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Whole-Farm Management to Reduce Nitrogen Losses from Dairy Farms

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Abstract. *Whole farm simulation provides a tool for evaluating the impact of nutrient conservation technologies and strategies on dairy farms. A farm simulation model was verified by simulating the production and nutrient flows of the De Marke experimental dairy farm in the Netherlands. Technology such as a low nitrogen emission barn floor, a covered manure storage, manure injection, and the interseeding of grass on corn land to absorb excess nitrogen were used on this farm to reduce nitrogen loss. Simulation of these practices on representative farms in southern Pennsylvania illustrated that nitrogen loss, primarily in the form of ammonia emission, could be reduced by about 35%. The cost of this technology was greater than the value of the nitrogen saved causing a reduction in the annual net return of $80/cow for a 100-cow farm and $74/cow for a 1000-cow farm.*

Keywords. Dairy farm, Simulation, Nutrient management, Nitrogen loss, Economics.

Introduction

Two constraints to long-term sustainability of dairy farms in America and many other countries are profitability and environmental impact. As the dairy industry adjusts to a more global market, the real price of milk has been stable or declining while production costs increase. Environmental concerns are also growing as we learn more about nutrient losses and their impacts. Measures can be taken to better utilize farm nutrients and reduce losses to the environment, but these changes often increase production costs and reduce net income (De Haan, 2001). Thus, the problem of reducing potential environmental impacts while maintaining or improving profitability is complex and requires a comprehensive evaluation of the farm in its environment.

Nutrient losses of most concern are nitrogen (N) and phosphorus (P). Nitrogen emission, primarily as ammonia, begins soon after manure is excreted and it continues until that manure is incorporated into soil. Incomplete decomposition through nitrification and denitrification can also create and emit nitrous oxide and nitric oxide into the atmosphere for some manure handling and storage practices. These gaseous emissions contribute to environmental problems such as acid rain and global warming. Over application of N to soil can lead to excessive leaching of nitrates into groundwater with associated health risks. Runoff losses of P, and in some situations N, may contribute to the eutrophication of surface waters.

A number of techniques have been tested or used to reduce N volatilization losses (Bussink and Oenema, 1998). This begins by feeding animals the amount and type of protein they need to minimize the N in excreted manure. Alternative floor designs and flushing systems can reduce ammonia loss from housing facilities, and covered manure storages reduce N emissions during long-term storage. Direct injection of manure into the soil or rapid incorporation with a tillage operation reduces volatile losses during and after field application.

Phosphorus is not volatile, and in general, it is less mobile than N. Strategies for reducing P loss again begin with proper feeding of the animals (Rotz et al., 2002b). Recent studies have shown that less P can be fed to dairy animals while maintaining animal health and production. With less fed, less is excreted in manure. Avoiding spreading on frozen soil and rapid incorporation of manure also reduce the potential for runoff loss. For best utilization of both P and N, an appropriate crop-producing land area is needed to recycle the nutrients produced by the animals on the farm.

Evaluation of nutrient conservation techniques and strategies requires a whole farm assessment (Aarts et al., 1992; Jarvis et al., 1996). One approach is to implement and test strategies over a number of years on an operating farm. This approach has been used on an experimental farm in the Netherlands called De Marke (Aarts, 2000). The farm has been in operation for about 10 yr using a number of nutrient conservation approaches. A disadvantage of this approach is that the results are specific to the soil and weather conditions of that location, and thus are not necessarily directly transferable to other farms and climates. Another approach is to use computer-simulated farms (Rotz et al., 1999b; Rotz et al., 2002b). Through simulation, nutrient conservation practices can be quickly assessed over a wide range of conditions. By linking the two approaches, the operating farm provides considerable information for verifying simulation results. The model can then be used to extrapolate those results to other farms in other areas.

Our objective was to evaluate the potential long-term environmental benefits and economics of N conservation practices for dairy farms. This was done by first calibrating and verifying the model through simulation of the De Marke farm. The model was then used to evaluate the N conservation practices employed at De Marke on simulated 100- and 1000-cow dairy farms for the soil and weather conditions of southern Pennsylvania.

Procedure

Extensive information is available for the production and nutrient flows on the De Marke farm, which provides an excellent database for model development, calibration, and evaluation. A whole farm simulation model called the Integrated Farm System (IFS) model (Rotz and Coiner, 2002) was further developed and calibrated to represent De Marke including the novel nutrient conservation techniques used on the farm. After successful representation of this farm, the model was used for long-term evaluation of these techniques on representative medium and large dairy farms in Pennsylvania.

