J. Dairy Sci. 84:1128–1139

Relationships Between Milk Urea Concentrations and Nutritional Management, Production, and Economic Variables in Ontario Dairy Herds

S. M. Godden,* K. D. Lissemore,† D. F. Kelton,†
K. E. Leslie,†
J. S. Walton,‡ and J. H. Lumsden,§
*Department of Clinical and Population Sciences,
University of Minnesota, St. Paul, MN, 55108
†Department of Population Medicine,
‡Department of Animal and Poultry Science,
and §Department of Pathobiology,
University of Guelph, Guelph, ON, N1G 2W1

ABSTRACT

The objectives of this study were to describe the relationships between milk urea concentrations and nutritional management, production, and economic variables in commercial dairy herds. Dairy Herd Improvement (DHI) test-day milk urea data, production data, and information on ration nutrient composition and feeding management programs were collected over a 13-mo period from 53 commercial Ontario dairy herds. Economic variables included gross milk revenue, feed costs, and income over feed costs. Herd mean milk urea concentrations had a positive relationship with dietary levels of crude protein (CP), rumen degradable protein (RDP), and rumen undegradable protein (RUP) and a negative relationship with dietary levels of nonfiber carbohydrates (NFC), forage:concentrate (F:C) ratio, NFC:CP ratio, and NFC:RDP ratio. These findings are consistent with experimental studies that used chemical methods of milk urea analysis. Herd mean milk urea concentration was not associated with feeding management (e.g., total mixed rations, component feeding, feeding frequency, or synchrony of forage and concentrate feeding).

Herd mean milk urea was not associated with either mean milk yield or linear score. Herd mean milk urea had a positive relationship with feed costs per cow per day but was not associated with gross milk revenue per cow per day. Herds with a high mean milk urea concentration tended to have lower income over feed costs per cow per day. High herd mean milk urea concentrations were associated with higher feed costs per kilogram of milk fat but lower gross milk revenue and lower income over feed costs per kilogram of milk fat. The results of this study demonstrate that DHI milk urea measurements produced by an infrared test method offer a useful tool for monitoring the efficiency of nitrogen utilization in commercial dairy herds. The results also suggest that diets may be balanced to achieve greater efficiency of nitrogen utilization, lower milk urea concentrations, and lower feed costs, while still achieving high milk production. This may lead to improved income over feed costs.
(**Key words:** urea, nutrition, production, economics)

Abbreviation key: F:C = forage:concentrate ratio, **IR** = infrared, **LS** = linear score, **MU** = milk urea (mmol/L), **NFC** = nonfiber carbohydrates, **SIP** = soluble intake protein, **SU** = serum urea (mmol/L).

INTRODUCTION

Considerable interest has developed in measuring urea concentrations as a way to monitor the efficiency of protein utilization in dairy herds. The early 1990s witnessed the commercial introduction of automated instrumentation that uses infrared (**IR**) spectrophotometric methods to estimate the concentration of urea in milk samples. Because individual cow milk samples are routinely collected by DHI field technicians, the use of IR technology by DHI laboratories offers a rapid and inexpensive means of measuring milk urea (**MU**) concentrations. However, information has been lacking for interpreting MU data, given the various sampling, cow (breed, parity, DIM), seasonal, herd management, and nutritional management factors that can all influence MU concentrations (Bruckental et al., 1989; Canfield et al., 1990; Carlsson et al., 1995; Ferguson et al. 1997a; Moller et al., 1993; Schepers and Meijer, 1998).

Received August 21, 2000.
Accepted December 21, 2000.
Corresponding author: S. M. Gooden; e-mail: godde002@tc.umn.edu.

Earlier research described much about the relationships between urea concentrations in serum and milk and nutritional management. Serum urea (**SU**) and MU concentrations have been shown to be sensitive to concentrations of dietary CP, RDP, RUP, and protein-to-energy ratios (Baker et al., 1995; Blauwiekel and Kincaid, 1986; Canfield et al., 1990; Carroll et al., 1988; DePeters and Ferguson, 1992; Howard et al., 1987; Kaim et al., 1983; Oltner and Wiktorsson, 1983; Roseler et al., 1993). However, most of these studies were performed with animals managed under research conditions, using SU measurements or chemical methods of MU analysis and interpreting data at the cow level. It has been recommended, both because of relative inaccuracies inherent in IR test results and because of large cow-to-cow variability in MU levels, that MU be interpreted at the group level, and not the individual animal level (Broderick and Clayton, 1997; Cannas et al., 1998; Godden et al., 2000a; Kolver and MacMillan, 1993; Oltner et al., 1985; Schepers and Meijer, 1998). To clinically validate the IR MU test, it needed to be determined if the same relationships between MU concentrations and nutritional management previously reported under experimental conditions would be observed under field conditions.

Another question that required study was that of the utility of MU testing. For this test to be useful to commercial producers, MU results should be associated with some economic measures or economically important biological effects, which are related to the efficiency of nitrogen utilization. It has been suggested that one of the benefits of the identification and correction of deficiencies, excesses, or imbalances in dietary protein and energy could be improved health and productivity of the animal. While several studies have reported a weak positive relationship (Carlsson et al., 1995; Oltner et al., 1985), others have reported either a negative relationship (Ismail et al., 1996), or no relationship (Baker et al., 1995; Carroll et al., 1988) between urea concentrations and milk production.

Another potential benefit of monitoring MU concentrations is that more efficient use of costly dietary protein could result in lower production costs and increased profitability. Roseler (1990) estimated a cost of $23,6000,000 ($0.09/cow per day) to the dairy industry in New York State because of feeding excess protein to dairy cows. He proposed a potential payback of between $0.01 and $3.96/cow per mo in feed savings from adjusting rations due to MU monitoring. Nelson (1995) projected a series of scenarios that would return $10.00 for each $1.00 invested in urea testing. However, these studies were based on estimates or projections. Field studies have been lacking that investigate the relationship between MU concentrations and efficiency of milk production.

The first objective of this study was to describe the relationship between MU concentrations and nutritional management of commercial dairy herds. The MU measurements were produced by IR analysis from routine DHI test-day milk samples and interpreted at the group level. The second and third objectives were to describe the relationship between herd mean MU concentrations and both milk production and economic variables, including gross milk revenue, feed costs, and income over feed costs. A fourth and final objective was to examine the relationship between nutritional management and economic variables, as a possible underlying explanation for the associations observed between MU and economic variables.

MATERIALS AND METHODS

Data Collection

Sixty commercial Holstein dairy herds were recruited to participate in a cost-of-production pilot project from December 1, 1995, to December 31, 1996. Participants were purposely selected to represent herds from across Ontario. These herds were enrolled in a routine Ontario DHI milk recording program. Test-day milk samples were transported to the Ontario DHI laboratory for routine analysis of milk fat percent, total protein percent, SCC, and MU concentration (mmol/L) [Note: Conversion formula: MUN (MU nitrogen, mg/dl) = MU (MU, mmol/L) × 2.8]. Milk urea concentrations were measured by an automated IR test method (Fossomatic 4000 milk analyzer; Foss North America, Brampton, Ontario). Test-day data were obtained electronically from Ontario DHI, following each test day, and transferred into a Microsoft FoxPro database file (version 2.6 for Windows, 1989 to 1994; Microsoft Corporation, Redmond, WA).

