



## **A Sensitivity Analysis of Nitrogen Losses from Dairy Farms**

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International attention has focused on agricultural production systems as non-point sources of pollution affecting the quality of streams, estuaries and ground water resources. The objective of the current study was to develop a model of nitrogen management on the dairy farm, and to perform sensitivity analyses in order to determine the relative importance of manipulating herd nutrition, manure management and crop selection in reducing nitrogen (N) losses from the farm. The importance of the method of N input to the farm (purchased feed, legume fixation, inorganic fertilizer, imported manure) was investigated, and the potential to reduce N losses from dairy farms was evaluated. Nitrogen balance equations were derived, and related efficiency coefficients were set to reference values representing common management practices. Total farm N efficiency (animal product N per N input), and N losses per product N were determined for different situations by solving the set of simultaneous equations. Improvements in animal diet and management that increase the conversion of feed N to animal product by 50% would increase total farm N efficiency by 48% and reduce N losses per product by 36 to 40%. In contrast, reducing losses from manure collection, storage and application to improve the percentage of manure N that becomes available in soil by 100% would only improve total farm N efficiency by 13% and reduce total N losses by 14%. Selecting crops and management that can use soil nutrients 50% more efficiently would improve total farm efficiency by up to 59% and reduce N losses by up to 41% depending on the predominant nitrogen sources to the farm. Legume production would reduce N losses per product compared with non-legumes. There was more than a five fold difference in N losses per animal product N between the most extreme scenarios suggesting considerable opportunity to reduce N losses from dairy farms.

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### **1. Introduction**

Animal agricultural production systems are a major source of pollution affecting the quality of water resources (Williams, 1995). The most often considered nutrient pollutants from agriculture are nitrogen (N), phosphorus (P), and methane (CH<sub>4</sub>).

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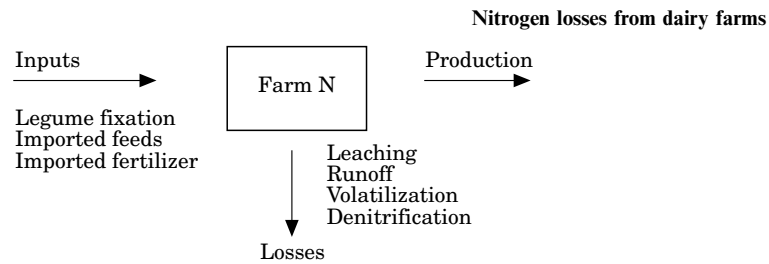


Figure 1. A one-compartment model of an animal enterprise.

Much of the previous research on nutrient management related to animal agriculture has focused on altering the impact of specific farm sub-components such as manure management (Gilbertson *et al.*, 1979; Van Horn *et al.*, 1994), soil conservation (Joshi *et al.*, 1994), crop production (Lemberg *et al.*, 1992; Vanotti and Bundy, 1994), herd density (Schmit and Knoblauch, 1995), or animal nutrition (van Vuuren and Meijs, 1987; Tamminga, 1992) to improve the overall efficiency of nutrient utilization and to reduce losses. Because agricultural scientists have specialized rather than integrated the entire system, it has been difficult to demonstrate the overall economic and environmental consequences of management decisions at the whole farm level. There has been limited discussion of the relative importance of different efforts to control nutrient pollution and the extent to which improvements in nutrient management are feasible (Aarts *et al.*, 1992; Halberg *et al.*, 1995). The logical and systematic examination of such issues should help us determine where and to what extent nutrients may be managed in animal enterprises.

Mathematical modeling is frequently used to determine future research directions, to predict the impact of management decisions and may be helpful for development of government policy (Berentsen *et al.*, 1992; Schnitkey and Miranda, 1993). Previous efforts have led to the development of a mathematical model of N flow on dairy farms (Dou *et al.*, 1996). This application includes enough detail to predict accurately the consequences of management practices on individual specified farms. For example, one can determine the impact of changes in a feeding program on nutrient inputs and losses from a farm with specified soil, cropping and manure management conditions. While this model is useful in the field on a farm-by-farm basis, it is difficult to use this model to predict or explain consequences that pertain more generally to a broader range of farms.

