Milk Urea Nitrogen Target Concentrations for Lactating Dairy Cows Fed According to National Research Council Recommendations[1]

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ABSTRACT

The objectives of this study were to develop and evaluate a mathematical model to predict milk urea N and to use this model to establish target concentrations. A mechanistic model to predict milk urea N was developed using raw data from 3 studies (10 diets, 40 cows, and 70 observations) and was evaluated with 18 independent studies (89 treatment means). For the independent literature data set, the model prediction error was approximately 35%; the majority of the error was due to variation among experiments. A mean of at least 25 cows was determined to be necessary for reliable model predictions. This model, which uses such data as protein intake and milk production, was used to predict milk urea N concentrations when cattle are fed according to National Research Council recommendations. Target values calculated in this manner for a typical lactation were 10 to 16 mg/dl, depending on days in milk. Target concentrations were sensitive to changes in milk production and amount of N intake and were relatively insensitive to body weight, parity, and grouping strategy. Analysis of data from the Lancaster Dairy Herd Improvement Association (n = 133,057) indicated that cows in the region were being fed diets containing approximately 17% crude protein, regardless of parity. A comparison to target milk urea N concentrations for this data indicated that cows were being fed 8 to 16% more protein than recommended by the National Research Council. Target milk urea N concentrations have been established, and dairy farmers now have a definitive way to interpret milk urea N concentrations.

(**Key words**: milk urea N, dairy nutrition, dairy management, modeling)

Abbreviation key: **BUN** = blood urea N, **MUN** = milk urea N, **NI** = N intake, **RMSPE** = root mean square prediction error, **UN** = urinary N excretion.

INTRODUCTION

Milk urea N (**MUN**) may be used as a management tool to monitor the nutritional status of lactating dairy cows. When adequate energy is in the diet of ruminant animals, both MUN and blood urea N (**BUN**) have long been known to be indicators of their protein status (2, 8, 10, 11, 14, 20, 22, 25). Variation in MUN has also been suggested to be related to the protein to energy ratio of the diet consumed (2, 8, 15, 18, 19).

In a previous study (26), urinary urea excretion was shown to have a positive linear relationship with BUN. Subsequently, this relationship has been demonstrated between MUN and total urinary N excretion (**UN**; 3, 14). Jonker et al. (14) further developed a mechanistic model that incorporated MUN and total milk protein to predict urinary and fecal N excretion, total N intake (**NI**), and N utilization efficiency in lactating dairy cattle. This model was suggested (14) as a basis for determining target MUN concentrations for cows fed according to NRC (17) recommendations.

The objectives of this study were 1) to evaluate a mechanistic model for predicting MUN, 2) to establish target MUN concentrations for cows fed according to NRC recommendations throughout a 305-d lactation, 3) to evaluate the sensitivity of predictions to various model inputs, 4) to determine changes in predicted MUN concentrations because of varying grouping strategies, and 5) to compare current MUN concentrations with target values for Lancaster DHIA data.

MATERIALS AND METHODS

Model Development and Evaluation

A previously published and evaluated model (14) that predicts UN and NI from MUN and total milk N was used as the basis for MUN predictions. The model equations (14) were reversed to predict UN and MUN from NI and total milk N (Table 1). Model predictions were then compared with residual (observed – predicted) values using raw data from 3

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TABLE 1. Model equations for predicting milk urea N (MUN) concentrations.

Prediction[1]	Equation
NI, g/d	Predicted from NRC[2]
UN[3], g/d	(Predicted NI × 0.83) − milk N − 97
MUN[3], mg/dl	Predicted UN/12.54

[1] NI = N Intake; UN = urinary N excretion; MUN = milk urea N.

[2] Reference (17).

[3] Equations adapted from a previously published mechanistic model (13). True digestibility of N = 0.83, metabolic N = 97 g/d, and urea clearance rate = 1254 L/d.

studies [10 diets, 40 cows, and 70 observations (14)]. These data had also been used to develop the coefficients for the original model and are thus identified as the developmental data set. Model predictions were also compared to residuals for a data set of independent observations from the literature [18 studies and 89 treatment means (14)]. Root mean square prediction error (**RMSPE**) and mean and linear bias of model predictions were determined (1). Model bias was further characterized using single and multiple regression analysis of residuals against selected variables. Statistical analyses were performed with JMP (12), and statistical significance was declared at $P < 0.05$ unless otherwise stated.

Target MUN Concentration

Target MUN concentrations were determined for cows fed according to NRC recommendations (17). Nitrogen intake was calculated throughout a standard 305-d lactation for cows fed diets balanced for RUP and RDP according to the NRC (17). The driving variables used to calculate NI for lactating dairy cows were milk production (kilograms per day), milk fat (percentage), BW (kilograms), live weight change (kilograms per day), parity (1, 2, or ≥3), and days pregnant. The NI was used to predict UN (Table 1), and this prediction was used to predict target MUN.

Lactation curves for daily milk production, milk fat percentage, and milk protein percentage were predicted using the equation (27)

$$y_n = an^b e^{cn}$$

where y_n = production character measured at week n of lactation, and a, b, and c = coefficients that define the shape of the lactation curve.

Milk production data from Lancaster DHIA (702 herds, 47,378 cows, and 133,057 observations) collected between July 1996 through April 1998 were used to parameterize the lactation curves for coefficients a, b, and c. Data were partitioned into first lactation, second lactation, and mature dairy cows (Table 2). Only records ≤ 305 DIM that included milk production, milk fat and protein percentage, MUN, and lactation number were included. These records were used to derive lactation coefficients (Table 3) for milk production, milk fat percentage, and milk protein percentage fitted to the equation structure described by Wood (27).

The lactation curves for daily BW were calculated from the equation (28)

$$C_n = Re^{-kn} + G\exp[h(1 - e^{-g(n-N)})]$$

where C_n = BW at week n of lactation, Re^{-kn} = BW available for loss at day n of lactation, $G\exp[h(1 - e^{-g(n-N)})]$ = total BW gain at week n of lactation, N = weeks of BW loss, and g, h, and k = coefficients that define the shape of the curve. The same coefficients (Table 3) were used as were previously published by

TABLE 2. Milk production and composition from Lancaster DHIA.[1]

Parameter	First lactation[2]		Second lactation[3]		Mature[4]	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Milk, kg/d	29.65	8.11	34.43	10.66	35.69	11.40
Milk fat, %	3.57	0.76	3.55	0.81	3.57	0.82
Milk protein, %	3.18	0.32	3.20	0.35	3.15	0.35
MUN,[5] mg/dl	16.32	5.63	16.64	6.01	16.15	6.04
DIM	151	84	145	85	141	85

[1] Data collected between July 1996 and April 1998.

