

Whole-Farm Nitrogen Balance on Western Dairy Farms¹

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ABSTRACT

Environmental legislation has made it necessary for livestock producers to be able to quantify and adjust the N balance on their farms. Whole-farm N balance and efficiencies were computed for 41 commercial dairies in Utah and Idaho using the University of Maryland Nutrient Balancer. The average N balance, or unaccounted for N, was 81 tonnes per year for the average herd size of 466 cows with 35.8% of the inputs accounted for in the outputs. The major inputs for farms that grew crops ($n = 23$, herd size = 284 total cows) were imported feed (57.4% of all inputs) and nitrogen fixation (30% of inputs). The major outputs were animal products (primarily milk and some meat, 80% of outputs). For farms that grew no crops ($n = 18$, herd size = 700 total cows), 98% of the inputs were from imported feed. Of the outputs, 57% of the N was in animal products and 42.9% in manure and compost. Whole-farm balance per product for those farms that grew crops was most affected by herd N utilization efficiency (kg feed N per kg product N), crop N utilization efficiency, and availability of manure N applied to crops, while manure N storage efficiency was of lesser importance. For farms that grew no crops, whole-farm N balance per product was most affected by herd N utilization efficiency and manure N storage efficiency. Maximizing conversion of feed N to product N was the best way to reduce whole-farm N balance.

(Key words: nitrogen balance, commercial dairies, western United States)

Abbreviation key: CNMP = comprehensive nutrient management plan, HNUE = herd nitrogen utilization efficiency, MNSE = manure nitrogen storage efficiency.

INTRODUCTION

The dairy industry, as well as other livestock enterprises, has been identified as a potential contributor to point and nonpoint source environmental pollution. It has been reported for the U.S. (Howarth et al., 2002) and Europe (van Egmond et al., 2002) that the main sources of reactive N in the environment are fertilizers and manure. The N in urine (more than half of the total N excreted) is quickly converted into ammonia by urease in the environment (Tamminga, 1992). Ammonia may be volatilized to the atmosphere and subsequently transferred through several environmental reservoirs contributing to reduced atmospheric visibility and particle matter, soil acidity, nitrate pollution of ground water, and eutrophication of streams, lakes, and estuaries (Galloway et al., 2002). Ammonia in soil is converted into nitrate ($\text{NO}_3\text{-N}$) that may leach into the groundwater or runoff into surface water as well as provide fertilizer for crops (Tamminga, 1992; Nelson, 1999). Concern arises regarding the N content in manure and its effects on groundwater, surface water, and air as it leaves the farm (Koelsch and Lesoing, 1999). In an effort to curb the detrimental effects of these potential environmental contaminants, the USDA and EPA have established that most animal feeding operations must develop a comprehensive nutrient management plan (CNMP) (US Department of Agriculture, 1999). It is difficult to measure the various N losses from farms on a routine basis, and strategies to control one type of loss (e.g., volatilization) often lead to increases in a different loss (e.g., leaching). Thus, whole-farm N balance (total farm N inputs minus N exports in products) is often considered as a means to estimate unaccounted for N that can become a hazard to the environment (Kohn et al., 1997). When this method effectively reduces whole-farm N balance, it not only benefits the producer from an environmental standpoint, but may also help producers comply with new environmental regulations.

Several researchers have examined ways of lowering overall farm N balance (Aarts et al., 1992; Dou et al.,

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1996; and Kohn et al., 1997). One method of lowering excess N produced on the farm is by ration manipulation so that protein in the ration is utilized more efficiently, thereby reducing potential N loss (Van Vuuren et al., 1993; Van Horn et al., 1994; Vagnoni and Broderick, 1997). If this method could effectively reduce whole-farm N balance, it would not only benefit the producer from an environmental standpoint, but could also favorably improve dairy economics.