De Marke Farm

De Marke was established in the early nineties for research and demonstration of efficient nutrient management on Dutch dairy farms. The farm was designed to meet stringent environmental norms for N, P, and foreign substances such as pesticides (Aarts, 2000). Goals included reducing the annual surplus of N on the farm to 128 kg/ha (114 lb/ac) with annual ammonia emission limited to 30 kg N/ha (27 lb N/ac), nitrous oxide emission limited to 3 kg N/ha, (2.7 lb N/ac), and nitrate in upper groundwater below 50 mg/liter (50 ppm). The annual goal for surplus P was less than 0.45 kg/ha (0.4 lb/ac) with a P contentl in the upper groundwater of 0.15 mg/liter (150 ppb). De Marke is located near Hengelo in the province of Gelderland. The farm was intentionally placed on soil that was among the driest and most prone to leaching in the Netherlands. The soil is deep sand with 30 cm (12 in) of humic topsoil and an available water holding capacity of about 50 mm (2 in).

Over the past 10 yr, the size characteristics of De Marke have been relatively constant with about 55 ha (136 ac) of cropland, 78 milking cows, and 57 young stock (table 1). Crop production has varied over this period, but grass production has remained relatively stable at about 56% of the farm area (table 1). For the first three years, fodder beets were grown. From 1996 to 1999, the cropping strategy included only grass and corn. Beginning in 2000, some of the corn area was replaced with triticale produced as silage. A portion of the grass has been rotationally grazed each year starting with about 8 h of grazing per day. Beginning in 2000, grazing was reduced to about 5 h per day with a reduction in the grazed area. Small amounts of irrigation were used under critical conditions to avoid crop death or to produce sufficient grass for limited grazing. High moisture ear corn was harvested with a novel machine that also harvested the stover into a separate truck for low quality silage production.

Extensive data were collected each year from the farm, including production and nutrient management information (Aarts, 2000). Yields and nutrient contents were monitored for each harvested crop and each purchased feed fed to the animals. Animal production data included milk production and components (table 1) and the number and size of animals brought onto or removed from the farm. Nutrient information included the amount and form of all nutrient flows including that in fertilizer, manure, atmospheric deposition, legume fixation, feeds, and animals. Nitrogen losses due to volatilization, denitrification, and leaching were also monitored or estimated. This information was used to develop detailed N and P balances for the farm (Aarts et al., 2000a; Aarts et al., 2000b; Hilhorst et al., 2001).

Several techniques or strategies were used in this farm system to increase nutrient use efficiency and reduce losses to the environment (Aarts, 2000). This began with efficient feeding of the animals. High forage diets were fed, supplemented with homegrown high moisture ear corn and relatively small amounts of purchased concentrate feeds. A unique floor system was used in the housing facility to separate urine from feces, which reduced the transformation of N to volatile ammonia and its subsequent loss. Urine and feces were combined and stored up to six months in a covered storage tank. Manure was applied through shallow injection on

Table 1. Crop area and animal production on the De Marke experimental farm, 1993 to 2001.

	1993	1994	1995	1996	1997	1998	1999	2000	2001
Cows	82	81.2	79.4	76.6	75.6	79.8	76.8	77.0	77.5
Heifers > 1 year old	29.9	28.8	24.4	27.3	29.3	26.4	30.6	24.6	22.5
Heifers < 1 year old	35.9	29.1	30.0	31.0	26.9	31.2	31.4	28.4	25.4
Cows per ha	1.5	1.4	1.4	1.4	1.4	1.5	1.5	1.4	1.4
Animal unit per ha	1.9	1.8	1.7	1.7	1.7	1.8	2.0	1.8	1.7
Milk (kg/ha)	11806	11623	11409	11919	11787	12516	13577	12768	12395
Milk (kg/cow)	8005	8102	8119	8791	8622	8516	9175	9099	9140
Fat content (%)	4.39	4.37	4.5	4.31	4.14	4.17	4.05	4.11	4.32
Protein content (%)	3.49	3.50	3.50	3.47	3.42	3.42	3.44	3.42	3.37
Grass (ha)	30.6	35.0	34.2	29.2	26.5	31.5	31.9	30.8	30.2
Corn silage (ha)	13.1	10.1	13.7	20.2	20.1	14.1	14.9	11.5	7.6
HM ear corn (ha)	5.8	7.1	4.6	7.1	8.7	8.7	5.1	6.6	9.3
Fodder beet (ha)	6.1	4.4	4.0	0	0	0	0	0	0
Triticale silage (ha)	0	0	0	0	0	0	0	5.9	7.8
Farm area (ha)	55.6	56.6	56.5	56.5	55.3	54.3	51.9	54.8	54.9

grassland and deep injection on arable land (Hilhorst et al., 2001). Minimum amounts of N fertilizer (120 kg N/ha; 107 lb N/ac) were used on grassland to maintain adequate yields and protein contents with no N or P fertilizer applied to other crops. A “catch crop” of annual ryegrass was broadcast seeded during the cultivation of corn land about 8 wk after the corn was established. In autumn following corn harvest, this crop took up residual and mineralized N to reduce potential leaching to groundwater.

