Efficiency of Use of Imported Nitrogen, Phosphorus, and Potassium and Potential for Reducing Phosphorus Imports on Idaho Dairy Farms

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ABSTRACT

Eight commercial dairies from south central Idaho were surveyed to estimate the whole-farm surpluses of N, P, and K and to investigate the possibility of reducing P excretions through dietary manipulation. Nitrogen, P, and K imports and exports were monitored in a 12-mo period, and samples from the diets, feeds, feces, urine, and manure were collected at regular farm visits. Soils from manure-amended fields were sampled in the spring and fall. In all cases, the largest import of N, P, and K to the dairy was with purchased feeds. Major nutrient export items were milk and manure and forages, in the case of a dairy with a large land base (dairy F). Whole-farm N surplus varied from 90 to 599 t/yr (91 to 222 kg/yr per cow). The efficiency of use of imported N varied from 25 to 64%, with dairy F having the greatest efficiency of imported N use. Phosphorus and K surpluses were also significant (average of 29 and 182 t/yr and 12 and 76 kg per cow per year, respectively). During the study period, dairy F was a net exporter of K. The average efficiency of use of imported P and K was 66 and 58%, respectively. Soil P levels in the 30-cm layer were above state threshold standards, most likely from overapplication of manure. Soil nitrate-N concentrations were also high, but K concentrations were within the accepted range. Average P content of the lactating cow diets at the start of the study was 0.49% and was reduced to 0.38%. The estimated reduction in imported P due to the reduced dietary P levels was from 5.7 to 61.4 t/yr per farm, or on average 12 kg per cow per year. This study demonstrated that in addition to exports with milk and manure, export of nutrients with forages produced on the farm (dairy F) is a major factor in reducing whole-farm N, P, and K surpluses.

Key words: nitrogen, phosphorus, potassium, nutrient management

INTRODUCTION

Public pressure, governmental regulations, and the motivation to be a good neighbor require dairy farmers

to pay close attention to nutrient inputs and outputs and to consider the environmental impact of their operation in the context of the whole production system. In areas with intensive animal agriculture, where animal units are highly concentrated, the land base is usually not sufficient to maintain a sustainable production of milk (or meat), which inevitably necessitates import of nutrients from outside the production system. As a result, if nutrients are not effectively removed from the system, accumulation occurs and endangers the quality of soil and ground and surface water resources.

Management practices at smaller scales (individual farms, for example) can have a profound effect on nutrient flows on a regional scale. Therefore, research efforts have been directed toward evaluating whole-farm N and P surpluses on dairy farms of various sizes (Bacon et al., 1990; Spears et al., 2003a,b; Cerosaletti et al., 2004). These studies suggested that large proportions of imported N and P were unaccounted for in products leaving the farm. Predictably, large on-farm surpluses would result in increased soil N and P levels, but soil mineral levels were not published in these reports. Only one comprehensive study investigated whole-farm N and P balances on large western dairies (Spears et al., 2003a,b), emphasizing the need for more nutrient-flow data on these distinctly different production systems. Except for the report by Cerosaletti et al. (2004), no other studies have examined whole-farm imports and exports of K, and none have been conducted on dairies in the western United States.

Research in Europe (Valk et al., 2000; Valk, 2002) and the United States (Wu and Satter, 2000; Wu et al., 2000; Knowlton and Herbein, 2002) have reevaluated the dietary P requirements of lactating dairy cows and demonstrated the potential of reducing nutrient losses from dairy operations through dietary manipulation (Satter et al., 2002; Klopfenstein et al., 2002; Cerosaletti et al., 2004). Such dietary manipulations can have a major impact on the overall surplus of nutrients at the individual farm level and the entire production system (Cerosaletti et al., 2004).

The objectives of this study were to (1) estimate the whole-farm surpluses of N, P, and K on several commer-

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Table 1. Characteristics of dairy farms participating in the study (n = 8)

Item	Average	SD	Minimum	Maximum
Number of lactating cows	2,149	1,966	550	5,668
Milk yield per cow, kg/yr	10,389	1,720	7,708	12,436
Total milk produced, t/yr	27,518	27,150	6,537	66,453
Milk N content, %	0.50	0.02	0.48	0.51
Arable land, ha	186	180	14	504
Total forage produced, ¹ t/yr	8,939	10,836	191	27,455
Corn silage	6,906	9,484	0	21,296
Alfalfa hay	883	1,178	0	3,178
Alfalfa haylage	761	1,190	0	2,981
Triticale silage	389	843	0	2,098

¹As-is basis. One dairy produced 575 t of earlage, which is not shown in this table.

cial dairy farms in south central Idaho; and (2) reduce P excretions and the overall farm P surplus through dietary manipulation.

