Feeding Strategy, Nitrogen Cycling, and Profitability of Dairy Farms

C. A. ROTZ,* L. D. SATTER,† D. R. MERTENS,† and R. E. MUCK†
*USDA/Agricultural Research Service, Pasture Systems and Watershed Management Research Laboratory, University Park, PA 16802-3702
†USDA/Agricultural Research Service, U.S. Dairy Forage Research Center, Madison, WI 53706-1108

ABSTRACT

On a typical dairy farm today, large amounts of N are imported as feed supplements and fertilizer. If this N is not recycled through crop growth, it can lead to large losses to the atmosphere and ground water. More efficient use of protein feed supplements can potentially reduce the import of N in feeds, excretion of N in manure, and losses to the environment. A simulation study with a dairy farm model (DAFOSYM) illustrated that more efficient feeding and use of protein supplements increased farm profit and reduced N loss from the farm. Compared to soybean meal as the sole protein supplement, use of soybean meal along with a less rumen degradable protein feed reduced volatile N loss by 13 to 34 kg/ha of cropland with a small reduction in N leaching loss (about 1 kg/ha). Using the more expensive but less degradable protein supplement along with soybean meal improved net return by $46 to $69/cow per year, dependent on other management strategies of the farm. Environmental and economic benefits from more efficient supplementation of protein were generally greater with more animals per unit of land, higher milk production, more sandy soils, or a daily manure hauling strategy. Relatively less benefit was obtained when either alfalfa or corn silage was the sole forage on the farm or when relatively high amounts of forage were used in animal rations.
(**Key words:** nitrogen, whole farm, simulation, environment)

Abbreviation key: DAFOSYM = Dairy Forage System Model.

INTRODUCTION

Dairy farming in the United States is facing two major challenges to remain a viable industry. The first is an economic challenge. Inflation-adjusted milk prices have remained stable or declined for many years, but the costs of most production inputs have continued to increase. As farm profit continues to decrease, production systems must become more efficient. One of the most effective ways of improving efficiency has been to increase the number of animals per unit of cropland. This has contributed to the development of the second challenge, the farm's impact on the environment.

Dairy farms have grown more dependent on the use of commercial fertilizer and the import of supplemental feeds. Their use has increased crop yields and milk production, which have improved the efficiency and profitability of the dairy industry. With heavy import of nutrients, though, there is greater opportunity for buildup of nutrients in the soil and the loss of excess nutrients to ground and surface waters.

Nitrogen in the form of CP is an important feed nutrient for high producing dairy cows. About 25 to 30% of the N consumed by lactating cows is transferred to the milk produced; the remainder is excreted in feces and urine (25). When applied to cropland, manure provides a good source of N for crop growth. Up to 50% of the N, though, can be lost to the atmosphere during handling, storage, and land application (3). Nitrogen incorporated into the soil is readily carried by moisture movement through the soil profile. Unless the N is applied in the proper amount and at the proper time, it can move below the root zone, where it is lost to ground water.

Thus, dairy farm efficiency must be improved while maintaining or reducing N losses to the environment. Nitrogen losses can be reduced by 1) improving the efficiency of animal use of feed protein, 2) reducing losses during manure storage and handling, and 3) using crop rotations that better utilize manure N. Of these three options, improvement in animal feed use offers quick and easy implementation with little investment, and more efficient feeding may reduce feed costs (13). One method of improving animal use is to improve biological efficiency through increased production (24). A related approach is to provide a better match of protein sources with the animal's needs. Feeding trials have demonstrated that feeding less RDP to lactating cows can reduce N excretion (23, 26).

Received May 24, 1999.
Accepted August 16, 1999.

The potential for reducing N losses through a change in feeding strategy has been demonstrated on actual farms. Monitoring nutrient flow in managed pathways of a Pennsylvania dairy farm illustrated that on-farm sources of N were not used efficiently (1). A change in feeding strategy reduced purchased feeds and decreased the import of N by 26%. In a comprehensive case study of a dairy farm in New York, overfeeding and inefficient use of protein was again found. More accurate matching of N sources with animal requirements was shown to reduce manure N excretion by 34% while improving net farm income by $40,200 (12).

To properly evaluate the issues of N management on dairy farms, a comprehensive approach is needed that integrates nutrient management with crop production, animal production, feed and manure handling, and farm economics (22). Models have been developed and applied that integrate portions of this system. Many models are used to assist in budgeting available manure nutrients to crop needs (10). Other models assist in planning and selection of the best manure handling system (9). At least one model has integrated the animal component with manure handling and crop production, but without an economic component (6). In an economic approach (20), a linear programming model was used to determine the economically optimal dairy herd intensity, manure application rate, and crop mix for unrestricted and restricted scenarios of N loss on dairy farms.

The Dairy Forage System Model (**DAFOSYM**) provides a comprehensive simulation model of the dairy farm in which all major components are modeled and integrated at a similar level of aggregation (3, 8, 16). This model has been used to evaluate and compare whole farm impacts of alternatives in manure handling (3, 8) and various options for alfalfa and corn silage production and feeding (2). The objective of this study was to use DAFOSYM to evaluate the whole farm effects of alternatives in protein feed supplementation on N losses and farm profit and the interaction of supplementation with other options in herd and feeding management.

MATERIALS AND METHODS

A simulation study was conducted to illustrate the consequences of feed management on farm nutrient loading and profitability. The effects of various management changes were evaluated on two farms representative of small and larger farms found in south central Wisconsin. Herd size, production level, soil type, manure handling practice, and the type and amount of forage were each varied along with the protein supplementation strategy to determine their interactive effects on farm nutrient balance and profit.

The Dairy Forage System Model

All simulations were performed using DAFOSYM, a model that integrates many biological and physical processes on a dairy farm (16). Crop production, feed use, and the return of manure nutrients back to the land are simulated over many years of weather (Figure 1). Growth and development of alfalfa, corn, and small grain crops are predicted with models based on ALSIM (7) and CERES (11) crop models. Performance and resource use in tillage, planting, and harvest operations are functions of the size and type of machines used and the weather conditions (8, 19). Field drying rate, harvest losses, and nutritive changes in crops are related to the weather, crop conditions, and machinery operations used (15, 17). Losses and nutritive changes during storage are influenced by the characteristics of the harvested crop and the type and size of structure used for storage (4, 5).

Feed allocation and animal response are related to the nutritive value of available feeds and the nutrient requirements of the six animal groups making up the dairy herd (18). The herd consists of young heifers, older heifers, nonlactating cows, and early-, mid-, and late-lactation cows. Diets for each group are formulated by a cost-minimizing linear programming approach. Protein requirements are determined with the NRC absorbed protein system (14) with only slight modification (18). One or two protein supplements are used to balance rations. These generally include a high RDP supplement and a low RDP supplement. Feed characteristics can be defined to describe essentially any supplement of each type including blended and hypothetical feeds.

Nutrient flows through the farm are modeled to predict potential nutrient accumulation and loss to the environment. The quantity and nutrient content of the manure produced is a function of the quantity and nutrient content of the feeds consumed (18). Nitrogen losses occur in the barn, during storage, and between field application and incorporation into the soil (3). Nitrogen transformation and movement in the soil is controlled by the rate of moisture movement and drainage from the soil profile as influenced by soil properties, rainfall, and the amount and timing of manure and fertilizer applications (21). A whole farm balance of P and K is determined that considers the import of nutrients in feed and fertilizer and the export in milk and animals (3, 18).

