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Nutrient Accounting at the Herd, Field, and Whole-Farm Levels on Two Pennsylvania Dairy Farms

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Abstract

The objective of this study was to evaluate nitrogen (N) and phosphorus (P) utilization efficiencies and environmental implications on two dairy farms and identify areas where veterinarians can make an impact. The study surveyed two commercial dairy farms in southeastern Pennsylvania, Farm A and Farm B. Each farm owner provided information regarding the management of animals, crops and animal waste. This information was used to calculate a nutrient flow for N and P at the herd, crop, and farm level. The herd-level evaluation accounted for nutrients directly entering the animals in the form of feed, captured in the body during growth, and exiting the animals as manure and milk. The crop-level nutrient balance accounted for manure and imported fertilizer spread on the fields, compared with the nutrient uptake rates of the crops grown. The whole-farm evaluation describes the nutrient flow across the farm boundaries.

Based on the information collected during this survey, both farms were net importers of N and P. However, efficiency of N and P were calculated as higher than previously reported in the literature. The milk nitrogen efficiencies on Farm A and Farm B were calculated to be 25% and 23%, respectively. The herd phosphorus utilization efficiency was calculated to be 46% and 39% on Farm A and B, respectively. Despite excellent nutrient utilization, the study identified management practice changes that would yield positive environmental and economic outcomes.

Keywords: dairy, nitrogen, phosphorus, nutrient utilization efficiency

Résumé

L'objectif de cette étude était d'évaluer l'efficacité d'utilisation de l'azote et du phosphore et son impact sur l'environnement dans deux fermes laitières tout en identifiant le rôle que les vétérinaires peuvent jouer dans ce contexte. L'étude a été menée dans deux fermes laitières (A et B) du sud-est de la Pennsylvanie. Chaque propriétaire de ferme a dévoilé sa gestion des animaux, des cultures et du fumier. Cette information a été utilisée pour calculer le bilan nutritif de l'azote et du phosphore au niveau du troupeau, de la culture et de la ferme. L'évaluation au niveau du troupeau prenait en ligne de compte l'entrée des substances nutritives par l'intermédiaire des aliments, favorisant la croissance de l'animal, de même que la sortie sous forme de fumier et de lait. Le bilan au niveau de la culture considérait l'épandage du fumier et l'utilisation d'engrais provenant de l'extérieur dans le champ comparé au taux d'absorption nutritive des cultures. L'évaluation au niveau de la ferme décrivait le passage des substances nutritives entre les limites de la ferme.

Sur la base de l'information recueillie durant cette étude, les deux fermes avaient un bilan net d'importation d'azote et de phosphore. Toutefois, l'efficacité d'utilisation de l'azote et du phosphore dans ces fermes était plus élevée que celle rapportée dans la littérature. L'efficacité de conversion de l'azote en substances laitières était de 25% dans la ferme A et de 23% dans la ferme B. L'efficacité d'utilisation du phosphore était de 46% dans la ferme A et de 39% dans la ferme B. En dépit de l'excellente utilisation des substances nutritives, cette étude a permis d'identifier des changements dans la gestion de la ferme qui auraient des retombées économiques et environnementales positives.

Introduction

The environmental impact of animal agriculture has been increasingly evaluated to address various pollution concerns in the public spotlight. Surface water eutrophication is one of the most pressing issues, as it has been linked with a number of problems such as fish kill, loss of biodiversity, and threats to public health in recreational waters. Also, the onset of harmful algal blooms can be a human health threat.[4] Nitrogen (N) and phosphorus (P) from agricultural systems are known to contribute to accelerated eutrophication of natural waters.[22,25] This is especially true in areas with intensive animal farming, where excess nutrients often lead to elevated nutrient losses. Duda and Finan showed that the greatest potential for accelerated eutrophication occurs in watersheds with intensive animal production.[9]

Continued water quality decline and mounting public concerns have prompted regulatory actions to be taken at local and national levels. Pennsylvania was the first state to enact a nutrient management law (Act 6, 1993). Many states have subsequently established nutrient management regulations to enhance agricultural nutrient use with a focus on animal feeding operations. More recently, the Environmental Protection Agency has finalized a rule intended to protect the nation's water quality by requiring concentrated animal feeding operations (CAFOs) to safely manage manure.[27] A CAFO, as it relates to a dairy, is broken into three categories: small, medium, and large. A large CAFO is any farm that has 700 or more mature dairy cattle. Small and medium CAFOs encompass farms with less than 200 and between 200-699 mature dairy cattle, respectively; however, they must also pose an increased environmental risk. These risks include transporting manure or wastewater via a man-made ditch or pipe into a primary waterway or having animals in direct contact with surface water.[28] The EPAs CAFO rule strengthens environmental safeguards by embracing a zero-discharge policy and requiring site-specific management plans to prevent runoff of excess nutrients into waters. Although large CAFOs were targeted primarily, smaller farms are being further investigated as the EPA realizes their additive effect.