The Integrated Farm System Model

Production systems were compared using the dairy option of the IFS model. This whole-farm simulation model is an expanded version of the former Dairy Forage System Model (DAFOSYM; Rotz et al., 1999b). Crop production, feed use, and the return of manure nutrients to the land are simulated over many weather years (Rotz and Coiner, 2002). Growth and development of alfalfa, grass, corn, soybean, and small grain crops are predicted from daily soil and weather conditions. Tillage, planting, harvest, and storage operations are simulated to predict resource use, timeliness of operations, crop losses, and nutritive changes in feeds. Feed allocation and animal response are related to the nutritive value of available feeds and the nutrient requirements of the animal groups making up the dairy herd (Rotz et al., 1999a). Nutrient flows through the farm predict potential nutrient accumulation and loss to the environment (Rotz et al., 1999b; Rotz et al., 2002b).

Simulated performance is used to determine production costs, income, and farm net return for each weather year. A whole-farm budget is used where investments in equipment and structures are amortized over their economic life considering a real rate of return. Annual resource requirements and outputs predicted by the model are used to determine annual operating expenditures and incomes (Rotz and Coiner, 2002). The annual net return to management and unpaid factors is determined as the sum of the incomes from the sale of milk, animals, and excess feed minus operating costs for animal maintenance, milking and feeding, feed production, and manure handling. By simulating and comparing production options, the long-term economic and environmental effects of production changes are analyzed. The model was previously used to evaluate N flows for various corn and grass cropping strategies on representative farms on sandy soils in northern Germany (Rotz et al., 2002c).

A few model changes were made to represent the conditions of the De Marke farm. These included changes in the soil, crop, and manure handling components. Nitrogen deposition through precipitation is higher in the Netherlands than in most areas of the U.S. due to higher N emissions to the atmosphere. This was modeled by increasing the N content of precipitation by 300% to a level of 62 g N/ha for each mm of precipitation (1.4 lb N/ac per inch). An adjustment was also made to the accumulation of soil organic N under grassland. In the decomposition of manure and residue N, the proportion of N allocated to the soil organic pool was increased from 20 to 50%, and that readily available for crop uptake was reduced accordingly.

The only change required in the crop component was the addition of a grass "catch crop" following corn or triticale. A simple routine was added to simulate the uptake and release of N for this winter crop, using functions from the CERES crop growth routines (Rotz and Coiner, 2002). Dry matter accumulation was predicted on a daily basis at a rate proportional to solar radiation level adjusted for temperature stress. Nitrogen uptake was then set assuming a 2% N concentration in this growth where growth was limited by the N available. When the crop was tilled into the soil in the spring prior to the establishment of the next crop, the accumulated crop N was transferred to the soil residue pool where decomposition and transformation were simulated with the original soil component model (Rotz and Coiner, 2002).

Two additions were made to represent new technology used in manure handling on the De Marke farm. The first was done to represent the floor system used in the cow housing facility. This grooved floor with holes allows urine to drain from the feces deposited on the floor into a collection area below. Because of this temporary separation, urease activity on the floor and the resulting ammonia volatilization are reduced (Swierstra et al., 2001). To represent this floor design in our model, N emission from the housing facility was reduced 50%. The second change was made to represent the covered manure storage. For this storage type, N emission from the storage facility was set to 1.2% of the total ammonia-N stored, which reduced N loss by about 92% from a top-loaded storage or about 56% from a bottom-loaded storage (Sommer and Hutching, 1995).

A final change was made to reduce ammonia emission from grazed pasture. An original assumption that 50% of the urine N deposited on pasture was volatilized and lost to the atmosphere was a little higher than that determined for the soil conditions of De Marke. This N emission on pasture was reduced to 38% to represent more rapid absorption of urine into the sandy soil. With rapid absorption, urease activity and ammonia emission were reduced.

Model Calibration and Evaluation

After setting the model parameters to represent the crop, machinery, harvest, animal, and manure handling characteristics of the De Marke farm, a simulation was executed to calibrate the model or improve the fit between simulated and actual performance. This was done by simulating the four weather years from 1996 to 1999 when crop and animal production were relatively constant (table 1). The farm was simulated using historical daily climate data collected at the site. Simulated crop yields and feed intakes were compared to actual farm data, which revealed a need for minor adjustments of the corn growth and animal components.

Initially, the corn growth model did not adequately represent the yields obtained in the cooler climate of northern Europe. A study on heat unit requirements for corn hybrids grown in eleven European countries indicated that a lower base temperature for growth and development was justified in this region (Derieux and Bonhomme, 1982). By reducing this base temperature in our model from 8 to 6°C (46 to 43°F), more accurate yield predictions were obtained for this region. The potential delay of corn silage harvest to obtain an acceptable maturity was also increased to four weeks. This allowed silage harvest to be delayed until mid October, which sometimes occurs under these prevailing cool growing conditions.

