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Efficiency of Use of Imported Magnesium, Sulfur, Copper, and Zinc on Idaho Dairy Farms

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ABSTRACT

Six commercial dairies from south central Idaho were surveyed to estimate the whole-farm surpluses of magnesium (Mg), sulfur (S), copper (Cu), and zinc (Zn). Mineral 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 Mg, S, Cu, and Zn to the dairy was with purchased feeds, from 91 (S) to 97% (Zn) of all imports. The major mineral export item was manure [from 60% (S) to 89% (Cu) of all exports] and forages, in the case of a dairy with a large land base. Export with milk represented on average only 8.6, 25, 2.1, and 11% (Mg, S, Cu, and Zn, respectively) of all exports. Thus, the conversion of the imported feed Mg, S, Cu, and Zn into milk was rather low (on a whole-farm scale): 5.6, 11, 1.4, and 5.2%, respectively. Concentrations of Mg, Cu, and Zn in the lactating cow diets from the participating dairies exceeded National Research Council (2001) recommendations on average by 85, 34, and 73%, respectively, which contributed to the inefficient use of imported minerals. Whole-farm Mg surplus varied from 4 to 54 t/yr (3 to 19 kg/cow per year). The efficiency of use of imported Mg varied from 27 to 88%. Sulfur surpluses were from 9 to 52 t/yr (12 to 40 kg/cow per year). Copper and Zn surpluses were also significant (average of 59 and 585 kg/yr and 0.05 and 0.4 kg/cow per year, respectively). The average efficiency of use of imported S, Cu, and Mg was 44, 62, and 56%, respectively and, as with Mg, varied significantly among the dairies. The results from this study suggest that reduction in the concentration of dietary Mg, Cu, and Zn is potentially the most efficient way of reducing overall excretions and whole-farm surpluses of these minerals.

Key words: dairy farm, nutrient management, magnesium and sulfur, copper and zinc

INTRODUCTION

Intensive animal production units often have a limited land base, which necessitates import of nutrients from outside the production system. If nutrients are not effectively removed from the system accumulation occurs, which endangers the quality of soil and ground and surface water resources. Recent studies have shown substantial nitrogen, phosphorus (Spears et al., 2003a,b; Hristov et al., 2006), and potassium (Hristov et al., 2006) surpluses on western dairy farms of various sizes. In the case of P, farm surpluses resulted in unacceptably high soil P levels (Hristov et al., 2006). At present, N and P are considered of primary environmental concern due to their effect on surface and ground water quality (Sharpley et al., 2000). Other elements, however, currently not environmentally regulated, are routinely overfed, or have low absorption efficiency and may be excreted in large quantities in animal manure.

Magnesium, sulfur, copper, and zinc are vital minerals in dairy cow nutrition (NRC, 2001). Deprivation of these nutrients will cause an array of physiological and metabolic disorders, inhibited ruminal microbial protein synthesis, loss of production, and eventually death of the animal (NRC, 2001; Underwood and Suttle, 2001). The absorption efficiency of these minerals from natural feedstuffs is relatively low (20 to 30%, Mg; 1 to 5%, Cu, and 15%, Zn; NRC, 2001), depends on the dietary concentration of the mineral, and is often a function of the interaction with other elements, or it depends entirely on the coavailability of other nutrients in the case of S (Underwood and Suttle, 2001). The mechanisms controlling absorption rates of minerals in the ruminant are extremely complex and are beyond the scope of this study. Because supplemental minerals are relatively inexpensive and are added to the diet in small amounts, Mg, S, Cu, and Zn salts are often supplemented to practical dairy cow diets. Low efficiency of absorption or high supplementation of a nutrient from

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the diet means larger amounts of this nutrient would be excreted with feces and urine. Compared with synthetic fertilizer, for example, dairy manure is considerably higher in Cu and Zn (McBride and Spiers, 2001). Feed supplements, footbath chemicals, and low absorption efficiency all contribute to the high mineral concentrations in cattle feces and urine. In monogastric animals, 95 to 99% of all ingested trace minerals may appear in feces (Purves, 1985; Payne et al., 1988; Nys, 2001) suggesting that these elements are grossly overfed or are very inefficiently utilized, or both, in these species. Overapplication of manure rich in minerals to soil is likely in areas with intensive animal production, increasing the risk of soil, surface, and groundwater contamination (Bolan et al., 2003; Ogiyama et al., 2005; Brock et al., 2006).