[2] n = 45,107.

[3] n = 35,686.

[4] n = 52,264.

[5] Milk urea N.

TABLE 3. Lactation curve coefficients for milk production, milk fat and protein percentages, and BW fitted to the equation structure described by Wood (27, 28).

Prediction	Coefficient[1]					
	a		b		c	
	$\bar{X}$	SE	$\bar{X}$	SE	$\bar{X}$	SE
First lactation[2]						
Milk, kg	3.1196	0.0060	0.2049	0.0036	–0.0161	0.0003
Milk fat, %	1.3927	0.0047	–0.1212	0.0029	0.0092	0.0002
Milk protein, %	1.1646	0.0019	–0.0603	0.0011	0.0073	0.0001
MUN,[3] mg/dl	2.2581	0.0091	0.2520	0.0056	–0.0118	0.0004
Second lactation[4]						
Milk, kg	3.3631	0.0063	0.2391	0.0040	–0.0257	0.0003
Milk fat, %	1.3489	0.0049	–0.1148	0.0031	0.0099	0.0002
Milk protein, %	1.1812	0.0019	–0.0739	0.0012	0.0087	0.0001
MUN, mg/dl	2.2708	0.0092	0.3150	0.0059	–0.0198	0.0004
Mature[5]						
Milk, kg	3.3817	0.0052	0.2769	0.0034	–0.0303	0.0003
Milk fat, %	1.4074	0.0039	–0.1385	0.0025	0.0106	0.0002
Milk protein, %	1.1909	0.0016	–0.0893	0.0010	0.0096	0.0001
MUN, mg/dl	2.2540	0.0081	0.3147	0.0053	–0.0208	0.0004
BW,[6] kg	0.0875	NA[7]	4.8307	NA	0.1666	NA

[1] Coefficients for lactation curves for Wood's equations [(27); $y_n = an^b e^{cn}$] parameterized with data from Lancaster DHIA.

[2] n = 45,107.

[3] Milk urea N.

[4] n = 35,686.

[5] n = 52,264.

[6] Data for BW correspond to previously published coefficients g, h, and k respectively (28; $C_n = Re^{-kn} + G \exp[h(1 - e^{-g(n-N)})]$).

[7] Not available.

Wood (28). Daily BW changes were calculated from the first derivative of the previous equation (28).

The predicted NI requirements were used to predict UN and target MUN concentration throughout lactation. An average daily MUN concentration was determined for the entire lactation weighted by milk production. Base target MUN concentrations were determined for a 600-kg second lactation cow. A 10,000-kg lactation was assumed with 3.5% milk fat and 3.0% milk protein. A BW loss of 40 kg was presumed to occur during the first 70 DIM. Pregnancy was assumed to begin at 100 DIM to avoid effects of pregnancy on predicted daily NI values.

Sensitivity Analysis

A sensitivity analysis was performed to examine the effects of milk production, milk fat percentage, milk protein percentage, BW, and parity on predicted MUN concentrations for the model. Parameters were investigated individually to determine their individual effects.

The effects of overfeeding and underfeeding protein compared with feeding at NRC (17) recommendations were examined. A 10% increase or decrease in protein feeding level was simulated. Milk production was assumed to be unchanged so that even with a decrease in protein consumption, protein requirements were still assumed to be met for milk production.

Grouping

The consequences of grouping cows by DIM on predicted MUN concentrations from the model were examined for 1-, 2-, 3-, and 5-group feeding systems. Dietary protein concentrations were established for each group at the 83rd percentile for milk production within each group (23). Dry matter intake was predicted according to NRC (17) to meet energy requirements for the predicted production level at each DIM. Subsequently, protein was predicted to be limiting for milk production during some of the lactation.

Protein-allowable milk was estimated (5) from available protein based on predicted DMI and dietary protein concentrations for milk production at the 83rd percentile. When protein-allowable milk was less than predicted milk production from the lactation

TABLE 4. Partitioning of root mean square prediction error (RMSPE) for model predictions for a developmental and an independent literature data set for urinary N (UN) and milk urea N (MUN).

Data Set	Mean	RMSPE	CV	Mean bias			Linear bias			Residual error[4]
				Bias[1]	$P<$	Error[2]	Bias[3]	$P<$	Error	
						(%)			(%)	(%)
Development (n = 70)										
UN, g/d	253	45.9	18.1	–22.08	0.001	23.14	–0.22	0.001	19.15	57.71
MUN, mg/dl	20.1	4.70	23.4	–1.69	0.005	12.93	–0.47	0.001	48.28	38.79
Evaluation (n = 89)										
MUN, mg/dl	16.2	5.42	33.5	–0.52	NS[5]	0.93	–0.60	0.001	52.58	46.49

[1] Mean observation – mean prediction.

[2] Percentage of total prediction error explained by bias.

[3] Slope of residual on prediction.

[4] 100 – [error (percent) mean bias + error (percent) linear bias].

[5] $P > 0.10$.

curve, milk production was predicted to decline. Because DMI is predicted from NE_L, this loss in production affects the NE_L required, subsequently decreasing DMI. The protein-allowable milk was used to predict a new DMI. This new DMI was then used to predict a new protein-allowable milk. This process was repeated through a 20-step iteration to derive the final milk production used to generate target MUN concentrations for the various grouping strategies examined.

MUN Comparison

Target MUN concentrations were determined for Lancaster DHIA for first lactation, second lactation, and mature dairy cows. Lactation curves using the previously derived coefficients were used to predict NI from NRC (17) recommendations as indicated earlier with actual production data (Table 2). For first lactation, second lactation, and mature cows, BW were assumed to be 550, 600, and 650 kg, respectively. The target MUN concentrations were subsequently compared with observed values averaged by DIM to determine the level of N feeding compared with NRC (17) recommendations. Effects of grouping were not examined.

RESULTS

Model Development and Evaluation

Figure 1 shows predictions for UN and MUN from the developmental data set compared with residual (observed – predicted) values. The RMSPE ranged from 18.1 to 23.4% of mean predictions (Table 4), which are higher than those reported for the prediction of UN from MUN (14). Regression analysis of residuals versus predictions indicated a significant mean or linear bias for both predictions, accounting for approximately half of the RMSPE (Table 4; Figure 1).