A spreadsheet model called the Maryland Nutrient Balancer (Kohn, 2001), based on the same principles as the worksheets developed by Dou et al. (1996, 1998), was developed to account for whole-farm N and P balances by quantifying all forms of N and P coming onto the farm as well as leaving the farm. By tracking N from the time it comes onto the farm to when it leaves, producers gain a better understanding of whole-farm N dynamics. This spreadsheet allows producers to determine the nutrient balance and also to look at "what if" scenarios for making management decisions.

Most of the research conducted on whole-farm N balance has been done with either computer models (Aarts et al., 1992; Kohn et al., 1997; Kuipers et al., 1999; Wang et al., 2000) or case studies involving 1 (Bacon et al., 1990; Dou et al., 1996; Van Horn et al., 1996; Klausner et al., 1998) or 2 dairies (Dou et al., 1998) and none have been carried out in the western United States. Koelsch and Lesoing (1999) reported whole-farm balances for 33 beef and swine confinement livestock operations in Nebraska, but no dairy. There is a need to better understand factors that affect N balance on dairy farms.

The objectives of this study were to: 1) determine whole-farm N balance of commercial dairies in the Intermountain West, and 2) determine the relative contributions of the herd, manure storage, and crop production components to differences in whole-farm N balance. The P balance of these same farms is the focus of a companion paper (Spears et al., 2003).

MATERIALS AND METHODS

Data and Sample Collection

Data were collected from 41 dairy farms (34 farms with Holstein and 7 farms with Jersey cows as the predominant breed) selected from 7 counties in Utah and 6 counties in Idaho. Farms were selected from counties that had at least 5000 dairy cows (Idaho Agricultural Statistics Service, 1999; Utah Agricultural Statistics Service, 1999). Within each county, producers were identified who were members of the DHI and willing to cooperate in the study. On 23 farms, one or more crops were grown, while on 18 farms all feedstuffs were purchased. Farms that grew crops bought 1.3 to 92.8%

of their feed and used 5 to 100% of their manure on-farm, while farms that did not grow crops exported all their manure.

Producers were initially contacted by phone, and then sent a letter outlining their involvement in the project. Producers were subsequently interviewed face-to-face to collect the information needed for the Maryland Nutrient Balancer (Kohn, 2001). The program was used to create a whole-farm N balance for each farm. Feed data were gathered from producer records which included actual receipts, ration sheets, and nutritional information directly obtained from their consultant. Tons of feed and fertilizer purchased was converted to tons of N using actual feed CP content and fertilizer N analysis provided by the farmer, when available, or using National Research Council (2001) values for feed when no analysis was available. Tons of crops grown and sold were also collected from the dairy farmer and converted to tons of N. All analysis of data was done on a DM basis. Required inputs were: tons of purchased feed and fertilizer, tons of crops grown and sold, number of cows purchased and sold, tons of manure exported and its N and P content, and annual milk weights sold. Production characteristics such as milk protein percentage (CP), rolling herd average milk, and cow and heifer numbers were also required inputs. An average number of animals for the whole year were used to determine the number of cows and heifers. Only one dairy contracted all heifer raising off-farm.

Nutrient inputs and outputs were reported for all farms for January through December 1999 except for one farm that underwent a major change of focus in 1999. The time period of June 1999 through May 2000 was reported for this farm. This farm was left in the analysis because the data included a complete year, overlapped 6 mo of the collection period for the other farms, and analysis could not detect it as an outlier. All other farms changed little during the data collection period. Farm information and manure samples were collected in the summer and fall of 2000 in order to have complete information for the 1999 year.

Five to 10 subsamples of stored manure (the number varying depending on farm size) were randomly collected from each storage facility on each farm and combined into a composite sample. Samples of manure in piles were taken from 6 to 8 inches into the pile at various sites ($n = 3$ to 5 samples per pile) in order to obtain a representative sample. Samples were immediately frozen and stored for later analysis of N content. Total tons of manure coming out of storage were estimated from Natural Resources Conservation Service values (U.S. Department of Agriculture-NRCS, 1992) and combined with the N concentration of the manure

Table 1. Calculations used by the Maryland Nutrient Balancer program.