MATERIALS AND METHODS

Participating Dairies

Eight dairies with 6 owners located in south central Idaho participated in this study. The dairies varied in size, milk yield per cow, and arable land but had similar manure management systems (Table 1). Three of the dairies had fewer than 1,000 lactating cows. Seven of the dairies had an average milk production during the study period of >9,000 kg. One dairy had an average milk production of 7,708 kg/yr. Seven dairies were entirely Holstein herds, and one had a mixed Holstein/Jersey cow herd. The facilities were free stall, open lot, or a combination of the 2 systems. In all dairies manure was accumulated in the dry lots and was removed twice a year. One dairy used all its manure on its own fields, whereas the others exported various amounts of manure. All dairies had lagoons of different sizes and mechanical solid separators. Lagoon water was used for irrigation within the farm. Dairies had various land bases. One dairy had only 14 ha of arable land, and one was a mixed crop/animal operation, completely satisfying its forage needs (504 ha). This latter dairy is referred to as dairy F in this article. All dairies produced some forages on their land (corn silage, alfalfa hay and haylage, triticale silage), but only 4 exported forages off the farm. All dairies were purchasing concentrate feeds and mineral/vitamin supplements. Four of the participating 8 dairies were owned by 2 families, and for the purpose of this analysis, each of these 2 ownerships was considered one entity (with a common accounting system). Thus, the nutrient balance data presented here are for 6 separate farms.

Sampling and Data Collection

Nutrient Imports and Exports. Data regarding the whole-farm nutrient imports and exports were collected

within a calendar year (January 1 through December 31, yr 1 of the project). Nutrient inflows and outflows were obtained from farm records during monthly visits. During each visit, data on purchases (feed, fertilizer, animals) and sales (forages, animals) were collected from computer files or written records. Feed purchase data were corrected for feed inventories present on the farm on January 1 and on December 31. Data on milk sales were obtained from the processing plants with permission of the farm owner. Amount of manure shipped was estimated based on the net weight of an average truckload and the number of loads that were shipped off the farm. Forages, manure, and lagoon water produced and used on the farm were considered not leaving the system and were not included in the nutrient exports.

Samples of complete diets (all dairies fed TMR), forages, concentrates and by-products, and mineral/vitamin supplements were collected on 4 separate visits from May through August during yr 1. At each visit, 3 random samples (approximately 200 g each) were taken from the concentrate feeds and by-products. These samples were combined per visit and stored refrigerated (4°C) until analyzed. At each visit, 6 random samples were taken from all forages present on the farm. Hay was sampled (100 g/sample) using a forage sampler (Nasco, Fort Atkinson, WI). Silage samples (300 g each) were taken from the silo after removing the top 30 cm of the silage. Hay samples were stored at 4°C and silage samples were kept frozen (20°C). Hay and silage samples were composited (per visit) before analysis. Mineral/vitamin supplements were sampled and later analyzed or (where available) the composition was recorded from the bag label. All lactating cow diets fed at the dairy were sampled separately. Five random TMR samples (500 g each) were collected at each visit, combined, and the composite sample was stored frozen (−20°C) for further analyses. Thus, 4 separate feed and TMR samples were analyzed for each dairy.

Five random dry manure and separator solids samples (500 g each) were collected at each visit. Dry ma-

nure samples were taken from each pen of cows fed a separate diet after removing the top 15 cm of the manure pile. Samples from each visit were combined and stored frozen (-20°C) for further analyses.

At each farm visit, fecal samples (200 g each) were collected from 15 randomly selected lactating cows receiving the same diet. Samples were collected from groups of cows representing all lactating diets fed at the dairy. Fresh fecal samples were obtained from the rectum or from the ground. One composite fecal sample per diet fed was stored frozen (-20°C) for further analyses.

At each farm visit, urine samples (300 mL each) were taken by massaging the vulva from 10 randomly selected lactating cows receiving the same diet. Samples were collected from groups of cows representing all lactating diets fed at the dairy. One composite urine sample per diet fed was acidified with 2 M H_2SO_4 (to pH <3.0), diluted 1:10 with distilled water, and stored frozen (-20°C) for further analyses. Both fecal and urine samples were collected in the morning when cows were locked for managerial purposes.

Two fields for soil sampling from each of the participating dairies were selected for monitoring of soil mineral composition. Each field followed a traditional 3- to 7-yr rotation that included small grains, corn, triticale, alfalfa, sugarbeets, or potatoes. The length of rotation and type of crops in a rotation depend on current markets, land rental agreements, and dairy feedstuff needs. All fields were sprinkler-irrigated, had been in production for more than 50 yr, and had been manured at least 2 of every 4 yr. The individual fields were selected based on consistency of dairy waste application over the past 5 to 6 yr and crop rotation that allowed for manure application. The fields received lagoon water via the irrigation system or dry manure via spreader trucks in the fall or spring. Each field was divided into 2 distinct areas that represented the soil and landscape features of a major portion of the field. Soil samples (a composite of several cores) were taken in the spring within each of the 2 distinct areas in the field to a depth of 60 cm in 30-cm increments. Thus, there were 4 soil samples collected from each field. The positions of the sampling points were recorded with a Global Positioning System and resampled in the fall using the same method as in the spring. Soils were analyzed for $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ (KCl), P (bicarbonate), and K (bicarbonate) at a soil analysis laboratory (Harris Laboratory, Lincoln, NE) using accepted agronomic methods (Gavlak et al., 2003).