Regression analysis of residuals for the developmental data set showed a prediction bias for many of the selected variables (Table 5), but most variables individually accounted for a small proportion of the residual error. Multiple regression analysis revealed that nearly half of the prediction error for both UN and MUN was due to random variation among cows, which included variation from study to study.

For the independent literature data set, MUN predictions had a larger RMSPE than the development data set (Table 4). The model had a significant linear bias (Figure 1C); MUN was overpredicted at high concentrations of predicted MUN that accounted for >50% of the error but no mean bias. Individual regression analysis indicated an effect on MUN prediction accuracy of nearly all variables for the independent literature evaluation data set (Table 6). Multiple regression analysis revealed the largest proportion of model error was due to random variation across experiments.

Target MUN

Lactation curves derived from the Lancaster DHIA data set were nearly identical for milk fat and protein percentage regardless of parity (Figure 2). Thus, lactation curve coefficients for milk fat and protein percentage were similar for all lactation groups (Table 3). First lactation cows had more persistent milk production after peak than did older cows (Figure 2A).

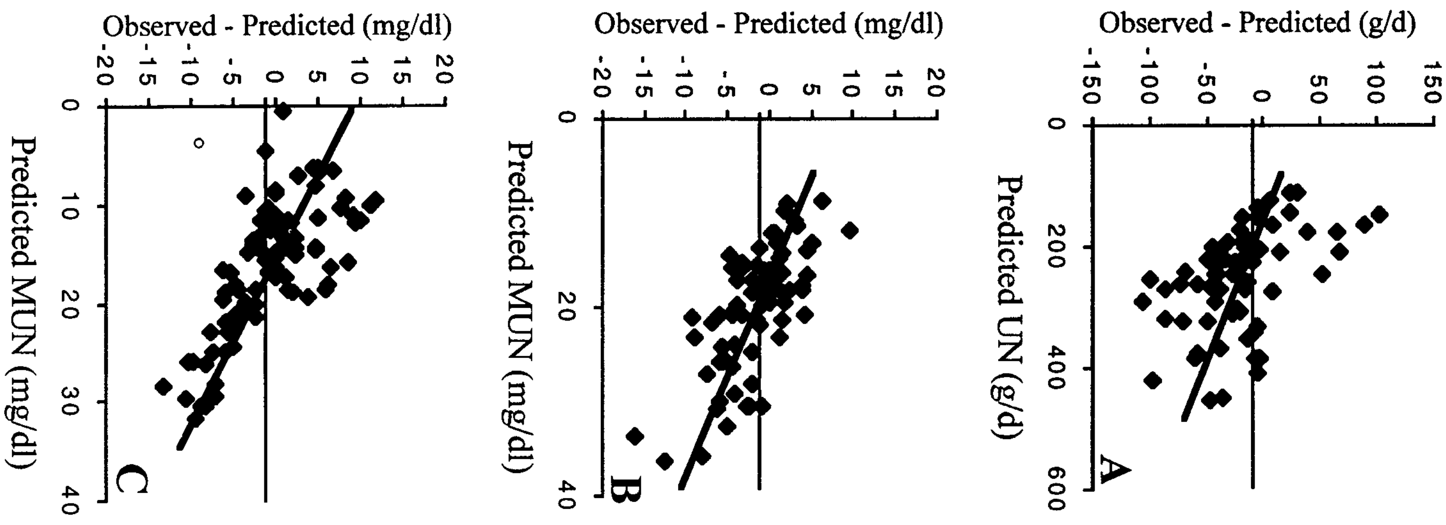

Figure 1. Residual (observed – predicted) compared with predicted urine N excretion (UN, grams per day) for the developmental data set with root mean square prediction error (RMSPE) = 45.9, slope = –0.23 ± 0.05, and intercept = 32.26 ± 14.24 (A) compared with predicted milk urea N (MUN, milligrams per deciliter); (B) for the developmental data set with RMSPE = 4.70, intercept = 7.71 ± 1.24, and slope = –0.47 ± 0.06; and compared with predicted MUN (milligrams per deciliter); and (C) for the independent literature evaluation data set with RMSPE = 5.42, intercept = 9.14 ± 1.06, and slope = –0.60 ± 0.06.

TABLE 5. Residual (predicted – observed) analysis for model developmental data set (n = 70 cow observations).

					MUN		Milk		DIM		BW		$BW^{0.75}$		CP	
Prediction[1]	R^2	Cow	Diet	Experiment	Slope[2]	r^2	Slope	r^2	Slope	r^2	Slope	r^2	Slope	r^2	Slope	r^2
		r^2														
Single[3]																
UN, g/d		0.76***	0.43***	0.35***	NS[4]	. . .	NS	. . .	NS	. . .	NS	. . .	NS	. . .	NS	. . .
MUN, mg/dl		0.81**	0.26***	NS	NS	. . .	0.13*	0.05	NS	. . .	–0.02*	0.05	–0.12*	0.05	0.49**	0.07
Multiple[5]																
UN, g/d	0.99	0.46[6]***	0.13***	0.34***	NS	. . .	NS	. . .	NS	. . .	NS	. . .	–6.06***	0.01	–31.92***	0.06
MUN, mg/dl	0.99	0.54***	0.08***	0.11***	NS	. . .	NS	. . .	–0.04**	0.01	–1.90*	0.01	11.35*	0.01	–3.09**	0.04

[1] UN = Urinary N excretion; MUN = milk urea N.

[2] Slope coefficient estimate of residuals (predicted – observed) for prediction.

[3] Regression analysis of residuals for UN and MUN respectively versus each parameter.

[4] $P > 0.10$.

[5] Multiple regression analysis of residuals (predicted – observed) for UN and MUN, respectively, versus variables; nonsignificant variables were excluded.

[6] Type III partial r^2.

*$P < 0.10$.