On dairy farms, nutrients flow through managed pathways, entering the farm via purchased commodities, such as feeds, fertilizers, and soil amendments or other processes (e.g. nitrogen fixation), and leaving the farm as production output like milk and sold crops. Within the farm, nutrients flow between the herd and the field as manure is collected and subsequently applied to field crops which are harvested for animal feeding (Figure 1). Inevitably, nutrient losses occur throughout the cycle through various mechanisms such as ammonia volatilization, leaching, and runoff. The challenge of managing nutrients on these farms is the interacting nature of the nutrient flows between animal and field components as well as the varying degree and multiple pathways of nutrient transfers between the farm and its surrounding environment.[8] The magnitude of these transfers is determined both by biological requirements and the management level. The latter depends not only

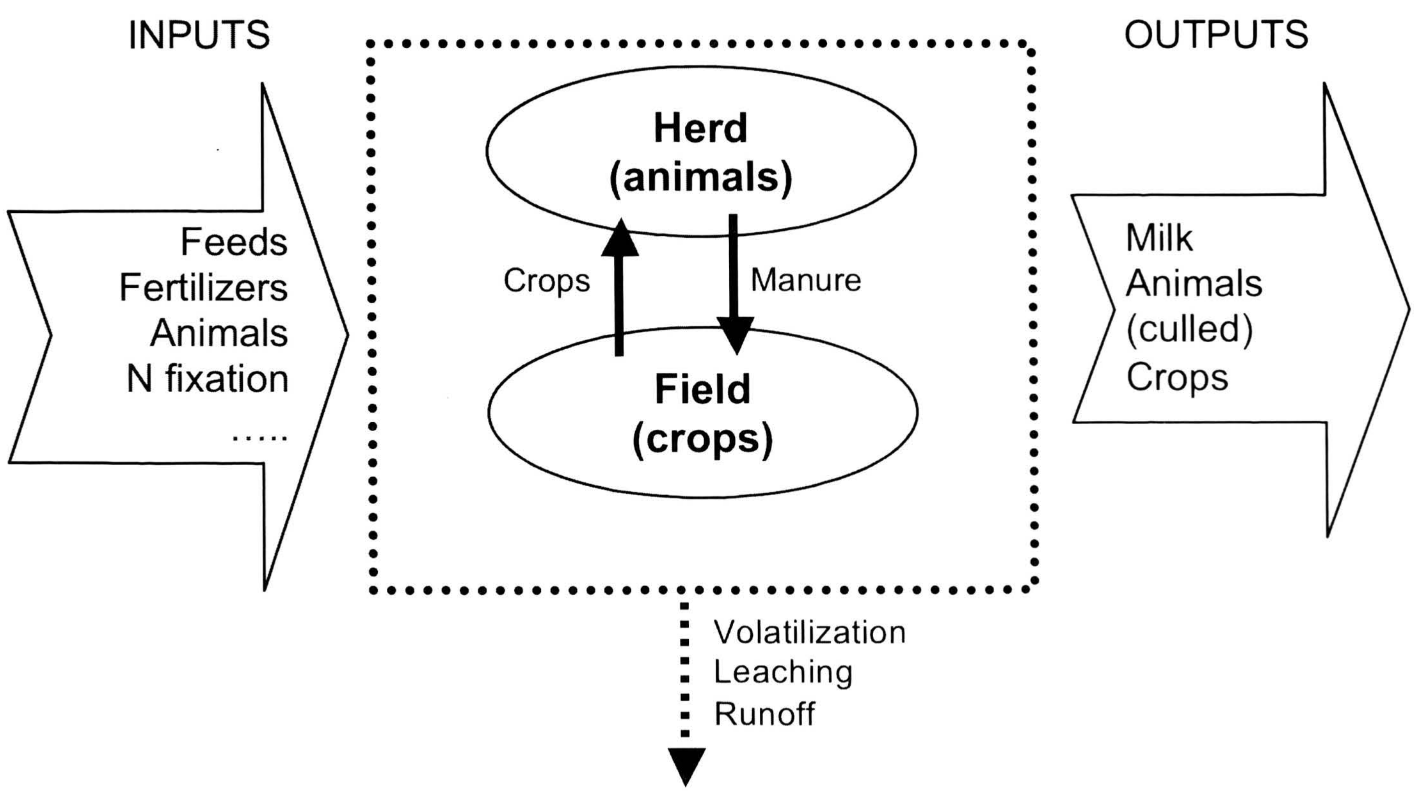

Figure 1. A schematic illustration of nutrients (nitrogen and phosphorus) flowing through a dairy farm as inputs and production outputs, nutrients cycling within farm between herd and field management components, and pathways for potential environmental losses.

on the producer but also the concerted efforts of farm service personnel, such as the nutritionist, the agronomist, and the veterinarian. Recent models have examined the role of management (fertility and recombinant bovine somatotropin (rBST) utilization) and disease (mastitis) on environmental impact.[5,10,11] Oftentimes, veterinarians can play a critical role, for example, by integrating reproductive efficiency, ration and forage characteristics, and cow health.