The DAFOSYM provides a useful tool for evaluating and comparing the long-term performance, environ-

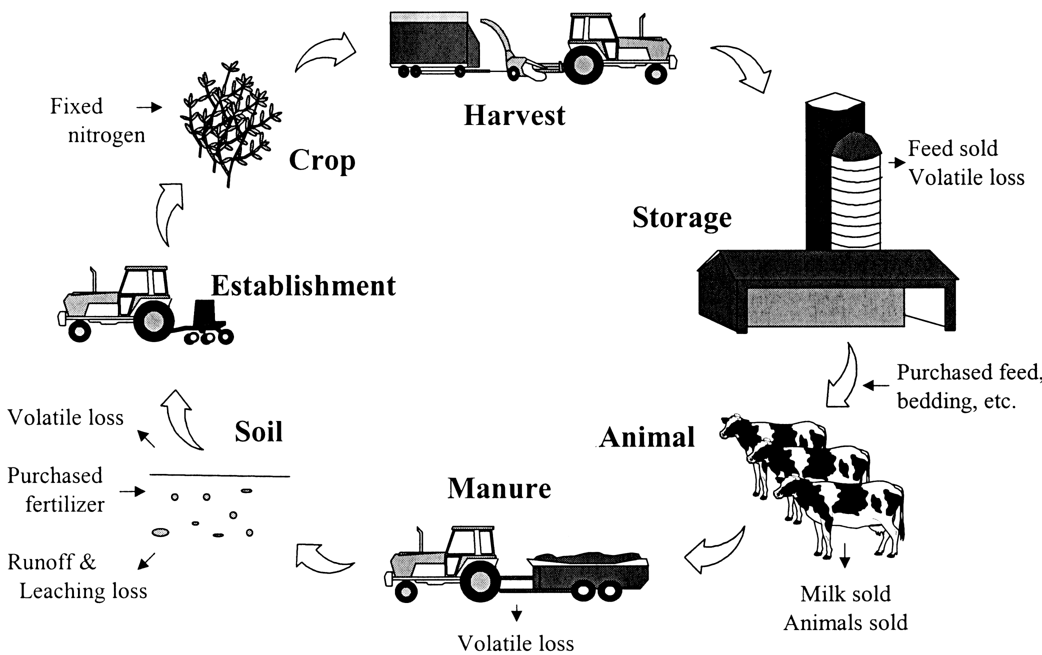

Figure 1. Dairy Forage System Model (DAFOSYM) simulates material and nutrient flows for various dairy farm systems over many years of weather to determine the performance, nutrient losses, and economics of the farm.

mental impact, and economics of alternative dairy systems. Simulated performance is used to predict the costs, income, and net return or profit of farms. By modeling several alternatives, the effects of system changes can be compared including resource use, production efficiency, environmental impact, and profitability. All production and economic information is determined for each simulated year of weather. The distribution of annual values obtained can then be used to assess the risk involved in alternative technologies or strategies as weather conditions vary.

Representative Farms

Two hypothetical farms were modeled to represent dairy farms in south central Wisconsin. The predominant soil on both farms was a loam of medium depth. The smaller farm included 60 mature animals plus replacement stock on 70 ha of land. Alfalfa was grown on 30 ha with 30 ha of corn and 10 ha of oats used as a cover crop for alfalfa establishment. This planting pattern represented a crop rotation in which 10 ha were rotated each year, producing 3 yr of alfalfa followed by 3 yr of corn and 1 yr of oats. Another variation of this farm included the same land area and crop rotation, but the herd size was expanded to 100 cows plus replacements. The largest farm included 400 cows on 320 ha of land. The crop rotation included 120 ha of alfalfa and 200 ha of corn. This crop production strategy represented 40 ha rotated through 3 yr of alfalfa, 1 yr of corn following alfalfa, and 4 yr of corn following corn. Nitrogen fertilizer was applied to all corn land at a minimum rate of 20 kg/ha. Simulations were done for 25 weather years with historical Madison, Wisconsin, weather data from 1966 through 1990.

On all farms, alfalfa was harvested by a four-cutting strategy with the first two cuttings harvested at a bud stage of development and the last two harvested at early bloom. Harvests began within 5 d of June 3, July 6, August 22, and October 15. All cuttings except the second on the smaller farm were harvested as silage wilted to moisture contents between 60 and 68%. The second cutting on this farm was harvested as dry hay in large round bales. Corn was harvested as silage and high moisture grain to fill the available silos; additional crop was dried. On the smaller farm, oats were primarily harvested as high moisture grain, and the straw was used as bedding. Postharvest crop yields over the 25-yr simulations averaged 10.2 tonnes of DM/ha for alfalfa, 14.7 tonnes of DM/ha for corn silage, 7.3 tonnes of DM/ha for corn grain, and 1.9 tonnes of DM/ha for high moisture oats.

Machinery and facilities for the two farms are listed in Table 1. Facilities included bunker silos for storing alfalfa and corn silages and tower silos for high-moisture grain. Manure was handled as a slurry that was stored up to 6 mo in a concrete tank (small farm) or plastic-lined earthen pond (larger farm). Tillage for all crops consisted of chisel plowing followed by disking, field cultivating, and planting operations. All crops were planted in the spring, and plowing was done in the fall. On the small farm, alfalfa was seeded with the oat crop. Most equipment used on the farm was purchased new, but a used price was assumed for smaller utility tractors, silage dump trucks, and manure spreading tank trucks (Table 1). To reduce harvest costs, grain crops were harvested as a custom-hired operation.

For the smaller farm, the herd included 60 Holstein animals (lactating and nonlactating) plus replacement stock. Replacements were 24 animals over 1 yr old and 28 under 1 yr old. When the herd size was increased to 100 cows, replacements included 40 animals over 1 yr old and 45 under 1 yr old. For the larger farm, numbers were 400 cows, 160 older heifers, and 180 younger heifers. Most analyses were done with annual milk production set at 10,000 kg/cow, but a lower production of 8000 kg/cow was used in one simulation. Cows were housed in a free-stall barn and milked in an appropriately sized parlor (Table 1). The culling rate of the herds was 35%, which set the number of first-lactation animals at 21 and 140 for the small and large farms, respectively. A mobile mixing wagon was used to prepare TMR for each animal group.

Prices were set to reflect long-term relative values of farm inputs and outputs in current dollars. Prices for machinery and storage facilities are listed in Table 1, and other prices and economic parameters are listed in Table 2. A real interest rate (approximately nominal rate minus inflation) of 6% per year was assumed on investments. Property tax was charged at 2.3% of the estimated assessed value of property. Property tax was not included on land, but an annual land charge of $245/ha was included.

Simulation Evaluations

Various evaluations were performed with DAFOSYM to determine the impact of system changes on feed production, feed use, milk production, manure production, nutrient losses, production costs, and net farm return. In the first evaluation, the impact of protein supplementation alternatives was examined on the small, 60-cow farm. All farm parameters were held constant except

TABLE 1. Machines and structures used for the analysis of two representative dairy farms.

	Small (60 or 100 cow) farm			Large (400 cow) farm		
Machine or storage type	Size	No.	Initial cost ($)	Size	No.	Initial cost ($)
Tractors	35 kW, used	1	10,000	35 kW, used	1	10,000
	65 kW	1	43,100	65 kW	1	43,100
	80 kW	1	53,500	100 kW	1	66,300
	—	—	—	164 kW	1	99,000
Skid steer loader	25 kW	1	16,000	35 kW	2	20,500
Mower-conditioner	2.7 m	1	12,000	4.3 m, rotary	1	24,000
Tandem rake	5.4 m	1	10,800	7.3 m	1	10,800
Round baler	6.0 tonne DM/h	1	11,200	—	—	—
Bale wagon	5.0 t	1	4500	—	—	—
Forage harvester	12 tonne DM/h	1	24,100	SP[2], 25 tonne DM/h	1	155,100
Forage hauling	dump wagons, 6 t	2	10,200	dump trucks, used	3	30,000
Feed mixer wagon	small, 4.5 tonne	1	13,900	large, 12 tonne	1	24,800
Manure pump/agitator	450 tonne/h	1	9500	450 tonne/h	1	9500
Manure spreader	12.5 tonne	1	12,600	tank trucks, used	3	30,000
Coulter-chisel plow	2.7 m	1	7900	4.9 m	1	14,200
Tandem disk harrow	3.7 m	1	8600	6.4 m	1	16,700
Field cultivator	3.7 m	1	8100	6.4 m	1	14,000
Corn planter	4 row	1	12,400	12 row	1	32,600
Grain drill	2.4 m	1	6800	3.7 m	1	11,300
Hay shed	100 tonne	1	10,000	—	—	—
Alfalfa silage bunkers	7.6 × 27 × 3.7 m	1	30,500	11.0 × 50 × 3.7 m	2	58,700
Corn silage bunkers	7.6 × 27 × 3.0 m	1	26,300	15.2 × 50 × 3.7 m	2	66,200
High moisture corn silo	5.5 × 18.3 m stave	1	16,900	7.6 × 24.4 m stave	1	36,700
Manure storage[1]	tank, 30 × 3 m	1	41,700	lined pond, 61 × 4.6 m	1	88,500
Machinery shed	—	1	60,000	—	1	150,000
Milking center	double four	1	130,000	double ten	1	230,000
Free stall barn[1]	—	1	51,000	—	1	340,000
Replacement housing[1]	—	1	25,600	—	1	168,000
Commodity storage[1]	—	1	1800	—	1	28,000

[1]For the 100-cow option, the free-stall barn, replacement housing, commodity storage, and manure storage were increased to initial costs of $85,000, $42,000, $7,000, and $52,135, respectively.