**$P < 0.05$.

***$P < 0.01$.

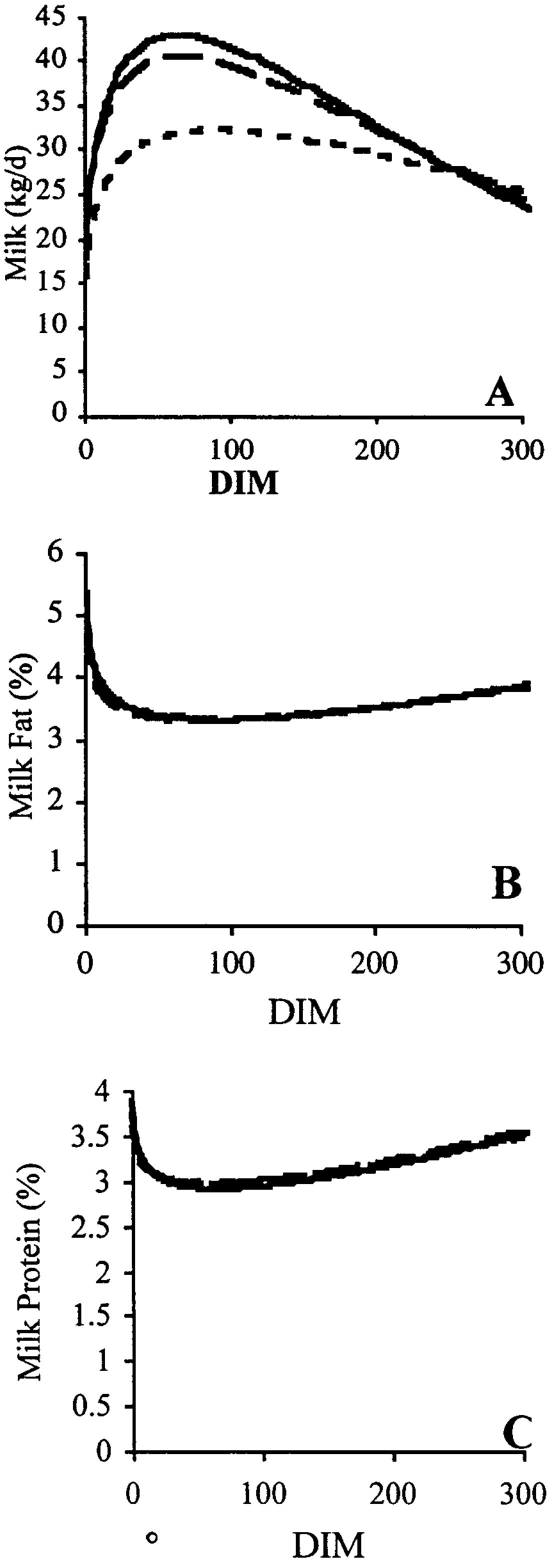

Figure 2. Predicted 305-d lactation curves of first lactation (– – – –), second lactation (———), and mature cows (— —) for milk production (kilograms per day (A); milk fat percentage (B); and milk protein percentage (C).

Mean MUN concentration predicted by the model weighted by milk production for the entire 10,000-kg lactation was 13.1 mg/dl (Table 7). Peak MUN concentration of 14.4 mg/dl occurred at 78 DIM. In contrast, peak milk production occurred at 65 DIM.

Sensitivity Analysis

The mean lactational MUN concentration for the model was most sensitive to feeding level relative to requirements and milk production and least sensitive to BW and parity (Table 7; Figure 3). The peak MUN concentration was predicted to occur at approximately 11 wk of lactation, regardless of changes in inputs (Figure 3), except for first lactation cows. When the NRC protein feeding level was altered by ±10%, mean MUN changed by approximately ±25%. A 2000-kg increase in milk production per lactation resulted in a 2.6-mg/dl increase in the mean target MUN concentration. Changes in parity at the same production level altered target MUN concentrations by <4%.

Grouping

For a 1-group TMR, cows in late lactation were predicted to be overfed protein, which increased predicted MUN concentrations in late lactation (Figure 4); peak MUN occurred at 305 DIM. An increase in mean lactational MUN of 7% for a 1-group TMR compared with individual feeding is expected when feeding at the 83rd percentile production level (Table 8), and peak MUN was anticipated to occur at 305 DIM. All other multiple grouping strategies by DIM resulted in <3% increase in mean lactational MUN concentration because of decreased overfeeding of protein in late lactation (Table 8; Figure 4). Predicted milk loss caused by protein limitation is <1.5% for all grouping scenarios examined.

MUN Comparison

Target MUN concentrations averaged 11.7, 12.8, and 13.0 mg/dl for first lactation, second lactation, and mature cows, respectively, for the Lancaster DHIA data set (Figure 5). Comparatively, actual MUN concentrations averaged 16.3, 16.8, and 16.2 mg/dl. These MUN concentrations would occur when the estimated CP percentage of diets consumed by cows averaged approximately 17% for all lactations, but NRC (17) recommended smaller amounts of CP, which differed depending on parity. Overfeeding of N compared with NRC (17) recommendations ranged from 8% for mature cows to 16.5% for first lactation cows (Table 9).

