. Minerals	9 306
3. Tallow	8 437	3. Corn Meal	15 056
B. Direct costs associated with decrease in crop production		B. Direct costs associated with increase in crop production	
1. Corn silage	974	1. Alfalfa hay crop silage	8 422
2. High moisture shell corn	5 332		
		C. Nutritional consultant and feed analyses	3 600
Total: Added income and reduced costs (X)	$97 789	Total: Reduced income and added costs (Y)	$57 591
Change in net farm income (X minus Y)			$40 198

Table 10. Feed intake for each cow group and changes in feed production required due to ration reformulation.

	Corn silage	Alfalfa silage	High moisture ear corn
Base ration, lb DM fed/head per day†‡			
Cow group 1	11.0	4.7	9.6
Cow group 2	5.8	10.2	15.7
Cow group 3	6.4	11.3	17.4
Cow group 4	12.7	5.3	10.9
Dry cows 1	10.5	6.0	4.5
Dry cows 2	13.0	0	3.5
Large heifers	0.0	21.2	0
Small heifers	2.7	2.7	1.4
Reformulated ration, lb DM fed/head per day†			
Cow group 1	9.1	8.0	10.6
Cow group 2	8.3	15.1	11.7
Cow group 3	4.7	22.4	5.7
Cow group 4	11.5	10.0	12.7
Dry cows 1	10.5	6.0	4.5
Dry cows 2	13.0	0	3.5
Large heifers	0	21.2	0
Small heifers	2.7	2.7	1.4
Base ration fed, tons DM/yr	633	974	715
Reformulated ration fed, tons DM/yr	605	1249	567
Base minus reformulated fed, tons DM/yr	−27	275	−147
Estimated storage losses, %	20	15	10
Change in feed requirement, tons DM/yr	−33	316	−162
Crop yield, tons DM/acre	5.9	5.8	3.9
Change in acres required	−6	55	−42
Direct cost, $/acre	$176	$153	$128
Total change in direct cost, $/yr	−$974	$8,422	−$5,332
Net change, $/yr:			$2,117

† Cow group 1 (63 head), cow group 2 (63 head), cow group 3 (63 head), cow group 4 (63 head), dry cows 1 (57 head), dry cows 2 (11 head), large heifers 2 (120 head), small heifers 2 (170 head).
‡ DM = dry matter.

all alternatives are provided in Rasmussen et al. (1996). Ration reformulation was associated with an increase in annual net farm income of $40 198. As detailed in Table 9, ration reformulation was cost effective because of an increase in milk production and a net decrease in cost of purchased feeds. Average herd milk production increased 1062 lb/cow per year during the study. However, only 30% of this increase was conservatively attributed to ration reformulation; 70% was attributed to factors external to the ration changes. The reformulated rations required decreased corn production and increased alfalfa silage (Table 10). The direct costs of production increased by $8400 for alfalfa and decreased by $6300 for corn (Table 9). Direct costs of crop production per acre were determined from farm records (Table 11).

Table 11. Value and direct cost of crop production.

Crop	Value	Direct cost	Return over direct cost	Land area	Return over direct cost
	—— $/acre ——			acres	
Corn silage	395	176	219	209	$45 786
Alfalfa haylage	231	153	78	255	19 806
High moisture ear corn	298	128	170	100	16 950
Hay	180	60	121	6	724
Total				570	$83 266
Average	302	156	146		

Table 12. Economic analysis of manure storage pond: initial cost, fixed (ownership) costs, and operating costs.

Item	Initial cost	Useful life	Fixed costs,$/year: Depreciation†	Repairs	Insurance	Interest‡
Earthen storage pond	$7 942§	20 yr	397	397	33	99
Road - 200 ft.	1 000	20 yr	50	40	13	
Pump	15 000	2500 hr	1500	¶	63	188

Item	Operating costs,$/year
Load, agitate, and unload remote storage	
Tractor repair, maintenance, fuel, and lubricant	414
Tank truck repair, maintenance, fuel, and lubricant	310
Pump repair and maintenance	397
Labor	611
Spread additional volume due to precipitation	
Tank truck repair, maintenance, fuel, and lubricant	206
Labor	157
Total annual ownership and operating costs, $/year	$4875

† Straight line depreciation.
‡ Interest charged at 2.5% real rate annually over 20 yr.
§ Storage pond initial cost includes construction cost of $1/cubic yard plus design and test pit excavation cost of $2000.
¶ Pump repair is a variable expense and charged at $4.80/h used.