It is the intention of this paper to develop a simple deterministic model of nitrogen management on the dairy production enterprise. The objectives for development of this model were: (i) to determine the extent to which nutrient losses from animal production systems may be reduced by altering management practices; and, (ii) to determine the relative importance of different management strategies related to the herd, crops or manure in reducing nutrient losses from the farm. For example, will improving manure utilization by increasing storage capacity reduce nutrient losses as much as improving animal nutrition by balancing dairy cattle rations for ruminally undegraded protein? An additional objective was to determine the theoretical maximum animal densities for efficient nutrient utilization on dairy farms.

### 1.1. A ONE-COMPARTMENT MODEL

A simple starting point for the development of a mathematical model of nutrient management is demonstrated in Figure 1. Nitrogen may enter the farm in various

forms and leave as production of milk, meat or cash crops or by leaching, runoff, volatilization, or denitrification (Stevenson, 1982). Optimal nutrient management may be to minimize the losses relative to the production. This system is represented mathematically as:

$$dN/dt = \text{Inputs} - \text{Production} - \text{Losses} \quad (1)$$

The change in nutrients ( $dN/dt$ ) on the farm (in crops, feeds, soils, animals) is a function of the inputs and outputs. The steady state assumption is that inputs to the system are balanced by outputs when considered as the average over a long enough period of time. This assumption is based on the law of mass conservation, and it allows for simplification of the model ( $dN/dt=0$ ) at the expense of representing details about the variation over time. While accumulation of N on the farm may enable lower losses for a period of time, the storage capacity will eventually be depleted and the system will be in steady state—even with regard to the most slowly adjusting nutrient compartment, the soil (Powelson, 1994). Given the steady state assumption,

$$\text{Inputs} = \text{Production} + \text{Losses} \quad (2)$$

Consider the definition of the fractional efficiency of production ( $k$ ) to be the fraction of input used for production,

$$k = \text{Production}/\text{Inputs} \quad (3)$$

The losses from the farm may be calculated from the inefficiency ( $1-k$ ) times the input.

$$\text{Losses} = (1-k) \text{Inputs} \quad (4)$$

There are two ways to reduce the losses from agricultural production (Equation 4): reducing inputs while maintaining or increasing the efficiency from the same inputs. The former solution would result in proportionally lower production, while the latter is more desirable for maintenance of economic activity and food production requirements. From a global perspective, we are most interested in maintaining or increasing food production to meet rising population demands, while minimizing the losses from that production (de Wit, 1992).

For example, if production is held constant with twice the efficiency, inputs could be reduced to half, and losses would be reduced by 59% [from  $1(1-0.15)=0.85$  to  $0.5(1-0.3)=0.35$ ]. In order to meet the increasing needs of global food production while reducing nutrient pollution, production will need to increase with higher efficiency. For example, doubling the efficiency from 0.15 to 0.3 with the same inputs could double food production and at the same time decrease the losses by 18% (from equation 4:  $1-0.15=0.85$  to  $1-0.3=0.7$ ).

## 2. Methods and assumptions

The practical application of a nutrient management model requires a more complex approach (Figure 2). Four balance equations were derived as follows:

$$\text{Consumption} = \text{Excretion} + \text{Production} \quad (5)$$

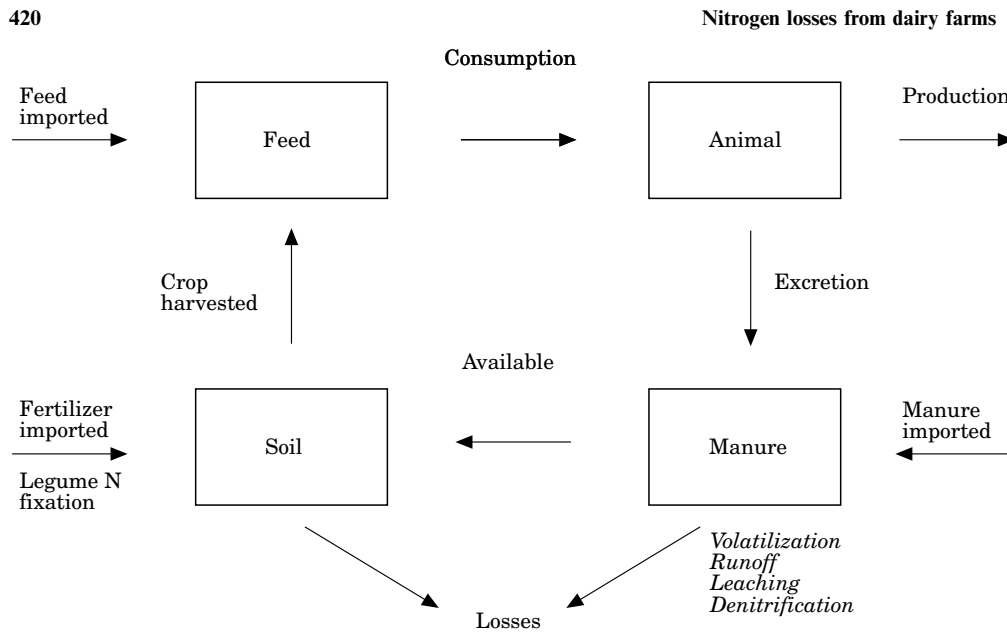


Figure 2. A four compartment model of an animal enterprise.

$$\text{Non-legume Crop} + \text{Legume Fixation} + \text{Feed Purchases} = \text{Consumption} \quad (6)$$

$$\text{Excretion} + \text{Manure Imported} = \text{Manure Available} + \text{Losses}_1 \quad (7)$$

$$\text{Fertilizer Purchases} + \text{Manure Available} = \text{Non-legume Crop} + \text{Losses}_2 \quad (8)$$

Although this model is applicable to management of any nutrient (N, P, K) by choosing the appropriate efficiency coefficients (e.g. phosphorus fixation and volatilization to and from air would be set to 0), the example provided is for N, and parameters will be used that apply to dairy farms. The following assumptions and boundaries will apply:

1. Steady state conditions were assumed for simplification. Non-steady state results can be calculated for the soil compartment by adding the net loss of soil N to the total losses, or by subtracting the net increase in soil N from the total N losses.

2. In the scenarios that follow, the amount of crop land in production was not changed. In each case, a 35 ha dairy farm was simulated to provide a tangible example. In reality, nitrogen losses can be reduced by decreasing the amount of land in production, and consequently the number of animals. If readers wish to determine the impact on a larger or smaller farm or group of farms, they may multiply each flow (input, production, loss) by the number of hectares divided by 35.

3. In this model, crop protein yield was held constant for non-legumes (180 kg N per ha) and legumes (270 kg N per ha). In reality, crop protein yield varies depending on crop selection, soil capacity, management and weather. Increasing the yield at a constant efficiency would have a similar effect on the predictions to increasing the crop land in production. Therefore, if readers are interested in this effect they may use a similar adjustment as described previously for changing land in production.

4. In this model, herd production level varied according to what was feasible at the

TABLE 1. Range in herd nitrogen efficiency, apparent crop uptake, and manure nitrogen availability on dairy farms managed for economic efficiency (Dou *et al.*, 1996).

System	Equation	Low	High	Effectors
Herd efficiency	Animal product N/Feed N	0.16	0.24	Diet formulation Animal grouping Production level
Crop uptake	Net feed N/Soil Available N	0.50	0.75	Crop selection Soil capacity
Manure availability	Soil available N/Manure N	0.25	0.50	Storage Collection Application

indicated herd efficiency, crop production and feed purchases. In practice, herd production depends on many factors including herd density and production per animal. This model shows the production level that is feasible on different types of farms at known efficiencies.