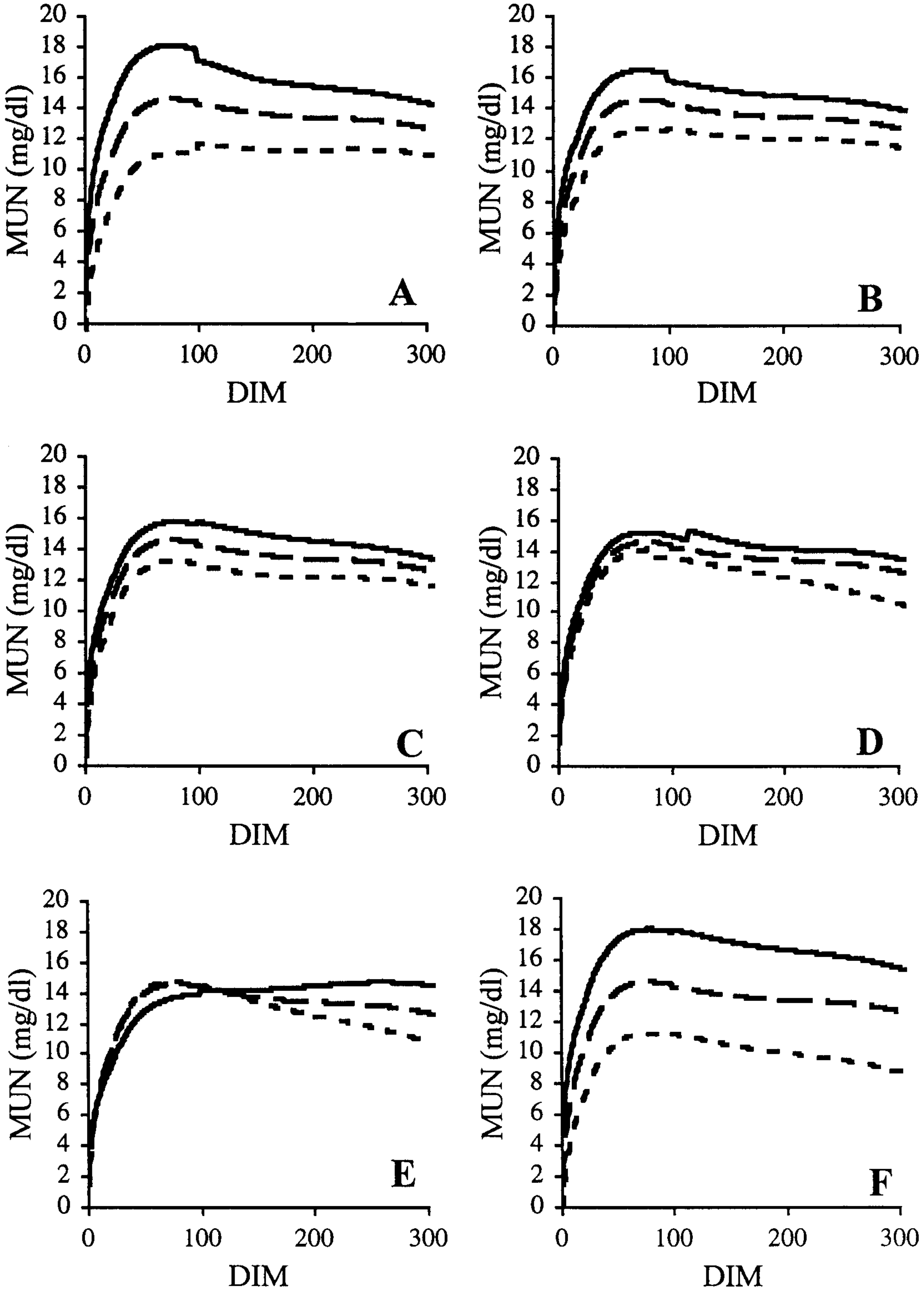

Figure 3. Predicted milk urea N (MUN, milligrams per deciliter) throughout a 305-d lactation for milk production (A) [12,000-kg (———), 10,000-kg (— —), and 8,000-kg (– – – –)], milk fat percentage (B) [4.0% (———), 3.5% (— —), and 3.0% (– – – –)], milk protein percentage (C) [3.3% (———), 3.0% (— —), and 2.7% (– – – –)], BW (D) [700 kg (———), 600 kg (— —), and 500 kg (– – – –)], parity (E) [first lactation (———), second lactation (— —), and third lactation (– – – –)], and NRC protein feeding level (F) [110% (———), 100% (— —), and 90% (– – – –)].

TABLE 6. Residual (observed – predicted) analysis for independent literature evaluation data set (n = 89 treatment observations) for milk urea N (MUN) in milligrams per day.

				MUN		Milk		DIM		BW		BW$^{0.75}$		CP	
MUN, mg/dl	R^2	Forage[1]	Experiment	Slope[2]	r^2	Slope	r^2	Slope	r^2	Slope	r^2	Slope	r^2	Slope	r^2
		r^2													
Single[3]		0.48***	0.91***	NS[4]	. . .	−0.40***	0.28	−0.03*	0.04	−0.05***	0.46	−0.33***	0.45	−0.63*	0.06
Multiple[5]	0.97	NS	0.10[6]***	0.75***	0.04	NS	. . .	NS	. . .	−0.01***	0.01	NS	. . .	−0.53***	0.01

[1] Effect of forage type (alfalfa silage, alfalfa hay, corn silage, grass hay, grass silage, mixed forage, oat silage, or pasture).

[2] Slope coefficient estimate of residuals (predicted – observed) for prediction.

[3] Regression analysis of residuals for MUN versus each parameter.

[4] $P > 0.10$.

[5] Multiple regression analysis of residuals (predicted – observed) for MUN versus variables; nonsignificant variables were excluded.

[6] Type III partial r^2.

*$P < 0.10$.

**$P < 0.05$.

***$P < 0.01$.

DISCUSSION

Model Function

Coefficients for the model are biologically relevant (Table 1), and, therefore, the model is mechanistic as opposed to an empirical model that merely draws associations between parameters. True digestibility of N was determined to be 0.83 with metabolic N of 97 g/d [$R^2 = 0.97$ (14)]. These data were used to predict UN as NI × true digestibility – milk N – metabolic N. The renal clearance rate of urea from the blood was determined to be 1254 L/d (14). This value was used to calculate MUN from UN, assuming MUN equilibrates with urea in blood.

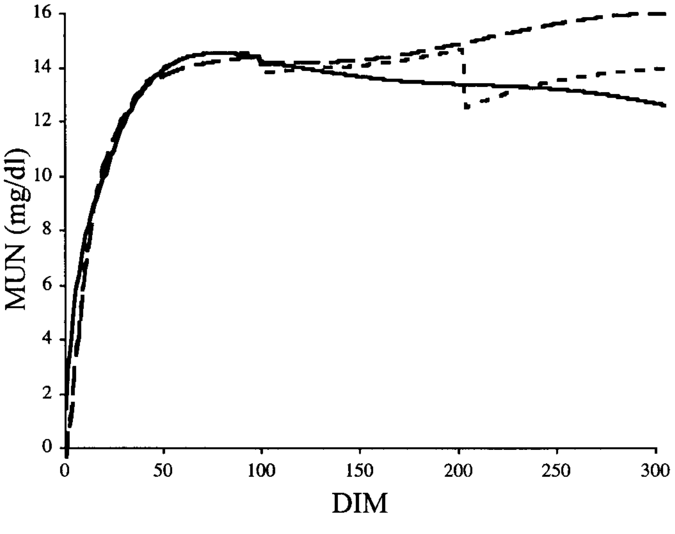

Figure 4. Predicted milk urea N (MUN, milligrams per deciliter) throughout a 305-d lactation for dairy cows fed individually (———), a 1-group TMR (— —), or a 3-group TMR (– – – –).