Three adjustments were made to allow better agreement between simulated and actual feed intake and performance of the herd. First, the maximum permitted fiber intake (Rotz et al., 1999a) was increased. This allowed more forage in lactating cow rations, which better represented actual diets on De Marke. Second, the maintenance energy requirement (Rotz et al., 1999a) of all animals was reduced by 10%. This allowed growing and lactating animals to maintain production with lower energy intakes. Energy intakes for the various animal groups of the De Marke herd agreed with published Dutch requirements (Van Es, 1978), but these intakes were somewhat lower than those commonly found in the US (NRC, 2001). A justification for this difference is uncertain, but it may be related to less variable and more suitable ambient temperatures for cattle in the Netherlands. Thirdly, absorbable protein requirements (Rotz et al., 1999a) were reduced by 10% to allow simulated and actual protein intakes to agree. The De Marke cows were fed relatively low protein diets compared to American standards (NRC, 2001), but the animals perform well on these diets. With these changes, annual feed use and N intake for the simulated herd agreed very closely to that of the actual farm.

After the model was calibrated for the cropping strategy of the 1996 to 1999 weather years, a further evaluation was done for the 2000 and 2001 weather years. In addition to the change in weather, parameter changes were made for the cropping and grazing strategies. The original 24.5 ha (60 ac) of corn were reduced to 18 ha of corn (44 ac) plus 6.5 ha (16 ac) of small grain followed by a grass catch crop. A triticale crop was simulated using the wheat component model with the long-term yield adjusted to be similar to the measured farm yield (Rotz and Coiner, 2002). Eight percent of the collected manure originally applied on the corn crop was applied on the small grain crop. Triticale was established in late September and harvested as silage around the third week in June (depending upon crop maturity and suitable weather; Rotz and Coiner, 2002). Grazing of the milking herd was reduced to 5 h per day with a 50% reduction in grazing area. This reduced the portion of the manure nutrients applied through grazing and increased the nutrients collected in the barn. The legume content in the grass sward was also increased a small amount to reflect more clover in the stand, which was observed on the farm.

With these parameter changes, the farm was simulated for the 2000 and 2001 weather years. Simulated nutrient flows and balances for the farm were compared to actual values for the De Marke farm to further validate the simulation procedure.

Simulation on American farms

After the model was calibrated and evaluated against the actual data of the De Marke farm, simulations were performed to evaluate these technologies on typical farms in Pennsylvania. Representative farms were described for 100-cow and 1000-cow herds to characterize medium and large dairy farms in this region. The soil was a Hagerstown silt loam with an available water holding capacity of 130 mm (51 in). Simulations were done for 25 weather years using Chambersburg, Pennsylvania historical data (1974 to 1998).

The 100-cow farm had a land base of 100 ha (247 acres) including 25 ha (62 acres) each of grass pasture and alfalfa with the remainder in corn. This cropping system provided most of the forage and grain feeds required by the herd for most weather years. The grassland was rotationally grazed with excess forage harvested as silage or hay in spring and early summer. Corn was harvested as silage and high moisture grain to fill available silos. Silos were sized so that about 40% of the herd's forage requirement was obtained from corn silage. Corn silage harvest began after September 1 with high moisture grain harvest after October 18. Alfalfa was harvested using a five cutting strategy with each harvest beginning at a bud stage of development. All cuttings were harvested as silage wilted to less than 68% moisture content except the second, which was harvested as dry hay.

Machinery and facilities were typical of those used in the region (Rotz et al., 2002a). All silages were stored in appropriately sized bunker silos. Manure was scraped and spread daily without incorporation. Sixty percent of the manure collected from the herd was applied to the corn land with 10% spread on alfalfa land prior to seeding. Remaining manure, including that deposited during grazing, was applied to the grassland. To complete the N needs of the crops, 60 kg/ha (54 lb/acre) of nitrate N was applied at corn planting and 50 kg N/ha was spread on grassland.

The herd included 100 Holstein cows (milking and dry) plus replacement heifers. Replacements included 32 heifers over one year old and 35 under one year old to fulfill an annual replacement rate of 30%. Annual milk production was 8,333 kg (18,350 lb)/cow. Cows were housed in a free stall barn when not on pasture. Straw bedding was used at a rate of 1.5 kg (3.3 lb)/cow per day. A mobile mixing wagon was used to prepare total mixed rations for each animal group. Feed supplements included corn grain and two protein feeds: soybean meal and a protein mix with low rumen degradability. The protein mix was a blend consisting of one-third feather meal, one-third blood meal, and one-third fish meal. Rations were formulated to meet the NRC (2001) recommended P requirements.

