A Meta-Analysis on the Relationship Between Intake of Nutrients and Body Weight with Milk Volume and Milk Protein Yield in Dairy Cows

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ABSTRACT

Previously observed strong relationships between dry matter (DM) intake and milk yield in dairy cows were the basis for this meta-analysis aimed to determine the influence of intake of specific dietary nutrients on milk yield and milk protein yield in Holstein dairy cows. Diets (563) from feeding trials published in the *Journal of Dairy Science* were evaluated for nutrient composition using 2 diet evaluation programs. Intake of nutrients was estimated based on DM intake and program-derived diet composition. Data were analyzed with and without the effect of stage of lactation. Models based on intake of nutrients improved prediction of milk yield and milk protein yield compared with DM intake alone. Intake of net energy of lactation was the dominant variable in milk yield prediction models derived from both diet evaluation models. Milk protein yield models also improved prediction over the DM intake model. These models were dominated by ruminally undegradable protein intake and included a number of energy-related intake variables. In most models, incorporating stage of lactation improved the model fit.

(Key words: dairy cow, nutrient intake, milk yield, milk protein yield)

Abbreviation key: AC = all cows, BIC = Bayesian information criterion, CHO = carbohydrates, CPM = model based on CPM Dairy, version 1.0, DIM1 = early-lactation cows (DIM < 100), DIM2 = mid- and late-lactation cows (DIM ≥ 100), MY = milk yield, MPY = milk protein yield, NRC = model based on NRC (2001), VIF = variance inflation factor.

INTRODUCTION

Dry matter intake and milk yield (MY) are fundamentally related in dairy cows. The lag between peak MY and peak DMI in the early stages of lactation ap-

pears to support the concept that intake is driven by milk production (NRC, 2001). Reports by Moore and Mao (1990), Rook et al. (1992), and Fuentes-Pila et al. (2003) confirmed the strong relationship between DMI and MY in the lactating dairy cow. A survey of a large data set including nutritional studies published in the *Journal of Dairy Science* (volumes 1 to 82) showed a moderate linear relationship ($r^2 = 0.47$) between DMI and MY (Hristov et al., 2000, 2004). In addition to DMI, intake of dietary energy and protein, or individual carbohydrate (CHO) and protein fractions may be important factors in controlling MY and milk protein yield (MPY) in dairy cows (DePeters and Cant, 1992; Hristov et al., 2004).

Dietary DM is a multicomponent entity. Diet evaluation and formulation models, using various procedures, have separated dietary CP and energy-yielding substrates into fractions characterized by different rates and extents of ruminal and total tract digestion (Jarriage, 1989; Sniffen et al., 1992; NRC, 2001). The Cornell Net Carbohydrate and Protein System fractionated feed CHO and proteins through physical or chemical methods (Sniffen et al., 1992); CPM Dairy, a computer program based on the Cornell Net Carbohydrate and Protein System principles, is commonly used in formulating diets for dairy cattle in the United States. In NRC (2001), information on feed protein degradability from in situ fermentation was used and CHO fractions were separated based on chemical analyses (NDF/ADF) or by difference (NFC). In this context, intakes of individual nutrients, rather than DMI, may be better predictors of MY and MPY in dairy cows.

Thus, the objective of this meta-analysis was to develop prediction models for MY and MPY in Holstein dairy cows based on DMI, intake of dietary nutrients (estimated with 2 diet evaluation models), and BW.

MATERIALS AND METHODS

Input Data

Diets (563 treatment means) from feeding trials (173) involving Holstein cows conducted in the United States

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Table 1. Summary statistics for intake variables and responses considered for the CPM and NRC models (n = 563).¹

	Mean	Median	Min	Max	SD
	kg/d (or as indicated)				
CPM models					
CP	4.0	3.9	2.0	6.1	0.64
RDP	2.6	2.6	1.2	4.1	0.46
RUP	1.4	1.3	0.7	2.8	0.32
Soluble protein	1.5	1.5	0.5	3.0	0.43
NE _L , Mcal/d	37.9	37.6	23.7	52.9	4.72
NDF	6.8	6.7	4.2	11.4	1.23
Nonstructural carbohydrates	9.4	9.3	4.6	14.1	1.64
Fermentable carbohydrate	9.0	9.0	6.2	12.7	1.05
Fermentable NDF	2.1	2.0	1.1	4.7	0.52
Carbohydrate fraction A	1.1	1.1	0.3	2.7	0.34
Protein fraction B1	0.46	0.47	0.03	1.01	0.179
Protein fraction B2	1.9	1.9	0.8	3.1	0.43
NRC					
CP	3.9	3.9	1.9	6.1	0.65
RUP	1.2	1.2	0.6	2.1	0.30
RDP	2.7	2.7	1.1	4.3	0.53
NE _L , Mcal/d	35.6	35.6	25.0	46.2	3.71
NFC	9.2	9.2	3.8	13.6	1.65
NDF	6.8	6.6	3.9	11.2	1.18
Forage NDF	4.9	4.8	1.3	9.1	1.16
Fat	0.88	0.77	0.43	1.94	0.321
BW (kg)	601	600	476	750	45.7
Response variables					
DMI	22.2	22.0	16.0	29.9	2.57
Milk yield	32.2	32.0	20.3	47.7	5.43
Milk protein yield	0.99	0.99	0.62	1.57	0.156