Overall nutrient efficiency, as well as nutrient losses, for dairy farms relies on the performance of individual components and the balance among these components. When developing strategies to manage N and P for minimal environmental pollution while maintaining crop and animal production, all components of a farm system must be considered. We conducted this study as part of an effort to identify critical control points of nutrient use efficiencies, and helping producers devise effective management strategies to reduce environmental footprint. Producer interviews, farm record acquisition, and data analysis were used to produce mass flows of N and P, which were calculated for the whole farm as well as for farm management components of the herd (animals) and the field (crops).

Materials and Methods

Farm Description

Farm A Farm records from May 1, 2007 to May 31, 2008 were obtained for the present study. Located in Chester County, Pennsylvania, Farm A has a Holstein herd consisting of 585 lactating cows, 91 dry cows, 281 breeding-age heifers, and 244 heifers less than 12 months of age at the time of this study. Milk yield, with the use of rBST, averaged 89.8 lb (40.8 kg) cow/day or 25,713 lb (11,688 kg) on a rolling yearly herd average as reported by the Dairy Herd Improvement Association (DHIA). High producing and heifer groups were milked three times daily while all others were on a twice-daily schedule. Components averaged 3.6 and 3.1% for milk fat and protein, respectively, as reported by DHIA. Average days-in-milk (DIM) and pregnancy rate were 197 days and 23%, respectively. Newborn calves were sent to a contract heifer rearer until 12 weeks of age before being brought back to the farm.

Main crops included alfalfa (430 acres), corn (573 acres), and grass (56 acres) plus 11 acres for wheat. Harvested crops were primarily used in diets fed to the animals, with only a small amount of hay, haylage, and wheat sold during the study period. Purchased feeds included canola meal, ground corn, blood meal, cotton hulls, soybean meal, and molasses, plus feed mill specific mixes such as Schiff meal (a local soybean meal with 7% fat content), a pre-mix, a mineral mix, a springer mix, top dress, heifer grain, and base mix. Rations were formulated by a veterinary nutritionist from the University of Pennsylvania. Separate rations were formulated for close-up and far-off dry cows, heifers, and three production levels within the lactating group. The rations were evaluated and reformulated multiple times per year depending on changes in feed availability. Crude protein concentrations, recorded on a dry-matter basis, averaged between 16 and 17%, and phosphorus averaged between 0.25 and 0.39% (Table 1). Routine veterinary care and herd health and management monitoring were performed by the Field Service and Field Investigation sections of the University of Pennsylvania's New Bolton Center, respectively.

The farm had free-stall barns bedded with sand. Manure handling differed for two groups of barns. The newly constructed barns were outfitted with a flush system and a sand separator; the latter separates out the sand (which was dried for re-use), solid manure, and liquid manure. A fraction of the liquid was recycled for flushing; the remainder of the liquid and the solid manure were spread to field crops in the spring and fall, mostly in April and October. For the other barns, manure from the alleyways was scraped into an adjacent holding pit equipped with a "picket fence" system for separating solids from liquid. This system allows rainwater and excess liquid from manure to drain from the upper holding pit through a slatted wooden fence into a lower holding tank via gravity. The semi-solid manure retained in the upper pit retains much of the P content, while the liquid slurry contains much of the soluble N.[17] The manure from both compartments of the picket system is spread on field crops. In addition, 31 tons of N fertilizer (30% N) and 1.7 tons of urea (45% N) were purchased, along with 845 tons of mushroom compost brought onto the farm, to fertilize the crops. Mushroom compost is a regionally available resource consisting of the leftover organic material on which mushrooms are grown within mushroom houses. The N and P composition varies based on the original substrate, for example horse manure, straw, or used grains, as well as growing

Table 1. Average crude protein and phosphorus of rations over study period on Farm A.

Ration	CP %	P %
Heifer 200 lb	18.1	0.42
Heifer 275 lb	15.7	0.35
Heifer 450 lb	15.7	0.35
Lactating 75 lb	17.5	0.36
Lactating 90 lb	17.9	0.36
Lactating 110 lb	19.0	0.37
Dry-far off	11.9	0.25
Dry-close up	15.1	0.28

conditions. On Farm A the N and P composition were analyzed to be 0.8 and 0.2%, respectively.

Farm B Farm records from May 1, 2007 to April 31, 2008 were obtained for Farm B. Also located in Chester County, Pennsylvania, this farm had a Holstein herd consisting of 317 milking cows, 34 dry cows, 202 heifers under breeding age (15 months), and 122 heifers from 15 months of age to freshening. With the use of rBST, milk yield averaged 80.7 lb (36.7 kg)/cow/day or 24,739 lb (11,245 kg) on a rolling yearly herd average as reported by DHIA. All cows in the lactating herd were milked twice daily. Components averaged 3.5 and 3.1% for milk fat and protein, respectively, as reported by DHIA. Average DIM and pregnancy rate over the study period were 178 days and 19%, respectively. Heifers raised on-farm became replacements, and any overflow animals were sent to a heifer rearer.