5. The efficiency coefficients (herd efficiency, crop uptake, manure availability) were set to values (Table 1) that represented the range which would be expected on dairy farms managed according to current guidelines for nutrient application and feeding as calculated with a separate mathematical model (Dou *et al.*, 1996). The lower limits were selected to represent farms with a lower level of management compared to the higher limits which represented a higher level of management (as described below). Animal nutritional efficiency might be as high as 0.24 or as low as 0.16 depending on herd production level, or whether rations of cattle are balanced for ruminally available and undegraded protein sources (National Research Council, 1989). Although individual animals may be more efficient than the levels chosen here, the herd efficiency is calculated by including the N flows through all animals in the herd including those in low production states (i.e. dry cows, growing heifers) and feed presented to but wasted by the herd would be included in these losses. The efficiency of crop N uptake and conversion to feed N might range from 0.75 to 0.5 and could be affected by fertilization practices (Killorn and Zourarakis, 1992), soil type (Stout and Jung, 1992) or selection of crops (Henry *et al.*, 1995). Lower uptakes due to crop failure were not considered here. The availability of manure N for crop production might be as high as 0.5 or as low as 0.25 depending on storage and application methods such as incorporating manure vs. surface spreading (Beegle *et al.*, 1994).

6. Four different management scenarios of a farm were simulated to represent the extremes of practices with these efficiencies. The first simulation was for an intensive farm that imported as much feed as possible (Feed Intensive) while still managing to use manure on existing crop land at the indicated efficiencies. In this case, neither legume N fixation nor chemically fixed N would be used.

The remaining three simulations were for low-input management with different sources of N inputs, but none of these scenarios would have used imported feeds. The herd sizes were therefore limited to what feeds were available on the farm. One scenario maximized the use of legumes grown on available crop land (Legume Intensive), and yet some land was used to grow non-legumes on which manure could be spread. A third scenario used no legumes, but produced all feeds on the farm from crops fertilized

with chemically fixed N and manure produced on the farm (Fertilizer Intensive). The fourth scenario represented a dairy farm that used as much manure as possible (at indicated efficiencies) from a neighboring farm to produce crops on the farm for the herd (Manure Importer).

### 3. Results and Discussion

The solving of this model provided quantitative estimates of the impact on nitrogen losses of changing these efficiencies and sources of N. This sensitivity analysis provides insight into the potential for altering nutrient losses from farms, and the most promising means to do so.

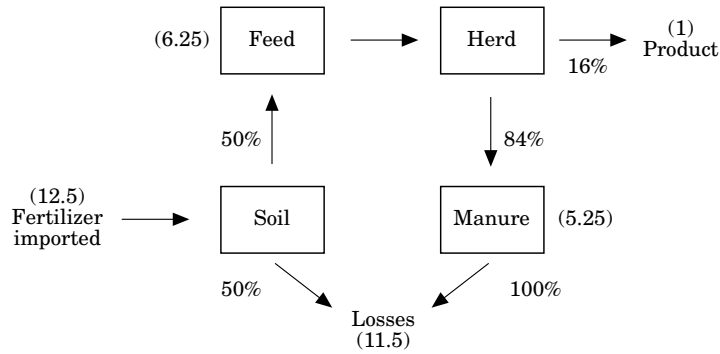
For an example of how these calculations are derived refer to Figure 3. In the first scenario, a low-input and inefficient farm is simulated. All of the feeds consumed would be produced on the farm with application of fertilizer to crops. For every unit of animal product, 11.5 units of N would be lost. These losses are incurred from both the process of manure disposal (no manure N is recycled to crop in this case) and crop production (not all fertilizer N becomes feed N). The impact of introducing a manure management program is simulated in the second scenario. Some of the manure N would be recycled to crop, and less chemical fertilizer would be required. The losses would be reduced to 10.2 units per unit of N captured in animal product. Finally, the impact of improving the nutritional efficiency of the herd is simulated. In this case, less feed is consumed to produce the same amount of milk. As a result there is less manure to manage (3.2 units vs. 5.25 units in the first two scenarios). Because less feed is consumed, there will also be less fertilizer applied to crops to produce the feed. These scenarios are simplifications because in reality, if an efficiency is improved, farmers are likely to increase production. However, the examples are relevant to maintaining the global desire for animal production with minimal N losses to water resources.