Dietary P Reduction Study. With the active involvement of the consulting nutritionists and the dairy owners, modified low-P diets were adopted in 7 of the 8 participating dairies in the second year of the

study. In all cases the reduced dietary P concentration was achieved through removing the inorganic P supplements from the diets. Following adoption of the low-P diets, TMR, fecal, and urine samples were collected from each dairy on 4 separate visits. Sampling began 3 mo after the dietary P reduction took place. Sampling protocols were as described in the previous section.

Chemical Analyses

Dry matter was determined by oven drying at 65°C . The TMR samples were analyzed for N, P, and K by Dairyland Laboratories Inc. (Arcadia, WI). Forages, concentrate and by-product feeds, feces, urine, manure, and separator solids were analyzed for N, P, and K by Oklahoma State University (Stillwater, OK; Jones and Case, 1990; Gavlak et al., 2003; Wolf et al., 2003).

Calculation of Whole-Farm Nutrient Surpluses

The following data were collected and used to calculate whole-farm surpluses of N, P, and K: (1) tons of individual feeds purchased during the calendar year, DM content of the feed, and concentration of N (CP/6.25), P, and K in feed DM; (2) tons of fertilizer purchased and N, P, K content; (3) number of animals purchased, live weight, and N, P, and K composition of the whole animal or weight gain; (4) estimated atmospheric N fixation by legumes grown on the farm; (5) amount of straw (for bedding) imported and N, P, and K concentration in straw; (6) amount of milk shipped from the farm and N, P, and K content of milk; (7) tons of feed sold off the farm, DM content, and N, P, and K concentrations; (8) number of animals sold, live weight, and N, P, and K composition of the whole animal or weight gain; and (9) tons of dry manure removed from the farm, DM content, and N, P, and K concentration in manure. In all cases, lagoon water was used for irrigation on the farm and was not considered in the nutrient surpluses analysis.

The amount of feed purchased and sold was obtained from farm records. Dry matter content was determined by oven drying. Forages, by-product feeds (canola meal, hominy feed, beet pulp, citrus pulp, distillers grains, wheat middlings, etc.), and manure were analyzed for N, P, and K content. Chemical composition of grains (corn, barley) was taken from NRC (2001). Mineral/vitamin supplements were analyzed for N, P, and K content, or composition was taken from labels, where available. Fertilizer composition was as specified by the manufacturer. Atmospheric N fixation by legumes grown on the farm was based on alfalfa hay and was assumed to be 60% of the N content of the forage, as analyzed. This figure was based on published fixation

Table 2. Average N, P, and K concentration (% of DM) of lactating cow diets, forages, feces, urine, manure, and separator solids from participating dairies (n = 8, unless specified otherwise)

Item	Average	SD	Minimum	Maximum
Nitrogen				
Lactating cow diets ¹	2.82	0.09	2.61	2.91
Alfalfa hay	3.55	0.29	3.30	4.20
Alfalfa haylage (n = 6)	3.17	0.40	2.42	3.56
Corn silage	1.51	0.26	1.25	1.83
Triticale silage (n = 4)	2.66	0.58	1.98	3.24
Manure	1.57	0.22	1.29	1.94
Feces	2.77	0.30	2.42	3.26
Urine (% as-is basis)	0.56	0.16	0.38	0.83
Separator solids	1.67	0.27	1.38	2.24
Phosphorus				
Lactating cow diets ¹	0.49	0.05	0.41	0.50
Alfalfa hay	0.26	0.04	0.22	0.36
Alfalfa haylage (n = 6)	0.34	0.03	0.28	0.36
Corn silage	0.21	0.02	0.17	0.24
Triticale silage (n = 4)	0.35	0.13	0.19	0.50
Manure	0.60	0.10	0.48	0.72
Feces	0.85	0.22	0.66	1.20
Urine (%)	ND ²			
Separator solids	0.27	0.07	0.18	0.37
Potassium				
Lactating cow diets ¹	1.90	0.20	1.61	2.16
Alfalfa hay	2.70	0.72	1.93	4.22
Alfalfa haylage (n = 6)	3.48	0.62	2.75	4.41
Corn silage	1.41	0.19	1.10	1.61
Triticale silage (n = 4)	3.86	1.77	1.63	5.76
Manure	2.36	0.63	1.19	3.25
Feces	0.55	0.16	0.32	0.77
Urine (%)	0.67	0.31	0.36	1.36
Separator solids	0.59	0.32	0.18	0.97

¹From TMR analyses. Data were averaged across lactating cow diets (fresh, mid, and high groups).

²Not detected (<0.01%).

rates for alfalfa from 128 to 208 kg of N/ha per year (Burns and Hardy, 1975). Thus, at the current average alfalfa hay yield of 8.75 t/ha (Idaho Agricultural Statistics Service, 2005; www.nass.usda.gov/id) and average N content of the alfalfa hays produced on the participating farms of $3.2 \pm 0.12\%$, the 60% fixation rate would amount to an average of 168 kg of atmospheric N fixed/ha per year. It is noted that these N fixation rates might be high for soils receiving large amounts of manure. All dairies imported some straw for bedding. Published composition of wheat straw (NRC, 2001) was used to calculate the amount of N, P, and K imported to the farm with bedding.