Major crops grown on this farm included corn (420 acres), alfalfa (160 acres), soybeans (160 acres), and grass (150 acres). Additional crops included 30 acres of wheat and 64 acres of barley. For the study period, all crops were used as feed on-farm except for the wheat and barley grains, as well as some shelled corn, that was sold. The homegrown feeds were supplemented and balanced with purchased feeds including ground corn, blood meal, various mineral mixes, and a grain mix. Diets were formulated and fed to groups of lactating cows according to stage of lactation; close-up and far-off dry cows; heifers three to six months and seven to 14 months of age; and pregnant heifers. These diets were evaluated and reformulated multiple times per year by a veterinary nutritionist from the University of Pennsylvania. Across all groups, the crude protein concentration averaged between 17 and 18% and P concentrations averaged between 0.29 and 0.35% on a dry matter basis (Table 2). As on Farm A, routine veterinary care and herd health and management monitoring were performed by the Field Service and Field Investigation sections of the University of Pennsylvania's New Bolton Center, respectively.

Table 2. Average crude protein and phosphorus of rations over study period on Farm B.

Ration	CP %	P %
Heifer 3-6 mo	18.1	0.31
Heifer 7-14 mo	16.2	0.32
Heifer pregnant	16.2	0.32
Lactating 75 lb	16.5	0.32
Lactating 95 lb	17.7	0.35
Lactating 100 lb	17.7	0.35
Dry-far off	17.1	0.32
Dry-close up	16.2	0.29

The barns were all sand-bedded free-stalls on a flush system. Flushed manure-sand mixture flowed down a graded cement slab, allowing separation of the sand. The sand is stacked into piles that are rotated to facilitate drying and re-use. After separating out the sand, the liquid portion flows downhill into a lagoon, while manure solids are retained in a holding pond. The liquid and solid manure are both spread onto fields in the spring and fall. Along with manure, 80 tons of liquid fertilizer (30% N) and 1,000 tons of mushroom compost were used to fertilize the crops. The mushroom compost had not been analyzed on this farm, thus percentages were estimated as 2.5% N and 0.7% P. These estimates were based on regional averages (Dr. Guo Mingxin, Delaware State University, personal communication, July 29, 2008).

Nutrient Mass Balance and Calculation

Nutrient balances were examined for the herd, the field, and the whole farm following nutrient flow pathways illustrated in Figure 1. For the herd, nutrient inputs included the amounts of N and P contained in purchased and homegrown feeds fed to the animals. Feed nutrients were calculated for the milking, dry, and heifer groups using farm records of amount fed for each feed type multiplied by the respective nutrient concentrations, then aggregated for the entire herd. At the other end of the nutrient flow (output), feed nutrient inputs were partitioned into milk, animal growth, and excreta (feces and urine). Milk nutrients were calculated from the quantity of milk produced (farm records) and nutrient concentrations (3.1% crude protein, divided by 6.33 to convert to N; 0.1% P). Nutrients captured in growth of heifers were estimated by measuring 10 randomly selected heifers using a weight tape at 12 weeks of age and at 13 months of age, converting the difference into net body growth. The nutrients captured in body growth were then calculated by multiplying the net growth by nutrient concentrations.[18] For dry cows, the N and P captured in the growth of the conceptus and the dam's body growth were estimated using CPM Dairy, a ration formulation/evaluation software that bases relevant calculations on NRC formula.[18] Nutrients in excreta for lactating cows, dry cows, and heifers, respectively, were calculated by the difference between feed nutrient inputs and the sum of nutrients in milk and/or in animal growth.

For field nutrient balance, sources of inputs included fertilizers and mushroom compost (farm record) plus animal excreta from the calculation described above. The amount of N fixation (as input) by the alfalfa crop was estimated by multiplying total N in the harvested crop by 0.6, using the equation described by Dou *et al.*[8] Field nutrient outputs were based on the amounts of harvested crops (farm records) multiplied by respective nutrient concentrations.[20]

At the whole-farm level, nutrient mass balance accounted for nutrient flows across the conceptual farm boundaries (Figure 1). Inputs included nutrients contained in fertilizers, mushroom compost, purchased feeds, N fixation by alfalfa, and heifers brought onto the farm (Farm A). Outputs included nutrients in milk, cows culled, and crops sold. The amounts of N and P in replacement heifers (input) or culled animals (output) were calculated based on body weight multiplied by respective nutrient concentrations.[17]

Results

Herd Nutrient Balance

Calculated nutrient mass flow and balance for each herd are shown in Table 3. For Farm A, total N flow amounted to 223 tons. This total N input through feed intake is partitioned into milk (42.8 tons), heifer growth (5.7 tons), and excreta (173 tons). Phosphorus mass flow amounted to 26.3 tons, which is partitioned into milk (8.7 tons), animal growth (1.6 tons), and excreta (17.1 tons). For Farm B, with a comparatively smaller herd size, nutrient mass flow was less in magnitude: total N input from feed intake was 104 tons, which was partitioned into milk (19.5 tons), heifer growth (1.5 tons), and excreta (83 tons). Farm B had total P input of 12.8 tons, which was partitioned into milk (4.0 tons), heifer growth (814 lb; 370 kg), and excreta (8.6 tons).