The large farm included 1000 Holstein cows plus 770 heifers raised to fulfill an annual replacement rate of 35%. Bovine somatotropin was used along with other management practices to maintain milk production at 11,300 kg (24,900 lb)/cow. Animals were housed year-around in a free stall barn. The land base was 600 ha (1,481 acres) with half of the land in alfalfa and half in corn. Appropriately-sized equipment was used for field, feeding, and manure handling operations. Manure was scraped daily and stored up to six months in an earthen pond. The manure storage covered 7,400 m^2 (79,700 ft^2) with an average depth of 4.6 m (15 ft). Manure was surface-spread using a custom or contract manure hauler with 65% applied to the corn land and the remainder applied to alfalfa. Starter fertilizer at 20 kg N/ha was applied with corn planting. All other model parameters were similar to those used for the smaller farm.

Prices were set to represent long-term average values in current dollars for Pennsylvania farms (Rotz et al., 2002a). Important prices included labor at \$12/h, milk at \$30/hL, and N fertilizer at \$0.55/kg N. Prices were held constant across simulated years, so that economic differences among years were solely due to weather effects on farm performance.

Manure handling technologies evaluated on these farms included a barn floor with fecal and urine separation, a covered manure storage, deep injection of manure, and a grass catch crop following corn. Price estimates were made to determine potential economic impacts of these technologies. The alternative barn floor was estimated to increase the initial cost of the free stall barn by 15%. A few different cover systems have been used on manure storages. Plastic covers with a 10-yr life span can be installed for about \$20/m^2 on large storages. On smaller tanks, a permanent cover can be added with about a 30% increase in the initial cost. Deep injection equipment is commonly available with a 30% greater initial cost and a 25% lower field capacity than more traditional broadcast spreaders. Annual ryegrass can be broadcast seeded in corn land for an added annual cost of about \$50/ha.

Simulations were first performed for the traditional farm systems. Parameter changes were then made to select the alternative technology and the farms were simulated again. A comparison of N losses and whole farm nutrient balances was used to determine the potential long-term reductions in loss using these technologies. The predicted annual costs and net return of the farm was then used to assess the increased costs incurred and the potential economic viability of these changes.

Results and Discussion

De Marke Farm Calibration and Evaluation

Actual and simulated nutrient flows for the De Marke farm over the calibration period are shown in table 2. Nutrient flows are the four-year averages over weather years 1996 to 1999. During these years, the farm was relatively stable in animal numbers, crops grown, and crop areas. Following the model changes implemented to represent this particular farm, simulated N and P flows compared very closely to values obtained on the actual farm. Nitrogen imports from fertilizer, feed, deposition, and fixation were all closely represented by the model with the total import within 1% of the actual. Losses through volatilization, leaching, and denitrification were also very similar with the total simulated loss within 2% of the actual. Simulated N export in animals sold was 20% higher than actual due to different assumptions on the protein content in animal body tissue or animals sold. Since this number was small, the total exported N was still within 2% of actual. Overall, the unaccounted or accumulated soil N simulated by the model was just 12% less than that calculated for the actual farm. This difference represented 4.3 kg N/ha (3.9 lb N/acre), which was a relatively small and unimportant difference.

Two minor differences occurred between simulated and actual predictions of P flow. The current model does not include the deposition of P through precipitation or the potential leaching of P through the soil profile. As illustrated by the actual values published for the De Marke farm, these flows are small and they offset one another (table 2). Simulated farm imports and exports

Table 2. A comparison of actual and simulated annual nutrient flows (kg[†]) for the De Marke farm in the Netherlands for weather years 1996-1999 with 31.5 ha (78 acres) of grassland and 24.5 ha (60 acres) of corn.

	Nitrogen		Phosphorus	
	Actual	Simulated	Actual	Simulated
Imports				
Fertilizer	3,747	3,780	36	36
Net feed[‡]	5,423	5,406	744	769
Deposition	2,671	2,600	48	---
N fixation	245	263	---	---
Total	12,086	12,049	828	805
Losses				
Volatilization	1,238	1,254	---	---
Barn and storage	572	578	---	---
Field	393	398	---	---
Pasture	273	278	---	---
Leaching	3,216	3,293	49	0
Denitrification	1,486	1,511	---	---
Total	5,940	6,058	49	0
Export				
Milk	3,652	3,634	607	628
Animals sold	450	555	137	160
Total	4,102	4,189	744	788
Unaccounted/accumulated	2,044	1,802	35	17

† Pound equal 0.45 times kg.

‡ Purchased feed minus the change in on-farm feed stocks.

of P were slightly greater than actual values, resulting in a similar accumulation of soil P on the farm of less than 1 kg P/ha (0.9 lb P/acre).