[2]Self-propelled.

TABLE 2. Economic parameters and prices assumed for various system inputs and outputs for the analysis of the representative dairy farms.

Parameter	Value[1]	Parameter	Value
Labor wage rate[2]	$22,000/person-yr	Selling price of feeds or animals	
Diesel fuel price	$0.29/liter	Alfalfa hay	$120/tonne DM
Electricity price	$0.08/kW-h	Corn silage	$70/tonne DM
Grain drying price	$1.18/pt/tonne DM	Corn grain	$115/tonne DM
Milk price	$30/hL	Cull cow	$0.88/kg
Milk marketing and hauling fees	$2/hL	Heifer	$1200/animal
Annual livestock expenses	$238/cow	Calf	$20/animal
Custom corn harvest charge	$64/ha		
Fertilizer prices		Buying price of feeds or bedding	
Nitrogen	$0.35/kg	Soybean meal	$250/tonne DM
Phosphorus	$0.44/kg	Protein mix	$330/tonne DM
Potassium	$0.27/kg	Corn grain	$120/tonne DM
Annual cost of seed and chemicals		Alfalfa hay	$135/tonne DM
New alfalfa	$200/ha	Straw bedding	$110/tonne DM
Established alfalfa	$15/ha	Mineral/vitamin mix	$325/tonne DM
Corn following alfalfa	$135/ha	Economic life	
Corn following corn	$155/ha	Structures	20 yr
Oats	$100/ha	Machinery	10 yr
Real interest rate	6.0%/yr	Salvage value	
Property Tax rate	2.3%/yr	Structures	0%
Annual land charge	$245/ha	Machinery	30%

[1]Prices were set to represent long-term relative prices in current value, which were not necessarily current prices.

[2]Labor inputs were 1.5, 2, and 10 full-time equivalent workers for the farms milking 60, 100, and 400 cows, respectively.

for the type of protein supplement used to meet the protein requirements of the herd. The first option was to use 44% CP soybean meal as the only protein supplement. A second option was to use a low RDP supplement. This supplement was a blend of 50% heat-treated (protected) soybean meal, 25% blood meal, and 25% swine meat and bone meal (Table 3). For a third option, the first two supplements were selected or blended to best meet the protein needs of each animal group. A fourth option was to use only roasted soybeans. These soybeans, like all other supplements, were purchased and imported to the farm. A fifth option was defined as precise protein supplementation. For this option, two hypothetical protein feeds were blended to precisely meet protein requirements of each animal group. The first was 100% RDP with no other feed value; the second was 100% RUP (Table 3). Although these feeds were hypothetical, in practice they most closely represented urea and protected AA for the degradable and undegradable feeds, respectively. With these hypothetical feeds, the model blended a ration that came as close as possible to a maximum efficiency in protein utilization using the farm produced forages.

In the second evaluation, effects and interactions were examined between animal density, milk production level, and protein supplementation. The number of cows was increased to 100 with 85 replacement heifers on the same land and crop base. Two milk produc-

TABLE 3. Nutritive characteristics and prices of various protein sources used for protein supplementation.

	Soybean meal	Protein mix[1]	Roasted soybeans	RD Feed[2]	RUP Feed[3]
Crude protein, % DM	49	58	42.8	281	281
Rumen protein degradability, % CP	70	43	50	100	0
Acid detergent insoluble protein, % CP	3.0	5.3	5.0	0	0
Net energy of lactation, Mcal/kg DM	1.94	1.77	2.18	0	0
Total digestible nutrients, % DM	84	77	94	0	0
Neutral detergent fiber, % DM	15	8	15	0	0
Phosphorus, % DM	0.68	1.78	0.65	0	0
Potassium, % DM	2.00	1.38	1.80	0	0
Purchase price, $/tonne DM	250	330	250	—	—

[1]A low RDP mix consisting of 50% heat-treated (protected) soybean meal, 25% blood meal, and 25% swine meat and bone meal.

[2]A hypothetical feed consisting of 100% RDP with no additional feed value.

[3]A hypothetical feed consisting of 100% RUP with no additional feed value.

tion levels were simulated: a high level of 10,000 kg/cow and a more moderate level of 8000 kg/cow. At each level, protein needs were met with either 44% CP soybean meal as the only source or with a combination of soybean meal and the low RDP mix.

In the third evaluation, effects and interactions of farm size, soil type, and protein supplementation were examined on the 400-cow farm. Simulations were done with either a medium loam or medium loamy sand as the predominant soil on the farm. Use of the more sandy soil illustrated the combined effects of reduced crop yields during most weather years and more rapid N movement through the soil profile. For each soil type, protein needs were met with either soybean meal as the only source or with a combination of soybean meal and the low RDP mix to determine interactions with protein feeding strategy.

In the next four evaluations, the interactions of protein supplementation with manure handling method, forage type, and the amount of forage in animal diets were examined. The base farm for these simulations was the small, 60-cow farm. Three protein supplementation strategies were used in each evaluation: 1) 44% CP soybean meal only, 2) both soybean meal and the low RDP mix, and 3) the precise protein supplementation strategy.

The effects of manure handling method were examined in the fourth evaluation. The manure storage system was removed and replaced with daily hauling. With daily hauling, manure was not incorporated within 2 wk of spreading so all volatile N was lost. To compensate for this lost N, an additional 20 kg of N fertilizer/ha was applied to the corn land. All other farm parameters remained the same.

In the base farm, about 35% of the annual forage requirement was met with corn silage and the remainder was alfalfa silage and hay. For the fifth evaluation, alfalfa silage production was increased and corn silage was removed from the farm. This was done by increasing the alfalfa land area to 40 ha, decreasing the corn area to 20 ha, and shifting the silos available for corn silage to use with alfalfa. This provided animal diets with more protein and particularly more RDP. In the sixth evaluation, corn silage was used as the only forage source. All alfalfa was removed, giving 60 ha of corn production. All of the bunker silo capacity was then available for corn silage. Nitrogen fertilizer application was increased to 120 kg/ha of corn land to compensate for less manure per unit of corn land and the loss of fixed N from alfalfa.

In all previous simulations, minimum forage diets were used to feed lactating cows. Under this assumption, forage use was held near the minimum required to maintain proper rumen function (18). Thus, greater amounts of grain and protein supplement were used to meet energy and protein requirements. In the final evaluation, the assumption was changed to allow maximum forage diets. The use of forage was maximized, so just enough grain and protein supplementation was used to meet animal requirements (18). Under this scenario, more of the protein and energy needs were met with forage and less supplementation was required.

RESULTS

The 25-yr average performance and economic results are discussed for the effects of protein supplementation and the interaction of these effects with farm size, production level, and soil type. These simulation results include the feeds produced, feeds bought and sold to meet the needs of the herd, and the milk production of the herd. Nutrient balance information includes the manure produced, the amount of N on the farm, N losses to the environment, and the whole-farm build up or shortage of P and K. The economic results include all major costs incurred, the income from milk, excess feed, and animal sales, and the net return to management. The interaction of protein supplementation with manure handling method and the type and amount of forage fed are presented in a more brief form where only feed use, N losses, and net return are discussed.