The model relies on principles of physiology. The prediction of UN (Table 1) is based on the law of mass conservation. A proportion of the total NI is absorbed from the gut by the cow, given by the true digestibility coefficient (14). This absorbed N has four ultimate fates: secretion as milk N, retention as tissue N, secretion as metabolic N, or excretion as UN. The metabolic N coefficient, determined by the Lucas test (16), can result from secretory and excretory materials. According to the conservation of mass, when milk, tissue, and metabolic N are subtracted from absorbed N, the result must be UN.

Absorbed N in the blood stream of a dairy cow results from the diffusion of ammonia across the rumen wall and transport of amino acid and peptides from the small intestine (14). Ammonia is toxic to the cow and is rapidly converted to urea in the liver (24). Absorbed amino acids and peptides that are not utilized for milk synthesis are deaminated in the liver for energy, and N is converted to urea (24). This urea becomes part of the BUN pool.

The prediction of MUN for the mechanistic model (Table 1) uses physiological principles. The coefficient represents the renal clearance rate of urea from blood (14). Urea is a small molecule that readily diffuses across cellular membranes. As milk is secreted in the mammary gland, urea diffuses into and out of the mammary gland, equilibrating with urea in the blood. Because of this process, MUN equilibrates with and is proportional to BUN (22).

TABLE 7. Effect of various factors on target lactational milk urea N (MUN) concentrations estimated from intake N predictions from the NRC (17).

	MUN			
	Mean[1]	Minimum[2]	Maximum	d[3]
	(mg/dl)			
Simulation[4]	13.1	1.4	14.4	78
Milk, kg				
+2000	15.7	3.4	18.0	76
–2000	10.5	0.0	11.0	82
Milk fat, %				
+0.5	14.7	2.8	16.4	77
–0.5	11.8	0.1	12.6	80
Milk protein, %				
+0.3	11.9	0.6	13.1	79
–0.3	14.4	2.2	15.9	78
BW, kg				
+100	14.0	2.1	15.1	77
–100	12.2	0.8	14.0	82
Parity				
1	13.5	2.3	14.6	275
3	12.7	0.6	14.6	79
NRC, %				
+10	16.5	3.2	18.1	83
–10	9.8	0.0	10.9	79

[1] Mean MUN weighted by milk production for the entire 305-d lactation.

[2] Minimum MUN concentration occurred at DIM = 1 for all simulations.

[3] Day of peak MUN concentration.

[4] Milk = 10,000 kg per lactation, milk fat = 3.5%, milk protein = 3.0%, BW = 600 kg, and parity = 2.

Because a constant volume of blood is cleared of urea per day by an animal in a normal physiological state, UN is proportional to BUN. These relationships allow MUN to be an excellent predictor of UN (3, 14) and vice versa as demonstrated in the current study.

The effects of energy availability and protein degradability on MUN levels are currently debated. Recent research (2) analyzing data collected from 35 conventional lactation trials showed no effect of total NE$_L$ (Mcal/d) and NPN (grams per day) intake or dietary concentration of NE$_L$ (megacalories per kilogram of DM) and NDF (percentage of DM) in single factor regression analysis. In multiple regression analysis in the same study (2), ruminal NH$_3$ (milligrams of N per deciliter) was not significant. Protein to energy ratio was significant in the study (2). The model used in the current study accounts for the effect of protein and energy interaction. When diet energy is low, milk production is lost, causing less protein secretion in milk, greater UN, and higher MUN.

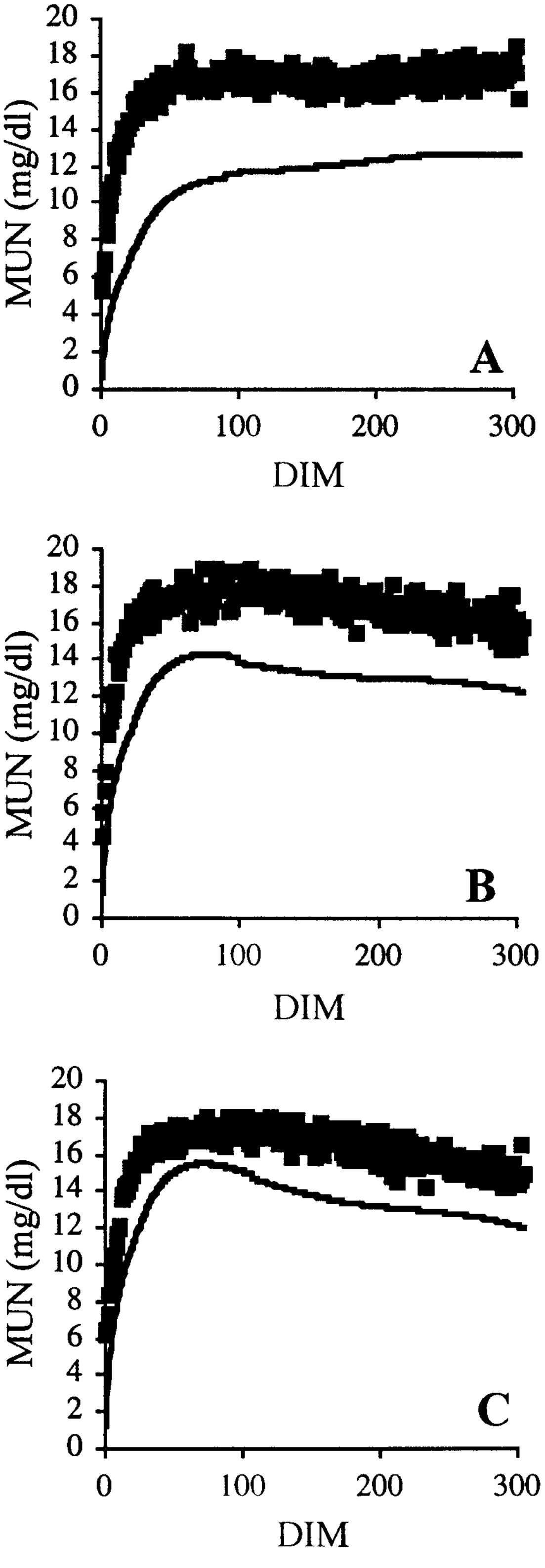

Figure 5. Observed milk urea N (MUN, milligrams per deciliter) from Lancaster DHIA (■) averaged by DIM compared to predicted MUN (———) throughout a 305-d lactation for first lactation (n = 45,107; A), second lactation (n = 35,686; B), and mature (n = 52,264; C) dairy cows.