Efficiency	Calculation
N inputs, kg	Imported feed N + imported bedding N + imported animals N + imported fertilizer N + legume fixation N
N outputs, kg	N in animal products + N in cash crops + N in exported manure and compost
Whole-farm N balance (or actual unaccounted N), kg	Total N input—total N output (a lower balance represents less unaccounted for N)
Herd N utilization efficiency	Kg N in product (milk and meat)/Kg N in feed
Manure N produced, kg	Animal N intake—N in animal product (milk and meat)
Manure N storage efficiency	Total kg manure N that is exported from farm or applied to crops/manure N produced
Manure N available to crop, kg	Kg manure N applied—N field loss (% loss to volatilization due to timing of incorporation into soil and frequency and seasonality of application. Range is from 20 to 88%)
Availability of applied manure	Manure N available to crop/manure N applied
Crop N utilization efficiency	Total N in crop/Total N available to crop (sum of available manure and fertilizer N)
Manure N applied, kg	Manure N stored + imported manure N (no farms imported in this study)—exported manure N

so that total tonnes of N coming out of storage could be compared with the amount going into storage.

Laboratory Procedures

Stored manure samples were analyzed for DM by drying in a forced air oven at 60°C, ground through a 1-mm mesh screen in a Wiley Mill, then further dried at 105°C. The DM content was then determined based on final weight of the sample (AOAC, 1984). Samples dried at 60°C were analyzed for N by the combustion method (AOAC, 1996) using a Carlo Erba Elantech NA 2100 Protein Nitrogen Analyzer (ThermoQuest, Italia S.p.A., Milan, Italy). Nitrogen content on an absolute DM basis was used in data analysis.

Calculations Within the Maryland Nutrient Balancer

The Maryland Nutrient Balancer (Kohn, 2001) calculated summaries and several efficiencies that were used in later analysis. These efficiencies and the methods used to calculate them are shown in Table 1.

Statistical Analysis

The data were analyzed as a completely randomized design with individual farm as the experimental unit. Descriptive statistics were analyzed from participating herds. All whole-farm N balances were converted to a per kilogram of milk and meat N basis (balance per product) prior to analysis to eliminate the effect of farm size on farm balance. A multivariate regression model was developed with whole-farm N balance per product as the dependent variable and herd nitrogen utilization efficiency (**HNUE**), manure nitrogen storage efficiency (**MNSE**), and crop N utilization efficiencies (Table 1)

as independent variables. Univariate regression models with whole-farm N balance per product regressed on HNUE, MNSE, whole-farm P balance per product (Spears et al., 2003), imported feed per product, milk production, herd size, manure exported per product, imported fertilizer per product, total N available to crop, total crop N, availability of manure N applied, and uptake of available N were analyzed to determine the relative importance of the components of each subsystem. Herd N utilization efficiency had the greatest impact on whole-farm N balance per product, therefore, factors influencing HNUE were analyzed further. Univariate regression of the dependent variable of HNUE was performed on the independent variables of herd P utilization efficiency (Spears et al., 2003), milk production per cow, herd size, and imported feed per product. Breed of cow did not significantly affect dependent variables; therefore, herds from both breeds were combined in the analyses. Regression analysis and ANOVA were performed in SAS (1996) using Proc GLM. Variables considered to be significantly different ($P < 0.05$).

RESULTS AND DISCUSSION

Description of Farms

Herds involved in the study provided a wide range of measured variables and, therefore, calculated efficiencies (Tables 2 and 3). Milk production per cow ranged from 3402 kg/year to 13,864 kg/year with an average of 10,254 kg/year, well above the year 2000 national average of 8276 kg/year (National Agricultural Statistics Service, 2001), and consistent with the average (10,143 kg/year) for herds in this region (Rocky Mountain DHIA Annual Summary, 2000). Herd size ranged from 57 cows to 1960 cows and averaged 466

Table 2. Summary of selected variables for farms that grew any crops (n = 23).