The important results to consider are the comparisons between the different strategies simulated, not the absolute values generated for any particular farm. Predicted values for a given farm such as N loss and net return may vary greatly dependent upon model assumptions, and thus should not be used to judge the viability of a specific farm. Relative differences between simulated systems though, provide meaningful evaluation of the effects of system changes.

Effects of Protein Supplementation

In the first evaluation, the 60-cow farm was simulated with the use of five different strategies for protein supplementation. Use of soybean meal as the only available supplement required overfeeding of protein to meet the RUP requirement. This occurred because protein in soybean meal is highly degradable in the rumen and most dairy rations require substantial amounts of RUP. This was especially true in diets containing large amounts of alfalfa silage, since alfalfa silage was very high in RDP. Diets formulated with the low RDP feed required less protein supplementation, and dietary protein was used more efficiently. Other strategies for improved protein efficiency included use of both of the previous supple-

TABLE 4. Typical rations generated for early lactation animals with different protein supplements.

Protein supplement	Alfalfa hay	Alfalfa silage	Corn silage	Grain	Protein 1	Protein 2	DM intake	Ration NDF	Ration NE_L	Ration CP	Ration RUP
	(kg/day)							(% DM)	(Mcal/kg DM)	(% DM)	
60-Cow farm											
Soybean meal only[1]	1.21	5.40	3.80	7.37	4.64	—	22.4	25.7	1.737	21.7	6.4
Soybean meal & mix[2]	1.21	5.40	3.80	9.92	0.00	1.72	22.0	25.7	1.728	17.4	6.6
Roasted soybeans[3]	1.17	5.23	3.68	8.40	—	3.05	21.6	25.7	1.773	18.3	6.7
Precise supplementation[4]	1.19	5.31	3.74	11.42	0.00	0.18	21.8	25.7	1.732	15.9	6.5
100-Cow farm (high production)											
Soybean meal only[1]	3.95	3.75	2.35	8.17	4.37	—	22.6	25.5	1.720	21.0	6.4
Soybean meal & mix[2]	3.94	3.74	2.34	10.59	0.00	1.63	22.2	25.6	1.711	17.1	6.5
100-Cow farm (moderate production)											
Soybean meal only[1]	3.20	3.03	1.90	6.55	3.60	—	18.3	25.5	1.720	21.1	6.4
Soybean meal & mix[2]	3.19	3.02	1.90	8.55	0.00	1.34	18.0	25.6	1.711	17.1	6.5
400-Cow farm											
Soybean meal only[1]	1.44	3.91	5.58	6.18	4.96	—	22.1	25.7	1.756	21.0	6.5
Soybean meal & mix[2]	1.45	3.93	5.61	8.82	0.00	1.82	21.6	25.8	1.749	16.3	6.6

[1]Protein 1 is 44% CP soybean meal only.

[2]Protein 1 is 44% CP soybean meal. Protein 2 is a low RDP mix consisting of 50% heat-treated (protected) soybean meal, 25% blood meal, and 25% swine meat and bone meal.

[3]Protein 2 is roasted soybeans only.

[4]Protein needs are met as efficiently as possible using two protein sources; the first is 100% RDP and the second is 100% RUP.

ments, roasted soybeans, or the precise supplementation strategy.

Typical diets formulated by the model are shown in Table 4. Protein supplementation had only a minor influence on the amount of forage fed. The amount of grain fed varied greatly to compensate for the energy contributed by the various protein supplements. During most weather years, diets formulated with both soybean meal and the low RDP mix were the same as those formulated with the mix alone. Only in a few of the years were the RDP levels in forage not sufficient because of harvest conditions and losses, and thus some soybean meal was used. Diets varied in CP content with only small differences in the NDF, NE_L, and RUP contents. As protein needs were met more efficiently, less CP was required and less excess protein or N was excreted.

A whole farm comparison of the strategies in which soybean meal or the low RDP mix (columns 1 and 2, Table 5) was used shows similar feed use except for grain and protein supplement feeds. With the low RDP feed, the amount of protein supplement used was reduced more than 60%. With less protein supplement in the diet, more corn grain was required to meet the animal's energy requirement. Thus with the use of the low RDP mix, about 69 tonnes DM of soybean meal and 3 tonnes DM of hay were replaced by 38 tonnes DM of corn grain and 26 tonnes DM of the protein mix.

As protein was used more efficiently with the low RDP feed, about 2300 kg (8%) less N was cycled through the farm (Table 5). Much of this reduced N was in the form of highly volatile ammonia. Consequently, annual N loss to the atmosphere was reduced by 20 kg/ha (26%). With less N applied to cropland in manure, leaching loss also decreased slightly (0.9 kg/ha or 6%). A design characteristic of DAFOSYM is that each year is simulated independent of other weather years. Thus, the annual carryover of N in the soil is not modeled; only the amount of N remaining in the soil and crop residue at the end of the cropping season is predicted. During the winter and spring months, a portion of this N may also move through the soil profile and be lost below the root zone. More efficient feeding of protein reduced this residual N by about 1.0 kg/ha, which indicates the potential for a further small reduction in leaching loss.

Use of the low RDP mix and corn grain in place of soybean meal caused a small decrease in the K content in manure. With less available K, more potash was needed to maintain crop production. Production costs were very similar between the two strategies except for the cost of purchased feeds. Despite the higher price of the protein mix, use of this mix reduced annual feed costs by $5800 ($97/cow). Income from excess feed sales decreased slightly allowing an increase in farm net return of $3800 or $63/cow per year (Table 5).

Allowing any combination of both protein sources in rations provided little additional improvement over the low RDP mix alone (columns 2 and 3, Table 5). Protein needs were met with 1.6 tonnes DM of soybean meal and 24 tonnes DM of the mix. Less N was excreted, which further reduced volatile loss a small amount. A slight decrease in purchased feed costs increased the net return an additional $3/cow per year. This was $66/cow per year greater than the net return attained using soybean meal alone.

Compared with the low RDP mix, use of roasted soybeans as the sole protein supplement provided slightly less efficient use of N and a similar net return for the farm (column 4, Table 5). Annual protein needs were met with 45 tonnes DM of roasted soybeans. The higher energy and lower protein contents of this feed allowed a decrease in corn use with a slight decrease in hay use and greater use of the protein supplement. Nitrogen losses from the farm were about 2 kg/ha greater than those attained with the low RDP mix. Although purchased feed costs were slightly greater than those for strategies using the low RDP mix, excess feed sales were also greater, providing a similar increase in farm net return.

The final scenario used the hypothetical feeds for precise supplementation of protein. This strategy provided a theoretical maximum efficiency for protein supplementation with the feeds produced on the farm. With these highly concentrated protein sources, relatively small quantities of the supplements were required. Compared with the least efficient method of soybean meal alone, this strategy reduced the N cycled through the farm by 42 kg/ha per year (10%). This reduced volatile loss, leaching loss, and residual N by about 25, 1.2, and 1.3 kg/ha per year, respectively. The economics of this hypothetical strategy were not particularly useful except to determine a breakeven price for these theoretical feeds. Compared with sup-

TABLE 5. Effect of protein supplementation on annual feed production, feed use, nutrient balance, production costs, and net return for a 60-cow dairy farm in south central Wisconsin[1].