TABLE 8. Effect of grouping on target lactational milk urea N (MUN) concentrations estimated from intake N predictions from the NRC (17).

	MUN				
Group[1]	Mean[2]	Minimum[3]	Maximum	Milk[4]	d[5]
	(mg/dl)			(kg)	
Individual[6]	13.1	1.4	14.4	10,000	78
1	14.0	0.0	16.0	9 905	305
2	13.4	0.0	14.6	9 865	305
3	13.4	0.0	14.7	9 892	203
5	13.4	0.0	14.2	9 916	82

[1] Grouped evenly throughout a 305-d lactation by DIM. Each group is fed protein concentration required at the 83rd percentile milk production level.

[2] Mean MUN weighted by milk production for the entire 305-d lactation.

[3] Minimum MUN concentration occurred at DIM = 1 for all simulations.

[4] Total milk production for 305-d lactation with predicted milk loss caused by grouping.

[5] Day of peak MUN concentration.

[6] Milk = 10,000 kg per lactation, milk fat = 3.5%, milk protein = 3.0%, BW = 600 kg, and parity = 2.

Model Evaluation

Developmental data set. The model contained both a mean and linear bias for both predictions, accounting for over 40% of the RMSPE (Table 4). The slope bias for the model would have resulted from reversing the equation from the original model to now predict a variable that previously was the predictor (4). The assumption of no tissue N gain or loss in the model further increased mean and linear bias for model predictions.

Regression analysis using the developmental data set (Table 5) indicated an effect of most variables on model error for all predictions. However, further analysis with multiple regression revealed the largest proportion of model error is due to random variation among cows. Because many of the other variables were highly correlated with an individual cow, their overall contribution to model error in the multiple regression analysis was small.

TABLE 9. Predicted daily mean nutritional parameters for Lancaster DHIA data set from actual and target milk urea N (MUN) concentrations.

	First lactation		Second lactation		Mature	
	$\overline{X}$	SE	$\overline{X}$	SE	$\overline{X}$	SE
NRC DMI,[1] kg/d	19.7	0.11	20.7	0.09	20.5	0.09
NI,[2] g/d	536	2.0	568	2.4	562	2.6
NRC NI,[1] g/d	460	2.3	509	2.4	520	2.8
CP,[3] % DM	17.04	0.06	17.16	0.04	17.14	0.04
NRC CP,[4] % DM	14.57	0.02	15.37	0.03	15.83	0.03

[1] Determined from NRC (17).

[2] NI = (MUN × 12.54 + Milk N + 97)/0.83 (13).

[3] CP = NI/NRC DMI.

[4] NRC CP = NRC NI/NRC DMI.

Independent literature data set. Because a total N balance was performed on only two experiments (six diets), UN predictions were not examined. The assumption of no tissue N gain or loss in the model increased the model error for the MUN prediction, contributing to the large linear bias (Table 4).

Although most parameters significantly contributed to model error from the individual regression analysis, the largest proportion of model error was due to variation among experiments in the multiple regression analysis (Table 6). Because many of the other variables were highly correlated with an individual experiment, their overall contribution to model error in the multiple regression analysis was small. Cow-to-cow variation may explain a large part of these effects but could not be evaluated because only treatment means were available for analysis. Effects may also result from the bias of different laboratory techniques for determining MUN (6). However, in different experiments in which the same technique was used, an experimental bias could still exist because of time of feeding compared with MUN sampling (9).

Although effects of forage type (alfalfa silage, alfalfa hay, corn silage, grass hay, grass silage, mixed forage, oat silage, or pasture) were significant in the individual regression analysis, this variation was completely explained in the multiple regression by differences among experiments. Therefore, forage effects may have been due to differences from experiment to experiment.

Body weight exhibited a significant effect on MUN predictions for both data sets (Table 5; Table 6) for the multiple regression analysis. Less than 3% of the unexplained model error was attributed to BW variation in the multiple regression analysis. In the previously published model (14), BW had a negative correlation with MUN concentration, which is consistent with previous research (18). Mechanistically, on the basis of dilution, when the same amount of urea is formed in the liver, a large animal will have more blood than a smaller animal, subsequently causing lower urea concentrations in both blood and milk (24) for the same amount of total urea. Larger cows are also more likely to have higher renal clearance rates (24). Variation in BW measurements caused by

TABLE 10. Effect of sample size on 95% CI for cows.

	Developmental data set[1]				Independent literature data set[2]			
Prediction[3]	1[4]	25	50	100	1	25	50	100
UN, g/d	±92[5]	±18	±13	±9	NA[6]	NA	NA	NA
MUN, mg/dl	±9.40	±1.88	±1.33	±0.94	±10.84	±2.17	±1.53	±1.08

[1] From root mean square prediction error for each prediction from developmental data set.

[2] From root mean square prediction error for each prediction from independent literature evaluation data set.

[3] UN = Urinary N excretion; MUN = milk urea N.

[4] Number of cows in sample.

[5] 95% CI = ±2 × root mean square prediction error/$\sqrt{\text{no. of cows in sample}}$.

[6] Not available.

gastrointestinal fill, milk volume in the udder, and methods of measurement appeared to add so much variation to the original model predictions (14) that the inclusion of BW in the current model was not justifiable.

Milk production exhibited a significant effect on the accuracy of MUN predictions for both data sets with the single regression analysis (Table 6), but this effect was not significant after we removed differences among studies. The models use milk production and protein content in the prediction of UN. The lack of an effect of milk production in the multiple regression analysis demonstrated that the model accurately accounted for this effect.

Sample size. As with any method to measure or predict a response, the confidence is greater for a mean as the sample size becomes larger. Table 10 shows the effect of sample size on the 95% confidence interval for each prediction. With the 95% confidence interval, the MUN prediction from the model for an individual observation could vary by ±48% from the actual MUN value for the developmental data set. However, this confidence interval would be reduced to ±9% for the mean of 25 randomly selected cows. The confidence interval for MUN prediction from the independent literature evaluation data set was ±13% for the mean of 25 cows. The current model and analysis can be used to predict variables accurately when 25 or more observations are averaged. As laboratory testing of MUN becomes more routine and consistent a reduction in this amount may occur.