Magnesium can affect P release in manure-amended soils. Nair et al. (2003) and Josan et al. (2005) suggested that crystallization of stable phosphate forms (calcium-P) in sandy soils is inhibited by the presence of high levels of Mg resulting from intensive manure application. These authors proposed a reduction in manure Mg concentration through dietary manipulation or pretreatment of manure before land application, as a method to minimize P release and the environmental impact of manure application. Copper and Zn are less mobile in soil (than N and P, for example) and accumulate over time with repeated dairy manure application (Brock et al., 2006). Accumulation of these micronutrients in soil can be toxic to plants and foraging animals (Ferket et al., 2002), particularly aquatic biota (Flemming and Trevors, 1989). In sandy soils, Cu and Zn mobility exceeded ordinary rates and was correlated to soil Cu and Zn levels, endangering ground water quality (Zhang et al., 2003). A similar behavior of these minerals would be expected in the silt clay soils of southern Idaho, where this study was conducted.

Although industrial activities are the major source of anthropogenic S (as SO_2) in soil (Nyborg, 1978), animal operations can also be a significant source of S pollution under certain circumstances. Hydrogen sulfide is produced from solid manure (NRC, 2003) and increased S levels in manure are likely to increase S emissions. On a regional basis, when the concentration of animal units is high, animal manure may be an important source of hydrogen sulfide, thus contributing to atmospheric S emissions and odor (NRC, 2003). In wetland environments, excess S from agricultural activities can indirectly contribute to the accumulation in fish and wildlife of toxic compounds, such as methylmercury, posing a threat to human health (Bates et al., 2002).

Whole-farm nutrient surpluses are an indirect measure of the potential impact that animal operations may have on soil, water, and air quality. To our knowledge, data on farm surpluses of environmentally important nutrients other than N, P, and K do not exist in the United States. Thus, the objective of this study was to estimate the annual whole-farm surpluses of Mg, S, Cu, and Zn on several commercial dairy farms in south central Idaho.

MATERIALS AND METHODS

Participating Dairies

This is the second of 2 articles from a project that evaluated whole-farm nutrient balances in commercial Idaho dairies. Eight dairies with 6 owners located in south central Idaho participated in the project (see Hristov et al., 2006). Due to missing data, 2 of the dairies (one owner) were excluded from the Mg, S, Cu, and Zn analyses. Thus, whole-farm Mg, S, Cu, and Zn surpluses were estimated for 6 of the participating dairies (5 owners). Detailed descriptions of the dairies can be found in the companion paper (Hristov et al., 2006). The dairies varied in size, milk yield per cow, and arable land, but had similar manure management systems (Table 1). The facilities were free-stall, open lot, or a combination of these. In all dairies, manure was accumulated in the dry lots and was removed twice a year. 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 (dairy F, hereafter) was a mixed crop/animal operation that completely satisfied its forage needs (504 ha). Dairy F used all its manure on its own fields, whereas the other dairies exported various amounts of manure. All dairies produced forages on their land (corn silage, alfalfa hay and haylage, and triticale silage) and some exported forages off the farm. In all cases, concentrate feeds and mineral-vitamin supplements were imported to the farm. One family owned 2 of the 6 dairies participating in this part of the project; for the purpose of this analysis these 2 dairies were considered 1 entity (with a common accounting system). Thus, the Mg, S, Cu, and Zn surplus data presented here are for 5 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). 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

Table 1. Characteristics of dairy farms participating in the study (n = 6)

Item	Average	SD	Minimum	Maximum
Number of lactating cows	1,446	1,057	550	2,807
Milk yield per cow, kg/yr	10,437	1,918	7,708	12,436
Total milk produced, t/yr	21,533	25,549	6,537	66,452
Arable land, ha	171	198	34	504
Total forage produced, t/yr[1]	7,407	11,364	191	27,455
Corn silage	4,967	9,178	0	21,296
Alfalfa hay	1,059	1,225	191	3,178
Alfalfa haylage	913	1,267	0	2,981
Triticale silage	467	918	0	2,098

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

the processing plants with permission of the farm owner. The 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, by-products, mineral-vitamin supplements and from the dry manure and separator solids were collected on 4 separate visits from May through August during the year of the study. A detailed description of the sampling procedures can be found in the companion paper (Hristov et al., 2006). At each farm visit, fecal samples (200 g each) were collected from 15 randomly selected lactating cows receiving the same diet and combined for further analyses. Spot urine samples were taken from 10 randomly selected lactating cows receiving the same diet and combined for further analyses. Fecal and urine samples were collected in the morning when cows were locked for managerial purposes.