Milk samples were analyzed for true protein and MUN (Washington DHIA, Burlington, WA). Nitrogen content of milk was found as (true protein $\div$ 6.38) + MUN. Concentrations of P (0.09%) and K (0.14%) were taken from NRC (2001).

The numbers of calves and heifers present on the farm during the study year were not used in the whole-farm import-export calculations, except as N, P, and K inputs and outputs (animals purchased or sold). Whole-body N content of growing and adult animals (2.53 and

2.88%, respectively) and whole-body P content (0.72%, both categories of animals) were taken from the Maryland Nutrient Balancer, v. 1.25 (Kohn, 2004). Whole-body K content was assumed to be equal to K requirements for growth (NRC, 2001). Thus, at 1.6 g of absorbed K requirement per kilogram of average daily gain and 90% absorption efficiency, the K content of the whole animal was assumed to be 0.18% for all categories of animals.

Whole-farm N, P, and K surpluses were estimated using Microsoft Excel 2000 (Microsoft Corp., Redmond, WA).

Statistical Analyses

Feed, manure, feces, urine, and milk samples from the 4 farm visits were analyzed separately and data were averaged per farm. The mean values were used in the statistical analysis. Descriptive statistics (chemical composition and nutrient imports/exports data) and simple (Pearson) correlations among nutrient import/export variables were carried out using PROC MEANS and PROC CORR procedures of the SAS software sys-

tem (SAS Institute Inc., 2004). Comparison of soil N, P, and K levels between spring and fall samples and dietary and fecal P concentrations before and after recommended reduction in dietary P were done using PROC MIXED procedure of SAS with farm as a random effect.

RESULTS AND DISCUSSION

Nitrogen, P, and K concentrations of lactating cow diets, the predominant forages, feces, urine, and manure are shown on Table 2. Forages purchased and fed to the lactating cows were typical for the northwest United States (Mowrey and Spain, 1999; except corn silage, which was fed in all participating dairies) and similar in composition to published values (NRC, 2001). Diets contained on average 17.6% CP, which is typical for high-producing dairy cow diets (Hristov et al., 2004c). Dietary P concentrations were higher than NRC (2001) recommendations. Other studies have also reported higher than recommended levels of P in dairy diets (Dou et al., 2003; Cerosaletti et al., 2004). The average concentration of K in the lactating cow diets from this study exceeded NRC (2001) recommendations (for a cow at 90 DIM, with BW of 680 kg, and milk yield of 40 kg). The average concentration of K in the forages fed was similar to published values (NRC, 2001), but some alfalfa hay samples were analyzed as extremely high in K.

Increasing dietary P results in increased concentration of acid-digest total P and water-soluble inorganic P in dairy feces (Chapuis-Lardy et al., 2004). In intensive agricultural systems, N:P ratios in manure are considerably lower than N:P required for plant growth, and excessive application of manure may exceed the assimilatory capacity of the soil and planted crops, leading to eutrophication of aquatic systems (Satter and Wu, 1999), identified by the US Environmental Protection Agency (USEPA, 1996) to be the most ubiquitous water quality impairment in the United States (Sharpley et al., 2000). Lentz and Westermann (2001), Leytem and Westermann (2003), and Turner et al. (2003) have found significant movement of insoluble P in some Idaho soils. As data from this study indicate (Figure 1), P levels in manure-amended soils from the participating dairies exceeded the state's recommended threshold concentrations for P of 40 mg/kg for soils where groundwater is >2.5 m from the surface and 20 mg/kg when groundwater is <2.5 m from the surface (Natural Resources Conservation Service, 1999). The excessive P concentration in the 30-cm sample is a clear indication of overapplication of animal manure on these fields. Fertilizer guides in the region do not recommend fertilizer application for any crops when P concentra-

Figure 1. Average ($n = 8$) and SE of soil N, P, and K concentrations in manure-amended soils from dairies participating in the survey. Soil P levels did not differ between the spring and fall samples: 140 and 142 ppm, SE = 16.6, $P = 0.922$ (30-cm sample) and 47 and 49 ppm, SE = 7.8, $P = 0.853$ (60-cm sample), respectively. Soil N levels did not differ between the spring and fall samples: 58 and 49 ppm, SE = 12.3, $P = 0.404$ (30-cm sample) and 37 and 34 ppm, SE = 8.6, $P = 0.648$ (60-cm sample), respectively. Soil K levels also did not differ between the spring and fall samples: 778 and 876 ppm, SE = 117.7, $P = 0.254$ (30-cm sample) and 562 and 615 ppm, SE = 97.5, $P = 0.580$ (60-cm sample), respectively.

tion exceeds 30 mg/kg in soil. No significant differences in P levels were observed between the spring and fall samples ($P = 0.922$ and 0.853 ; 30- and 60-cm samples, respectively). Nitrate-N (Figure 1) was >40 mg/kg for 5 of the 8 dairies, and 2 were over 80 mg/kg. These high N concentrations are more than the crop needs for optimal growth and represent an environmental concern. Although 3 dairies had optimal levels of soil N, soils were excessively high in P. Potassium concentrations (Figure 1) were above optimal but not toxic. These soil concentrations illustrate the need to improve whole-farm N and P efficiency and maintain better control over the whole-farm nutrient surpluses.