We examined apparent nutrient use efficiency for the lactating group by dividing milk N (or P) by relevant feed N (or P) intake, as well as for the whole herd by dividing the sum of milk and animal growth N (or P) by total input of the herd. Farm A had N efficiency of 0.25 for the lactating group and 0.22 for the whole herd. Apparent efficiency for P use was greater, 0.46 for the lactating group and 0.40 for the whole herd. Farm B had apparent nutrient use efficiencies slightly less than farm A: 0.23 vs 0.21 for N and 0.40 vs 0.35 for P when comparing the lactating group to the whole herd. Literature reports efficiencies ranging from 0.19 to 0.26 for N and 0.29 to 0.32 for P (Table 6). Comparatively, the two farms in the present study had N efficiencies within the

Table 3. Herd nutrient input and output (lb) and apparent efficiency during the study period.

	------------Farm A------------		------------Farm B------------	
	Nitrogen	**Phosphorus**	**Nitrogen**	**Phosphorus**
Input (animal groups) †				
Heifer	82,159	11,972	31,642	4,506
Lactating cows	345,158	38,258	169,323	20,601
Dry cows	20,042	2,501	4,220	473
Total	447,359	52,731	205,185	25,580
Output				
Milk‡	85,652	17,490	39,043	7,973
Heifer growth§	11,486	3,190	3,064	814
Dry cow*	1,703	488	403	79
Excreta"				
Lactating	259,503	20,768	130,553	12,628
Dry	18,339	2,006	3,827	394
Heifer	70,673	8,782	28,773	3,683
Totals	447,357	52,724	163,153	25,571
Apparent efficiency€				
Whole herd	0.22	0.40	0.21	0.35
Lactating cows only	0.25	0.46	0.23	0.39

† Based on actual rations and feed inventories.
‡ Calculated as milk production x 3.1% / 6.33 for N, milk production x 0.1% for P.
§ Estimated at a daily gain of 2.22 lb as calculated from weights of three-month and 14-month heifers with estimated N concentration of 2.7% and P concentration of 0.75%.
* Average body weight gain plus fetal growth, determined as % of feed intake based on diet analysis in CPM Dairy.
" Feed nutrient intake – milk nutrient (lactating cows) or – heifer growth (heifers), or – pregnant growth and body weight gain (for dry cows).
€ Sum of N or P in milk and heifer growth plus dry cow growth, divided by sum of N or P in feed intake for the whole herd; milk nutrient / feed nutrient for lactating cows.

literature range, whereas P efficiencies were greater than the previously reported range. The high P utilization efficiencies can largely be attributed to the fact that the diets were not supplemented with mineral phosphorus.

Not surprisingly, nutrients in excreta accounted for the largest portion of the mass of nutrients flowing into and out of the herd: 78-80% of the N and 61-67% of the P (Table 3). Another commonly used method for estimating the amount of manure nutrients for manure management planning purposes is to calculate the amount of animal waste and its nutrient contents based on animal inventories (numbers, body weight) and book values of unit manure and manure nutrient production published by the American Society of Agriculture Engineers (ASAE).[1] Using the ASAE approach, we calculated manure nutrients to be 131.5 tons of N and 20.6 tons of P for Farm A and 71.7 tons of N and 11.3 tons of P for Farm B, respectively. These are 14 to 24% underestimation for N and 21 to 31% overestimation for P compared to the mass balance-based results we derived in the present study (Table 3). Clearly, the mass balance approach requires more detailed data and greater efforts, but provides more accurate results than the simple approach of using ASAE book values. It must be pointed out that the amounts of nutrient in fresh excreta (Table 3) provide an approximation for the magnitude of nutrients that must be carefully managed for beneficial use in crop production. These nutrients, once excreted, would be subject to potential environmental losses. The actual amounts of nutrients eventually available for field applications, generally less than that in fresh excreta, are affected by a number of factors such as manure collection method, storage facility and duration, and field spreading time and conditions.

Field Nutrient Balance

Estimated N and P mass flow in the field component of the two farms are presented in Table 4. As mentioned earlier, nutrient losses occur during manure handling, storage, and application. Generally speaking, about half of excreta N is in the form of urea in urine.[7,8] Once excreted, urinary urea is rapidly converted into ammonia, which is subject to volatilization loss. For P, some losses may occur due to lack of complete collection and/or barnyard runoff. Therefore, the amounts of manure nutrients available for field applications will always be less than that in fresh excreta. Based on literature synthesis, we assume that 65% of the N in fresh excreta is available for field application (see Table 1 in Dou *et al*, 1996 for summary of literature data).[7] Unlike N, P compounds in excreta or stored manure have little chance of volatilization loss given its chemical nature, therefore we assume that 90% of the P in fresh excreta are available for field application. Using this assumption, there would be 112.7 tons N and 15.4 tons P on Farm A, and 53.9 tons N and 7.8 tons P on Farm B for field spreading (Table 4). In reality, Farm A's records showed that approximately 71 tons N and 10.8 tons P were applied in manure during the study period (manure application data on Farm B was not available).