Test-day production data were used to calculate the mean milk production and mean milk component data. Gross milk revenue was calculated based on the multiple-component pricing formula used to pay Ontario producers ($5.1721/kg of milk fat, $8.3913/kg of total protein, and $1.1822/kg of other solids). This pricing formula was stable for the entire study period. Gross milk revenue was calculated on the basis of both dollars per cow per day and dollars per kilogram of milk fat. The latter basis of measurement was selected because the Canadian dairy industry operates under a supply management, or quota, system, by which production is restricted based on the total kilograms of milk fat shipped.

Herd management information describing characteristics such as milking frequency, housing, nutritional management, ration changes, and reproductive management programs, was collected through a questionnaire that was mailed to, and completed by, the herd manager. All but two participants submitted a completed questionnaire by mail. Administration of the questionnaire via a telephone interview was required to complete the questionnaire for the last two participants.

Feed inventory data for the milking herd was collected via a report completed by the producer and DHI herd management specialist at the end of each month. This report documented all feedstuffs and the quantities that were fed to the milking herd for that month. Standard feed prices ($/dry metric tonne) were assigned for forages and grains as follows: dry hay, haylage, and big baleage, regardless of plant species = $100; corn silage = $85; grainlage (e.g., barlage or oatlage) = $140; pasture = $50; oats, barley, wheat and mixed grains = $140; high moisture corn and dry shelled corn = $150. Producers reported the prices for all other purchased feeds including custom complete feeds, commercial top-dresses, commodity feeds, feed additives, and minerals. Forage and high moisture corn samples were submitted to Agri-Food Laboratories (503 Imperial Road North, Guelph, ON) for analysis of nutrient composition using IR test methods. Feed samples were submitted on either a monthly basis or whenever the producer began feeding new or different forages. Feed mills and nutritionists working with individual producers provided the ingredient profile for all purchased feeds such as complete feeds, top-dresses, premixes, mineral packages, or feed additives. We then used reported textbook values (NRC, 1988) or ingredient specifications provided by the feed mill to calculate the nutrient composition for all of these latter nonforage purchased feeds.

All information describing the type, quantity, nutrient composition, and costs for all feedstuffs fed to the milking herd, for each herd and for each month, were manually entered into a database file. This information was then compiled, using the Spartan Ration Evaluator Program (Michigan State University, 1992), to calculate the average nutrient composition of the ration fed per cow per day, and to calculate the feed costs on the basis of both dollars per cow per day and dollars per kilogram of milk fat, for each herd and for each month of the study (i.e., the 'herd-month' ration). If the ration was reported to be rebalanced sometime during the month and there was no way to be certain of the nutrient composition of the ration fed on test day then these particular 'herd-month' rations were omitted from further analysis. Income over feed costs were then calculated for each herd for each test day (income over feed costs = gross milk revenue - feed costs) on the basis of both dollars per cow per day and dollars per kilogram of milk fat.

Statistical Analysis

Relationships between MU concentration and nutritional management. Simple correlation coefficients were calculated among nutrient variables using Proc Corr in SAS (SAS, 1996) and those with a high correlation $R > 0.75$) were not placed in the same models due to collinearity. Univariate linear regression models were developed using Proc Mixed in SAS (SAS, 1996) to test the relationship between herd mean MU concentration (dependent variable) and variables describing the ration nutrient composition (independent variables). Ration descriptor variables tested included DMI, CP, RDP, soluble intake protein (**SIP**), RUP, nonfiber carbohydrates (**NFC**), NE_L, TDN, ADF, NDF, NFC:CP ratio, NFC:RDP ratio, NFC:SIP ratio, NFC:RUP ratio, and forage-to-concentrate (**F:C ratio**) ratio. All ration nutrient composition variables, except for those expressed as a ratio, were expressed both as a percentage of the total DM in the diet and on the basis of total kilograms of DM fed. The variable herd was entered in the class and random statements to control for random herd effects and for the fact that observations were repeated within the herd over different test days.

A similar univariate modeling process was used to examine other factors including facilities (tie stall or free stall), feeding strategy (TMR or component fed), access to pasture (yes or no), feeding frequency of all feeds (times fed/d, including 'pushing up' of feed), synchrony of feeding concentrates and forages (1 = synchronous, 2 = fed more than 1 h apart), sample type (a.m., p.m., or pooled), herd size (1 = large [> 100 cows], 2 = small [< 101 cows]), season (1 = January to March, 2 = April to June, 3 = July to September, 4 = October to December), average parity, and average DIM.

Independent variables that were significant in univariate models at $P < 0.25$ were carried forward together into a multivariate model to describe herd mean MU concentration (dependent variable). Covariates that were not significant at $P < 0.05$ in the final multivariate model were subsequently removed by backwards elimination.

Relationships between MU concentration and production. Linear regression, using Proc Mixed in SAS (SAS, 1996), was used to investigate the relationship between the herd mean MU concentration (mmol/L) (independent variable of interest) and each of the following measures of milk production (dependent variables of interest): 1) uncorrected herd mean milk yield (kg/cow per day), 2) herd mean milk yield while controlling for milk fat and total protein contents as additional covariates in the model (kg/cow per day), 3) weighted mean milk fat percentage, 4) weighted mean total protein percentage, 5) weighted mean milk fat yield (kg/

cow per day), 6) weighted mean total protein yield (kg/cow per day), and 7) mean linear score (**LS**). Linear score, the logarithmic transformation of SCC, was used because SCC is not normally distributed. We considered developing models that used either FCM or energy-corrected milk as the dependent variable describing production; however, it was considered more appropriate to develop models for milk yield (dependent variable) while controlling for milk fat and total protein as separate variables in the model, since the latter method uses 'real' data, while the former methods would have used 'calculated' data produced from a standardized formula (Bernard, 1997; Nordlund, 1987).

The approach to model development was the same for each of the seven measures of production considered. The variable herd was included in the class and random statements of all models to control for random herd effects and for the fact that measures were repeated within herd on different test days. Potential confounding variables, including parity, DIM, season (January to March, April to June, July to September, or October to December), and test type (a.m., p.m., or pooled), were offered to all models. All nonsignificant variables, with the exception of the variable describing herd mean MU concentration (the independent variable of interest), were subsequently removed by a backwards elimination process with $P > 0.05$. Because nonlinear relationships had been observed between milk production parameters and MU concentrations in a cow-level analysis (Godden, 2000b), the model was tested for the presence of a quadratic term for the variable describing herd mean MU concentration. Finally, the model was tested for the presence of interaction terms between remaining variables.