Whole-Farm Nitrogen Imports and Exports

Table 3 depicts N imports, exports, and whole-farm N surplus for the dairies participating in this study. Consistent with previous reports (Spears et al., 2003a), N imported with feedstuffs was the major import to the farm—on average 90% of all N imports. Because most dairies grew alfalfa forage, the second largest N import item was N fixation. The proportion of N imported with fertilizer was low (0 to 33 t/yr, considering soil test values) for most of the dairies, except for dairy F, which grew a large amount of forages (13% of the total N imports). Dairy F imported only 43% of its total imported N as feed N, and N fixation was a major N import comprising 38% of all N imports. The average N imported with purchased animals was low (1.7% of

Table 3. Averaged whole-farm N imports and exports (t/yr, unless specified otherwise; n = 6)

Item	Average	SD	Minimum	Maximum
Imports				
Feeds	460.5	329.1	107.4	890.0
Fertilizer	7.0	13.1	0	33.3
Atmospheric fixation ¹	25.1	36.3	0	96.6
Animals	8.5	12.8	0	30.3
Bedding	8.6	3.4	3.5	13.6
Exports				
Milk	104.9	94.1	32.0	275.7
Feeds	23.7	49.3	0	123.8
Manure	51.9	48.3	0	129.7
Animals	15.4	15.5	3.3	44.5
Produced with forages on the farm	105.0	137.0	9.6	377.3
Total imports	509.8	319.2	208.7	927.9
Total exports	195.9	124.5	69.2	411.2
Overall surplus	313.9	218.0	89.5	599.4
Surplus per 1,000 kg of milk produced, kg/yr	17	6	9	24
Surplus per cow, kg/yr	169	47	91	222
Efficiency, ² %	41	14	25	64

¹Fixation assumed at 60% of alfalfa N yield (see Materials and Methods).

²(Total exports ÷ total imports) × 100.

the total), and some dairies did not import any animals during the study period. All dairies imported straw for bedding, and N imports with this item represented 1.7% of all N imports, on average.

The average proportion of N exported as milk from the participating dairies was 54% of all N exported. The estimated milk N efficiency (milk N exports/feed N imports) was 23% and was similar to the 23% reported by Spears et al. (2003a, which included exports of all animal products) and to European data (25%; Børsting et al., 2003). These figures are close to observations from a larger meta-analysis in which average efficiency of transfer of feed N into milk protein N was estimated at $24.7 \pm 0.14\%$, with minimum and maximum values of 13.7 and 39.8%, respectively (Hristov et al., 2004c). The average proportion of N exported with animals (sold or culled) was 8%. The combined figure of 62% of N exported as animal products is similar to that reported by Spears et al. (2003a). For most dairies, manure was the second largest N export, on average 27% of the total. Dairy F, however, was utilizing all of the manure produced for its own crop production. Spears et al. (2003a) reported that, for Western dairies, N exported with manure was on average 34% of all N leaving the farm. All dairies participating in this study produced various amounts of forages, and in most cases, these forages did not leave the farm. The average proportion of N exported as forages was 12% (of the total N export) but varied significantly among the dairies. Thus, dairy F exported 77% of its N as forages and only 20% as milk.

The average whole-farm N surplus was 314 t/yr, but varied significantly among the dairies. The average ef-

ficiency (N output/N input) of use of N imported to the farms was 41% and was similar to the 36% reported by Spears et al. (2003a). The most efficient dairy in this study was dairy F with N efficiency of 64%. This dairy was satisfying all of its forage needs, was a relatively small dairy (550 cows), had relatively high milk yield per cow (11,887 kg/yr), and was exporting large amounts of N with farm-grown forages. Remarkably, this dairy was not exporting any manure. The dairy with the lowest N efficiency (25%) was a large 2,800-cow dairy, had slightly lower milk yield per cow (10,748 kg/yr) compared with dairy F, and had the lowest proportion of manure N exported from the farm of the total N exports (16% compared with 26% on average for all farms).