Two fields from each of the participating dairies were selected for soil sampling and monitoring of soil mineral composition. A detailed description of the soil sampling protocol was published in the companion paper (Hristov et al., 2006). 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 either lagoon water via the irrigation system or dry manure via spreader trucks in the fall or spring. Soil samples (a composite of several cores) were taken in the spring and fall. Soils were analyzed for Mg, S, Cu, and Zn at a soil analysis laboratory (Harris Laboratory, Lincoln, NE) using accepted agronomic methods for the region and type of soils (Gavlak et al., 2003).

Chemical Analyses

Dry matter was determined by oven-drying at 65°C. Samples of the TMR were analyzed for Mg and S by Dairyland Laboratories, Inc. (Arcadia, WI) and for Cu and Zn on an Iris inductively coupled plasma atomic emission spectrophotometer (Thermo Jarrell Ash Corp., Franklin, MA) following extraction with nitric acid (Soon, 1998). Forages, some concentrate, and all by-product feeds (canola meal, fish meal, beet pulp, citrus pellets, mill run, wheat bran, corn screenings, cottonseed meal, dry distillers grain, etc.), feces, urine, manure, and separator solids were analyzed for Mg, S, Cu, and Zn by Oklahoma State University, Stillwater (Jones and Case, 1990; Gavlak et al., 2003; Wolf et al., 2003).

Calculation of Whole-Farm Nutrient Surpluses

A detailed description of the approach used to estimated whole-farm Mg, S, Cu, and Zn surpluses is provided in the companion paper (Hristov et al., 2006). In brief, farm imports and exports of Mg, S, Cu, and Zn were estimated based on the amount of feed, fertilizer, bedding, animals, milk, and manure entering or leaving the farm during the study year (corrected for inventories on January 1 and December 31) and concentration of Mg, S, Cu, and Zn in these products. In all cases, lagoon water was used for irrigation on the farm; that is, it did not leave the farm and was not considered in the nutrient surpluses analysis.

The amount of feed purchased and sold was obtained from farm records. Forages, by-product feeds, and manure were analyzed for Mg, S, Cu, and Zn content. Mineral composition of cereal grains (corn, barley) and soybean meal was taken from NRC (2001). Mineral-vitamin supplements were analyzed for Mg, S, Cu, and Zn content, or composition was taken from product labels when available. Origin of the minerals (e.g., organic vs. inorganic) was not recorded. Fertilizer composition was as specified by the manufacturer. Published composition of wheat straw (NRC, 2001) was used to calculate the amount of Mg, S, Cu, and Zn imported to the farm with bedding. Concentrations of Mg (0.015%), S (0.030%), Cu (0.15 mg/kg), and Zn (4 mg/kg) in milk were taken from NRC (1989, 2001). The numbers of calves and heifers present on the farm during the study year were not used in the whole-farm import and export calculations, except as Mg, S, Cu, and Zn inputs and outputs (animals purchased or sold). Whole-body Mg, Cu, and Zn content was assumed to be equal to Mg, Cu, and Zn content of tissue: 0.45 g/kg, 1.15 mg/kg, and 24 mg/kg (NRC, 2001, derived from multiple sources), respectively. Whole-body S content was assumed to be 0.15% (NRC, 2001). These concentrations are comparable to earlier estimates published by McDonald et al. (1995).

Whole-farm Mg, S, Cu, and Zn 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 import/export data) were carried out using PROC MEANS (SAS Institute, 2004). Comparison of soil Mg, S, Cu, and Zn levels between spring and fall samples was done using PROC MIXED of SAS with farm as a random effect.

RESULTS AND DISCUSSION

Magnesium, S, Cu, and Zn concentrations of lactating cow diets, the predominant forages, feces, urine, and manure are shown in Table 2. Mean concentrations of Mg, S, and Zn in alfalfa forage and corn and triticale silages were similar to published values (NRC, 2001), but there was significant variability among dairies, particularly with some forages (e.g., Mg in alfalfa haylage). Copper concentration in alfalfa hay was lower than NRC (2001) published values, but Cu concentration in corn and triticale silages was similar to the NRC (2001) values. The diets contained on average 0.37% Mg, 0.25% S, 21 mg/kg Cu, and 109 mg/kg Zn. These concentrations, except S, were higher than dietary levels recommended by NRC (2001). Except for S, concentration of the minerals studied was relatively low in urine because feces are the major route of Mg, Cu, and Zn excretion in cattle. Fecal Mg, Cu, and Zn concentrations were within the range reported by Safley et al. (1984) for 7 North Carolina dairies. Some separator solids samples had extremely high levels of Cu, presumably due to Cu contamination from footbaths.