Parameter	Mean	SD	Minimum	Maximum
Total herd size of cows	284	297	57	1450
Herd size of heifers	242	233	35	1125
Milk production, kg per cow	9,732	2,405	3,402	12,659
Milk protein, %	3.33	0.293	2.90	4.02
Herd N utilization efficiency ¹	0.203	0.052	0.126	0.362
Manure storage efficiency ²	0.357	0.144	0.064	0.659
Crop N utilization efficiency ³	1.140	0.288	0.386	1.752

¹Kg N in product (milk and meat)/kg N in feed.

²Total amount of manure N that is exported from farm or applied to crops/N in excreted manure (calculated by mass balance equation that is N in feed–N in product).

³Total N in crop/Total N available to crop (sum of available manure and fertilizer N).

cows. Herd N utilization efficiency ranged from 0.126 to 0.362 with an average of 0.213, suggesting that 21.3% of all N fed to the herd (cows and replacement heifers) was converted into either milk or meat N based on the law of mass conservation used by the Balancer to make this calculation. Close to half of the farms in this study (44%) imported all feed.

Farms were further divided into those that grew any crops (Table 2) and those that grew no crops (Table 3). Farms that grew crops averaged 284 cows with a range of 57 to 1450 cows. Milk production averaged 9732 kg/cow per year with a range of 3402 to 12,659 kg/cow per year. Average HNUE was 20.3%, MNSE was 35.7% and crop N utilization was 114%. For farms that grew no crops, average herd size was 700 cows with a range of 62 to 1960. Milk production averaged 10,922 kg/cow per year with a range of 6568 to 13,864 kg/cow per year. Average HNUE was 22.5%, MNSE was 26.4%, and crop N utilization efficiency was 0.0 (no crops were grown). The average HNUE for farms that grew no crops was about 2% higher and the MNSE was about 9% lower ($P = 0.063$ for difference between the two groupings) than farms that grew crops.

Whole-Farm N Balance

Whole-farm N balance for dairies in the West was consistent with other studies in that imported feed was

the single largest N input and animal products, milk and meat, were the largest source of output (Table 4). Farms that grew crops had inputs from fertilizer for crop application and legume fixation from alfalfa that were not present for those farms that grew no crops. Those farms that grew no crops had 98% of their inputs as imported feed because they had no need for fertilizer and had no crops for legume fixation. These farms also exported a greater amount of manure and compost because they had little or no land for application. Herd size was significantly larger for those farms that grew no crops, but on a per animal basis, there was little difference in whole-farm N balance between the two groups.

Average whole-farm N balance for all farms, expressed as tonnes of N per year, is shown in Table 4. Our results show a positive whole-farm N balance, indicating that more N is coming onto farms than is being accounted for in the sale of product (mostly milk, some meat), exported crops, and exported manure. Previously reported whole-farm N efficiencies (N in total outputs divided by N in total inputs $\times 100$) ranged from 15% (Aarts et al., 1992) to 46% (Bacon et al., 1990). The average whole-farm N utilization efficiency (output/input) for the farms in this study was 35.8%. This means that 64.2% of the N coming onto the farm could not be accounted for in product, cash crops or compost and manure. A large portion of this N was probably lost

Table 3. Summary of selected variables for farms that grew no crops (n = 18).

Parameter	Mean	SD	Minimum	Maximum
Herd size of cows	700	586	62	1960
Herd size of heifers	404	396	0	1400
Milk production, kg per cow	10,922	2,047	6,568	13,864
Milk protein, %	3.27	0.295	2.90	3.85
Herd N utilization efficiency ¹	0.225	0.041	0.168	0.290
Manure storage efficiency ²	0.264	0.168	0.060	0.680
Crop N utilization efficiency ³	0.0	0.0	0.0	0.0

¹Kg N in product (milk and meat)/kg N in feed.

²Total amount of manure N that is exported from farm or applied to crops/N in excreted manure (calculated by mass balance equation that is N in feed–N in product).

³Total N in crop/Total N available to crop (sum of available manure and fertilizer N).

Table 4. Average whole-farm N balance per farm, expressed as tonnes of N/year, as calculated by the Maryland Nutrient Balancer (n = 41). Average herd size was 466 cows and milk production was 10,254 kg/cow per year. Nitrogen balance is the difference between inputs and outputs.