Nitrogen lost from manure as ammonia was not measured in this study and consequently was not included in the surplus and efficiency estimations. Ammonia losses from manure are large and occur rapidly after feces and urine are mixed. Nitrogen in fecal matter is predominantly undigested feed N, microbial N, and N from endogenous origin. The main form of N in urine, however, is urea (Bristow et al., 1992), and ammonia emitted from livestock facilities is mainly a product of urinary urea breakdown (Rom and Dahl, 1997). If mixed with feces, urea is quickly converted into ammonia by the abundant urease activity present in fecal matter. Depending on factors such as pH, air velocity, temperature, and concentration, a large proportion of ammonia can be rapidly volatilized and lost to the environment (Monteny and Erisman, 1998; Ni, 1999; NRC, 2003). Moreira and Satter (2002) suggested that losses of ammonia from manure can be estimated based on

Table 4. Averaged whole-farm P imports and exports (t/yr, unless specified otherwise; n = 6)

Item	Average	SD	Minimum	Maximum
Imports				
Feeds	69.9	54.4	23.1	161.3
Fertilizer, kg/yr	52	127	0	312
Animals	2.4	3.6	0	8.6
Bedding	1.5	0.6	0.6	2.4
Exports				
Milk	19.3	17.8	5.9	51.7
Feeds	3.1	6.3	0	15.9
Manure	18.6	17.0	0	45.5
Animals	3.9	3.9	0.8	11.3
Produced with forages on the farm	9.2	11.4	0.6	30.9
Total imports	73.9	54.5	25.9	171.2
Total exports	44.9	31.0	18.0	95.9
Overall surplus	28.9	28.0	2.7	75.3
Surplus per 1,000 kg of milk produced, kg/yr	1.2	0.4	0.4	1.6
Surplus per cow, kg/yr	12	4	5	17
Efficiency, ¹ %	66	14	48	90

¹(Total exports ÷ total imports) × 100.

the N:P ratio in fresh urine and feces and aged manure. This approach is based on the assumption that there are no losses of manure P through volatilization. Thus, any changes in N:P ratios will be a quantitative indication of the amount of N lost through volatilization. We used this approach to estimate ammonia N losses from manure in this study and the effect of these losses on the overall whole-farm N surplus. The average proportion of urinary to fecal N as excreted by the cow (g/d) was assumed to be 1.57 ± 0.11 based on feeding trials conducted in our laboratory, in which total fecal and urinary N excretions were measured (Hristov and Ropp, 2003; Hristov et al., 2004a,b; Foley et al., 2004; and Hristov et al., 2005). This ratio and the concentration of N in feces were used to estimate N concentration and consequently N:P ratio in freshly excreted manure. We assumed no P excretion with urine. This assumption was based on our own measurements (urinary P was below 0.01% in 4 samples and was not detected in the remaining urine samples) and on data from Van Horn et al. (1994), James et al. (1999), Wu et al. (2000), and Knowlton and Herbein (2002), who found very low urinary P concentrations and negligible contribution of urinary P to total P excretion in cattle. Fecal and manure N and P concentrations were as measured in this study (Table 2). Thus, N:P ratio in fresh manure was estimated to be 8.09 ± 0.62 , and that of dry manure samples was 2.62 ± 0.13 (Table 2). Based on these 2 values, we estimated the proportion of manure N lost as ammonia N for each dairy $[(1 - 2.62 \div 8.09) \times 100]$. The average proportion of manure N lost as ammonia was estimated at 66% (SD = 6.51 kg; minimum and maximum of 58 and 75%, respectively). Assuming 0.306 kg of N excreted per cow (680 kg of BW) per day (USDA, 1992; EPA, 2004), the average amount of N excreted

annually from the dairies participating in this study would be 240 t (SD = 220 t; minimum and maximum of 61 and 633 t, respectively). Based on this value and the average manure ammonia N loss of 66%, the average annual ammonia N losses would be 159 t (SD = 151 t; minimum and maximum of 36 and 437 t, respectively), or 74 kg per lactating cow (SD = 7.3 kg; minimum and maximum of 65 and 84 kg, respectively). This would represent 28% of the total N imported to the farm (SD = 11%; minimum and maximum of 14 and 47%, respectively). When the estimated ammonia N lost from manure was added to the N exported from the farms, the average whole-farm surplus of N was decreased to 154 t (SD = 134 t; min and max of 54 and 393 t, respectively) and the overall efficiency of use of imported N was increased to 68% (SD = 15%; minimum and maximum of 51 and 91%, respectively). This figure is significantly higher compared with the 41% efficiency when ammonia losses were not accounted for in the whole-farm N surplus (Table 3). Nitrogen lost to the atmosphere as ammonia can hardly be considered an efficient use of feed resources, and its emissions are currently being regulated in the United States (<http://www.eh.doe.gov/oepa/guidance/cercla/rqs-gen.htm>).

The ammonia N losses estimated in this study are higher than those reported by Demmers et al. (1998) and Koerkamp et al. (1998) and published by the Environmental Protection Agency (2004). However, summarized data by Rotz (2004) suggest that volatile N losses from cattle facilities can be as high as 40 to 90% of the total N excreted. Using component prediction models and a whole-farm simulation model, Rotz and Oenema (2005) estimated total ammonia N losses from northeastern US dairies at 47 to 87 kg/cow, depending on the type of housing and manure management practices.

A case study by Rumburg et al. (2004) reported annual ammonia emissions from a dairy as high as 170 kg/cow.

Whole-Farm Phosphorus Imports and Exports

Similar to the N imports-exports data and reports by Spears et al. (2003b) and Cerosaletti et al. (2004), P imported with feedstuffs was the major P import to the farm in this study—on average 95% of all P imports (Table 4). The proportion of P imported with fertilizer was low (or zero) on most of the dairies, including dairy F (1.2% of the total P import). The average P imported with purchased animals was 3.2% of the total P imports. Phosphorus imports with bedding straw represented on average 2.0% of all P imports.