Soil Mg, S, Cu, and Zn levels are shown in Figure 1. Soil Mg levels were normal for manured soils in the region (Mahler et al., 1985). Sulfur levels were higher than average for the region (Mahler et al., 1985) and the high levels at 31 to 60 cm indicate that S may be high at greater depths. The S levels indicate that excessive S is being added through the manure, because these levels are not common in unmanured cropped soil. Average soil Zn concentrations were within the recommended levels for cropped soils in the region (Mahler et al., 1985), but Cu concentrations were significantly higher than the maximum recommendations (Mahler et al., 1985), particularly in the 30-cm sample, indicating overapplication of Cu with manure. One dairy had a soil Cu concentration of 21.2 mg/kg in the 30-cm sample. There was no difference (P = 0.120 to

Table 2. Average concentration (% or mg/kg of DM) of Mg, S, Cu, and Zn in lactating cow diets, forages, feces, urine, manure, and separator solids from participating dairies (n = 6, unless specified otherwise)

Item	Average	SD	Minimum	Maximum
Magnesium, %				
Lactating cow diets[1]	0.37	0.03	0.34	0.41
Alfalfa hay	0.32	0.02	0.30	0.35
Alfalfa haylage	0.29	0.10	0.13	0.41
Corn silage	0.17	0.03	0.13	0.21
Triticale silage (n = 4)	0.22	0.11	0.13	0.39
Manure	0.74	0.10	0.61	0.90
Feces	0.85	0.12	0.68	1.03
Urine	0.02	0.01	0.01	0.03
Separator solids	0.40	0.08	0.26	0.50
Sulfur, %				
Lactating cow diets[1]	0.25	0.02	0.24	0.30
Alfalfa hay	0.34	0.03	0.31	0.39
Alfalfa haylage	0.31	0.06	0.21	0.38
Corn silage	0.12	0.03	0.09	0.16
Triticale silage (n = 4)	0.28	0.08	0.18	0.37
Manure	0.42	0.04	0.38	0.51
Feces	0.29	0.06	0.19	0.36
Urine	0.52	0.17	0.35	0.90
Separator solids	0.32	0.06	0.21	0.38
Copper, mg/kg				
Lactating cow diets[1]	21	5	15	29
Alfalfa hay	3	0.7	5	7
Alfalfa haylage	6	1	5	8
Corn silage	4	1	3	6
Triticale silage (n = 4)	10	4	5	15
Manure	74	32	32	124
Feces	65	22	32	86
Urine	0.1	0.1	ND[2]	0.2
Separator solids	646	970	35	2,761[3]
Zinc, mg/kg				
Lactating cow diets[1]	109	35	54	151
Alfalfa hay	21	3	17	26
Alfalfa haylage	28	6	24	39
Corn silage	20	4	15	25
Triticale silage (n = 4)	38	14	22	56
Manure	156	43	98	232
Feces	275	41	207	316
Urine	1.4	0.2	1.1	1.7
Separator solids	141	24	108	184

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

[2]ND = not detected.

[3]This extremely high Cu level was due to $CuSO_4$ being used in footbaths at one dairy. This dairy was excluded from the Cu surplus analysis (Table 5) because data for $CuSO_4$ imports were not collected.