The crop nutrient management plan had a smaller effect on net farm income than ration reformulation, because the farm was already following fertilizer recommendations fairly closely. Decreases in commercial fertilizer purchases and application costs resulted in an increase in net farm income of $1350 (Table 8). However, the efficient use of manure during the growing season was constrained by a manure storage capacity of only 10 d. This necessitated applying manure to 40 acres of designated "idle" land.

To alleviate the manure disposal problem, construction of a pond was considered to store manure during the growing season and at other times when fields were unavailable for spreading. A manure storage pond would allow the idle land to be used for production. The value and direct costs of crop production on these 40 acres were estimated from an average value of all crops grown on the farm, weighted in proportion to their acreage (Table 11). The net value of crops produced on the acreage formerly used for manure disposal was $5840. Added costs of transporting manure to the pond were included as equipment and labor. The annual ownership and operating costs of the manure storage pond added $4875 to costs (Table 12). Thus, annual net farm income was expected to increase by $2315 with the manure storage pond and crop nutrient management plan (Table 8).

A potential constraint for constructing a manure storage pond was the availability of equipment and labor to spread manure in the spring. When custom labor and equipment were considered, net farm income decreased by $4043 (Table 8). Thus, the impact on net farm income of the crop nutrient management plan with or without manure storage was small compared with the magnitude of farm business revenues.

DISCUSSION

Implications for Farm Management

This paper outlines a process to limit excess nutrients on dairy farms by increasing the efficiency with which nutrients are used in both animal and crop production. Nutrient exports were increased because milk production rose, partly in response to ration reformulation. Nutrient imports were decreased because (i) animals used feed nutrients more efficiently, (ii) farm-produced feeds were substituted for purchased feeds, and (iii) manure nutrients replaced some purchased fertilizers. The more efficient allocation of resources and better use of information resulted in economic efficiencies as measured by increases in net farm income. This result is consistent with that of other researchers, in which practices designed for more efficient nutrient use were both economically positive and environmentally sound (Coote et al., 1975; Johnson et al., 1991; Lemberg et al., 1992).

Nutrient management planning should decrease excess nutrients by providing an optimal nutrient supply for both crops and animals. However, these practices decrease the nutrient safety factor that, on the case farm, had been an intrinsic part of feeding management and fertilizer application practices. We did not attempt to predict a production loss associated with limiting the supply of nutrients to the cows or crops in this analysis. In fact, these practices may have increased productivity, as described below.

In addition to increased nutrient use efficiency, implementing the animal and crop nutrient management plans had the ancillary benefits of promoting better information collection on the farm and a higher level of management awareness of production issues. The crop nutrient management plan resulted in recording of manure application rates to each field and encouraged an increase in uniformity of manure application and more confidence in reducing excess fertilizer for "safety factor applications. Implementing the CNCPS model invoked a series of changes that contributed to increased milk production, including: (i) Closer monitoring of dry matter intake, and early identification of feed intake problems when they arose. (ii) More frequent and accurate feed analysis. (iii) Greater attention to bunker-silo and feed-bunk management to preserve forage quality and optimize feed intake and rumen function. (iv) More effective control of ration mixing and delivery, to ensure that the ration as designed was actually available to the cow. (v) More accurate monitoring of milk production and cow body condition.

Implementing the crop nutrient management plan may also have some benefits that were not explicitly measured. The 40 acres that were used as manure disposal fields received 29 000 to 47 000 gal of manure per acre compared with 4000 to 7000 gal typically recommended in the nutrient management plan. The environmental impact of this practice was not measured because the analysis of the LEACHN model in Part II was not adequate to predict the environmental effects of this practice, because the conditions were so far from the normal range on which the model was developed. However, it seems obvious that eliminating this practice by building a manure storage pond and implementing the crop nutrient management plan would have a positive impact on water quality.