Relationships between MU concentration and economic variables. Linear regression, using Proc Mixed in SAS (SAS, 1996), was used to evaluate the relationship between herd mean MU concentration (mmol/L) (independent variable of interest) and each of the following dependent variables: gross milk revenue, feed costs, and income over feed costs. These analyses were performed when dependent variables were described on the basis of both dollars per cow per day and dollars per kilogram of milk fat. The model building process was the same as for that described above, with models controlling for significant potential confounders (season, DIM, and parity) and for random herd effects. These models were developed when the variable describing herd mean MU was calculated either by a simple average or an average weighted by milk yield. However, because statistical inferences and estimates were found to be the same between these two model types, we decided to present a final model that used a simple average for calculating herd mean MU concentration, as this is the number currently being reported to producers by DHI laboratories.

Relationships between nutritional management and economic variables. Linear regression models were developed using Proc Mixed in SAS (SAS, 1996) to evaluate the relationship between several variables describing ration nutrient composition (independent variable of interest) and each of the following dependent variables: gross milk revenue, feed costs, and income over feed costs, expressed on the basis of both dollars per cow per day and dollars per kilogram of milk fat. These were univariate models that controlled for random herd effects. Independent variables selected to describe ration nutrient composition included CP, RDP, SIP, RUP, and NFC, and were expressed on the basis of percentage of total DM fed, percentage of total protein fed, total kilograms fed, and dietary energy:protein ratios.

RESULTS

Of the 60 herds originally enrolled, 53 completed the study. Reported reasons for withdrawal from the study related either to a perceived lack of value of the 'cost-of-production' pilot project, or an inability or unwillingness to complete the required monthly reports. Of those completing the study, 38 herds (72%) were housed in tie-stall barns and 15 (28%) were housed in free-stall barns. Twenty-six herds (49%) fed a TMR, while the remaining 27 herds (51%) fed a component-based ration. Alfalfa haylage, corn silage, and dry alfalfa hay were the predominant forages fed among study herds. Other forages fed included alfalfa baleage, oatlage, barlage, and sorghum. Only seven herds relied on pasture as a significant forage source, which was accounted for in balancing the ration. Energy and protein concentrate feeds were typical of the region and included high moisture corn, dry shelled corn, oats, barley, wheat, custom or commercially prepared protein supplements, soybean meal, roasted soybeans, corn distillers grains, wet brewers grains, corn gluten meal, meat meal, fish meal, urea, canola meal, and dry brewers grains.

A total of 281 distinct 'herd-month' rations were used in the final regression analysis. This represented 45 herds (single-group TMR = 18, two-group TMR = 4, and component fed = 23). Average milk yields and MU concentrations were 29.9 kg/cow (SD = 3.7; range = 19.9 to 41.3) and 4.9 mmol/L (SD = 0.9; range = 2.7 to 7.7), respectively. Summary statistics describing herd characteristics and other production parameters, ration nutrient compositions, and the economic variables of gross milk revenue, feed costs, and income over feed costs are presented in Tables 1, 2, and 3, respectively.

Table 1. Test-day herd characteristics and production information for 281 mo for which ration information was available from 45 study herds.

Parameter	Mean	SD	Minimum	Maximum
Test-day herd characteristics				
Number of cows milking	44	28.2	13	177
Mean DIM	166	24.1	100	232
Mean parity	2.4	0.3	1.6	3.2
Test-day herd mean production				
Milk yield (kg/cow/d)	29.9	3.7	9.9	41.3
Milk fat (%)	3.7	0.2	2.6	4.5
Total protein (%)	3.3	0.1	2.8	3.6
Milk fat yield (kg/cow/d)	1.1	0.1	0.6	1.7
Total protein yield (kg/cow/d)	1.0	0.1	0.6	1.4
Milk urea concentration (mmol/L)	4.9	0.9	2.7	7.7
Linear score	2.8	0.5	1.5	4.4

Table 3. Description of milk revenues and feed costs for 281 'herd-month' records from 45 herds.

Parameter	Mean	SD	Minimum	Maximum
$/cow/d				
Gross milk revenue	15.93	1.84	9.90	22.63
Feed costs	4.19	0.71	2.66	7.66
Income over feed costs[1]	11.74	1.74	6.93	16.54
$/kg of milk fat				
Gross milk revenue	14.42	0.62	12.84	18.03
Feed costs	3.83	0.64	2.49	6.18
Income over feed costs[2]	10.60	0.84	7.88	13.12

[1]Income over feed costs/cow/d = (gross milk revenue/cow/d − feed costs/cow/d).

[2]Income over feed costs/kg of milk fat = (gross milk revenue/kg of fat − feed costs/kg of fat).

Relationships Between MU Concentration and Nutritional Management

Variables describing ration nutrient composition having a positive relationship with herd mean MU in univariate analysis ($P < 0.25$) included DMI, CP, SIP, RDP, and RUP. Variables having a negative relationship with herd mean MU in univariate analysis included NFC and the ratios NFC:CP, NFC:RDP, NFC:RUP, and F:C. Variables related to feeding or herd management that were associated with herd mean MU concentration in univariate analysis ($P < 0.25$) included test type (a.m., p.m., or pooled) and facilities (tie stall or free stall). Other covariates carried forward into the final multivariate models ($P < 0.25$ in univariate analysis) included season and DIM.

Four final multivariate models were developed. The first and second final models included protein and energy as individual main effects and offered either CP or RDP and RUP as the protein variables of interest, respectively. The third and fourth final models offered energy and protein variables as the ratio terms NFC:CP or NFC:RDP, respectively. In these multivariate models, herd mean MU had a positive relationship with CP and RDP and had a negative relationship with NFC, and the ratios NFC:CP, NFC:RDP, and F:C. While the variables describing facilities (tie stall vs. free stall) and mean DIM were removed during the backwards elimination process, the variables describing season and test type remained in all final multivariate models. A likelihood ratio test determined that all four final models were of equal fit. Thus, only one final model offering CP and NFC as individual main effects was selected to present in these results (Table 4).

Table 2. Description of milking cow rations fed, by herd and month, for 45 commercial dairy herds (n = 281 'herd-months').

Ration Parameter	Mean	SD	Minimum	Maximum
DMI (kg/cow/d)	23.1	2.0	16.2	28.3
DM (%)	60.5	8.4	32.7	78.7
F:C Ratio[1]	1.1	0.3	0.6	2.2
CP (% DM)	17.5	1.9	14.1	25.5
SIP (% CP)[2]	37.8	7.7	17.4	59.6
RDP (% CP)	65.5	4.1	52.8	75.2
RUP (% CP)	34.5	4.1	24.8	47.2
ADF (% DM)	19.4	2.5	12.6	27.4
NDF (% DM)	31.3	3.4	21.1	45.0
NFC (% DM)[3]	39.4	4.0	28.2	48.0
NE_L (Mcal/kg DM)	1.7	0.1	1.5	1.8
TDN (% DM)	72.8	2.7	54.2	82.6

[1]F:C Ratio = Forage:concentrate ratio.