Variable	Average	SD	Minimum	Maximum
Nitrogen inputs	125.83	134.33	12.66	670.71
Imported feed	105.99	134.56	4.49	659.86
Imported bedding	1.31	2.19	0.00	12.80
Imported animals	0.89	2.10	0.00	8.85
Imported fertilizer	4.85	10.51	0.00	63.40
Legume fixation	12.81	21.01	0.00	89.54
Nitrogen outputs, kg	45.01	55.50	5.42	240.97
Animal products	28.48	30.68	3.25	119.90
Cash crops	1.04	3.35	0.0	18.42
Manure/compost	15.49	30.06	0.0	148.63
N balance (potential loss)	80.84	85.98	6.40	455.17
Output/input, %	35.8			

through volatilization and represents a major portion of the N flow on these dairies. Loss of N through volatilization needs to be controlled as more states begin to enact laws regarding odor from dairies. In addition, a source of N loss could be the drying step used to analyze manure samples. Heating the sample would volatilize any remaining ammonia N and underestimate the N content of the sample. This loss may or may not be significant because most of the ammonia may have all ready volatilized before the sample was taken (R. Kohn, personal communication). Also, none of the dairies incorporated manure in less than 7 d. This would have allowed any remaining ammonia to no longer be available for crops. The values in this paper are based on the assumption that minimal amounts of N were lost due to drying the sample prior to analysis.

One problem with comparing efficiencies between studies is that not all studies use the same categories for inputs and outputs. For example, the farm analyzed by Bacon et al. (1990) showed a high whole-farm N

utilization efficiency, but they did not make allowance for N-fixation by legumes.

Average whole-farm N balance was then subdivided and computed separately for farms that grew crops and those that did not (Table 5) because the amount of land base for crops can affect interpretation of whole-farm N balances. Most of the farms reported in the literature were small dairies with sufficient land to have an outlet for manure produced on the farm (Dou et al., 1996; Van Horn et al., 1996; Klausner et al., 1998). Dairies in the western United States are unique because of larger herd size and the fact that many dairies include only enough land base to house the animals plus a buffer around the dairy (i.e., less than 0.4 ha per cow). On farms where crops were grown, total tonnes/year of unaccounted for N was less than on those farms where no crops were grown (Table 5), primarily due to differences in herd size. Increased inputs of N associated with crop production increased the total N balance on farms that grew crops and made the output/input percent on farms

Table 5. Average of whole-farm N balance per farm for those farms that grew crops (n = 23) and those farms that grew no crops (n = 18), expressed as tonnes N/year or kg N/animal, as calculated by the Maryland Nutrient Balancer. Nitrogen balance is the difference between inputs and outputs.

Variable	Grew crops		Grew no crops	
	tonnes per yr	kg per animal ¹	tonnes per year	kg per animal ¹
Nitrogen inputs	76.36	188.55	189.68	210.29
Imported feed	43.82	108.19	185.93	206.13
Imported bedding	0.75	1.86	2.02	2.24
Imported animals	0.23	0.57	1.74	1.93
Imported fertilizer	8.66	21.39	0.0	0.00
Legume fixation	22.88	56.50	0.0	0.00
Nitrogen outputs	21.81	53.85	74.87	83.01
Animal products	17.42	43.01	42.75	47.40
Cash crops	1.85	4.58	0.0	0.00
Manure/compost	2.54	6.26	32.12	35.61
N balance (potential loss)	54.54	134.68	114.82	127.29
Output/input, %	28.6	—	39.5	—

¹Animals includes cows plus half the number of heifers (i.e., 2 heifers = 1 cow).

Table 6. Multiple regression analysis results of whole-farm nitrogen (N) balance per kg N in milk and meat, for farms that grew at least one crop ($R^2 = 0.903$).