¹CPM = CPM Dairy, a computer program based on the Cornell Net Carbohydrate and Protein System principles; NRC model is based on NRC (2001).

and Canada published in the *Journal of Dairy Science* (volumes 73 through 83)* were evaluated for nutrient composition using 2 diet evaluation models: CPM Dairy [version 1.0; Cornell University, Ithaca, NY; University of Pennsylvania, Kennett Square, PA; and William H. Miner Agricultural Research Institute, Chazy, NY; (CPM)] and National Research Council (2001) (NRC). Nutrient intakes were estimated based on published DMI and CPM- or NRC-derived compositions. Feeds (and level of processing) listed in the publications were matched with feeds from feeding model libraries. The chemical composition of dietary energy and proteinaceous concentrates was not edited. Whenever available (in 46.5% of the studies), CP and NDF concentration of forages were modified to reflect actual published, dietary concentrations. Although the output from these nutritional programs may not reflect the actual nutrient composition of each diet, it does provide reasonable estimates. Details on feed ingredients and diet composition are given in Hristov et al. (2004) and Table 1.

Compared with our previous work (Hristov et al., 2004), the size of the data set used in this analysis was reduced to involve only studies in which BW of the cows was published. The data were analyzed both as a set (all cows; AC), without regard to DIM and as cows grouped into 2 categories according to lactation stage: early-lactation cows (DIM < 100; DIM1) and mid and late-lactation cows (DIM ≥ 100; DIM2). This grouping was based on the assumption that DMI is limiting milk production in the early stages of lactation (wk 12 to 16; Kertz et al., 1991; Roseler et al., 1997b), whereas cows beyond 100 DIM would normally be in positive nutrient (energy) balance.

The response variables were MY and MPY. The average (±SD) DMI of the cows involved in this study was 22.2 ± 2.6 kg/d with a minimum of 16.0 and a maximum of 29.9 kg/d. Average MY was 32.2 ± 5.4 kg/d and had a minimum of 20.3 and maximum of 47.7 kg/d. Average milk fat and milk protein concentrations were 3.5 ± 0.4 and 3.1 ± 0.21%, respectively. Average MPY was 0.99 ± 0.16 kg/d with a minimum and maximum of 0.62 and 1.57 kg, respectively. Average milk protein N efficiency [(milk protein yield ÷ 6.38) ÷ N intake] was 24.9 ± 4.2% with a minimum and maximum of 13.7 and 43.6%, re-

*A complete list of references used in the meta-analysis is available as a data supplement online (<http://jds.fass.org>).

spectively. Mean BW was 601 ± 46 kg (minimum 476, maximum 750 kg). The dietary variables derived from the feeding programs and considered in this structural analysis are given in Hristov et al. (2004). Ratios among protein and energy variables and BW were considered for having potential relationships with the response variables. In this analysis, not all variables were present across all observations in the data set. Hence, the number of observations used for regression analyses varied between MY and MPY models depending on the regressor variables available.

Statistical Analyses

Details on variable selection and statistical analysis were similar to Hristov et al. (2004). As an initial step, the data were inspected for similarity among the nutritional variables. Because most of the data were derived from computational nutritional programs, some variables were essentially numeric derivatives of others, and thus, would be redundant as regressors in any subsequent analysis. This situation could be quickly assessed by calculating simple linear correlations among the nutritional variables. Pairs of explanatory variables having correlation values larger than 0.80 were considered to indicate sufficient redundancy to warrant action. In most cases, only one variable of the pair was selected for further analysis. Preference in these cases was given based on the biological relevance or the reliability of the analytical procedures used to derive the variables (NDF vs. effective NDF, for example).