[2]SIP = Soluble intake protein.

[3]NFC = Non fiber carbohydrates.

Relationships Between MU Concentration and Production

The results of the final multivariate models describing the relationships between herd mean MU and various production parameters are presented in Table 5. While there was a positive relationship ($P < 0.05$) between herd mean MU and both milk fat and total protein percents (Table 5: models 3 and 5, respectively), there tended to be a strong negative trend ($P = 0.056$) in the relationship between mean MU and the uncorrected milk yield (kg/cow per day) (Table 5: model 1). However, there was no relationship between herd mean MU and either total protein yield, LS, or milk yield after correcting for milk fat and total protein contents in the model (Table 5: models 6, 7, and 2, respectively) ($P > 0.05$). A positive relationship was observed between herd mean MU and milk fat yield ($P < 0.05$) (Table 5: model 4).

Relationships Between MU Concentration and Economic Variables

The results of the final multivariate models describing the relationship between herd mean MU and gross

Table 4. Final mixed model describing the relationship between test day herd mean milk urea concentration and nutritional management: offers energy and protein descriptors as NFC and CP.

Dependent Variable:	Test-day herd mean milk urea concentration (mmol/L) (Mean = 4.9; SD = 0.9; range = 2.7 to 7.7).			
Variable	Level	Estimate	SE of Estimate	*P* Value
INTERCEPT	. . .	4.66	0.54	. . .
Season	Jan.–Mar.	–0.049	0.11	0.66
	Apr.–June	–0.28	0.10	0.0066
	July–Sept.	0.39	0.11	0.0003
	Oct.–Dec.	referent	. . .	. . .
Sample type	AM	–0.45	0.19	0.023
	PM	–0.20	0.19	0.29
	Pooled	referent	. . .	. . .
F:C Ratio[1]	. . .	–0.55	0.19	0.0038
CP (kg DM/cow/d)	. . .	0.49	0.099	0.0001
NFC (kg DM/cow/d)[2]	. . .	–0.11	0.045	0.013

[1]F:C Ratio = Forage-to-concentrate ratio.

[2]NFC = Nonfiber carbohydrates.

milk revenue, feed costs, and income over feed costs are presented in Table 6. While there was no relationship between herd mean MU and gross milk revenue, when calculated on a dollars per cow per day basis, there was a positive relationship with feed costs/cow per day. A scatter plot of test-day herd mean MU (mmol/L) versus feed costs/cow per day is presented in Figure 1. There was a trend ($P = 0.15$) for a negative relationship between herd mean MU and income over feed costs/cow per day.

When calculated on the basis of dollars per kilogram of milk fat, a positive relationship was observed between herd mean MU and feed costs per kilogram of milk fat ($P < 0.05$). However, there was a negative relationship between herd mean MU and both gross milk revenue per kilogram of milk fat and income over feed costs per kilogram of milk fat ($P < 0.05$).

Relationships Between Nutritional Management and Economic Variables

Results of univariate models describing the relationships between nutritional management and economic variables, on a dollars per cow per day basis, are presented in Table 7. Gross milk revenue/cow per day had a positive relationship with CP (% of DM), RDP (kg/d), SIP (kg/d), and NFC (kg/d), and a negative relationship with NFC:SIP ratio. There was a trend for a positive relationship ($P = 0.058$) between gross milk revenue/cow per day and F:C ratio. No relationship was observed between gross milk revenue/cow per day and the other descriptors of ration nutrient composition. Results were much more consistent when the relationship between ration nutrient composition and feed costs/cow per day were examined. Most variables describing dietary protein levels (all CP and RUP variables and most RDP

Table 5. Multivariate regression models describing the relationship between test-day herd mean bulk urea concentration (mmol/L) and production variables.

Model[1]	Production parameter	Estimate for herd mean MU (mmol/L)	SE of Estimate	*P* Value
1	Milk yield (kg/cow/d)[2]	–0.34	0.18	0.057
2	Milk yield (kg/cow/d)[3]	–0.014	0.18	0.94
3	Milk fat (%)[4]	0.088	0.017	0.0001
4	Milk fat yield (kg/cow/d)[4]	0.019	0.0072	0.0094
5	Total protein (%)[4]	0.12	0.042	0.0058
6	Total protein yield (kg/cow/d)[4]	–0.0066	0.036	0.27
7	Linear score	0.0081	0.028	0.78

[1]Models control for random herd effects and for effects of season, parity, and DIM.

[2]Model uncorrected for milk fat and protein contents.

[3]Model corrected for milk fat and total protein contents.

[4]Production parameters weighted by milk yield.

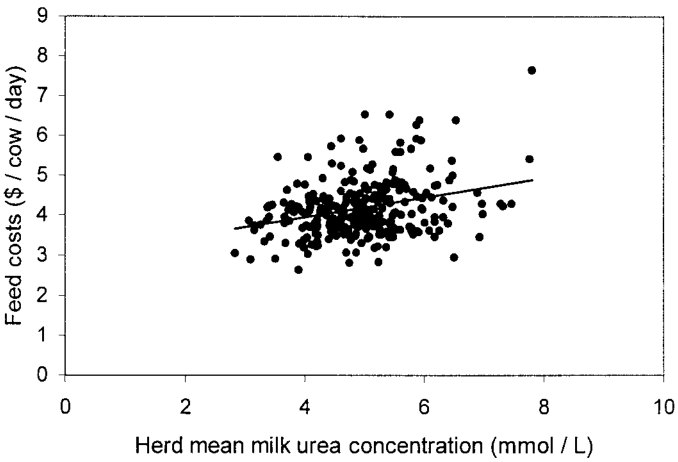

Figure 1. Test day herd mean milk urea concentration versus feed costs. Note: Regression line indicates significant positive relationship ($P < 0.05$).

and SIP variables) had a positive relationship with feed costs/cow per day. The ratios NFC:CP, NFC:RUP, and F:C all had a negative relationship with feed costs/cow per day. The variables describing CP, RDP, or SIP were inconsistently related with income over feed costs/cow per day. For example RDP (% of CP) and SIP (% of DM or % of CP) had a positive relationship with income over feed costs/cow per day, while CP (% of DM or kg/d), RDP (% of DM or kg/d) were not related to income over feed costs/cow per day. However, RUP (kg fed, % of CP, and % of DM) consistently had a negative relationship with income over feed costs/cow per day.

When we considered economic variables described on the basis of dollars per kilogram of milk fat (results not shown here), gross milk revenue was not associated with any of the variables describing ration nutrient composition ($P > 0.05$). However, feed costs had a consistent positive relationship with dietary protein descriptors ($P < 0.05$). The ratios of NFC:CP, NFC:RUP, and F:C all had a negative relationship with feed costs/kg of milk fat. Finally, the variables describing dietary protein generally had a negative relationship with income over feed costs/kg of milk fat, while the ratios NFC:CP, NFC:RDP, NFC:RUP, and F:C all had a positive relationship with income over feed costs/kg of milk fat.