Differences among studies in the independent literature data set demonstrate the need to be cautious about interpretation of model predictions for dairy cows that are not similar to those from the original data set. The original data set included only high producing Holstein cows. The independent literature data set included high producing, higher BW Holsteins as well as lower producing, lower BW Jersey and Red and White Nordic dairy cows. These differences in BW and production could account for differences in the RMSPE for the independent literature data set compared with the original data set. Adjusting the renal clearance rate of urea for BW may be appropriate (14). To establish a 95% confidence interval for model predictions, the RMSPE of the independent literature data set provides a more conservative estimate.

Target MUN Concentrations

Target MUN concentrations across the lactation resembled lactation curves for milk production (Figure 2; Figure 3). Milk production drives the requirement for N in lactating dairy cows fed according to the NRC (17). As milk production increases, when cows are fed according to NRC recommendations, predicted MUN concentrations increase linearly because of higher NI and N excretion. Subsequently, target MUN concentrations are extremely sensitive to changes in milk production.

Sensitivity of target MUN concentrations to changes in milk fat and protein percentages occur for two reasons. For NRC (17) predicted NI requirements, milk fat percentage (along with volume) drives the N requirement for lactation (17). The model prediction for UN uses total milk N and affects target MUN concentrations. Increased milk protein percentage reduces target MUN concentrations because more NI is partitioned to milk protein.

Target MUN concentrations were generally insensitive to changes in parity and BW. Differences in target MUN concentrations among parity groups (Table 7) are due to increased NRC (17) maintenance predictions of first and second lactation cows to allow for growth. A 100-kg change in BW produced little change in target MUN, but larger differences can be expected to cause larger differences in MUN concentrations. Rodriguez et al. (21) reported lower MUN content in milk from Jersey cows compared with the MUN content from milk from Holstein cows, and Ferguson et al. (7) observed Jersey cows to have higher MUN than Holstein cows from Pennsylvania DHIA data. These discrepancies were likely caused by four factors: BW, milk production, milk fat and protein percentage, and NI. Renal clearance rates and blood volume may increase as animal size increases (24) and could affect differences in MUN observed between breeds as well.

The amount of protein fed with regard to NRC (17) protein requirements has the greatest effect on target MUN concentrations. Feeding more than NRC recommendations for NI by 10% increases lactational MUN by 13%. This excess NI results in elevated feed costs and excess UN excreted into the environment. This response clearly demonstrates that MUN is very sensitive to overfeeding protein and will be useful in field applications.

Grouping strategies. Grouping by DIM appears to have little effect on predicted target MUN concentrations. A 1-group TMR elevates target MUN levels by <7% over the individual feeding of a cow every day of lactation to meet NRC recommendations for NI. Previously, Dunlap et al. (5) showed that grouping strategies had a similar impact on N excretion, which is consistent with these results. Predicted milk production loss because of protein limitation was minimal.

MUN Comparison

Elevated MUN levels compared with target concentrations for the Lancaster DHIA data set indicated an excess feeding of N compared with NRC (17) recommendations (Table 9). Although the NRC recommends that CP concentrations differ based on parity, results clearly indicated that, on average, cows in the data set were being fed at the same CP level (approximately 17% CP) regardless of parity.

Overall, the excess feeding of N to cows from the Lancaster DHIA data set can result in excess N loading to the environment and potentially decreased income. Decreased income can result from elevated feed costs caused by overfeeding protein and milk loss because of the energy cost associated with excreting excess N from the cow (13). Feeding excess N to dairy cows can contribute to N loading of water resources, and MUN can be used to quantify this within a watershed (13).

Applications

The primary field application of the model is the interpretation of MUN concentrations. When a group of cows has a mean MUN concentration higher than the target MUN values at a given level of production, excess CP is consumed. The number of cows in the group must also be considered for the precision of the target MUN range.

Reformulating the diet at that production level with a lower protein concentration could reduce feed costs. However, before a diet can be reformulated, the specific cause of high MUN should be identified. High MUN can be caused by a number of nutritional and management factors, and these factors should be carefully examined to determine which is the source.

A first area to examine is the production of the cows compared to the dietary expectations for production. An elevated MUN (above target levels) would indicate that excess protein is being consumed at that production level. Either the diet has been balanced for a level of milk production that is unrealistic or cows are not producing to their potential. Depending on circumstances, different paths can be used to reduce MUN.

The first step in both scenarios is to examine ration formulation because we need to determine if the diet is formulated to meet the cows' nutrient needs. If the ration is simply balanced for a level of production that is unachievable, rebalancing the ration at lower levels will reduce excess protein intake and reduce MUN concentration. If cow production is being hindered, an examination of ration formulation could reveal an inadequate supply of energy for the desired production level. Correcting energy deficiency could increase milk production and subsequently lower MUN concentration.

Elevated MUN and lost milk production can also result from improper balancing of RDP and RUP. Excess protein degradation in the rumen (higher levels of RDP compared to requirements) can lead to high MUN concentrations (2). However, excess protein in the tissues (higher levels of RUP compared to requirements) can result in elevated MUN (2). Proper balancing of protein fractions can reduce MUN and increase milk production.

When ration formulation appears to be correct, several other factors can be considered. Nutrient composition of forages can change dramatically from field to field and cutting to cutting, so proper and timely forage testing is required for accurate diet formulation. If any of the feed ingredients have heat damage, a significant proportion of bound protein may reduce absorbed protein. Subsequently, MUN may be lower than expected. Close examination of the current diet will help elucidate the cause of high MUN and lead to appropriate dietary changes to reduce MUN.

Elevated MUN could also occur because of management factors. An improperly mixed TMR can result in inadequate distribution of nutrients allowing some cows to consume more protein than others. Careful consideration needs to be given so that any particular diet ingredient is not over or underfed. If, for example, soybean meal is overfed and corn meal is underfed, there will be an excess of protein in the diet relative to available energy, and high MUN concentrations will result. Determining whether the amount of protein in a diet meets NRC recommendations without compromising milk production is difficult because a number of factors may be the source of difference (i.e., feed variation, feed mixing, and nutrient requirements).

The model may also prove invaluable for environmental applications. By comparing actual MUN concentrations with target levels, N flows on a single farm can be examined, and improvements in N utilization may be identified. Using target values for MUN may also prove useful for regional estimation of the potential to reduce N loading to water resources from dairy farms.

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