#### 3.1. NITROGEN SOURCE

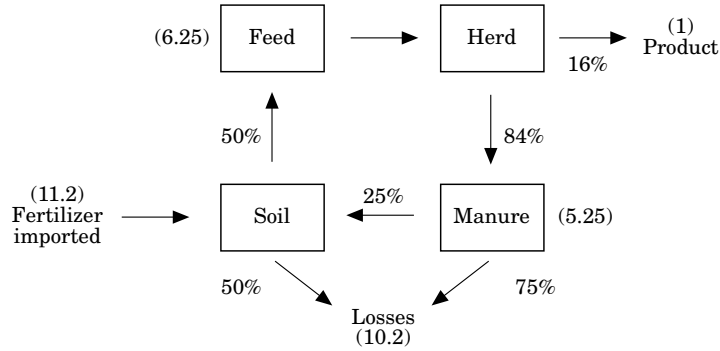
Importing feeds from off the farm (Feed Intensive) would enable greater nitrogen inputs (15.8 vs. 6.2, 6.0 and 12.0 tonnes N in Table 2) and hence greater animal production compared with producing all feeds on the farm in the other scenarios (5.3 vs. 2.0, 1.5 and 1.5 tonnes N in Table 2). This practice would also result in greater total loss of N from the farm (10.5 vs. 4.2, 4.8 and 10.5 tonnes N in Table 2). Provided that adequate crop land is available for use of manure, the losses would not increase as much as animal production so that importing feeds would result in the lowest losses relative to production (2.0 vs. 2.1, 3.2 and 7.0 tonnes N in Table 2), and the highest production relative to inputs to the farm (0.34 vs. 0.30, 0.25 and 0.13 in Table 2). The prediction of improved efficiency of N utilization on the farm due to imported feeds contradicts some previous observations that suggested a linear increase in losses per product relative to herd density (Frink, 1969). The previous study may have included farms that produced more manure than could be used at the efficiencies assumed here.

Nutrient losses associated with animal agriculture result from inefficiencies in utilization of both fertilizer and manure. Importing feeds to a farm would reduce the nutrient losses from that farm, but losses would be transferred to the farm where the feeds were imported from, and the level of losses from both farms combined may not be affected. Likewise, exporting manure from a farm may make the farm appear more nutrient efficient but the farm that uses the manure would appear less efficient. The

No manure management



With manure management



Impact of herd management

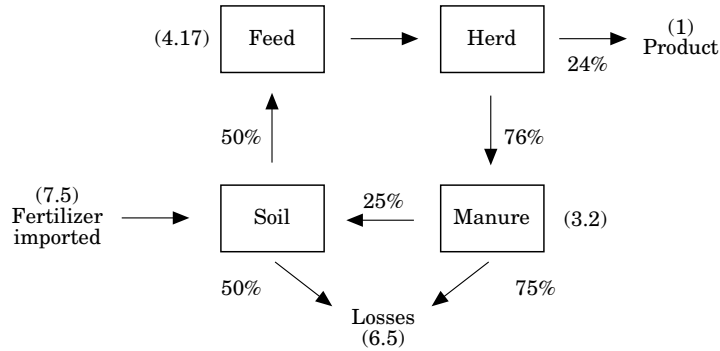


Figure 3. Three examples of calculation of N flows through a dairy farm system. Flows through a compartment are represented in units of N in brackets (), and the percentage of each compartment that flows in each direction is indicated. For example, 84% of feed N (6.25) flows to manure (5.25).