DISCUSSION

Relationships Between MU Concentration and Nutritional Management

In this observational study, herd mean MU had a positive relationship with levels of dietary CP, RDP, and RUP, and a negative relationship with levels of NFC, the NFC:CP ratio, and the NFC:RDP ratio. These findings are consistent with the results of experimental studies (Baker et al., 1995; Blauwiekel and Kincaid, 1986; Canfield et al., 1990; Carroll et al., 1988; DePeters and Ferguson, 1992; Howard et al., 1987; Kaim et al., 1983; Oltner and Wiktorsson, 1983; Roseler et al., 1993). The results of this study indicate that, when measured by an IR test method, and when interpreted at the group level, MU measurements produced from routinely collected DHI milk samples offer a useful tool to monitor the efficiency of nitrogen utilization in commercial dairy herds.

Housing factors (tie stall vs. free stall), TMR versus component feeding, feeding frequency, and synchrony of offering forages and concentrates were not associated with herd mean MU in this study. A limited number of studies have reported that SU concentrations were lower in herds that fed a TMR and in herds that had feed available continuously, compared with component fed herds, wherein protein and energy feedstuffs may be offered less frequently and not always at the same time (Carroll et al., 1988; Thomas and Kelly, 1976). Other studies have suggested that urea concentrations may remain more constant throughout the day in animals with high frequency or continuous feeding (Fol-

Table 6. Multivariate regression models describing the relationship between test-day herd mean milk urea concentration (mmol/L) and gross milk revenue, feed costs, and income over feed costs.

Model number[1]	Economic variable	Estimate for herd mean MU (mmol/L)	SE of Estimate	*P* Value
$/cow/d				
1	Gross milk revenue ($/cow/d)	0.018	0.091	0.85
2	Feed costs ($/cow/d)	0.20	0.044	0.0001
3	Net milk revenue ($/cow/d)	–0.14	0.098	0.15
$/kg milk fat				
4	Gross milk revenue ($/kg)	–0.18	0.043	0.0001
5	Feed costs ($/kg)	0.17	0.041	0.0049
6	Net milk revenue ($/kg)	–0.29	0.051	0.0001

[1]Models control for random herd effects and effects of season, parity, and DIM.

Table 7. Univariate regression models[1] describing the relationship between economic variables and ration nutrient composition.

Ration item descriptor (independent variable)	Basis of measuring economic performance (dependent variables)					
	Gross milk revenue ($/cow/d)		Feed costs ($/cow/d)		Income over feed cost ($/cow/d)	
	Estimate	*P* Value	Estimate	*P* Value	Estimate	*P* Value
CP (kg/d)	. . .	NS	0.72	0.0001	. . .	NS
CP (% of DM)	0.46	0.0078	0.084	0.0007	. . .	NS
RDP (kg/d)	0.66	0.0045	0.80	0.0001	. . .	NS
RDP (% of total DM)	. . .	NS	0.059	0.068	. . .	NS
RDP (% of CP)	. . .	NS	–0.025	0.029	0.062	0.017
SIP (kg/d)	0.85	0.0021	0.47	0.0001	. . .	NS
SIP (% of total DM)	. . .	NS	. . .	NS	0.15	0.044
SIP (% of CP)	. . .	NS	–0.016	0.014	0.045	0.0022
RUP (kg/d)	. . .	NS	1.73	0.0001	–1.13	0.0058
RUP (% of total DM)	. . .	NS	0.18	0.0001	–0.28	0.0099
RUP (% of CP)	. . .	NS	0.025	0.029	–0.062	0.017
NFC (kg/d)	0.20	0.0092	0.26	0.0001	. . .	NS
NFC (% of total DM)	. . .	NS	. . .	NS	. . .	NS
NFC:CP ratio	. . .	NS	–0.25	0.047	. . .	NS
NFC:RDP ratio	. . .	NS	. . .	NS	. . .	NS
NFC:SIP ratio	–0.17	0.027	. . .	NS	–0.20	0.0053
NFC:RUP ratio	. . .	NS	–0.095	0.0048	0.15	0.057
F:C ratio	–0.68	0.058	–0.87	0.0001	. . .	NS

[1]All models control for random herd effects.

man et al., 1981; Thomas and Kelly, 1976). The difference in results between ours and previous studies may possibly be explained by a relatively small number of herds or loss of variation and information due to interpretation of data at the herd level, and not the cow level. It may also be possible that other unmeasured herd management factors, nutritional factors, or individual cow feeding behavior may have overshadowed the effects of the herd management factors examined. Yet another possibility could be that the rate of rumen degradation of feedstuffs, and hence the synchrony of the availability of energy and nitrogen to rumen microbes, may be of greater importance in determining how much excess rumen ammonia is converted to urea, as opposed to the synchrony of offering the actual feedstuffs to the cow. The effect of feeding management strategies on MU concentrations requires further study.

The variable describing sample type (a.m., p.m., or pooled milk samples) was offered as a covariate into all models. Despite the use of different methods of MU analysis among different studies (e.g., IR versus wet chemistry), studies have consistently reported differences in MU concentration between morning (a.m.) and evening (p.m.) milk samples, with concentrations generally being lower in a.m. than in p.m. samples (Broderick and Clayton, 1997; Ferguson et al., 1997b; Miettinen and Juvonen, 1990). Experimental studies have demonstrated that MU concentrations are highest within a 2 to 6 h period after eating (Gustaffson and Palmquist, 1993). It has been reported that the observed differences between a.m. and p.m. MU concentrations may be influenced by differences in the feeding-to-milking intervals between these two milking periods (Godden, 1998).

While some studies examining individual cow data have reported that MU concentrations were lower in first-lactation heifers than in older cows (Godden et al., 2000b; Oltner et al., 1985), others have found no such relationship (Canfield et al., 1990). Several studies examining individual cow data have reported that urea levels vary considerably by stage of lactation (Bruckental et al., 1989; Carlsson et al., 1995; Godden et al., 2000b). Carlsson et al. (1995) reported that MU concentrations were lowest immediately after calving, increased to reach a maximum between 3 and 6 mo of lactation, and then slowly declined in later lactation (Carlsson et al., 1995). The relationships between both parity and stage of lactation are possibly due to underlying nutritional factors, physiological changes, or both. In this observational study, neither mean parity nor mean DIM were related with herd mean MU, possibly because important underlying nutritional factors were controlled for in these models. This suggests that the association between stage of lactation and urea concentration is explained by underlying nutritional management, and so agrees with the conclusions of Schepers and Meijer (1998). Another explanation may be that variation was lost by interpreting data at the herd level, leading to the findings of a lack of association where one might truly exist.