Following this calibration of the model, a similar comparison of simulated and actual flows was performed for weather years 2000 and 2001 to further evaluate simulation accuracy (table 3). Two major feeding changes were introduced in 2000, which included replacement of a portion of the corn with triticale and a reduction in grazing time. Simulated and actual N flows were again similar. Greater differences often occurred between individual flow values, but most differences were within 10%. An exception was the N imported in feed. Farm records showed higher grass and corn grain yields than the model predicted for these weather years. These higher yields provided excess forage that was stored on the actual farm. This accumulation of feed nutrients offset a portion of the purchased feed nutrients creating a reduction in the net nutrient import. Simulated P imports were greater than the actual values, again due to the difference in net feed import. Simulated exports were also a little higher. This occurred because the P content of milk on the actual farm decreased about 10%, apparently as a result of less P being fed. This effect on milk P was not modeled. Overall, both the simulated and actual farm data showed a small deficit in the whole farm P balance. The difference between simulated and actual was less than 1 kg P/ha (0.9 lb P/acre), which would not be an important difference for long-term farm management. This further evaluation supports that the model was able to satisfactorily reproduce the N and P flows, including the N losses, determined for this well-managed experimental farm.

Table 3. A comparison of actual and simulated nutrient flows (kg†) for the De Marke farm in the Netherlands for weather years 2000-2001 with 31.5 ha (78 acres) of grassland, 18 ha (44 acres) of corn and 6.5 ha (16 acres) of triticale.

	Nitrogen		Phosphorus	
	Actual	Simulated	Actual	Simulated
Imports				
Fertilizer	3,044	3,030	0	0
Net feed‡	4,231	4,950	641	703
Deposition	2,688	2,863	48	---
N fixation	987	784	---	---
Total	10,950	11,627	689	703
Losses				
Volatilization	1,145	1,161	---	---
Barn and storage	576	636	---	---
Field	451	389	---	---
Pasture	118	136	---	---
Leaching	2,743	3,382	49	0
Denitrification	1,546	1,079	---	---
Total	5,434	5,622	49	0
Export				
Milk	3,648	3,702	551	640
Animals sold	439	512	144	147
Total	4,087	4,214	695	787
Unaccounted/accumulated	1,429	1,791	-55	-84

† Pound equal 0.45 times kg.

‡ Purchased feed minus the change in on-farm feed stocks.

Pennsylvania Dairy Farms

The manure handling and N conserving practices implemented on the De Marke farm were then evaluated on medium and large sized farms in southern Pennsylvania. Major performance and economic characteristics of the medium 100-cow farm are listed in column 1 of table 4. This farm had a land base that allowed 88% of the long-term feed requirements of the herd to be produced on the farm. The milk production level was typical of that maintained in this region on well-managed farms using rotational grazing during the summer. With a daily haul manure system without timely incorporation into the soil, N volatile loss was relatively high. With a relatively large land base to spread that manure, leaching and denitrification losses from the soil were similar to those determined in previous studies in this region (Rotz et al., 2002a). The large land base and the home production of most of the feed requirement allowed a long-term neutral P balance for the farm. The difference between farm income and production costs yielded an average annual net return to management and unpaid factors of $436/cow.

Implementing the N conservation technologies on this farm greatly reduced the N losses to the environment, with little impact on feed production and other performance measures. The reduction in N loss was primarily in the form of ammonia volatilization. With less volatile loss in the barn, during storage, and following field application, more N was available for crop uptake. With the use of long-term manure storage, the need for manure application to grassland (beyond that deposited during grazing) was eliminated and that manure was applied to corn land. This allowed a reduction in N fertilizer application to corn land to 20 kg N/ha (18 lb N/acre). The grass catch crop absorbed excess N from corn land in the fall, and carried it through the winter months for release back to the corn crop the following year. The net result was that leaching and denitrification losses of N remained similar to that of the original farm (column 2 vs. column 1, table 4). Overall, ammonia emission to the atmosphere was reduced by 60% with total N loss from the farm reduced 35%.

These changes had little effect on the whole-farm balance of P, but there was potential advantage in P distribution within the farm. On the original farm, excessive P was applied to the grassland, because that was the only land available for manure spreading during portions of the year. With long-term storage, that manure was applied to corn land. If this grassland were rotated throughout all the farmland, this excess application of P would not be a problem. If this grassland were permanent pasture, as is often the case in this region, large amounts of P could accumulate on this land increasing the risk for future losses. In addition, rapid incorporation of manure into corn land would reduce the potential for runoff loss of P to the watershed.

The economic impact of these changes is difficult to predict due to the uncertainty in estimating the costs for implementing these practices. Use of the initial cost assumptions established for this analysis provides a general indication of the cost and benefit of using the technology. The economic return is relatively small compared to the cost. The primary benefit to the farmer is a saving of 40 kg N/ha (36 lb N/acre) in fertilizer applied to the corn land. This annual savings is about 2,000 kg of N fertilizer with a value of $1,100 or $11/cow. This offsets a small portion of the increase in production costs incurred giving a reduction in annual net return of $80/cow.