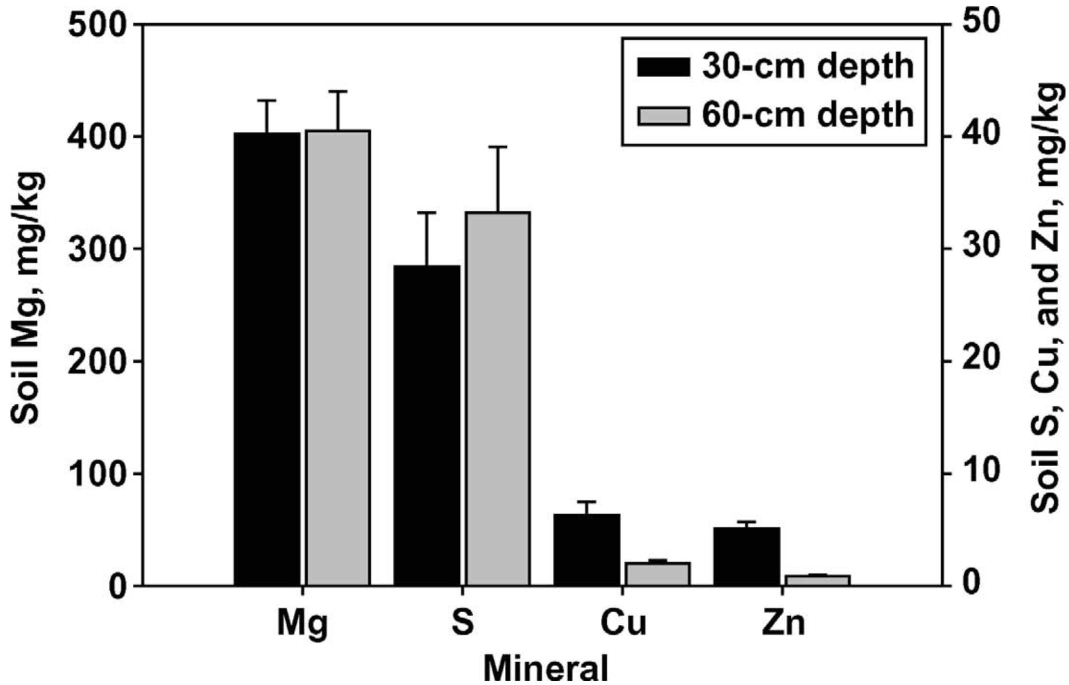

Figure 1. Average (n = 6) and standard errors of soil Mg, S, Cu, and Zn concentrations in manure-amended soils from participating dairies. Soil Mg levels did not differ between the spring and fall samples: 390 and 426 mg/kg, SE = 26.9, $P = 0.120$ (30-cm sample) and 399 and 422 mg/kg, SE = 28.7, $P = 0.303$ (60-cm sample). Soil S levels did not differ between the spring and fall samples: 30 and 28 mg/kg, SE = 3.6, $P = 0.673$ (30-cm sample) and 32 and 26 mg/kg, SE = 3.9, $P = 0.274$ (60-cm sample). Soil Cu levels did not differ between the spring and fall samples: 6.7 and 9.0 mg/kg, SE = 2.22, $P = 0.401$ (30-cm sample) and 2.3 and 2.9 mg/kg, SE = 0.61, $P = 0.459$ (60-cm sample). Soil Zn levels did not differ between the spring and fall samples: 4.9 and 5.2 mg/kg, SE = 0.57, $P = 0.596$ (30-cm sample) and 0.9 and 1.2 mg/kg, SE = 0.19, $P = 0.202$ (60-cm sample).

0.673) in the average Mg, S, Cu, and Zn concentrations between the spring and fall soil samples.

Whole-Farm Mg Imports and Exports

Table 3 depicts Mg imports, exports, and whole-farm Mg surplus for the dairies participating in this study. Magnesium imported with feedstuffs was the major import to the farm; on average, 94% of all Mg imports. Only the dairy that grew a large amount of forages (dairy F) imported Mg with fertilizer (3.6% of the total Mg imports). The average Mg imported with purchased animals was low (0.2% of the total) and some dairies did not import any animals during the study period. All dairies imported straw for bedding and Mg imports with this item represented, on average, 5.5% of all Mg imports.

The average proportion of Mg exported as milk from the participating dairies was 8.6% of all Mg exports. The estimated whole-farm milk Mg efficiency (milk Mg exports ÷ feed Mg imports) was 5.6%. The average proportion of Mg exported with animals (sold or culled) was 0.7% of all exports. In all dairies, manure was the largest Mg export, on average 80% of the total. Dairy F, however, utilized all of the manure produced for its own crop production. With this dairy, the major Mg export item was forages, 91% of all exported Mg. 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 Mg exported as forages was 10.7% (of the total Mg exports).

The average whole-farm Mg surplus was 16 t/yr, but varied significantly among the dairies. The average efficiency (Mg output ÷ Mg input) of use of Mg imported to the farms was 67%. The most efficient dairy in this study had Mg efficiency of 88% and the least efficient dairy had Mg efficiency of 27%. The dairy with the lowest Mg efficiency was a large 2,800-cow dairy and had the lowest proportion of manure Mg exported from the farm of the total Mg exports (72% compared with 89 to 94% for all other farms except dairy F).