Table 4. Nutrient mass flow (lb) in the field (crops) and apparent efficiency.

	Farm A		Farm B	
	Nitrogen	**Phosphorus**	**Nitrogen**	**Phosphorus**
Input (applications)				
Manure	225,410†	30,820†	107,853	15,503
Fertilizer§	20,163		48,000	
Mushroom Compost	13,174*	304*	49,999"	14,001"
Legume fixation€	114,090		28,800	
Total	372,837	31,124	234,652	29,504
Output				
Harvest crops	165,836	49,874	123,015	26,631
Apparent efficiency‡	0.44	1.46	0.52	0.90

† Calculated by multiplying nutrients in excreta by 0.65 for N and 0.90 for P.
‡ Calculated as total N or P in harvested crops / (manure + fertilizer + mushroom compost N or P).
§ Using 30% N fertilizer and tonnage information from farm records.
* Analysis of N and P concentration and tonnage applied taken from farm records.
" Estimated N and P concentrations from mushroom farms in the area.
€ Total N in harvested legumes (alfalfa) multiplied by 0.60.[6]

The discrepancy between our estimation and Farm A's records may be due to several factors. First, there was an indication that the farm record of manure N applied referred to fertilizer equivalent N instead of total N. Fertilizer equivalent N of manure is typically a fraction of the total N.[14] It is not clear whether manure P was also discounted in the farm records. Second, it is likely that there was manure remaining in storage toward the end of the study period, which was not accounted for in the farm application records. Furthermore, animal manure is notoriously heterogeneous. A sample used for laboratory analysis (and farm record-based calculations) would not be representative unless a great deal of effort is taken. According to a previous study,[6] a good representative sample should be a composite of at least five sub-samples for agitated manure systems, or 25 for un-agitated systems. Farm A did use agitated sampling; however, further collection technique was unknown. Also, only one manure analysis was available over the period of data collection although the nutrient analysis was likely to have varied over time. Considering these various factors, we believe that the estimated manure N and P applications in Table 4 based on the simple assumptions above provide an adequate approximation under the given circumstances.

Clearly, manure was the largest source of nutrients for growing crops on both farms (Table 4). Other sources of nutrients included chemical fertilizers, mushroom compost, and symbiotic fixation of N from the air by alfalfa. The latter contributed a substantial amount of N to the system, 57.0 tons on Farm A and 14.4 tons on Farm B.

The amounts of nutrients removed in harvested crops (i.e. nutrient output in the field component) totaled 82.9 tons of N and 24.9 tons of P on Farm A, and 61.5 tons of N and 13.3 tons of P on Farm B (Table 4). Apparent nutrient efficiency, calculated by dividing crop nutrient removal by the amount of nutrient input, would be 44% for N and 146% for P on Farm A, and 52% for N and 90% for P on Farm B. Previous research showed P efficiency of 66% in the field component of some western dairy farms.[24]

Whole-Farm Nutrient Balance

Nutrient mass flow across the conceptual farm boundaries during the study period is presented in Table 5. A total of 196 tons of N and 11.5 tons of P entered Farm A, of which 62% and 83% were in purchased feeds. Farm B had 86.1 tons of N and 8.8 tons of P as total nutrient inputs; purchased feeds, chemical fertilizers, and mushroom compost accounted for similar proportions of

Table 5. Whole-farm nutrient mass flow (lb) during the study period and apparent efficiency.

	Farm A		Farm B	
	Nitrogen	**Phosphorus**	**Nitrogen**	**Phosphorus**
Input				
Feed purchased	242,029†	19,182†	44,683‡	3,373‡
Chemical fertilizer§	20,163†		48,000	
Mushroom compost§	13,174†	3,346†	49,999	14,001
Legume fixation*	114,090		28,800	
Heifer"	2,022	548	794	216
Total	391,478	23,076	172,276	17,590
Output				
Milk sold€	85,653	17,490	39,043	7,973
Cows culled^	6,120	1,659	3,091	836
Crops sold`	15,096	2,284	19,899	4,444
Total	106,839	21,433	62,033	13,253
Apparent efficiency$^{\alpha}$	0.27	0.93	0.36	0.75

† Based on farm inventories and nutrient analyses.
‡ Based on feed inventories and feed dictionary nutrient concentrations.
§ Same calculations as shown in Table 2.
* Calculated as 40% of total Alfalfa N input assuming 60% of N was atmospheric.
" Heifers entering herd x body weight x nutrient concentration of tissues (book value).
€ Calculated as milk production x 3.1% / 6.33 for N, milk production x 1% for P.
` Sales taken from farm records and nutrient concentrations from Agronomy Guide.
^ Using farm cull rate of 26% x total head x average Holstein body weight x N and P tissue concentration book values.
$^{\alpha}$ Total outputs / total inputs.

the N input, whereas most of the P (80%) was from the mushroom compost.