A key assumption in crop nutrient management planning was the application of manure based on the requirement for N. However, this resulted in an overapplication of P and K on most fields. When application rates were based on P, there was an excess supply of manure. This result has important implications for dairy farm sustainability: either more land or a reduction in animal numbers would be required.

Challenges and Benefits of the Approach

Knowledge integration links plant and animal nutrient requirements and responses to various soil, crop, animal, environmental, and management conditions. The need for a multidisciplinary approach in this process has been well documented (Altieri, 1989; Fretz et al., 1993; Hildebrand, 1990; Lockeretz, 1991; Neher, 1992; National Research Council, 1991; Temple et al., 1994), and the benefits of on-farm research have also been noted (Dlott et al., 1994; MacRae et al., 1989; Murray et al., 1994a; Stevenson et al., 1994; Temple et al., 1994). Simulation and representative farm modeling have been an important part of sustainable agriculture research (Coote et al., 1975; Domanico et al., 1986; Rotz et al., 1989; Westphal et al., 1989; Johnson et al., 1991; Lemberg et al., 1992; Schmit and Knoblauch, 1994). This work differs from previous research in that the role of cattle nutrition in the development of nutrient management plans was explicitly incorporated, and the study was conducted on a working, commercial farm.

This part of the study linked animal science, crop science, and economics. In part II, the work of soil scientists and engineers is combined. The multidisciplinary aspect of the study was both positive and challenging. As noted by Murray et al. (1994b), interactions across disciplines forced each person to think about his or her own discipline from a new perspective. On the other hand, the process of integrating knowledge was not simple or obvious. For example, there was no mechanism to determine a crop rotation that would optimize both animal and crop production. Also, differences among disciplines in the collection of data and formulation of recommendations had to be resolved. For example, volatilization losses of N were viewed positively from the standpoint of mass nutrient balances but negatively from the standpoint of environmental quality. Also, the combination of on-farm data collection and modeling was challenging, because some participants were uncomfortable with the assumption-making inherent in using models.

Working with a commercial farm helped give the project a practical focus and higher visibility among farmers and forced the team to think about information that was useful to farmers. However, much of the data that were necessary for this project were not needed for daily farm operation and hence were not routinely recorded by the producer. For example, manure application rates were not recorded until the study began. A related problem was that the farm was continually changing even as data were being collected. Milk production, cow numbers, forage quality, animal rations, animal intake, and manure composition all varied from season to season. Even though dry matter intake and percentage of forage in the ration increased during the ration reformulation, actual acreages of alfalfa and corn did not change substantially. Farm produced feed carryover from one year to the next and variation in yields and set-aside land confounded the link between ration feed use and crop acres planted. Finally, because the scientific team did not control management practices on the farm, comparative experiments were impossible.

This report describes the process of integrating knowledge to increase dairy farm sustainability. For this task, a tremendous amount of data had to be collected and integrated using workbooks or stand-alone software programs that were not connected. Although the results for the case study farm were site specific, the process should be transferable to other farms. However, development of integrated crop and animal nutrient management plans and economic evaluation on a large number of farms will require the development of computerized decision aid tools to integrate the process.

CONCLUSIONS

A multidisciplinary team working with dairy producers developed a process to evaluate overall farm nutrient status; refine dairy cattle diets to increase nutrient use efficiency, decrease nutrients excreted, and reduce the import of nutrients as purchased feeds; develop a crop nutrient management plan to maximize the use of manure nutrients; and evaluate the effect of these plans on farm profitability.

For the case study farm, mass nutrient balances indicated 60 to 72% of imported N, P, and K were in excess of nutrient exports from the farm; 60 to 80% of the imported nutrients were from purchased feeds. Evaluation and refinement of the diets resulted in a reduction in protein content of the rations by 2 percentage points while supporting a 13% increase in milk production and a 34% decrease in total N excretion. Partial budgets projected that ration reformulation increased net farm income before taxes by $40 200. Implementation of the crop nutrient management plan was expected to decrease fertilizer purchases and application expenses by $1350, but construction of a remote manure storage pond and custom spreading of manure in the spring resulted in a $4000 decrease in net farm income. Soil testing, manure analyses, feed analyses, and monitoring of animal dry matter intake were among the critically important tools in soil, crop, and animal nutrient management planning.

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