Whole-Farm S Imports and Exports

Similar to the Mg imports and exports data, S imported with feedstuffs was the major S import to the farm in this study; on average 91% of all S imports (Table 4). The proportion of S imported with fertilizer

Table 3. Averaged whole-farm Mg imports and exports (t/yr, unless specified otherwise; n = 5)

Item	Average	SD	Minimum	Maximum
Imports				
Feeds	37.5	26.4	15.4	71.7
Fertilizer, kg/yr[1]	704	—	—	—
Animals, kg/yr	78	144	0	335
Bedding	2.2	0.9	0.9	3.4
Exports				
Milk	2.1	1.5	1.0	4.5
Feeds	2.6	5.0	0	11.6
Manure	19.4	19.3	0	51.8
Animals, kg/yr	158	114	55	307
Produced with forages on the farm	7.5	9.5	0.5	23.6
Total imports	39.9	26.5	19.5	74.3
Total exports	24.3	17.4	12.6	54.9
Overall surplus	15.6	21.5	3.6	53.9
Surplus per 1,000 kg of milk produced, kg/yr	0.9	0.6	0.4	1.8
Surplus per cow, kg/yr	9	6	3	19
Efficiency,[2] %	67.1	24.0	27.4	87.7

[1]Only one dairy, dairy F, imported Mg with fertilizer (704 kg/yr).

[2]Efficiency = (total exports ÷ total imports) × 100.

was low (or zero) on most of the dairies, including dairy F (9% of the total S imports). The average S imported with purchased animals was 0.6% of the total S imports. Sulfur imports with bedding straw represented on average 3.9% of all S imports.

The average proportion of S exported as milk from the participating dairies was 25% of all S exports. The estimated whole-farm milk S efficiency (milk S exports ÷ feed S imports) was 11%. The average proportion of S exported with animals was 2.9%. Similar to Mg, manure was the major S export item on all dairies; the average S exported with manure was 60% of the total S exports. The average proportion of S exported as feed (forages) was 16% (of the total S exports) and varied considerably among the dairies. Dairy F exported 81% of its S as forages and only 16% as milk.

The average whole-farm S surplus was 25.6 t/yr and varied significantly among the dairies. The average efficiency (S output ÷ S input) of S imported to the farms was 44%. The most efficient dairy in this study had S efficiency of 57% and the least efficient dairy had S efficiency of 27%. The dairy with the lowest S efficiency also had the lowest Mg efficiency. This dairy was exporting only 0.9 t of S/yr with forages produced on the farm and, similar to Mg, had significantly lower than the average proportion of manure S exported from the farm of the total S exports (43% compared with 76% on average for all dairies).

Table 4. Averaged whole-farm S imports and exports (t/yr, unless specified otherwise; n = 5)

Item	Average	SD	Minimum	Maximum
Imports				
Feeds	39.2	23.4	19.2	68.9
Fertilizer	1.9	2.9	0	6.5
Animals, kg/yr	248	462	0	1,071
Bedding	1.7	0.7	0.7	2.6
Exports				
Milk	4.3	3.0	1.9	9.1
Feeds	2.8	4.6	0	9.7
Manure	10.4	10.5	0	28.1
Animals, kg/yr	507	366	175	983
Produced with forages on the farm	7.3	9.5	0.5	23.7
Total imports	43.1	25.1	20.6	71.0
Total exports	17.4	10.1	10.1	34.5
Overall surplus	25.6	18.0	9.0	52.1
Surplus per 1,000 kg of milk produced, kg/yr	1.9	0.9	1.0	3.4
Surplus per cow, kg/yr	19.9	11.7	11.9	40.3
Efficiency,[1] %	43.5	12.3	26.6	56.7

[1]Efficiency = (total exports ÷ total imports) × 100.

Table 5. Averaged whole-farm Cu imports and exports (kg/yr, n = 4)[1]

Item	Average	SD	Minimum	Maximum
Imports				
Feeds	142.5	86.8	18.8	205.7
Animals	0.03	0.04	0	0.09
Bedding	9.4	4.6	3.6	14.4
Exports				
Milk	2.0	1.7	1.0	4.5
Feeds	7.7	9.6	0	20.8
Manure	82.7	80.0	0	192.3
Animals	0.3	0.2	0.1	0.7
Produced with forages on the farm	16.1	19.4	1.1	43.9
Total imports	152.0	83.7	33.2	216.9
Total exports	92.7	72.3	22.0	193.5
Overall surplus	59.2	59.9	10.1	133.8
Surplus per cow	0.05	0.04	0.01	0.11
Efficiency,[2] %	61.6	25.1	38.3	95.0

[1]One dairy that was using $CuSO_4$ in footbaths was excluded from the Cu surplus analysis because data for $CuSO_4$ imports were not collected.

[2]Efficiency = (total exports ÷ total imports) × 100.