Studies have generally reported that while concentrations of total protein and true protein (mostly casein) in milk are lower during the summer months, the NPN fraction of milk, which includes urea, increases (Carlsson et al., 1995; Ferguson et al., 1997a; Verdi et al., 1987). Ferguson et al. (1997a) reported, using cow-level DHI data from 1909 Pennsylvania dairy herds, that MU concentrations (mmol/L; mean ± SD) varied by season as follows: winter 1996, 5.00 ± 0.071; spring 1996, 5.35 ± 0.075; summer 1996, 5.83 ± 0.086; fall 1996, 5.07 ± 0.093. Results were very similar in this study, with herd mean MU concentrations being highest in the months from July to September.

The association between MU concentrations and season is difficult to describe because it has the potential to be confounded by stage of lactation and nutritional effects. Moller et al. (1993), who reported elevated blood and serum urea concentrations in pasture-grazing cows, attributed seasonal variation in MU concentration to seasonal changes in pasture protein and energy components. Australian spring pasture contained 20 to 30% CP but only 5 to 20% soluble carbohydrate. Thus, conditions were created for a high protein:energy ratio, which could result in elevated urea concentrations (Moller et al., 1993). Studies are generally lacking that describe nonnutritional factors associated with season that may also affect MU concentrations. In our study, the variable ‘season’ remained significant in the multivariate model, even though variables describing the ration nutrient composition were included, and so controlled for, in the model. This suggests that factors related to season, other than just seasonal changes in ration nutrient composition, were influencing herd mean MU. It is possible that the contribution of CP and RDP from pasture was underestimated in the ‘herd-month’ rations produced. However, a variable describing whether or not cows had access to pasture was not significantly associated with herd mean MU. Other seasonally related factors that may contribute to the association between season and MU could include ambient temperature, humidity, and water intake. However, these hypotheses could not be tested as these factors were not measured in this study.

Relationships Between Herd Mean MU Concentration and Production

Milk yield. Herds with high mean MU concentrations had a strong tendency to have lower mean uncorrected milk yields/cow per day ($P = 0.057$). However, this negative relationship disappeared after correcting for both mean milk fat and total protein contents in the model. The latter model was considered the most appropriate to describe test-day production as it is more closely related with how milk revenue is calculated when using a component-based pricing formula (Eicker et al., 1997). These findings suggest that cows may be fed to achieve high milk yields without necessarily feeding for high MU concentrations. These findings are consistent with those of a cow-level study that concluded that diets can be balanced efficiently to yield a relatively high total protein content and low concentrations of urea without sacrificing milk yield (Baker et al., 1995). These results are also consistent with those of an observational study of 29 Swedish dairy herds that reported no correlation between bulk tank MU concentrations and milk yield (Gustafsson, 1993).

Some experimental studies performed at the cow level have described a weak positive relationship between MU and milk yield (Carlsson et al., 1995; Oltner et al., 1985), while other studies have reported either no relationship (Baker et al, 1995; Carroll et al., 1988) or a negative relationship (Ismail et al., 1996).

The conflicting findings among various studies regarding the relationship between MU and milk yield might have several explanations. An explanation for a positive relationship between MU and production is that higher protein feeding, associated with higher MU concentrations, also supports higher milk production (Oldham, 1984). This may be due to a combination of factors including greater amino acid availability for milk protein synthesis, improved availability of energy through deamination of amino acids, improved efficiency of utilization of absorbed nutrients, or improved DMI (Macleod et al., 1984; Oldham, 1984). However, there is a pattern of diminishing returns, in that milk yield responses to additional protein eventually become incrementally smaller (Chalupa, 1984).

Conversely, an explanation for a negative relationship between MU and production is that the energy tax associated with the conversion of excess amounts of ammonia to urea may contribute to lower available energy for milk production (Nelson, 1995). The conversion of ammonia to urea in the liver has been estimated to cost the animal 12 Kcal/g of excess nitrogen excreted (Van Soest, 1994). Vandehaar (1998) predicted that if a cow producing 45 kg of milk/d and eating 25 kg of DM/d required 17% CP in its diet, then feeding an extra two percentage points of protein (a diet of 19% CP) would amount to an energy expense of 0.36 Mcal/d. However, studies have reported contradictory results when describing the relationship between dietary protein intake, MU, and indicators of energy balance, including BCS, BW, postpartum weight loss, weight gain, and circulating concentrations of insulin and NEFA (Blauwiekel and Kincaid, 1986; Broderick and Clayton, 1997; Carroll et al., 1988; Howard et al., 1987; Ismail et al., 1996; Kaim et al., 1983; Ruegg et al., 1992).

Other factors influencing the relationship between MU and production could include the type and quality of dietary protein provided, including amino acid availability. While MU concentration may be sensitive to levels of CP, RDP, and RUP, it has been reported not to be associated with amino acid balance (Baker et al., 1995). Additionally, although high MU concentrations will indicate the relatively high protein:energy ratio, they do not necessarily indicate which of these two nutrients is in relative excess or deficiency (Oltner and Wiktorsson, 1983). The latter study observed that MU concentrations remained moderate so long as levels of protein and energy were balanced relative to one another, whether or not they were both fed in excess, both underfed, or both fed at recommended levels (Oltner and Wiktorsson, 1983). Clearly, variations in any or all of these nutrient composition variables could result in different levels of production among different studies, leading to contradictory findings as to the nature of the relationship between MU and production.

Linear score. Herd mean MU was not associated with herd mean linear score, even though previous cow-level analysis of the same data set described a negative relationship between cow-level MU and linear score (Godden et al., 2000b). The discrepancy between cow-level and herd-level findings may be because there was a loss of variation when linear scores were interpreted at the herd level. Another factor may be that there are fewer data points when data is described at the herd level. A discussion of the nature of the relationship between MU and linear score is provided in a previous paper (Godden et al., 2000b).

Relationships Between Herd Mean MU Concentration and Economic Variables

The goal of most commercial dairy producers is to feed and manage the herd to achieve high milk production. The gross efficiency of milk production is greater for high-producing cows because a greater proportion of the total DMI is used for milk production, and not maintenance. However, the relationship between milk production and either dietary energy or protein inputs is not linear. Yield responses eventually begin to diminish in spite of additional inputs (Oldham, 1984). In these situations, the margin between income and feed costs will diminish as well. The challenge, then, is to improve the biological and economic efficiencies of the dairy cow by maintaining or improving production per cow, while controlling or lowering feed costs. This can be measured as income over feed cost (income over feed cost = gross milk revenue − feed costs). Ontario dairy producers must focus on this as a primary goal, while also managing within a supply management (or quota) system, in which production is restricted based on the total kilograms of milk fat shipped. Under this system, milk revenue is determined by a multiple-component pricing formula wherein a premium is paid for protein ($8.39/kg), compared with what is paid for milk fat ($5.17/kg). As such, Ontario dairy producers who want to maximize their milk revenue must do so by trying to maximize the total protein yield produced for every kilogram of milk fat shipped, while still meeting their quota demands for total kilograms of milk fat shipped. This should be done while still achieving high milk yields per cow, to maximize the biological efficiency of the cow, and while controlling feed costs.