Multiple linear regression was then used to investigate the structural relationship among the responses, MY and MPY, and DMI and the remaining nutrient intakes obtained from CPM and NRC programs. Because the data used in this meta-analysis were collected from multiple studies conducted over many years, the random effects of each study needed to be accounted for in the modeling process (St-Pierre, 2001). In this case, random effects were incorporated into the estimation procedure using a mixed model framework. The general form of the mixed model is as follows:

$$\mathbf{Y} = \mathbf{X}\beta + \mathbf{Z}\gamma + \varepsilon, \quad [1]$$

where $\mathbf{Y}$ is the response being modeled, $\mathbf{X}$ is a matrix of the intercept term and the nutritional variables, and β is a vector of the corresponding regression coefficients. These terms represent the fixed portion of the model and are equivalent to those found in a standard multiple linear regression. The additional components, $\mathbf{Z}$ and γ , account for the random effects due to the various studies; $\mathbf{Z}$ represents either all or a portion of the variables

present in $\mathbf{X}$, and γ is a vector of their associated coefficients; ε is a random error term and is assumed to be normally distributed with a mean of 0 and constant variance.

To account for the precision of each study, each regression analysis was weighted by the reciprocal of the squared response standard errors, as reported in each study (St-Pierre, 2001).

Because some intake regressors still exhibited collinearity, subsets of regressors were created within each of the CPM and NRC datasets. In each case, the subsets were chosen such that any highly correlated variables were separated, i.e., they did not occur within the same subsets, and the variance inflation factor (**VIF**), a statistic measuring collinearity, for the subset was less than 30. To identify a final model from each subset, the backwards elimination technique described by Oldick et al. (1999) and Firkins et al. (2001), was used for variable selection. At each stage of elimination, the P value and VIF of each variable were evaluated as described in Oldick et al. (1999). Once the selection process had identified a reduced model, all possible 2-way interactions and quadratic terms derived from the remaining variables were added to the model. The backwards elimination procedure was then repeated, except that main effects remained in the model, even when nonsignificant, if they were involved in any significant interaction or squared term.

Estimation for all models was carried out using the method of restricted maximum likelihood assuming a diagonal variance-covariance (variance component) structure among the regressors. A final model for each response was selected from the subset candidates based on the lowest value of the Bayesian information criteria (**BIC**), the smallest final set of regressors (model parsimony), parameter significance, residual analysis, and biological relevance. In addition, mean and linear bias of the selected models was assessed following St-Pierre (2003). All statistical computations were carried out using the PROC MIXED, PROC REG, PROC CORR, and PROC GPLOT procedures of the SAS software system (SAS Institute, 2004).

RESULTS

Diets included in the study contained corn silage, alfalfa silage, and hay as predominant forages, corn and barley grains as main energy concentrates, and solvent-extracted soybean meal as the main protein supplement. The diets represented a wide range of CP and RDP concentrations; respectively, the intake of these nutrients varied significantly among diets (Table 1). Diet evaluation models differed slightly in derivation of common variables such as CP, NDF, RUP, and RDP.

Table 2. Significant ($P < 0.05$) simple correlations among intake variables and responses considered in the CPM model ($n = 557$).¹

	CP	RUP	SolProt	NE _L	NDF	NSC	FCHO	FNDF	CHOA	ProtB1	ProtB2	DMI	MY	MPY	BW
CP	1	0.72	0.69	0.63	0.41	0.41	0.29	NS	0.24	0.65	0.56	0.79	0.47	0.49	0.26
RUP		1	0.14	0.59	0.38	0.33	0.24	0.11	0.11	0.15	0.61	0.63	0.39	0.42	0.26
SolProt			1	0.25	0.28	0.22	NS	NS	0.27	0.64	-0.12	0.50	0.29	0.26	0.17
NE _L				1	0.21	0.77	0.69	NS	0.24	0.33	0.59	0.86	0.57	0.62	0.26
NDF					1	-0.14	0.22	0.72	0.28	0.17	0.11	0.53	0.14	0.14	0.10
NSC						1	0.73	-0.43	0.21	0.27	0.38	0.71	0.39	0.47	0.33
FCHO							1	0.11	0.35	0.11	0.40	0.67	0.28	0.35	0.31
FNDF								1	NS	-0.22	0.13	NS	NS	NS	-0.12
CHOA									1	0.12	NS	0.37	0.19	0.12	0.26
ProtB1										1	0.28	0.49	0.30	0.28	0.10
ProtB2											1	0.49	0.30	0.41	0.16
DMI												1	0.52	0.57	0.33
MY													1	0.92	0.30
MPY														1	0.37
BW															1

¹Intake and production data are in kilograms per day (megacalories per day for NE_L). SolProt = Soluble protein; NSC = nonstructural carbohydrates; FCHO = fermentable carbohydrates; FNDF = fermentable NDF; CHOA = carbohydrate fraction A; ProtB1 = protein fraction B1; ProtB2 = protein fraction B2; MY = milk yield; MPY = milk protein yield.

NS = Nonsignificant ($P > 0.05$).

A larger difference was observed for NE_L likely due to the different approach in estimating energy content of feeds in NRC (NRC, 2001).