Whole-Farm Cu Imports and Exports

Whole-farm Cu surplus analysis was done on 4 dairies only; one dairy, which was using $CuSO_4$ in footbaths, was excluded from the analysis because data for $CuSO_4$ imports were not collected. As with Mg and S, Cu imported with feedstuffs was the major Cu import to the farms, on average 94% of all Cu imports (Table 5). Copper imported with purchased animals was insignificant and imports of Cu with bedding straw were on average 6.2% of all Cu imports.

Due to the low Cu content of milk, the average proportion of Cu exported as milk from the participating dairies was only 2.1% of all Cu exports. The estimated average milk Cu efficiency (milk Cu exports ÷ feed Cu imports) was 1.4%. The average proportion of Cu exported with animals was insignificant for all dairies. For all dairies, manure was the main Cu export item; the average Cu exported with manure was 89% of the total Cu exports. As with the other minerals, dairy F did not export any Cu with manure, but was exporting a large amount of Cu with the forages produced on the farm: 95% of all Cu exports.

The average whole-farm Cu surplus was 59 kg/yr and, as with Mg and S, varied significantly among the dairies. The average efficiency (Cu output ÷ Cu input) of Cu imported to the farms was 62%. The most efficient dairy (95% efficiency) imported 200 kg of Cu/yr and exported 192 kg of Cu/yr with manure and approximately 1 kg of Cu/yr with milk. The Cu efficiency for dairy F was 66% because all manure was retained on the farm. The dairy with the lowest Cu efficiency (38%) imported 206 kg of Cu/yr with feeds and exported only 69 kg/yr with manure and 9 kg/yr with forages.

Whole-Farm Zn Imports and Exports

Zinc imported with feedstuffs was the major Zn import to the farms; on average 97% of all Zn imports (Table 6). Like Cu, Zn was not imported with fertilizer to the farms. Zinc imported with purchased animals was only 0.3% of all imports and Zn imports with bedding represented on average 2.3% of all Zn imports.

The average proportion of Zn exported as milk from the participating dairies was 11% of all Zn exports. The estimated average milk Zn efficiency (milk Zn exports ÷ feed Zn imports) was 5.2%. The average proportion of Zn exported with animals was only 1.5% of all Zn exported off the farm. As with the other minerals studied, manure was the main Zn export item. The average Zn exported with manure was 82% of the total Zn exports. For dairy F, the main export item was feed as 76% of the Zn leaving the farm was with the forages. Two other dairies also exported smaller amounts of forages (3 and 21 kg of Zn/yr) and exports of Zn with forages sold off the farm were 0.8 and 4.2% of all Zn exports.

The average whole-farm Zn surplus was 585 kg/yr, ranging from 48 to 1,825 kg/yr. The average efficiency of use of Zn imported to the farms was 56%. Dairy F, with its large export of Zn with forages (102 kg of Zn/yr) was the most efficient farm (74% efficiency). The dairy with the lowest Zn efficiency (40%) was a larger 2,368-cow dairy, which did not export any forages off the farm. Zinc exports with manure represented 92% of all Zn exports for this dairy. Compared with another dairy of similar size (2,807 cows), this dairy had lower average milk production and exported less Zn with milk (73 vs. 121 kg/yr, respectively).

Table 6. Averaged whole-farm Zn imports and exports (kg/yr, n = 5)

Item	Average	SD	Minimum	Maximum
Imports				
Feeds	1,076	1,107	143	2,986
Animals	3	5	0	12
Bedding	25	11	10	38
Exports				
Milk	57	40	26	121
Feeds	25	43	0	102
Manure	428	408	0	1,107
Animals	8	6	3	16
Produced with forages on the farm	58	75	3	187
Total imports	1,104	1,110	181	3,022
Total exports	519	401	134	1,197
Overall surplus	585	711	48	1,825
Surplus per cow	0.4	0.3	0.1	0.8
Efficiency,[1] %	55.9	12.6	39.6	73.7

[1]Efficiency (total exports ÷ total imports) × 100.