Production or cost parameter	Protein 1[2]	Protein 2[2]	Both sources[2]	Roasted soybeans[3]	Precise suppl.[4]
Alfalfa silage production, tonne DM	198	198	198	198	198
Alfalfa hay production, tonne DM	68	68	68	68	68
Corn silage production, tonne DM	129	129	129	129	129
Grain production, tonne DM	151	151	151	151	151
Alfalfa purchased (sold), tonne DM	(36)	(33)	(33)	(39)	(33)
Corn grain purchased (sold), tonne DM	11	49	49	26	71
RDP supplement purchased, tonne DM	69	—	1.6	—	0.8[4]
RUP supplement purchased, tonne DM	—	26	24	45[3]	2.4[4]
Average milk production, kg/cow	10,000	10,000	10,000	10,000	10,000
Nitrogen cycled on farm[5], kg	28,224	25,903	25,845	26,059	25,293
Nitrogen imported, kg	19,946	17,354	17,306	17,784	16,703
Nitrogen exported, kg	8284	7768	7772	8074	7654
Nitrogen lost by volatilization, kg	5362	3958	3924	4061	3598
Nitrogen lost by leaching, kg	1003	939	937	943	921
Residue and unused soil nitrogen, kg	570	500	498	504	481
Phosphorus required, kg	143	129	136	142	137
Potassium required, kg	729	1494	1496	1276	1753
Field and feeding machinery cost, $	40,184	40,195	40,194	40,142	40,199
Fuel and electric cost, $	3893	3897	3896	3854	3898
Feed and machinery storage cost, $	17,936	17,936	17,936	17,936	17,936
Labor cost, $	33,000	33,000	33,000	33,000	33,000
Seed, fertilizer, and chemical cost, $	8616	8879	8879	8807	8966
Purchased feed and bedding cost, $	23,429	17,615	17,434	19,181	13,653
Animal and milking facilities cost, $	27,346	27,346	27,346	27,346	27,346
Livestock expenses, $	14,280	14,280	14,280	14,280	14,280
Milk hauling and marketing fees, $	11,640	11,640	11,640	11,640	11,640
Land charge and property tax, $	18,587	18,587	18,587	18,587	18,587
Total production cost, $	198,911	193,375	193,192	194,773	189,505
Milk, feed, and animal sale income, $	198,079	196,323	196,349	197,692	195,932
Net return to management, $	–832	2948	3157	2919	6427

[1]Sixty mature cows and 52 replacement heifers on 70 ha of cropland simulated over 25 yr of Madison, Wisconsin, weather.

[2]Protein 1 is 44% CP soybean meal only. Protein 2 is a low RDP mix consisting of 50% heat-treated (protected) soybean meal, 25% blood meal, and 25% swine meat and bone meal.

[3]Protein supplement is roasted soybeans only.

[4]Protein needs are met as efficiently as possible using two protein sources; one is 100% RDP and the other is 100% RUP. Assumed price of each is $500/tonne DM.

[5]Average amount of N cycled through the farm each year from manure, fertilizer, legume fixation, and precipitation.

plementation practices with the low RDP mix, the producer could afford to pay up to $2.50/kg of DM for these hypothetical protein feeds to improve N utilization and farm profit.

The form of protein supplementation had a moderate influence on the environmental impact and profitability of this dairy farm. When diets were formulated to meet animal requirements–shifting from a relatively inefficient protein source to a theoretically most-efficient source-the amount of N cycled through the farm was reduced by 10%. Nitrogen volatilization was reduced 33% and leaching loss was reduced 8%. Use of well-balanced rations containing low RDP feeds reduced N losses nearly as much as this theoretical maximum while providing an increase in farm net return.

Increased Animal Density

For the next evaluation, the same farm was used except that the herd size was increased to 100 cows plus replacements. This increased the number of animal units (1000 kg of BW) from 0.9 to 1.5/ha. With more animals on the farm, larger amounts of forage and grain were purchased and imported to the farm. An additional 272 tonnes DM of hay, 125 tonnes DM of corn grain, and 12 tonnes DM of soybean meal were fed (column 1, Table 6 vs. column 1, Table 5). The increased importation of feed led to much greater nutrient loading on the farm. With more N cycled in manure, N volatilization and leaching losses increased 64 and 39%, respectively. Phosphorus and K balances moved from a shortage to an excess condition where they accumulated in the soil.

Although the increase in animal density greatly increased N loss to the environment, the N loss per unit of milk shipped from the farm did not increase. Since milk produced on the farm increased 67%, the volatile loss per unit of milk produced did not change compared to the 60-cow option, and the leached N loss per unit of milk actually decreased. For a holistic assessment, though, one would have to consider the N lost in producing the extra feed imported to the farm.

Most production costs increased with the larger herd. Machinery, fuel, and labor costs all increased with more feeds fed and more animals milked. With the elimination of P and K fertilizers, fertilizer costs decreased $380/yr. Feed costs increased considerably, but income also increased with more milk sold. Overall, farm net return or profit improved by $32,600/yr making the operation more financially viable. Therefore, the increase in animal numbers per unit land area improved profitability but increased the potential degradation of the environment.

An improvement in protein feed efficiency provided a greater reduction in N loss compared to that found with fewer animals. Nitrogen volatilization was reduced 26 kg/ha (21%), and leaching loss was reduced 0.9 kg/ha (4%) by including the low RDP feed in rations (columns 1 and 2, Table 6). Annual net return of the farm increased about $5100 or $51/cow, which was $15/cow less than that found with 60 cows. Therefore, improving the efficiency of protein use provided greater environmental benefit per unit of land but less economic benefit per animal when high animal numbers caused excess nutrient loading.

Lower Milk Production

Milk production was decreased to 8000 kg/cow per year on the small farm with 100 cows. With lower milk production, feed intake decreased. Thus, less hay and corn grain were purchased and imported to the farm (Table 6). About 8% less protein supplement was required when soybean meal was the sole source or when it was used along with the low RDP mix.

The overall N balance improved slightly at lower production. Less N was excreted, so about 1600 kg less N was cycled on the farm from manure and other sources. With less N on the farm, about 8% less N was lost by volatilization with 4% less lost by leaching (Table 6). The buildup of P and K decreased with less importing of feeds. Most production costs decreased with lower feed requirements, but farm income also dropped, providing a negative net return for the farm.

There was little interaction between the efficiency of protein feeding and production. More efficient feeding of protein provided similar reductions in N losses at either milk production level. At the lower production, the improvement in net return obtained by using the low RDP feed was $46/cow per year, $5/cow per year less than that obtained at the higher production level.

Increased Farm Size

Increasing the farm size to 400 cows on 320 ha greatly increased feed production, environmental impacts, production costs, and net return (Table 7). On a land or animal unit basis, though, N loss was not that different from that of the smaller farm. This larger farm maintained 1.3 animal units/ha of land base, which fell between the 0.9 and 1.5 animal units/ha for the 60 and 100-cow options on the smaller farm. Nitrogen cycled on the farm (from manure, fertilizer, legumes, and rain) was 425 kg/ha per year, which was similar to that on the 60-cow farm. Nitrogen volatilization and leaching losses per hectare were slightly

TABLE 6. Effect of number of animals, milk production, and protein supplementation strategy on annual feed production, feed use, production costs, nutrient balance, and net return of a 100-cow dairy farm in south central Wisconsin.[1]

	High production		Moderate production	
Production or cost parameter	Strategy 1[2]	Strategy 2[3]	Strategy 1	Strategy 2
Alfalfa silage production, tonne DM	198	198	198	198
Alfalfa hay production, tonne DM	68	68	68	68
Corn silage production, tonne DM	129	129	129	129
Corn grain production, tonne DM	151	151	151	151
Alfalfa purchased, tonne DM	236	238	188	190
Corn grain purchased, tonne DM	136	182	92	134
Soybean meal purchased, tonne DM	81	1.5	74	2.4
Protein mix purchased, tonne DM	—	28	—	25
Average milk production, kg/cow	10,000	10,000	8000	8000
Nitrogen cycled on farm[4], kg	37,045	34,162	35,410	32,813
Nitrogen imported, kg	29,619	26,761	27,097	24,476
Nitrogen exported, kg	10,260	10,013	9240	8970
Nitrogen lost by volatilization, kg	8774	6927	8034	6387
Nitrogen lost by leaching, kg	1398	1338	1337	1280
Residue and unused soil nitrogen, kg	994	914	925	852
Phosphorus accumulation, kg	779	784	584	588
Potassium accumulation, kg	4729	3773	3881	3019
Field and feeding machinery cost, $	41,197	41,184	40,882	40,877
Fuel and electric cost, $	4713	4708	4500	4498
Feed and machinery storage cost, $	18,848	18,848	18,843	18,848
Labor cost, $	44,000	44,000	44,000	44,000
Seed, fertilizer, and chemical cost, $	8232	8232	8232	8232
Purchased feed and bedding cost, $	74,995	69,927	62,031	57,216
Animal and milking facilities cost, $	32,749	32,749	32,749	32,749
Livestock expenses, $	23,800	23,800	23,800	23,800
Milk hauling and marketing fees, $	19,399	19,399	15,520	15,520
Land charge and property tax, $	18,909	18,909	18,909	18,909
Total production cost, $	286,842	281,753	269,466	264,649
Milk, feed, and animal sale income, $	318,585	318,600	261,379	261,149
Net return to management, $	31,743	36,844	−8087	−3500

[1]One hundred mature cows and 85 replacement heifers on 70 ha of cropland simulated over 25 yr of Madison, Wisconsin, weather.