Factor	Estimate	SE	% SS	P-value
Intercept	10.5	0.577		<0.0001
Herd N utilization efficiency	-17.08	2.499	54.2	<0.0001
Crop uptake of available N	-2.02	0.377	33.4	<0.0001
Availability of manure N applied to crops	-3.29	1.237	8.2	0.016
Manure N storage efficiency	-1.80	0.944	4.2	0.073

that grew no crops better by 11%. The average herd size for farms that grew no crops was nearly 2.5-fold higher than for farms that grew crops, but when the data were corrected for number of animals per farm (Table 5), the amount of unaccounted for N was slightly higher per animal for farms that grew crops compared with farms that grew no crops. On a whole-farm basis, the higher positive N balance makes these farms a greater potential threat to the environment (especially odor) than those that grew crops. In this study, farms without crops typically had a larger herd size, higher milk production per cow, greater tonnes of manure exported, and no imported fertilizer or legume fixation.

Effects of Subsystems on Whole-Farm Balance/Product

A multiple regression analysis was used to determine the relative impact of the subsystems (herd, crops, and manure management) on whole-farm balance per product (tonnes unaccounted for N per tonne milk and meat N). The multiple regression analysis for farms that grew crops is shown in Table 6. A total of 90% of the variation in farm nitrogen balance was explained by the efficiencies of the farm components. Herd N utilization efficiency explained 54.2% and crop uptake of available N explained 33.4% of the observed variation. Estimated availability of manure N applied to crops and MNSE explained about 12% of the variation among farms. Even though MNSE was the least important of the subsystems in this model, it is still a significant factor when determining how to decrease whole-farm N balance per product (see Table 8). These results are in agreement with those of a sensitivity analysis on mod-

eled dairy farms reported by Kohn et al. (1997). Aarts et al. (1992) also found improving HNUE to be important in decreasing overall farm N balance. Wang et al. (2000) estimated that increasing forage yield by 50%, compared with yields from their base herd, would decrease whole-farm N mass balance by 29%. Paul et al. (1998) suggested that increasing HNUE not only decreased N in the manure, but the N might also be less susceptible to volatilization and more likely to be incorporated by crops. Again, results from this study support the concept that the most important method to improve whole-farm N balance is improved HNUE.

The multiple regression analysis of whole-farm N balance per product on farm subsystems for farms that did not grow crops is shown in Table 7. The model accounted for 97% of the variation in whole-farm N balance per product. Herd N utilization efficiency accounted for 50.6% and MNSE accounted for 49.4% of the observed variation. For farms that grew no crops, MNSE became more significant than for farms that grew crops because with no land base there were no sources of variability except for the N in manure and compost. In both farm groupings, HNUE accounted for a significant portion of the variation in whole-farm N balance per product.

On farms where crops were grown (Table 8), univariate regression analysis of whole-farm N balance per product with crop N utilization efficiency was correlated ($R^2 = 0.324$, $P = 0.005$; negative slope). It was also interesting that on some farms, crop N utilization efficiency was greater than 1.0, meaning N in the crop was greater than the N available for the crop as calculated by the program. We do not have enough data to determine the reason for this, but some possibilities are that N fixation

Table 7. Multiple regression analysis results of whole-farm nitrogen (N) balance per kg N in milk and meat for farms that did not grow any crops ($n = 17^1$; $R^2 = 0.97$).

Factor	Estimate	SE	% SS	P-value
Intercept	6.85	0.226	—	<0.0001
Herd N utilization efficiency	-14.32	0.938	50.6	<0.0001
Manure N storage efficiency	-3.41	0.226	49.4	<0.0001

¹One herd was excluded from the analysis because it was an outlier. The R^2 with that herd included was 0.841.

Table 8. Relationship of selected variables to whole-farm nitrogen (N) balance per kg N in milk and meat, for farms that grew at least one crop (n = 23) and farms that grew no crops (n = 18).