The large farm, as most larger farms in this region, has a smaller land base per animal unit. All forage for the herd was produced on the farm and all grain and concentrate feeds were purchased and imported onto the farm (column 3, table 4). This importation of feed nutrients leads to excessive amounts of N cycled through the farm system, and thus large losses. Although the use of manure storage with more timely application and incorporation of manure reduces the N losses per animal unit, the loss per unit of farmland is considerably higher than that on the smaller farm (column 3 vs column 1, table 4). The importation of feed nutrients also leads to a substantial accumulation of soil P on the farm.

Table 4. Effect of using technologies for nitrogen conservation on annual feed production, feed use, production costs, nutrient balances, and net return of simulated dairy farms in southern Pennsylvania.

Production or cost parameter	100-cow†		1000-cow‡	
	Traditional system§	Nitrogen conservation¶	Traditional system#	Nitrogen conservation¶
Alfalfa hay and silage production, t DM¶¶	224	224	2,559	2,559
Grain crop silage production, t DM	172	173	3,718	3,705
Corn grain production, t DM	229	231	0	0
Grazed forage consumed, t DM	90	89	0	0
Corn grain purchased, t DM	62	61	3,024	3,017
Supplemental feed purchased, t DM	40	40	759	761
Milk production, kg/cow¶¶	8,600	8,600	11,300	11,300
Nitrogen cycled on farm††, kg/ha¶¶	317	297	517	441
Nitrogen imported, kg/ha§§	197	177	396	397
Nitrogen exported, kg/ha	63	63	140	217
Nitrogen lost by volatilization, kg/ha	81	32	125	40
Nitrogen lost by leaching, kg/ha	33	33	49	42
Nitrogen lost by denitrification, kg/ha	20	23	32	32
Phosphorus accumulation, kg/ha	0	0	10	0
Potassium accumulation, kg/ha	0	0	26	0
Feed production cost, $/cow	904	914	352	373
Manure handling cost, $/cow	122	189	237	289
Purchased feed and bedding cost, $/cow	275	277	799	801
All other costs‡‡, $/cow	1,035	1,038	996	996
Total production cost, $/cow	2,336	2,418	2,384	2,459
Milk, feed and animal sale income, $/cow	2,772	2,774	3,614	3,615
Net return to management, $/cow	436	356	1,230	1,156
Standard deviation in net returns, $/cow	138	144	133	136

† 100 mature cows and 67 heifers on 100 ha (247 acres) in alfalfa, corn and grass with a moderate milk production simulated over 25 yr of Chambersburg, Pennsylvania weather.

‡ 1000 mature cows and 770 heifers on 600 ha (1,480 acres) in alfalfa and corn with a high milk production simulated over 25 yr of Chambersburg, Pennsylvania weather.

§ Manure hauled daily and surface spread with delayed incorporation.

¶ Nitrogen conservation technologies include a barn floor for feces and urine separation, a covered six-month manure storage, manure injection, and the use of a grass catch crop following corn. The 1000-cow farm also includes the export of 27% of the manure produced.

Includes a six-month earthen storage, surface spreading, and timely incorporation of manure.

†† Average N cycled through the farm each year from manure, fertilizer, legume fixation, and precipitation.

‡‡ Includes annual costs of milking and housing facilities, livestock expenses, milk labor, and property tax.

§§ Includes 43 or 23, 57, 16, and 81 kg N/ha from feed, fertilizer, precipitation, and legume fixation, respectively on the 100-cow farm and 10, 201, 21, and 164 kg N/ha for those imports on the 1000-cow farm.

¶¶ Tons equal 1.1 times tonnes, pounds equal 0.45 times kg, and pounds/acre equal 0.9 times kg/ha.

With an initially high level of excess N in the farm system, reducing loss has no direct benefit to the producer. In fact, reducing ammonia emission from the barn or storage only increases excess N on cropland, inducing greater leaching and denitrification losses from the soil. In order to improve manure nutrient use efficiency on this farm, a portion of the manure produced must be exported. For this particular simulated farm, exporting 27% of the manure produced allowed the farm to maintain a long-term neutral P balance. This scenario, combined with the use of the N conservation technologies, reduced N losses through volatilization, leaching, and denitrification by 68, 14, and 0 %, respectively (column 4 vs. column 3, table 4). This analysis does not account for the losses that would occur from the manure exported from the farm. With deep injection of that manure, volatile losses should be minimal, but leaching losses would likely be similar to those on the original farm. If half of this exported manure were applied in the fall without a cover crop, leaching loss would be higher than on the original farm with traditional technology.

On this 1000-cow farm, there was no economic return to the producer for implementing these changes. With excess N available, reduced N loss had no economic value. This analysis assumes that the farm would be applying the exported manure on neighboring farms at the original farm's expense. If the producer were able to sell this manure, there would be some return. The fertilizer replacement value for this manure would be about $45,000 or $45/cow. The increased production costs incurred were $74/cow, so selling the manure for its full fertilizer value could offset about 40% of the increased cost of production.