Managed nutrient output totaled 53.4 tons of N and 10.7 tons of P on Farm A, of which 80% and 82% was associated with milk sold. For Farm B, 31.0 tons of N and 6.6 tons of P left the farm, with nutrients in milk accounting for 63% and 60% of the N and P, respectively. Apparent nutrient efficiencies at the whole-farm level, calculated as the managed output divided by the input, were 0.27 (N) and 0.93 (P) for Farm A, and 0.36 and 0.75 for Farm B (Table 5). Compared to previous studies (Table 6), P efficiencies are toward the higher end on both farms whereas N efficiency appeared to be in the lower range on Farm A, but in the higher range on Farm B.

Discussion

It is interesting to note that the two farms differed in terms of apparent nutrient use efficiencies. For the herd component, Farm A had higher efficiencies in N and P for both lactating group and whole herd than Farm B (Table 3). For example, for the lactating cow group, with each 100 lb (45 kg) of N (or 100 lb (45 kg) of P) intake through feed consumption, 25 lb (11.4 kg) of N (or 46 lb (20.9 kg) of P) was captured in milk on Farm A, but Farm B captured 23 lb (10.5 kg) of N (or 39 lb (17.7 kg) of P). The difference between the two farms, two lb (0.91 kg) of N or seven lb (3.2 kg) of P per 100 lb (45 kg) input, would end up in excreta with potential environmental consequences. Another way to look at the issue is the amount of nutrients in excreta per unit nutrient captured in milk. The lactating cow group excreted 3.03 lb (1.38 kg) of N and 1.19 lb (0.54 kg) of P per one lb (0.45 kg) of N and one lb (0.45 kg) of P in milk on Farm A, which are less than Farm B (3.34 lb (1.52 kg) of N and 1.58 lb (0.72 kg) of P excreted per one lb (0.45 kg) of N or P in milk). Fine tuning nutrient balance of the rations on Farm B may help enhance nutrient use efficiency and reduce environmental footprint. For the field component as well as at the whole farm level, Farm A was more efficient in P, but less efficient in N compared to Farm B (Table 6). For Farm B, mushroom compost contributed 47% and 80% to the total P input of the field and the whole farm.

Table 6. Nitrogen and phosphorus utilization efficiency on dairy farms in herd, field, and at the whole-farm level in present study as compared to literature reports.

	Nitrogen			Phosphorus		
	Herd	**Field**	**Whole-Farm**	**Herd**	**Field**	**Whole-Farm**
Present study						
Farm A	0.22	0.44	0.27	0.40	1.46	0.93
	(0.25)			(0.46)		
Farm B	0.21			0.35		
	(0.23)	0.52	0.36	(0.39)	0.90	0.75
Literature*						
Kohn R[15]	0.16‡					
	0.24‡					
Powell J[21]	(0.25)			(0.29)		
Tylutki T[26]	0.23§			0.29§		
Spears R[24]				0.30	0.67	0.63
Dou Z[6]	0.26	0.44	0.28			
	0.20	0.99	0.30			
Jonker J[13]			0.28			
Paul J[19]			0.23			
Hristov A[12]			0.41			0.66
			0.64			0.9
			0.25			0.48
Sonneveld M[23]			0.28			0.92
Kuipers A[16]			0.24			0.46
Arriaga A[2]	(0.25)			(0.32)		

† Value in parenthesis is for lactating cows only.
‡ Represent the extremes of the range of herd nitrogen efficiencies noted in Kohn R, Dou Z, Ferguson J, Boston R: A sensitivity analysis of nitrogen losses from dairy farms. *J Environ Manage* 50:417-428, 1997.
* Complete literature citations are available in the Reference section of this paper.
§ N and P efficiencies represent a combined average over a five-year period.

There is a clear trend of lower efficiency for N compared for P. This is true on both farms and for all farm components (the herd, the field, and the whole farm; Table 6). This is mainly attributed to the different intrinsic nature of the two nutrients. Nitrogen, an essential element of proteins in feeds, is excreted in feces as organic-N of undigested feed residues and in urine as urea-N. The latter is readily converted to ammonia in the natural environment, and ammonia is subject to volatilization loss throughout manure handling and application. After field application, manure N is also vulnerable for potential losses via leaching and runoff. On the other hand, P is relatively stable with limited losses when manure is handled properly. However, P accumulation in soils has been a problem on animal farms due to P applications exceeding crop removal, leading to elevated P loss through surface runoff and subsurface drainage and contributing to water quality declines.[25] For Farm B in the present study, there is a small excess of P applied compared to P removal by harvest crops (Table 4). A balance can be easily achieved by limiting the use of mushroom compost. For Farm A, there is a negative balance of P in the field component as more P is removed in harvest crops than applied (Table 4). Monitoring soil available P levels and maintaining it at the optimum range according to the Penn State agronomy guide [20] would help sustain soil fertility and crop yields on this farm.