[2]All protein supplementation is met through the use of 44% CP soybean meal.

[3]Protein supplements include 44% CP soybean meal and a low RDP mix consisting of 50% heat-treated (protected) soybean meal, 25% blood meal, and 25% swine meat and bone meal.

[4]Average amount of N cycled through the farm each year from manure, fertilizer, legume fixation, and precipitation.

greater for the large farm compared to the 60-cow option, but much less than that with 100 cows on 70 ha. Volatilization losses per animal unit were 20% less for the 400-cow herd relative to the others because more corn silage was used on this farm. With more corn silage and less alfalfa silage in diets, less highly volatile ammonia N was excreted. Manure sources of P and K exceeded crop needs, causing a buildup of 4 and 43 kg/ha for the two minerals, respectively. This again fell between that found for the two herd sizes on the small farm.

The annual net return for the larger farm was $251,000 or $627/cow. This was a sizable increase over that obtained with any of the options for the smaller farm indicating a more economically sustainable production system. A summary of all simulations thus far indicates that increasing farm size does not necessarily increase nutrient losses to the environment, and it can substantially improve profitability. Good management practices must be used, though. This series of simulations indicates that for best use of N, animal density must be maintained at less than 1.3 animal units per hectare of cropland.

There was more benefit for improving protein feeding efficiency on this larger farm per unit of land, but on an animal unit basis it fell between the 60 and 100 cow options on the smaller farm. Nitrogen volatilization loss, leaching loss, and residual N were reduced 28, 1.4, and 7 kg/ha (31, 8, and 34%), respectively, by including the low RDP feed in rations. The reduction in volatile loss was about 35% greater than that on the small farm with 60 cows and similar to that with 100 cows. Net return for the farm improved by $66/cow per year, which was similar to that found with

60 cows and 30% greater than that with 100 cows on 70 ha.

Predominant Soil Type

By shifting the 400-cow farm from a predominantly loam soil to a loamy sand soil, crop yields decreased and N movement through the soil increased due to the lower water holding capacity of the sandy soil. The average annual decrease in yield was 12, 18, and 17% for alfalfa, corn silage, and corn grain, respectively. Since the corn silage silo was filled to the same capacity in either case, the reduction in corn yield was reflected in less grain production (Table 7). With less feed produced, more hay and grain were imported to the farm. Slightly less protein supplement was required with the more sandy soil due to higher protein concentrations in the lower yielding corn silage crop and the importing of more alfalfa hay.

Nitrogen volatilization was similar across soil types, but leaching losses more than doubled. Leaching loss increased because more moisture movement occurred in the porous loamy sand soil and the moisture movement carried more of the soil N below the root zone. Phosphorus and K accumulations were also greater because of the lower crop yields. With less feed obtained from the cropland, more nutrients were imported to the farm in purchased feed.

Farm profitability was less on the sandier soil, but it remained very viable; the annual net return was $525/cow. With lower crop yields, harvest costs decreased slightly, purchased feed costs increased, and the income from excess feed sales decreased. This led to a $41,000 decrease in the annual net return.

TABLE 7. Effect of soil type and protein supplementation strategy on annual feed production, feed use, nutrient balance, production costs, and net return of a representative 400-cow dairy farm in south central Wisconsin.[1]

	Medium loam soil		Medium loamy sand soil	
Production or cost parameter	Strategy 1[2]	Strategy 2[3]	Strategy 1	Strategy 2
Alfalfa silage production, tonne DM	976	976	842	842
Corn silage production, tonne DM	1207	1207	1204	1204
Corn grain production, tonne DM	742	742	494	494
Alfalfa purchased, tonne DM	244	275	411	437
Corn grain purchased, tonne DM	185	426	458	678
Soybean meal purchased, tonne DM	494	59	458	58
Protein mix purchased, tonne DM	—	152	—	140
Average milk production, kg/cow	10,000	10,000	10,000	10,000
Nitrogen cycled on farm[4], kg	135,996	120,385	131,295	116,934
Nitrogen imported, kg	100,658	84,525	102,694	88,116
Nitrogen exported, kg	40,182	37,994	33,042	31,965
Nitrogen lost by volatilization, kg	28,597	19,773	29,416	20,776
Nitrogen lost by leaching, kg	5752	5304	13,339	12,513
Residue and unused soil nitrogen, kg	6880	4564	8665	6722
Phosphorus accumulation, kg	1328	1380	2461	2496
Potassium accumulation, kg	13,783	8861	16,990	12,464
Field and feeding machinery cost, $	116,496	116,450	113,760	113,728
Fuel and electric cost, $	20,840	20,825	20,094	20,088
Feed and machinery storage cost, $	54,417	54,919	53,550	53,793
Labor cost, $	220,000	220,000	220,000	220,000
Seed, fertilizer, and chemical cost, $	40,812	40,812	40,812	40,812
Grain drying cost, $	1245	1239	383	379
Purchased feed and bedding cost, $	235,498	202,334	276,543	248,447
Animal and milking facilities cost, $	85,082	85,082	85,082	85,082
Livestock expenses, $	95,200	95,200	95,200	95,200
Milk hauling and marketing fees, $	77,872	77,872	77,872	77,872
Land charge and property tax, $	85,577	85,577	85,577	85,577
Total production cost, $	1,033,039	1,000,310	1,068,873	1,040,978
Milk, feed, and animal sale income, $	1,283,885	1,277,381	1,278,829	1,275,359
Net return to management, $	250,846	277,071	209,956	234,381

[1]Four hundred mature cows and 340 replacement heifers on 320 ha of cropland simulated over 25 yr of Madison, Wisconsin weather.

[2]All protein supplementation is met through the use of 44% CP soybean meal.

[3]Protein supplements include 44% CP soybean meal and a low RDP mix consisting of 50% heat-treated (protected) soybean meal, 25% blood meal, and 25% swine meat and bone meal.

[4]Average amount of N cycled through the farm each year from manure, fertilizer, legume fixation, and precipitation.

TABLE 8. Interaction of the manure handling strategy, type of forage, and the amount of forage in the diet with the type of protein supplement used and their combined effect on feed use, nitrogen loss, and farm net return for a representative 60-cow dairy farm in south central Wisconsin.

Stategy	Forage use	Grain use	Protein 1[1] use	Protein 2[2] use	N volatile loss	N leach loss	Net return
	(kg/cow)				(kg/ha)		($/cow)
Base farm (from Table 5)							
Soybean meal only	5983	2700	1147	—	77	14.3	–14
Both protein sources	6033	3327	27	341	56	13.4	53
Precise supplement[3]	6033	3698	13	40	51	13.1	—
Daily haul of manure							
Soybean meal only	5950	2750	1160	—	133	10.3	37
Both protein sources	6000	3360	23	403	99	10.3	105
Precise supplement	6000	3728	13	42	92	10.3	—
All alfalfa silage							
Soybean meal only	6433	2962	778	—	92	13.5	–32
Both protein sources	6450	3410	0	273	76	13.1	16
Precise supplement	6433	3653	0	28	71	12.9	—
All corn silage							
Soybean meal only	5767	1948	1708	—	49	17.9	13
Both protein sources	5750	2352	955	280	36	17.0	60
Precise supplement	5883	3293	115	57	35	17.0	—
Maximum forage diet							
Soybean meal only	7417	1988	898	—	84	14.7	–45
Both protein sources	7467	2477	0	323	67	14.0	10
Precise supplement	7467	2745	0	38	62	13.7	—

[1]Soybean meal with 44% CP except for the precise supplementation strategy where this supplement is defined as 100% RDP.