In the current study, no relationship was found between herd mean MU and gross milk revenue/cow per day. However, a positive relationship was observed between herd mean MU and feed costs/cow per day. While not significant, herds with a higher mean MU tended to have lower income over feed costs/cow per day. This relationship deserves further investigation. The results of this study suggest that herds with lower mean MU achieved the same high gross milk revenue/cow per day and income over feed costs/cow per day as did herds with higher MU concentrations. This should be encouraging to dairy producers if future environmental regulations are implemented to restrict the amount of excess nitrogen excreted on dairy farms.

When calculated on the basis of dollars per kilogram milk fat, a positive relationship was found between herd of mean MU and feed costs, while a negative relationship was between herd mean MU and both gross milk revenue and income over feed costs. The negative relationship with gross milk revenue was attributed, in part, to a positive relationship between MU and milk fat yield (kg/cow per day) and to the lack of a relationship between MU and total protein yield. Thus, higher herd mean MU concentrations were associated with a relatively smaller protein yield for every kilogram of milk fat shipped. And, since a premium is paid for total protein, the gross revenue/kg of milk fat was generally lower for herds with a higher mean MU. The fact that feed costs/kg of milk fat were positively associated with herd mean MU concentrations further contributed to finding a significant negative relationship between herd mean MU and income over feed costs/kg of milk fat.

Relationship Between Nutritional Management and Economic Variables

In this study, feed costs had a positive relationship with herd mean MU, regardless of the basis for calculation (dollars per cow per day or dollars per kilogram of milk fat). Variables describing levels of dietary protein (CP, RDP, and RUP) have been positively associated with urea concentrations (Baker et al., 1995; Blauwiekel and Kincaid, 1986; Canfield et al., 1990; Carroll et al., 1988; DePeters and Ferguson, 1992; Howard et al., 1987; Kaim et al., 1983; Roseler et al., 1993). Feeding higher levels of costly dietary protein will generally result in higher feed costs. Therefore, the positive relationship observed between herd mean MU and feed costs is likely partly indirect in nature, explained by the positive relationship between MU levels of dietary protein. This contributed to the negative trend observed in the relationship between herd mean MU and income over feed costs/cow per day and the significant negative relationship observed between herd mean MU and income over feed costs/kg of milk fat.

CONCLUSIONS

Herd mean MU concentrations had a positive relationship with dietary levels of CP, RDP, and RUP, and a negative relationship with levels of NFC, and with the ratios of NFC:CP, NFC:RDP, NFC:RUP, and F:C. These findings are consistent with those of earlier experimental studies that had used chemical methods of MU analysis and that had interpreted data at the individual animal level. Factors related to feeding management (e.g., TMR versus component feeding, frequency of feeding, synchrony of offering forage, and concentrate feeds) were not associated with test-day herd mean MU in this study. After controlling for ration nutrient composition, season was associated with herd mean MU, with the highest levels occurring between July and September. This suggests that additional season-related factors, other than just ration nutrient composition, may also affect MU concentrations.

Herd mean MU concentration was not associated with milk yield (kg/cow per day) after controlling for milk fat content, total protein content, season, parity, DIM, and random herd effects in the model. Similarly, herd mean MU was not associated with herd mean LS.

Herd mean MU was not related to gross milk revenue/cow per day, but had a positive relationship with feed costs/cow per day. Herds with high mean MU concentrations tended to have lower income over feed cost/cow per day. This relationship requires further investigation. Herd mean MU had a positive relationship with feed costs per kilogram of milk fat, but had a negative relationship with both the gross milk revenue and income over feed costs per kilogram of milk fat. Since the supply management system in Ontario restricts production based on the total kilogram of milk fat shipped, herds with lower herd mean MU concentrations generally benefited from greater efficiency of quota utilization.

The negative trend in the relationship between herd mean MU and income over feed costs/cow per day and the significant negative relationship between herd mean MU and income over feed costs/kg of milk fat may be partially indirect in nature, attributable to the fact that feeding higher levels of dietary protein seemed to result in both higher feed costs and higher MU concentrations, but with no corresponding improvement in gross milk revenue.

The results of this study demonstrate that DHI MU measurements produced using an IR test method offer a useful tool to monitor the efficiency of nitrogen utilization in commercial dairy herds. While herd mean MU concentrations will not be highly predictive of either gross milk revenue, feed costs, or income over feed costs, high herd mean MU concentrations could signal an opportunity to investigate and perhaps modify the ration nutrient composition in such a way as to make more efficient use of expensive dietary protein. This could result in lower MU concentrations, reduced excretion of excess nitrogen into the environment, and lower feed costs, all while maintaining high milk yields, high gross milk revenue, and potentially improving the efficiency of production as measured by higher income over feed costs.

ACKNOWLEDGMENTS

This study was funded by grants from the Ontario Ministry of Agriculture, Food and Rural Affairs. In-kind support, technical assistance, and test day data was provided by field staff, laboratory staff and herd-management specialists of the Ontario Dairy Herd Improvement Association. The authors would also like to gratefully acknowledge those producers who participated in this study. Finally, we express our gratitude for the invaluable assistance provided by Shelley James, Paul Page, Antonie Vonk Noordegraaf, Mohammed Shoukri, and Victoria Edge.

REFERENCES

Baker, L. D., J. D. Ferguson, and W. Chalupa. 1995. Responses in urea and true protein of milk to different protein feeding schemes for dairy cows. J. Dairy Sci. 78:2424–2434.

Bernard, J. K. 1997. Milk production and composition responses to the source of protein supplements in diets containing wheat middlings. J Dairy Sci 80:938–942.

Blauwiekel, R., and R. L. Kincaid. 1986. Effect of crude protein and solubility on performance and blood constituents of dairy cows. J. Dairy Sci. 69:2091–2098.

Broderick, G. A., and M. K. Clayton. 1997. A statistical evaluation of animal and nutritional factors influencing concentrations of milk urea nitrogen. J. Dairy Sci. 80:2964–2971.

Bruckental, I., D. Drori, M. Kaim, H. Lehrer, and Y. Folman. 1989. Effects of source and concentration of protein on milk yield and reproductive performance of high-producing primiparous and multiparous dairy cows. Anim. Prod. 48:319–329.

Canfield, R. W., C. J. Sniffen, and W. R. Butler. 1990. Effects of excess degradable protein on postpartum reproduction and energy balance in dairy cattle. J. Dairy Sci. 73:2342–2349.

Cannas, A., A. Pes, R. Mancuso, B. Vodret, and A. Nudda. 1998. Effect of dietary energy and protein concentration on the concentration of milk urea nitrogen in dairy ewes. J. Dairy Sci. 81:499–508.

Carlsson, B. J., J. Bergstrom, and B. Pehrson. 1995. Variations with breed, age, season, yield, stage of lactation, and breed in the concentration of urea in bulk milk and individual cow's milk. Acta Vet. Scand. 36:245–254.