At the field as well as the whole-farm level, P balance can be further improved by lowering the import of mushroom compost on Farm B or closely monitoring soil available P supplies on Farm A. The considerable difference between the two farms in terms of N efficiency, 0.27 for Farm A and 0.36 for Farm B at the whole-farm level, is largely due to large feed imports on Farm A, as well as the type and proportion of homegrown feeds. Increasing the acreage of alfalfa on Farm A may lower its needs on imported protein and thus enhance N efficiency. Of course, such a management change must be carefully examined, with comprehensive considerations given to soil conditions, crop yield potential, and the needs of balancing components of proteins (soluble vs rumen undegradable proteins, for example) with energy and other nutrients against animal needs. This will require the concerted efforts of the producer, the agronomist, the nutritionist, and the veterinarian. Overall, results from the present study demonstrate that maintaining a balance of nutrient inputs and output on dairy farms is attainable.

Of the three components examined (herd, field, and the whole farm), nutrient use efficiency of the herd (animals) is the lowest (Table 6), which presents opportunities for increasing nutrient efficiency. Although largely determined by the animals' biological processes and limitations, management interventions are possible to push nutrient use toward considerably higher efficiencies. Toward this end, veterinarians can play a proactive role. Veterinarians are integrated into all aspects of animal health, which allows them to identify the areas where improvements may be made in order to enhance herd productivity and nutrient use efficiency.

As noted earlier, these areas include milk yield, heifer growth, and nutrition, among others. The impact of mastitis on eutrophication was studied by Hospido and Sonesson in which a Life Cycle Assessment showed that by decreasing mastitis there is a reduction in environmental impact.[11] This reduction is a direct result of increasing milk yield and thereby increasing nutrient utilization efficiency.[11]

Reproductive efficiency also contributes to overall farm efficiency in the lactating herd by increasing the proportion of days in peak milk per lactation, thereby diluting the N and P maintenance requirements and increasing the percentage of N and P captured in products. In the replacement herd, age at first calving (determined by heifer growth and efficiency of reproductive programs) also impacts overall farm efficiency. Replacement animals account for up to 15% of the total on-farm ammonia emissions at commercially common fertility rates.[10] Lowering the age at first calving from the industry average of 25.2 months[29] to a more desirable goal of 22 months would decrease non-productive animal nutrient excretion, therefore improving farm N and P efficiency.

A model by PC Garnsworthy showed that by increasing fertility rates it was possible to decrease ammonia emissions by nine to 17%.[10] The model focused on decreasing days to first insemination, increasing estrus detection, and increasing conception rates through management, nutrition, and genetics. Veterinarians play a crucial role in monitoring reproductive parameters on the farm, and devising and implementing heat detection and synchronization programs to improve reproductive outcomes. Also, captured product in the form of milk yield and heifer growth rely on finely tuned rations which must be reassessed and reformulated over time to accommodate changes in feeds as well as animal needs. A direct correlation of ration P levels with manure P levels was found in a study by Toor *et al.* Manure samples were taken from herds being fed rations with varying phosphorus concentrations, and upon analysis the high-P diets (10.6 g P/kg) had 40% greater manure P than cows fed low-P diets (3.6 g P/kg).[25] The authors concluded that lowering P in diets would improve overall P balance on farms by decreasing excretion in manure, accumulation in soil, and thus potential for loss into waterways.[25] Veterinarians can serve as the primary nutritionist, as was the case on Farm A and Farm B, or play an important role in identifying when rations must be re-evaluated since nutritional imbalances often manifest as suboptimal growth, lowered production, or clinically with increased metabolic and infectious diseases occurring in the periparturient period. These disease processes have clear economic consequences, such as decreased milk production and fertility, increased treatment cost, and higher cull rate, but also have environmental impacts by decreasing milk production and diverting nutrients toward maintenance, thereby reducing nutrient utilization efficiency.[11] Consequently, the study and implementation of nutrient accounting is imperative to the sustainable intensification of food animal agriculture. Nutrient accounting is a low-cost investment that has the potential to yield both economic and environmental benefits.

Conclusions

The present work showed that both farms studied had nutrient balances at the whole-farm level that met or exceeded those previously reported in the literature. In the authors' opinion there is, however, still room for improvement. Herd management and resulting production efficiency are the critical control points for further enhancing nutrient utilization on both farms. Although largely determined by the biological processes of the animals, multiple management practices can be employed to help improve nutrient efficiency as well as productivity. Precise ration balancing according to growth and lactation stage, reproductive strategies to reduce maintenance cost and increase fertility rate, and increased milk production are some of the most effective management interventions. Food animal veterinarians, having knowledge of nutrition and dairy herd management, can be a valuable part of the management team that addresses the primary areas of impact on nutrient efficiency. By including an awareness of nutrient utilization efficiency in their management recommendations, veterinarians can convey the value in the breadth of their knowledge while aiding both producers and their communities.

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Additional Resources

For educational resources regarding nutrient management planning visit University of Nebraska-Lincoln's Manure Management website: http://water.unl.edu/web/manure/resources

A comprehensive worksheet for on-farm use is available at: http://www.ianrpubs.unl.edu/epublic/live/rp188/build/rp188.pdf

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