The average proportion of P exported as milk from the participating dairies was 43% of all P exports. The estimated milk P efficiency (milk P exports ÷ feed P imports) was 27.6% and was within the range (23 to 47%) reported by Spears et al. (2003b) for western dairies and somewhat lower than the 35 to 40% reported for New York dairies by Cerosaletti et al. (2004). These figures are close to observations from a larger meta-analysis in which average efficiency of transfer of feed P into milk was estimated at $30.5 \pm 0.21\%$, with minimum and maximum values of 12.4 and 50.0%, respectively (data from Hristov et al., 2004c). The average proportion of P exported with animals (sold or culled) was 8.6%. For most dairies, manure was an important P export item; the average P exported with manure was 41% of the total P exports. As with N, dairy F was utilizing all of the manure P produced on the farm for its own crop production. Spears et al. (2003b) reported that P exported with manure was on average 31% of all P leaving the farms. All dairies in the current study produced various amounts of forages, and in most cases these forages did not leave the farm. The average proportion of P exported as forages was 7% (of the total P exports), which was significantly less than the N export with forages and varied considerably among the dairies. Dairy F, for example, exported 68% of its P as forages and only 25% as milk.

The average whole-farm P surplus was 29 t/yr and varied significantly among the dairies. The average efficiency (P output/P input) of use of P imported to the farms was 66% and was similar to the 62% reported by Spears et al. (2003b). As with N, the most efficient dairy in this study was dairy F with P efficiency of 90%. This dairy had a P surplus of only 2.7 t/yr, or 10% of the total P imports. The major factor for this low surplus was the large export of P with forages produced on the farm (15.9 t of P/yr). The dairy with the lowest P efficiency (48%) was the same dairy that had the lowest N efficiency. This dairy was exporting only 1.9 t of P/

Figure 2. Average dietary and fecal P concentrations before and after recommended reductions in dietary P were adopted ($n = 5$). Dietary P was reduced ($P = 0.007$; $SE = 0.017$), but fecal P was only numerically decreased ($P = 0.167$; $SE = 0.068$).

yr with forages produced on the farm and, similar to N, had significantly lower than the average proportion of manure P exported from the farm of the total P exports (25% compared with 41% on average for all dairies).

Dietary P Reduction Study. One of the objectives of this project was to reduce fecal P excretions through dietary means. In cooperation with the consulting nutritionists and the dairy owner, 7 of the 8 participating dairies reduced their dietary P to NRC (2001) recommended levels in the second year of the study. Following removal of mineral P supplements from the diet, average dietary P levels were reduced from 0.49 (yr 1) to 0.38% (yr 2), $SE = 0.017$ ($P = 0.007$; Figure 2). This reduction of 24%, however, resulted in only numerical decreases (average of 16%; $P = 0.167$) in fecal P concentrations (from 0.87 to 0.73%, respectively; $SE = 0.068$). Although, samples from 15 cows/visit were collected during 4 farm visits, a significant diurnal variability in fecal P concentrations has been reported (Wu et al., 2000), and the averaged values used in this analysis may not reflect the actual fecal P concentrations. Nevertheless, the decreased import of feed P would have an important impact on the overall P surplus on these dairies. We estimated that due to the reduced P levels of the diet, the net reduction in P imports would range from 5.7 to 61.4 t/yr (average of 26.0 t/yr, $SD = 21.6$ t/yr), or from 7.6 to 21.7 kg per cow per year. The estimated average reduction in P imports per lactating cow would be 11.9 kg/yr ($SD = 5.58$ kg), ranging from 7.6 to 21.7 kg/yr. This reduction would have an equivalent effect

Table 5. Averaged whole-farm K imports and exports (t/yr, unless specified otherwise; n = 6)

Item	Average	SD	Minimum	Maximum
Imports				
Feeds	276.3	208.7	39.2	564.7
Fertilizer	0.3	0.8	0	2.1
Animals	0.6	0.9	0	2.2
Bedding	23.4	9.3	3.9	37.1
Exports				
Milk	30.1	27.7	9.2	80.4
Feeds	22.5	45.1	0	113.5
Manure	65.2	50.0	0	140.4
Animals	1.0	1.0	0.2	2.8
Produced with forages on the farm	77.2	98.8	3.9	267.8
Total imports	300.7	209.1	78.4	593.7
Total exports	118.8	52.9	54.9	189.2
Overall surplus	181.9	187.1	-44.5	484.1
Surplus per 1,000 kg of milk produced, kg/yr	8	9	-7	16
Surplus per cow, kg/yr	76	89	-81	172
Efficiency, ¹ %	58	50	18	157

¹(Total exports ÷ total imports) × 100.

on the overall P surplus and, respectively, the efficiency of imported P use on the farm. In a similar attempt, Cerosaletti et al. (2004; 25% reduction in dietary P) reported an estimated 33% reduction in fecal P concentrations and a 49% reduction in the whole-farm P balance on a New York dairy.