DISCUSSION

Similar to our previous data for N, P, and K (Hristov et al., 2006) and published research by others (Spears et al., 2003a,b; Cerosaletti et al., 2004), the major import item for all studied minerals was feed. Unlike N and P (milk efficiency of 21% for N and 26% for P; Hristov et al., 2006), the conversion of the imported feed Mg, S, Cu, and Zn into milk was rather inefficient (on a whole-farm scale): 5.6, 11, 1.4, and 5.2%, respectively. The bulk of the exported minerals left the dairy with the manure (from 60% for S to 89% for Cu). Part of the reason for this high manure export rate is the relatively low efficiency of utilization of trace minerals in livestock. As indicated earlier, availability of Mg, Cu, and Zn from natural feedstuffs is low in dairy cows. Thus, absorption efficiency of Mg varies from 11 to 37%, that of Zn is set at 15%, and absorption efficiency of Cu is between 1 and 5% (NRC, 2001). Inorganic sources of these minerals are readily available, but absorption efficiencies vary dramatically: from 5% for Cu from $CuSO_4$ through 12% for Zn from ZnO, to 70% for Mg from MgO (NRC, 2001). Dietary requirements for S are requirements for S-amino acids and microbial protein synthesis in the rumen (NRC, 2001; Underwood and Suttle, 2001). Sulfur from microbial protein is readily absorbable, but elemental S is much less available for absorption (NRC, 2001). The requirements for these minerals would also greatly depend on interactions with other minerals in the diet and, in the case of S, on the availability of N for synthesis of microbial protein (Underwood and Suttle, 2001).

It is obvious from the present data that the efficiency of utilization of imported Mg, S, Cu, and Zn is rather low and significant amounts are excreted with manure, which, in the case of Cu, has increased Cu levels of manure-amended soils to nearly 3 times the average for the region. Dairies involved in this study were feeding dietary Mg, S, Cu, and Zn above NRC (2001) recommendations: 0.37 vs. 0.2% of DM, Mg; 0.25 vs. 0.2%, S; 21 vs. 15.7 mg/kg DM, Cu; and 109 vs. 63 mg/kg, Zn. The NRC requirements for dietary minerals are adequate and additional increase is unnecessary and certainly undesirable environmentally. It also has to be kept in mind that the requirements for some minerals might be overestimated in the current NRC (2001). For example, little or no animal response was obtained by dietary S levels above 0.1 to 0.15% (DM basis; ARC, 1980), but the NRC (2001) requirement for S was set at 0.2%, which represents a 33 to 100% increase.

Williams et al. (1999) suggested 5 general approaches to reducing mineral emissions from industrial livestock facilities. Among these, reducing the total amount of minerals in the ration (thus, minimizing their concentration in manure) and improving the efficiency of animal mineral use are clearly the most feasible (Ferket et al., 2002; Mateos et al., 2005). It is unlikely, however, that the efficiency of absorption of dietary minerals can be significantly increased. Thus, it appears that reduction in the concentration of dietary minerals, including Mg, S, Cu, and Zn, could be a relatively easy and efficient way of reducing overall excretions and whole-farm surpluses of these minerals. Experiments with pigs demonstrated that reductions in dietary trace element concentrations could profoundly affect the levels of these minerals in manure. For example, a reduction in Zn content in piglet diets from 3,000 to 150 mg/kg reduced the concentration of Zn in the slurry from 1,860 to 450 mg/kg (Mateos et al., 2005). Dietary manipulations have also been successful in reducing excretion of environmentally important nutrients such as P (Valk et al., 2000; Wu et al., 2000; Cerosaletti et al., 2004; Hristov et al., 2006) and N (Kebreab et al., 2001; De

Boer et al., 2002; Olmos Colmenero and Broderick, 2006). In pasture systems, provision of available energy to the diet decreased urinary and fecal losses of several minerals, including Mg (Berry et al., 2001). Thus, reduction of dietary mineral levels and more precise formulation of animal mineral requirements remains the strategy most likely to succeed in reducing macro- and micromineral excretions from livestock operations.

CONCLUSIONS

Feed was the major import route of Mg, S, Cu, and Zn on commercial dairy farms in Idaho, representing from 91 (S) to 97% (Zn) of all imports. Imports of these minerals with fertilizer, animals, and bedding were insignificant. Concentrations of Mg, Cu, and Zn in lactating cow diets from the participating dairies exceeded NRC (2001) recommendations on average by 85, 34, and 73%, respectively. The excess minerals were excreted in manure, which was the major export item for all minerals studied. Forage sold off the farm was a major export route for one dairy that was a mixed crop/animal operation. On a whole-farm scale, the efficiency of utilization of imported feed Mg, S, Cu, and Zn for milk production was rather low and significant amounts were excreted with manure, which, in the case of Cu, resulted in increased Cu levels of manure-amended soils. We conclude that reduction in the concentration of dietary Mg, Cu, and Zn is the most efficient way of reducing overall excretions and whole-farm surpluses of these minerals.

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