Use of the N conservation technologies also caused a small increase in the year-to-year variation in farm net return (table 4). This increase occurred because the greater dependence upon manure N and the variability in that N source led to slightly greater annual fluctuations in corn yield.

Economic Implications

These simulations illustrate that the use of this type of technology to reduce N losses from US dairy farms cannot be justified based upon economic benefit to the producer. Economic returns or incentives for the producer are small relative to the added cost. A similar analysis determined a similar conclusion for Dutch dairy farms (De Hann, 2001). With the relatively small profit obtained in dairy production today, implementation of these technologies to reduce negative environmental impact could cause many farms to close. If society desires these changes, then society will need to help pay the added cost through some type of government support or higher milk prices. Without such assistance, we may loose our dairy industry to other countries with less stringent environmental standards.

The economic costs generated in this study are tentative and perhaps higher than necessary. Since some of this technology is not currently available or widely used, more cost effective procedures may be developed. For example, use of a low emission floor system that separates urine and feces is projected to be relatively expensive. A less costly approach may be to use a flushing system with a disinfectant in the solution (Ogink and Kroodsma, 1996). This technique was also found to reduce volatile loss in the barn by about 50%, but concerns relative to animal health must still be addressed.

The interactions among these N conserving technologies make it difficult to separate the benefits of individual steps. For example, reducing barn loss is of no benefit if steps are not taken to retain that N through storage and field application. Even though they need to be viewed as a full package, some of the measures are more cost effective than others. The most cost effective technique is deep injection of manure when a cropping and tillage system is used that allows this practice. The added equipment and operating cost of $12/cow per year may be returned in the fertilizer value of the N saved. Further benefit may come through odor reduction.

When manure nutrients are applied in the fall, a catch crop of grass may also be beneficial by carrying the N and other nutrients through the winter months. For the simulated 100-cow farm, the predicted N savings using the catch crop was 15 kg N/ha. The annual fertilizer value of this amount of N is about $8/ha ($3.20/acre) or $8/cow. Compared to the annual cost of about $25/cow for this strategy, the net cost to the producer is $17/cow.

Benefits from covered manure storages are variable. When a storage tank is used, a beneficial practice is to load the storage by pumping manure into the bottom. This allows a crust to form over the manure surface, which can reduce ammonia emission by about 80% (Sommer and Hutchings, 1995). When this practice is used, justification for using a tight cover is difficult, based upon the small amount of additional N saved. For the 100-cow farm, this difference was less than 2 kg N/ha (1.8 lb N/acre). In situations where crust formation would not occur, a sealed cover would provide greater benefit for the investment. Compared to a top loaded (no crust) open storage on this same farm, the saving would be about 14 kg N/ha with an economic value of $8/cow. This is a little less than the annualized cost of the cover (estimated at $12/cow) providing a net cost of $4/cow.

The most difficult step is to reduce the loss occurring in the barn. This loss increases with ammonia N concentration, temperature, and pH of the manure (Sommer and Hutchings, 1995). Major investments in new floor designs are costly and difficult to justify based upon the N conserved (De Hann, 2001). The estimated 15% increase in the free stall barn cost, increased annual production costs by $15/cow. The saving in N was about 13 kg N/ha on our simulated 100-cow farm. If this N is carried through the various handling steps and used in crop growth, its fertilizer value is about $7/cow for a net cost of $8/cow.

Model Availability

Other farm management options and combinations of options can be evaluated with the Integrated Farm System Model. For those interested in further analysis and comparison of farm production systems, a Windows® version of the model is available from the Internet home page of the Pasture Systems and Watershed Management Research Unit (http://pswmru.arsup.psu.edu). The program operates on computers that use any Microsoft Windows® operating system. To obtain a copy of the program, including an integrated help system and reference manual, the home page can be accessed at the address given, where instructions for downloading and setting up the program are provided.

Conclusion

Through calibration of parameters related to the base temperature for corn growth and the fiber intake constraint, maintenance energy requirement, and protein requirement of animals, the IFS model was able to satisfactorily reproduce the long-term feed production and use and the N and P flows of the De Marke experimental dairy farm in the Netherlands. Technologies used on the De Marke farm to increase nutrient use efficiency and reduce N loss included a low emission floor system in the housing facility, a covered manure storage, deep injection of manure on arable land, and underseeding of grass in corn to take up and carry excess soil N through the fall and winter seasons. Simulation of these technologies on representative farms in southern Pennsylvania illustrated that N loss, primarily in the form of ammonia emissions, could be reduced by about 35%. The cost of this technology package exceeded the value of the N saved however, causing a reduction in annual net return of $80/cow for a 100-cow farm and $74/cow for a 1000-cow farm.

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