TABLE 2. Predicted nitrogen flow through four different management scenarios for a 35-ha dairy farm assuming high nitrogen efficiency\*

Item	Type of farm (N source)			
	Feed intensive†	Legume intensive‡	Fertilizer intensive§	Manure imported¶
Crop Production, tonnes N	6.3	8.3	6.3	6.3
N Input, tonnes	15.8	6.2	6.0	12.0
Animal Product, tonnes N	5.3	2.0	1.5	1.5
N loss, tonnes	10.5	4.2	4.8	10.5
N Loss/Product N	2.0	2.1	3.2	7.0
Animal Product N/Input N	0.34	0.30	0.25	0.13

\*Herd N efficiency (0.24), apparent crop uptake of N (0.75), and manure N availability (0.50) were set to high levels.

†As much feed would be imported as possible without producing more manure than could be used on available crop land.

‡The herd feed requirements would be met with legume crop production on the farm, and production of non-legumes from crops using manure.

§The herd feed requirements would be met with non-legume crops produced on the farm.

¶The herd feed requirements would be met with non-legume crops produced on the farm fertilized with enough imported manure to meet but not exceed crop requirements.

combined efficiency of both farms would be improved only if one farm had the capacity to use an import (feed or manure) more efficiently than the producing farm, or if the producing farm could provide the export more efficiently than the consuming farm. In the current model, using imported feeds or manure would only transfer losses to a different location. One could speculate that there are regions where water resources are less vulnerable to cropping losses, and therefore these regions would be better suited for feed exports.

Farms using legume fixed nitrogen had more efficient N utilization than farms using chemically fixed N as the source of N input to the system (0.30 vs. 0.25 in Table 2). In this model, legume fixed N was assumed to be converted to feed with 95% efficiency. Some fixed N would remain in the field (harvest losses, roots, etc.). Some of this residue might be lost when decomposed but generally legume fixation would place N in closer proximity to crop roots than fertilizer application (Andrews and Russelle, 1991). The apparent efficiency of conversion to feed from inorganic soil N would be lower than that for legume owing to leaching, runoff, or denitrification from the soil N compartment. From this point of view, losses from farms could be minimized by growing legumes in place of crops that require chemical fertilizer. Growing legumes for feed production would differ from using legumes as green manure for subsequent non-legume crop production. The later case involves synchronization of N release from legume decay and N demand by the non-legume crop (Stute and Posner, 1995).

### 3.2. PARTIAL EFFICIENCIES

The results from the model demonstrate that improving animal nutritional efficiency would have the greatest proportional impact on total farm efficiency in most cases

TABLE 3. The impact of improving herd efficiency, apparent crop uptake, manure availability, or all three on N flow through a feed intensive dairy farm\*†

Item	Low‡ efficiency	Improve herd§ efficiency	Improve crop§ uptake	Improve manure§ availability	High¶ efficiency
Crop Production, tonnes N	6.3	6.3	6.3	6.3	6.3
N Input, tonnes	53.7	60.0	33.7	23.7	15.8
Animal Product, tonnes N	9.6	15.9	6.4	4.8	5.3
N loss, tonnes	44.1	44.1	27.3	18.9	10.5
N Loss/Product N	4.6	2.8	4.3	3.9	2.0
Animal Product N/Input N	0.18	0.27	0.19	0.20	0.34

\*As much feed would be imported as possible without producing more manure than could be used on available crop land at the indicated efficiencies.

†Herd N efficiency (0.16 or 0.24), apparent crop uptake of N (0.50 or 0.75), and manure N availability (0.25 or 0.50) were set to high or low levels.

‡All efficiencies were set low.

§All efficiencies were set low except the designated efficiency which was set high.

¶All efficiencies were set high.

TABLE 4. The impact of improving herd efficiency, apparent crop uptake, manure availability, or all three on N flow through a legume-intensive dairy farm\*†

Item	Low‡ efficiency	Improve herd§ efficiency	Improve crop§ uptake	Improve manure§ availability	High¶ efficiency
Crop Production, tonnes N	9.0	9.0	8.8	8.6	8.3
N Input, tonnes	8.5	8.6	7.8	7.1	6.2
Animal Product, tonnes N	1.5	2.2	1.4	1.4	2.0
N loss, tonnes	7.0	6.4	6.4	5.7	4.2
N Loss/Product N	4.9	3.0	4.5	4.2	2.1
Animal Product N/Input N	0.17	0.25	0.18	0.19	0.32

\*The herd feed requirements would be met with legume crop production on the farm, and production of non-legumes from crops using manure.