[2]A low RDP mix consisting of 50% heat-treated (protected) soybean meal, 25% blood meal, and 25% swine meat and bone meal. For the precise supplementation strategy, this supplement was defined as 100% RUP.

[3]A stategy where hypothetical sources of pure RDP and pure RUP are used to meet animal protein requirements.

The method of protein supplementation did not have much interactive effect with soil type. Since leaching losses were greater on the sandier soil, more efficient feeding of protein provided a greater reduction in leaching loss. This benefit was still small (2.6 kg/ha or 6%), however, indicating that it may have little practical value. The economic benefit of $61/cow per year was a little less than the difference between the two feeding strategies on loam soil.

Manure Handling Strategy

When manure is hauled daily, incorporation and preservation of N becomes difficult. Manure is normally spread on the surface and incorporated after a few weeks or months. During the time between application and incorporation, most of the volatile N contained in the manure is lost to the atmosphere. When a daily haul strategy was compared to the base farm that used a 6-mo storage system, volatile N loss increased by 70% (Table 8). Since more of the N was lost to the atmosphere, less was available in the soil profile during the winter months. Thus, leaching loss decreased about 25%. With the elimination of the storage tank, farm net return increased about $50/cow per year. Extensive comparisons of manure handling systems are reported by Borton et al. (3) and Harrigan et al. (8).

The emphasis of this analysis was the interaction between protein supplementation and manure handling. The excess N consumed when soybean meal was used as the only supplement was excreted in urine as highly volatile N. Since daily hauling provided a greater opportunity for volatilization, more efficient protein use had a greater impact. With the daily haul system, use of both protein sources reduced N volatilization by 34 kg/ha compared to the use of soybean meal alone (Table 8). This difference was 21 kg/ha for the base farm that used a 6-mo storage and more timely incorporation of manure. Since most of the excess N was lost to the atmosphere, the N available in the soil profile was not affected by the efficiency of protein use by the animal. Therefore, N leaching was essentially the same for all types of protein feeding.

Use of precise supplementation, or the theoretical maximum efficiency in protein feeding, provided only a small additional reduction in N loss. This difference in N loss between the use of the low RDP feed and the theoretical precise supplementation of protein was small (5 to 10% decrease) for either manure handling strategy as well as all other management strategies evaluated. This implies that near maximum efficiency in protein feeding can be attained with well balanced diets using low RDP feeds under most management scenarios.

Type of Forage

In feeding systems that rely heavily on alfalfa silage, formulated diets are relatively high in CP or total N content. Much of this N is highly degradable NPN. When corn silage was removed from the farm and replaced with alfalfa silage, the amount of protein supplement needed decreased by 30% (Table 8). The protein required, though, was low RDP. Use of soybean meal as the sole supplement lead to more volatile N in manure and thus greater volatile loss. Leaching loss was less than that of the base farm because less leaching occurred under alfalfa.

Feed protein supplementation had less impact on N loss and farm profit compared to the base farm that included both alfalfa and corn silages. Use of the low RDP supplement reduced N volatilization by 16 kg/ha, which was 24% less than that obtained on the base farm. Net return was improved by $48/cow per year, which was 28% less than that found on the base farm. Therefore, as more alfalfa silage was used in the farm system, there was less environmental and economic benefit to improve protein supplementation. This occurred because of the large amount of highly degradable N in alfalfa silage. An RUP source was well utilized in this system. Even with this type of supplementation though, considerable excess N was excreted. The large amount of excreted N reduced the relative benefit of more efficient protein supplementation.

When all forage on the farm came from corn silage, much more protein supplementation was needed (Table 8). In this case, the more degradable and less expensive soybean meal was the primary supplement. The balance of RDP and RUP requirements was met more efficiently across all animal groups, causing less excess N to be excreted. This provided a 36% reduction in N volatilization compared to the base farm. With a greater percentage of the land in corn, more commercial fertilizer was required and N leaching was increased by 25%. Since corn silage-based rations supplemented with soybean meal provided a better match to animal requirements than was obtained with alfalfa-based diets, use of a low RDP feed with corn silage had less opportunity for benefit. The decrease in N loss and the increase in farm profit obtained through more efficient feeding of protein were about 30% less than that obtained on the base farm that used both alfalfa and corn silages.

Maximum Forage Diets

By feeding more forage in animal diets, less grain and protein supplement was used (Table 8). The need for protein supplementation decreased primarily because more high-protein alfalfa was fed. This also meant that a low RDP supplement was preferred. With this feeding strategy, the environmental and economic benefits for more efficient supplementation of protein were less than that obtained with less forage in the diets. These differences were relatively small, with 4 kg/ha less N loss and $12/cow per year less improvement in farm net return.

DISCUSSION

Many characteristics of a dairy farm can influence the nitrogen losses that occur from the farm. In this series of simulations, effects of animal density, milk production level, soil type, manure storage, and the amount and type of forage used were determined for specific scenarios. It is interesting to compare the N loss obtained with the various system changes as a measure of the relative sensitivity of the system to these changes (Figure 2). Caution is needed in generalizing these results across farms because interactions with other characteristics can greatly influence these results. Although the major components of the model have been validated to actual data, no attempt was made to validate these specific findings to real farm information.

Farm changes made in these simulations showed relatively small impacts on the amount of N leached from the farm except for the change in soil type (Figure 2). Shifting from a loam soil to a loamy sand soil increased leaching loss by 24 kg/ha. All other system

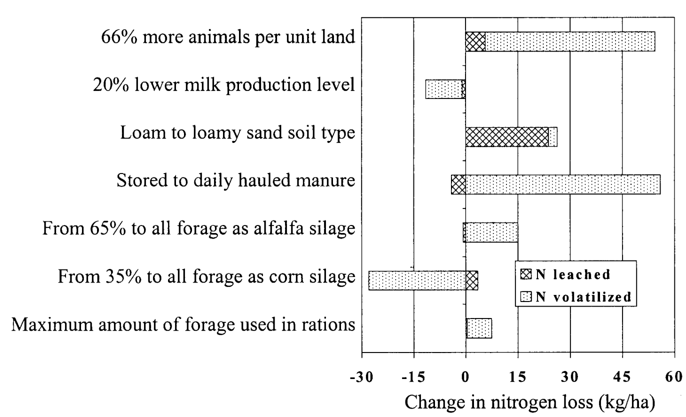

Figure 2. Effect of animal, soil, manure, and forage system changes on the amount of N leached or volatilized from representative dairy farms where soybean meal is used as the sole protein supplement in animal rations.

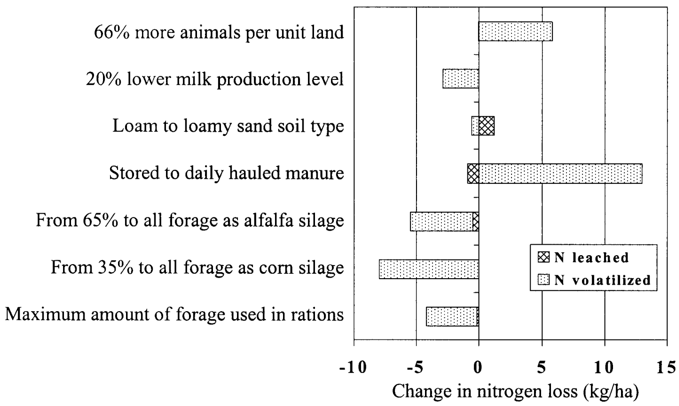

Figure 3. Effect of animal, soil, manure, and forage system changes on the difference in N losses from representative dairy farms obtained by changing the feeding strategy from soybean meal as the sole protein supplement to the use of a well balanced combination of soybean meal and a less rumen degradable protein feed.

changes influenced leaching loss by less than 10 kg/ha. Volatile N loss was influenced most by animal density and daily manure hauling. Adding 66% more animals to the land base increased volatile loss by 50 kg/ha. Compared to manure storage with timely incorporation into the soil, daily hauling of manure without incorporation increased volatile loss by 55 kg/ha. The greatest reduction in N volatilization (28 kg/ha) was obtained by using more corn silage on the farm. With more corn silage, there was less excess RDP in animal diets and thus less volatile N excreted.