Independent variable	Grew crops		Grew no crops	
	R ²	P-value	R ²	P-value
Herd N utilization ¹	0.671 ⁴	<0.0001	0.493 ⁴	0.001
Manure N storage efficiency ²	0.423 ⁴	0.001	0.304 ⁴	0.018
Whole-farm P balance ³ /P product	0.142	0.076	0.254	0.033
Imported feed/product	0.213	0.026	0.488	0.001
Milk production/cow	0.005 ⁴	0.742	0.042 ⁴	0.412
Herd size	0.089 ⁴	0.168	0.026 ⁴	0.520
Manure exported/product	0.043 ⁴	0.341	0.240 ⁴	0.039
Imported fertilizer/product	0.065	0.239	—	—
Total N available crop	0.140	0.078	—	—
Total crop N	0.051	0.299	—	—
Availability of manure N applied	0.022 ⁴	0.496	—	—
Crop N utilization efficiency	0.324 ⁴	0.005	—	—

¹Kg N in product (milk and meat)/kg N in feed.

²Total amount of manure N that is exported from farm or applied to crops/N in excreted manure (calculated by mass balance equation that is N in feed–N in product).

³Kg P inputs–kg P outputs.

⁴Denotes relationship with a negative slope.

by legumes was underestimated (alfalfa is the principal crop in this region), or there was carryover of N in the soil from previous years that was unaccounted for. The program only looked at the balance for a single time period, not multiple years.

On farms where crops were not grown, exported manure per product was negatively correlated with whole-farm N balance ($R^2 = 0.24$, $P = 0.039$; Table 8). This makes sense because exported manure or compost is one of the few options available to these farms for improvement of whole-farm N balance. Koelsch and Lesoing (1999) proposed exporting manure as an efficient means of lowering farm N balance. Although this has been shown to lower whole-farm N balance, the N in the manure does not simply disappear when taken off farm. As noted by Kohn et al. (1997), caution must be taken not to see this as a quick fix. For a single herd that does not grow crops, this could be an effective way to balance a CNMP, but it could be a problem from a watershed perspective. Univariate regression analysis of MNSE with whole-farm N balance per product for farms that grew no crops was negatively correlated ($R^2 = 0.304$, $P = 0.018$; Table 8). Again, manure handling becomes important because they have fewer options and must make better use of the subsystems available to them.

Whole-farm P balance per product was correlated with whole-farm N balance per product for farms that grew no crops ($R^2 = 0.254$, $P = 0.033$; Table 8) and showed a trend ($P = 0.076$) for farms that grew crops. Many states are passing regulations based on soil P levels, rather than N levels and this study suggests that improvement in the whole-farm balance of one nutrient is associated with improvement of the other.

Herd N Utilization Efficiency

Herd N utilization efficiency was significantly related to whole-farm N balance per product for both farms that did and did not grow crops (Table 8); therefore, factors influencing HNUE were analyzed. When all dairies in this study were analyzed together, herd size was positively correlated with the HNUE ($R^2 = 0.11$, $P = 0.036$). Farms that had more than 500 cows (n = 14) had a significantly higher HNUE (23.5% SD = 4.2) than farms that had less than 500 cows (20.2% SD = 4.9) (n = 27). However, when the farms were analyzed based on whether a farm did or did not grow crops, there was no relationship between HNUE and herd size (Table 9), probably due to sample size. Larger farms appeared to be more consistent in converting feed N into product than smaller farms. Increased cow numbers may allow for better grouping strategies to be employed in herd management. St-Pierre and Thraen (1999) showed that optimal grouping strategy would increase herd efficiency by providing nutrients where they were most needed. The larger farms in this study did have increased numbers of groupings of cows compared with smaller farms. Interestingly, the number of heifers per farm was not related to whole-herd N balance or HNUE for farms that grew or did not grow crops (data not shown). However, for farms that did not grow crops, the ratio of heifers to cows per farm showed a trend relative to either whole-farm N balance per product ($P = 0.059$) or HNUE ($P = 0.051$; negative slope, Table 9). This is interesting because many dairies with little land base are considering contracting the raising of their heifers off-farm. This data suggests that reducing the number of heifers relative to the number of cows on a

Table 9. Relationship of selected independent variables to herd N utilization efficiency¹ for farms that grew at least one crop (n = 23) and farms that grew no crops (n = 18).