†Herd N efficiency (0.16 or 0.24), apparent crop uptake of N (0.50 or 0.75), and manure N availability (0.25 or 0.50) were set to high or low levels.

‡All efficiencies were set low.

§All efficiencies were set low except the designated efficiency which was set high.

¶All efficiencies were set high.

(Tables 3 to 5). For example, total farm efficiency in terms of animal product N per input N is calculated to be 0.27 with improved herd efficiency compared with 0.19 or 0.20 with crop or manure improvements (Table 3). Improving the apparent crop uptake of available soil N (a function of the crop, fertilizer and soil) would have a greater impact on total farm efficiency than a proportionally similar improvement in manure availability (a function of manure collection, storage and application). Some of the gains from improving fertilizer or manure partial efficiencies would be subsequently lost from the nutrient cycle before they would be translated to increased animal production, while all of the improvements in herd nutritional efficiency would be realized immediately. Observation of the effect of strict manure management legislation in Denmark from the mid 1980s to the early 1990s showed results that were consistent

TABLE 5. The impact of improving herd efficiency, apparent crop uptake, manure availability, or all three on N flow through a fertilizer-intensive dairy farm\*†

Item	Low‡ efficiency	Improve herd§ efficiency	Improve crop§ uptake	Improve manure§ availability	High¶ efficiency
Crop Production, tonnes N	6.3	6.3	6.3	6.3	6.3
N Input, tonnes	11.3	11.4	7.1	10.0	6.0
Animal Product, tonnes N	1.0	1.5	1.0	1.0	1.5
N loss, tonnes	10.3	9.9	6.1	8.9	4.5
N Loss/Product N	10.3	6.5	6.1	8.9	3.0
Animal Product N/Input N	0.09	0.13	0.14	0.10	0.25

\*The herd feed requirements would be met with non-legume crops produced on the farm.

†Herd N efficiency (0.16 or 0.24), apparent crop uptake of N (0.50 or 0.75), and manure N availability (0.25 or 0.50) were set to high or low levels.

‡All efficiencies were set low.

§All efficiencies were set low except the designated efficiency which was set high.

¶All efficiencies were set high.

with the present analysis (Schröder, 1995). In this case, the slight reduction in N loss from the region resulted from increased efficiency in animal production, rather than the imposition of manure management legislation.

This model did not include the improvement to crop efficiency that might be expected from increased soil organic matter as a result of manure application (Baldock and Musgrave, 1980; Powelson, 1994). The model also ignored the interaction of efficiencies. For example, efforts to improve one subsystem may exacerbate losses from a different subsystem. These interactions can be examined on a case by case basis with a more detailed model (Dou *et al.*, 1996). However, the main effects are more easily understood with the simplified approach handled in this paper.

The investigator may be more interested in reducing total losses of N from a farm than reducing N losses as a fraction of production. For example, if the only concern is to reduce N losses in a region, less intensive methods of agriculture may be promoted to reduce total N losses (as well as production). On the other hand, if the goal is to reduce losses while maintaining productivity, the losses divided by production level will be used to evaluate effectiveness. On a global basis, the latter must be the case (de Wit, 1992).

### 3.3. MAXIMUM FARM INTENSITY

One nutrient management problem is that farms may produce more manure than can be efficiently used on available crops. This problem is especially apparent when herd size is large relative to land resources. In these cases, much of the feeds consumed on the farm are purchased and there is limited crop land for utilizing the manure in an environmentally sound manner. The model was used to determine how much animal feed could be imported without producing more manure than could be used on the farm for a unit of crop production.