The more notable results of this study are the interacting effects of these various system changes with the benefits received from more efficient feeding of protein (Figure 3). More efficient protein feeding had the greatest potential for reducing N leaching loss on a sandy soil. For all other system changes, the impact on leaching loss was relatively minor because leaching loss was small compared to volatile loss. The benefit of reduced volatile N from more efficient protein feeding increased most through the switch from stored manure to daily manure hauling. This benefit decreased the most compared to the base farm with the shift to all corn silage on the farm. This occurred because corn silage-based diets were balanced with less excess protein in rations. With less excess protein, more efficient feeding of protein had less benefit. Increasing the amount of alfalfa silage produced and used on the farm or the amount used in rations had similar effects. In either case, the reduction in volatile loss through more efficient use of protein supplements was about 5 kg/ha less than that of the base farm.

CONCLUSIONS

Among the farm characteristics evaluated, a change from loam to loamy sand soil provided the greatest increase in N loss by leaching (24 kg/ha of cropland). An increase in the number of animals on the farm or a shift to a daily manure hauling strategy provided the greatest increases in volatile N loss (about 50 kg/ha).

More efficient feeding of protein supplements reduced N loss from the farm. Compared with using soybean meal as the sole protein supplement, adding a low RDP feed to animal diets reduced volatile N loss by 17 to 31% (13 to 34 kg/ha) with a small reduction (about 1 kg/ha) in N leaching loss. This combination of feed supplements provided similar N losses as obtained with a theoretical maximum protein feeding efficiency using available forages.

In all scenarios evaluated, there was economic incentive for improving the efficiency of protein supplementation. Using a more expensive but lower RDP supplement along with soybean meal improved the net return of simulated farms by $46 to $69/cow per year.

Environmental and economic benefits of using more efficient supplementation of protein were generally greater for greater animal densities, higher milk production, sandier soils, or with the use of a daily manure hauling strategy. Less benefit was obtained when either alfalfa or corn silages were the sole forage on the farm or when relatively high amounts of alfalfa forage were used in animal rations.

ACKNOWLEDGMENTS

This work was supported by the USDA's Agricultural Research Service and a grant from the USDA's National Research Initiative Competitive Grants Program, award number 94-37502-0970.

REFERENCES

1 Bacon, S. C., L. E. Lanyon, and R. M. Schlauder, Jr. 1990. Plant nutrient flow in the managed pathways of an intensive dairy farm. Agron. J. 82:755–761.
2 Borton, L. R., C. A. Rotz, J. R. Black, M. S. Allen, and J. W. Lloyd. 1997. Alfalfa and corn silage systems compared on Michigan dairy farms. J. Dairy Sci. 80:1813–1826.
3 Borton, L. R., C. A. Rotz, H. L. Person, T. M. Harrigan, and W. G. Bickert. 1995. Simulation to evaluate dairy manure systems. Appl. Eng. Agric. 11:301–309.
4 Buckmaster, D. R., C. A. Rotz, and D. R. Mertens. 1989. A model of alfalfa hay storage. Trans. ASAE 32:30–36.
5 Buckmaster, D. R., C. A. Rotz, and R. E. Muck. 1989. A comprehensive model of forage changes in the silo. Trans. ASAE 32:1143–1152.
6 Dou, Z., R. A. Kohn, J. D. Ferguson, R. C. Boston, and J. D. Newbold. 1996. Managing nitrogen on dairy farms: An integrated approach I. Model description. J. Dairy Sci. 79:2071–2080.
7 Fick, G. W. 1977. The mechanisms of alfalfa regrowth: a computer simulation approach. Search. Agric. 7:1–28.

8 Harrigan, T. M.; W. G. Bickert, and C. A. Rotz. 1996. Simulation of dairy manure management and cropping systems. Appl. Eng. Agric. 12:563–574.
9 Inagaki, T., and T. M. Harrigan. 1997. Manure cost plus: a machinery management program for manure handling equipment. Paper No. 974048. ASAE, St. Joseph, MI.
10 Jacobs, L. W. 1995. Computer Programs to Assist with Manure Management. Proc. Soil Sci. Soc. Am. Madison, WI.
11 Jones, C. A., and J. R. Kiniry, ed. 1986. CERES-Maize: A Simulation Model of Maize Growth and Development. Texas A&M Univ. Press, College Station.
12 Klausner, S. D., D. G. Fox, C. N. Rasmussen, R. E. Pitt, T. P. Tylutki, P. E. Wright, L. E. Chase, and W. C. Stone. 1998. Improving dairy farm sustainability. I: an approach to animal and crop nutrient management planning. J. Prod. Agric. 11:225–239.
13 Kohn, R. A., Z. Dou, J. D. Ferguson, and R. C. Boston. 1997. A sensitivity analysis of nitrogen losses from dairy farms. J. Environ. Mgmt. 50:417–428.
14 National Research Council. 1989. Nutrient Requirements of Dairy Cattle. 6th rev. ed. Natl. Acad. Sci., Washington, DC.
15 Rotz, C. A. 1995. Loss models for forage harvest. Trans. ASAE 38:1621–1631.
16 Rotz, C. A., D. R. Buckmaster, D. R. Mertens, and J. R. Black. 1989. DAFOSYM: a dairy forage system model for evaluating alternatives in forage conservation. J. Dairy Sci. 72:3050–3063.
17 Rotz, C. A., and Y. Chen. 1985. Alfalfa drying model for the field environment. Trans. ASAE 28:1686–1691.
18 Rotz, C. A., D. R. Mertens, D. R. Buckmaster, M. S. Allen, and J. H. Harrison. 1999. A dairy herd model for use in whole farm simulations. J. Dairy Sci.
19 Savoie, P., L. D. Parsch, C. A. Rotz, R. C. Brook, and J. R. Black. 1985. Simulation of forage harvest and conservation on dairy farms. Agric. Syst. 17:117–131.
20 Schmit, T. M., and W. A. Knoblauch. 1995. The impact of nutrient loading restrictions on dairy farm profitability. J. Dairy Sci. 78:1267–1281.
21 Shaffer, M. J., A. D. Halvorson, and F. J. Pierce. 1991. Nitrate leaching and economic analysis package (NLEAP): model description and application. Pages 285–298 *in* Managing Nitrogen for Groundwater Quality and Farm Profitability. R. F. Follett, D. R. Keeney, and R. M. Cruse, ed. Soil Science Society of America, Madison, WI.
22 Tamminga, S. 1992. Nutrition management of dairy cows as a contribution to pollution control. J. Dairy Sci. 75:345–357.
23 Tomlinson, A. P., W. J. Powers, H. H. Van Horn, R. A. Nordstedt, and C. J. Wilcox. 1996. Dietary protein effects on nitrogen excretion and manure characteristics of lactating cows. Trans. ASAE 39:1441–1448.
24 Vandehaar, M. P. 1998. Efficiency of nutrient use and relationship to profitability on dairy farms. J. Dairy Sci. 81:272–282.
25 Wilkerson, V. A., D. R. Mertens, and D. P. Casper. 1997. Prediction of excretion of manure and nitrogen by Holstein dairy cattle. J. Dairy Sci. 80:3193–3204.
26 Wohlt, J. E., S. L. Chmiel, P. K. Zajac, L. Backer, D. B. Blethen, and J. L. Evans. 1991. Dry matter intake, milk yield and composition, and nitrogen use in Holstein cows fed soybean, fish or corn gluten meals. J. Dairy Sci. 74:1609–1622.

APPENDIX

For those interested in further analysis and comparison of dairy production systems, a Windows® version of DAFOSYM is available from the home page of the Pasture Systems and Watershed Management Research Laboratory (http://pswmrl.arsup.psu.edu). The program operates on computers that use any Microsoft Windows® operating system. To obtain a copy of the program, the home page is accessed through the Internet at the address given. Instructions for downloading and setting up the program are provided.