Independent variable	Grew crops		Grew no crops	
	R ²	P-value	R ²	P-value
Number of heifers per cow	0.032	0.415	0.217 ³	0.051
Herd size	0.103	0.135	0.068	0.296
Milk production/cow	0.099	0.143	0.281	0.024
Herd P utilization efficiency ²	0.539	<0.0001	0.186	0.074
Breed	0.015	0.583	0.046	0.393
Imported feed/product	0.097 ³	0.147	0.980 ³	<0.0001

¹Herd N utilization efficiency = N in product (milk and meat)/N in feed.

²Herd P utilization efficiency = P in product (milk and meat)/P in feed (Spears et al., 2003).

³Denotes relationship with a negative slope.

dairy would increase HNUE efficiency and decrease whole-farm N balance per product; both desirable goals.

There was also a positive correlation between HNUE and milk production ($R^2 = 0.281$, $P = 0.024$; Table 9) for farms that grew no crops, but no relationship for farms that grew crops. This may be a function of the slightly higher HNUE and milk per cow for farms that grew no crops compared to those farms that grew crops. It may also mean that for farms that grew no crops, maximizing conversion of feed N to product N left less N to be handled in manure and compost. Other studies have shown that increased HNUE was associated with a slightly negative relationship with milk yield (Dinn et al., 1998) or no relationship (Dhiman and Satter, 1997). Results from this study show that all herds that produced 13,000 kg/yr or more had HNUEs of close to 25% suggesting that a greater proportion of consumed N is being used for milk and meat and less for maintenance of the animal.

Herd P utilization efficiency (Spears et al., 2003) was correlated with HNUE ($R^2 = 0.539$, $P \leq 0.0001$; Table 9) for farms that grew crops, while farms that grew no crops showed a trend ($P = 0.074$). Although we cannot determine the reason for the difference between farms based on whether they did or did not grow crops, we suggest two possible explanations for why HPUE and HNUE might be related. The first may be related to the composition of milk. Wu et al. (2001) reported a positive relationship between milk protein and P concentrations. It was suggested that because phosphate bridges hold casein micelles in milk together, increased milk protein would require an increase in milk phosphorus, even though this form of P comprises only a small fraction of the total milk P. The second may be that rations properly balanced for P are likely balanced for protein. It is interesting to note that in a study where adjustments were made to lower whole-farm N balance (Bacon et al., 1990), whole-farm P balance was also decreased.

Imported feed N per product was not correlated with HNUE ($P = 0.147$; Table 9) for farms that grew crops, but was correlated ($R^2 = .98$, $P \leq 0.0001$; Table 9) with farms that did not grow crops. This is likely due to the fact that farms that grew crops only bought enough feed to supplement the amount grown on-farm while farms that grew no crops bought all of their feed. For farms that grew feed, legume fixation/product and imported N fertilizer/product were more important than imported feed/product.

CONCLUSIONS

Whole-farm N balance for dairies in the West was consistent with other studies in that imported feed was the single largest N input and animal products, milk and meat, were the largest source of output (Table 4). Farms that grew crops had inputs from fertilizer for crop application and legume fixation from alfalfa that were not present for those farms that grew no crops.

Multiple regression analysis showed that whole-farm N balance per product was associated with HNUE, crop N utilization efficiency, availability of manure N applied to crops, and MNSE for farms that grew crops. For farms that grew no crops, HNUE and MNSE were the most important subsystems. The most important subsystem on these dairies was how efficiently a cow converted feed N to product N and should be the first concern in lowering whole-farm N balance per product. After HNUE is optimized, the next subsystem to optimize is crop N utilization efficiency. Crop selection and N application methods most appropriate to the area of production should be considered for this subsystem. Manure handling should not overshadow herd and crop N efficiencies in attempts to improve N balances. Regulations should be based on some measure of performance such as nutrient balance rather than on the incorporation of specific technologies such as a certain manure storage system (Lanyon, 1994). Whole-farm N

balances are useful tools for evaluating N management on a dairy farm.

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