The maximum feed N imported to the farm that can be used at the desired efficiencies can be derived from the first scenario (not producing so much manure that it cannot be applied to crops; Table 3). With all efficiencies set to high levels, about 2.5 units of

feed N could be imported and recycled efficiently per unit of crop production ( $\text{Input N/Crop N} = 15.8/6.3 = 2.5$ ). Imported feed (or imported feed plus legumes produced on farm) could comprise 71% of the total feed N consumed by the herd ( $\text{Input N}/[\text{Crop N} + \text{Input N}] = 15.8/[6.3 + 15.8] = 0.71$ ). This is the theoretical maximum intensity (feed imports per crop produced) under the conditions of the given efficiencies. If the farm intensity exceeds the maximum level for a given set of efficiencies, there would be no reduction in nutrient losses from changing management practices without reducing nutrient inputs or increasing exports (Young *et al.*, 1985).

The animal density (animal units per ha; 1 animal unit = 454 kg animal mass) corresponding to this intensity (feed imports per crops on farm) can be calculated from a more complete model based on individual farm conditions (Dou *et al.*, 1996). In practice, the amount of manure N that can be used efficiently depends on the type of crops grown on the farm and animal requirements. For example, if 9 tonnes per ha of grass dry matter is produced with 2% N, 180 kg of N ( $0.02 \times 9000$  kg) can be harvested per ha. This transfers to an allowable feed import of 450 kg N ( $180 \text{ kg} \times 2.5$ ). Milk N produced could be as high as 151 kg (not including non-lactating animals) with the high efficiencies [ $0.24 \times (450 + 180)$ ]. If the milk is 0.5% N, then 30 240 kg of milk could be produced on 1 ha per year at maximum efficiency ( $151/0.5\%$ ). This could be accomplished with about 3.4 high-producing cows and their replacements ( $30\,240/9000 \text{ kg yr}^{-1} \text{ cow}^{-1}$ ) or 5 animal units per ha ( $3.4 \times 666 \text{ kg/cow} \div 454 \text{ kg/animal unit}$ ). If the on-farm crop N yield was higher, more manure could be used efficiently and animal density could be increased.

#### 3.4. POTENTIAL FOR REDUCED NITROGEN LOSSES

The overall farm efficiency of N use was as high as 0.32 (Table 4; N input from legume fixed N and high efficiencies) and as low as 0.09 (Table 5; N input from fertilizer and low efficiencies). This range excludes predictions where N losses were shifted to or from other farms by importing feeds or manure. The losses per product N could be reduced to a fifth of the worst case scenario. These ranges indicate considerable potential to reduce nitrogen losses from dairy farms without adverse affects on production. Similar calculations could be undertaken for other nutrients. Previous work has suggested that the application of several specific practices could reduce nutrient losses by as much as 35%, but such analyses did not consider the full range of practices currently available for modification (Aarts *et al.*, 1992).

The present analysis demonstrates the broad areas of management that show promise for reducing nutrient losses, but if these practices are already widely practiced in a region, or conversely if there are practical barriers (i.e. cost) to their widespread adoption, there is little true opportunity to promote them in the field. Nonetheless, the potential for reducing nutrient losses by altering diet formulation or herd management is clearly evident, and these technologies can often be delivered quickly in a cost-effective manner. In contrast, there is less opportunity to reduce nitrogen losses by improving manure storage and application methods, yet these technologies require the greater capital investment and longer time commitment. Further research is needed to determine the potential for improvements in sensitive regions, and to identify the barriers to adoption of the favorable practices.

Nutrient management research, extension and legislation have been directed toward manure and soil management especially on intensive operations. The present analysis indicates that there is a great potential to reduce N loading by improving herd nutritional

efficiency, and by optimizing crop selection to control the source of N input to the farm and to improve crop nutrient uptake. Decreasing feed inputs to a farm could decrease both N losses and milk production, but there is little reason to suggest that a farm cannot efficiently obtain 70% of the feed N from purchased feeds or legumes produced on the farm.

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