Whole-Farm Potassium Imports and Exports

As with N and P, K imported with feedstuffs was the major K import to the farms—on average 92% of all K imports. Except for dairy F (2.6% of the total K imports), none of the participating dairies imported any K as fertilizer to their farms (Table 5). Potassium imported with purchased animals was insignificant, and imports of K with bedding straw were on average 7.8% of all K imports.

The average proportion of K exported as milk from the participating dairies was 25% of all K exports. The estimated average milk K efficiency (milk K exports/feed K imports) was 11%. The average proportion of K exported with animals was insignificant for all dairies. For most farms, manure was the main K export item; the average K exported with manure was 55% of the total K exports. As with N and P, dairy F utilized all of the manure produced on the farm for its own crop production but was exporting a large amount of K with the forages produced on the farm: 92% of all K exports. All dairies grew alfalfa forages, and because of the high K content of alfalfa forages, exports with forages sold off the farm were relatively high for some farms, 5.6 to 16.3% (except dairy F) of the total K exports.

The average whole-farm K surplus was 182 t/yr and, as with N and P, varied significantly among the dairies. Dairy F, with its large export of K with forages, was in

a negative K balance (-44.5 t/yr), i.e., this dairy was a net exporter of K during the year of the study. The average efficiency (K output/K input) of K imported to the farms was 58%. When dairy F was excluded from the analysis, the average whole-farm K surplus for the remaining dairies increased to 227 t/yr, and the average efficiency decreased to 38%. Apparently, as with N and P, dairy F had the most efficient use of imported K in this study. Again, the major factor for this low surplus—high efficiency was the large export of K with forages produced on the farm (113.5 t K/yr). The dairy with the lowest K efficiency (18%) exported 17.9 t of K/yr with forages produced on the farm and only 48.5 t of K/yr with manure (compared with 106 and 140 t of K/yr, respectively, for the other 2 dairies of similar size). Studies investigating whole-farm K balance are scarce. Cerosaletti et al. (2004) estimated 20 to 76 kg per cow K surplus and efficiency of imported K use of 18 to 45% for 2 smaller New York dairy farms. The average surplus of K per cow per year and efficiency of imported K use in the current study (excluding dairy F) were 108 kg (SD = 50 kg) and 38% (SD = 12.5%), respectively.

Correlations

Within its limitations, correlation analysis is useful in identifying relations between import-export items and overall farm surpluses and efficiency of use of imported nutrients. Nitrogen import with feed correlated ($P < 0.05$) positively to N exports with milk and animals, and import of N with fertilizer correlated ($P < 0.05$) positively with N exported from the farm with forages produced on the farm. As expected, the whole-farm N surplus correlated ($P < 0.05$) positively with feed N imports, but also with milk N exports ($P = 0.053$), the

latter resulting from the positive correlation ($P < 0.05$) between milk N exports and feed N imports. Efficiency of farm use of imported N was correlated ($P < 0.05$) positively only with feed N exports. Similar trends were observed for P; P exports with milk correlated positively ($P < 0.05$) with feed exports, and P produced on the farm with forages correlated ($P < 0.05$) positively with fertilizer P imports and feed P exports. Manure P (and N) exports correlated ($P < 0.05$) positively with imported animal P (and N). Similar to N, whole-farm P surplus correlated ($P < 0.05$) positively with feed P imports and milk P exports, but the correlation with animal exports was also significant ($P < 0.05$). The efficiency of use of imported P was significantly correlated ($P < 0.05$) only with P imports with fertilizer, which resulted from the high correlation between the latter and feed P exports. Correlations among K import-export variables and whole-farm K surplus and efficiency of imported K use were similar to those for N and P. However, milk K export did not correlate ($P = 0.299$) with overall farm K surplus. The efficiency of use of imported N correlated ($P < 0.05$) positively with fertilizer K imports and K exports with feed and the amount of forage K produced on the farm. Similar to N and P, these latter correlations emphasize the importance of producing and selling forages off the farm, in addition to milk and manure exports, for maintaining low nutrient farm surpluses. This is also evident from the greater N, P, and K efficiency of dairy F compared with the other participating dairies, which did not produce and sell nearly as much forage as did dairy F.

CONCLUSIONS

Nitrogen, P, and K purchased with feedstuffs were the major import items, and milk, manure, and forages sold off the farm were the major export items on commercial dairy farms in Idaho. The whole-farm import-export analysis indicated net accumulation of N, P, and K on the farm. Exports of nutrients with milk and manure were not sufficient to achieve whole-farm balance and sustainability of the dairy operations, and greater than recommended levels of dietary P and K were partially responsible for the observed low efficiency of use of imported nutrients. As a result of the whole-farm P surplus, soil P levels on manure-amended fields were unacceptably high and above state threshold standards. Reduced dietary P levels adopted by some of the participating dairies resulted in significant reduction of P imports and showed potential for reducing whole-farm P surplus. This study demonstrated that, in addition to milk and manure exports, export of nutrients with forages produced on the farm is a major factor in reducing whole-farm N, P, and K surpluses.

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