Carroll, D. J., B. A. Barton, G. W. Anderson, and R. D. Smith. 1988. Influence of protein intake and feeding strategy on reproductive performance of dairy cows. J. Dairy Sci. 71:3470–3481.

Chalupa, W. 1984. Discussion of protein symposium. J. Dairy Sci. 67:1134–1146.

DePeters, E. J., and J. D. Ferguson. 1992. Nonprotein nitrogen and protein distribution in the milk of cows. J. Dairy Sci. 75:3192–3209.

Eicker, S., J. Fetrow, C. Guard, G. Jones, and S. Stewart. 1997. Incorporating nutritional services with veterinary services. *In* Dairy Herd Evaluation: A Computer-Aided Approach. Pre-convention Seminar: 30th Annu. Conf. Am. Assoc. Bovine Pract., Montreal, QC.

Ferguson, J. D., N. Thomsen, D. Slesser, and D. Burris. 1997a. Pennsylvania DHIA milk urea testing. J. Dairy Sci. 80 (Suppl. 1):161. (Abstr.)

Ferguson, J. D., N. Thomsen, B. Vecchiarelli, and J. Beach. 1997b. Comparison of BUN and MUN tested by different methods. J. Dairy Sci. 80 (Suppl. 1):161. (Abstr.)

Folman, Y., H. Neumark, M. Kaim, and W. Kaufmann. 1981. Performance, rumen and blood metabolites in high-yielding cows fed varying protein percents and protected soybean. J. Dairy Sci. 64:759–768.

Godden, S. M. 1998. Evaluation of a milk urea assay, and the relationship between milk urea concentrations and nutritional management and performance in Ontario dairy herds. Doctoral (D.V.Sc.) Thesis. University of Guelph. Guelph, ON.

Godden, S. M., K. D. Lissemore, D. F. Kelton, J. H. Lumsden, K. E. Leslie, and J. S. Walton. 2000a. Analytic validation of an infrared milk urea assay and effects of sample acquisition factors on milk urea results. J. Dairy Sci 83:435–442.

Godden, S. M., K. D. Lissemore, D. F. Kelton, K. E. Leslie, J. S. Walton, and J. H. Lumsden. 2000b. Factors associated with milk urea concentrations in Ontario dairy cows. J Dairy Sci. 83:2672–2672.

Gustafsson, A. H. 1993. Acetone and urea concentration in milk as indicators of the nutritional status and the composition of the diet of dairy cows. Uppsala, Sweden. Swedish Univ. Agric. Sci., Dept. Anim. Nutr. Mngmt. Rep. 222:1–41.

Gustafsson, A. H., and D. L. Palmquist. 1993. Diurnal variation of rumen ammonia, serum urea, and milk urea in dairy cows at high and low yields. J. Dairy Sci. 76:475–484.

Howard, H. J., E. P. Aalseth, G. D. Adams, L. J. Bush, R. W. McNew, and L. J. Dawson. 1987. Influence of dietary protein on reproductive performance of dairy cows. J. Dairy Sci. 70:1563–1571.

Ismail, A., K. Diab, and J. K. Hillers. 1996. Effect of selection for milk yield and dietary energy on yield traits; bovine somatotropin, and plasma urea nitrogen in dairy cows. J Dairy Sci. 79:682–688.

Kaim, M., Y. Folman, H. Neumark, and W. Kaufmann. 1983. The effect of protein intake and lactation number on post-partum body weight loss and reproductive performance of dairy cows. Anim Prod. 37:229–235.

Kolver, E. S., and K. L. MacMillan. 1993. Short term changes in selected metabolites in pasture fed dairy cows during peak lactation. Pages 77–81 *in* Proc. N.Z. Soc. Anim. Prod. 53:77–81.

Macleod, G. K., D. G. Grieve, I. McMillan, and G. C. Smith. 1984. Effect of varying protein and energy densities in complete rations. J. Dairy Sci. 67:1421–1429.

Miettinen, P. V., and R. O. Juvonen. 1990. Diurnal variation of serum and milk urea levels in dairy cows. Acta Agric. Scand. 40:289–296.

Moller, S., C. Matthew, and G. F. Wilson. 1993. Pasture protein and soluble carbohydrate levels in spring dairy pasture and associations with cow performance. Proc. N.Z. Soc. Anim. Prod. 53:83–86.

Nelson, A. J. 1995. Practical application of MUN analysis. Pages 35–45 *in* Proc. 4th Annu. NE Dairy Prod. Medicine Symposium. Syracuse, New York.

Nordlund, K. 1987. Adjusted corrected milk. Bovine Pract. 19:87–89.

NRC. 1989. Nutrient Requirements of Dairy Cattle. National Academy Press. Washington, DC. 6th revised edition.

Oldham, J. D. 1984. Protein-energy interrelationships in dairy cows. J Dairy Sci. 67:1090–1114.

Oltner, R., and H. Wiktorsson. 1983. Urea concentrations in milk and blood as influenced by feeding varying amounts of protein and energy to dairy cows. Livest. Prod. Sci. 10:457–467.

Oltner, R., M. Emanuelson, and H. Wiktorsson. 1985. Urea concentration in cows milk in relation to milk yield, live weight, lactation number and composition of feed given. Livest. Prod. Sci. 12:45–57.

Roseler, K. K. 1990. The role and economic impact of milk parameters to monitor intake protein in lactating dairy cattle. Masters Thesis, Cornell University, Ithaca, NY.

Roseler, K. K., J. D. Ferguson, C. J. Sniffen, and J. Kerrema. 1993. Dietary protein degradability effects of plasma and milk urea nitrogen and milk nonprotein nitrogen in Holstein cows. J. Dairy Sci. 76:525–534.

Ruegg, P. L., W. J. Goodger, C. A. Holmberg, L. D. Weaver, and E. M. Huffman. 1992. Relation among body condition score, serum urea nitrogen and cholesterol concentrations, and reproductive performance in high-producing Holstein dairy cows in early lactation. Am. J. Vet. Res. 53:10–14.

SAS Institute Inc. 1996. Release 6.12. Cary, NC.

Schepers, A. J., and R. G. Meijer. 1998. Evaluation of the utilization of dietary nitrogen by dairy cows based on urea concentration in milk. J. Dairy Sci. 81:579–584.

Thomas, P. C., and M. E. Kelly. 1976. The effect of frequency of feeding on milk secretion in the Ayrshire cow. J. Dairy Sci. 43:1–7.

Vandehaar, M. J. 1998. Efficiency of nutrient use and relationship to profitability on dairy farms. J. Dairy Sci. 81:272–282.

Van Soest, P. J. 1994. Nutritional ecology of the ruminant. Cornell University Press. Ithaca, New York.

Verdi, R. J., D. M. Barbano, M. E. Dellavalle, and G. F. Senyk. 1987. Variability in true protein, casein, nonprotein nitrogen, and proteolysis in high and low somatic cell milks. J. Dairy Sci. 70:230–242.