Correlation matrices for the 2 datasets are shown in Tables 2 and 3. Milk yield correlated (Pearson correlation) positively ($P < 0.001$) to DMI and intake of NE_L, CP, RUP, and nonstructural carbohydrates in the CPM data set. Correlation to CPM-derived fermentable carbohydrate (CHO) and carbohydrate fraction A and protein fractions B1 and B2 was relatively weaker or nonsignificant (fermentable NDF). The correlation between MPY, DMI, and other intake variables paralleled those for MY. For the NRC data set, MY was highly correlated to NE_L, DMI, fat, and protein fractions intakes. Milk protein yield was correlated to NE_L, DMI, CP, and NFC intakes. With the exception of RDP and CP in the NRC

data set, correlations among regressor variables were below 0.80 for both datasets.

Modeling

For each response, the backwards selection procedure was used to identify a model, which had acceptable residual structure, VIF, BIC, and model parsimony, as outlined above. All final models showed good prediction with residuals that had no discernible trend or pattern. All model residuals were tested for significant mean and linear biases. In all cases, the biases were either nonsignificant or small relative to the measured standard errors based on analyses similar to St-Pierre (2003). Residual plots for the models with the lowest

Table 3. Significant ($P < 0.05$) simple correlations among intake variables and responses considered in the NRC model ($n = 557$).¹

	CP	RUP	RDP	NE _L	NDF	ForNDF	NFC	Fat	DMI	MY	MPY	BW
CP	1	0.60	0.88	0.74	0.45	0.24	0.38	0.18	0.79	0.47	0.49	0.25
RUP		1	0.18	0.61	0.25	NS	0.30	0.31	0.53	0.37	0.42	0.18
RDP			1	0.57	0.41	0.30	0.28	NS	0.67	0.37	0.37	0.21
NE _L				1	0.40	NS	0.68	0.53	0.92	0.59	0.63	0.25
NDF					1	0.59	-0.10	0.15	0.56	0.16	0.16	0.11
ForNDF						1	-0.13	-0.13	0.27	NS	NS	NS
NFC							1	NS	0.70	0.36	0.45	0.35
Fat								1	0.26	0.41	0.36	NS
DMI									1	0.52	0.57	0.33
MY										1	0.92	0.30
MPY											1	0.36
BW												1

¹Intake and production data are in kilograms per day (megacalories per day for NE_L). ForNDF = forage NDF; Fat = dietary fat; MY = milk yield; MPY = milk protein yield.

NS = Nonsignificant ($P > 0.05$).

Figure 1. Weighted residuals (weighted observed – weighted predicted) vs. weighted predicted milk yield (MY) and milk protein yield (MPY). A) MY, DMI model (model 1); B) MPY, DMI model (model 6).

BIC value (AC or DIM models) are shown in Figures 1, 2, and 3.

Milk Yield Models

Estimated MY models are shown in Table 4. Net energy of lactation intake and fermentable CHO and protein fraction B2 intakes were significant factors in the CPM-AC and CPM-DIM models (models 2 and 3). Intake of fermentable CHO had a negative influence in the model. Incorporation of CPM-derived intake variables instead of DMI (model 1) substantially improved model fit as measured by the 29- to 138-unit decrease in BIC and improved overall residual structure (Figure 1A). Incorporation of DIM into the CPM model (model 3) improved model fit as measured by the 109-unit de-

Figure 2. Weighted residuals (weighted observed – weighted predicted) vs. weighted predicted milk yield (MY). A) CPM-DIM model (model 3); B) NRC-DIM model (model 5). CPM = CPM Dairy, a computer program based on the Cornell Net Carbohydrate and Protein System principles; NRC = model based on NRC (2001).

crease in BIC as well as an improved relationship between observed and predicted values and overall residual structure (Figure 2A). Intake of protein fraction B2 showed significantly different coefficients for DIM1 and DIM2 classes. In both the full and reduced models, protein fraction B2 had significant interactions with the random effects of study.

The NRC models (models 4 and 5) included NE_L supply, RUP intake, and BW as explanatory variables. The models also contained an interaction between RUP intake and BW. Similar to the CPM models, incorporation of NRC-derived intake variables instead of DMI (model 1) improved the model fits, as BIC was 56 and 212 units

Figure 3. Weighted residuals (weighted observed – weighted predicted) vs. weighted predicted milk protein yield (MPY). A) CPM-DIM model (model 8); B) NRC model (model 9). CPM = CPM Dairy, a computer program based on the Cornell Net Carbohydrate and Protein System principles; NRC = model based on NRC (2001).

smaller for the AC and DIM models, respectively, than for the DMI model. As was seen in the CPM data set, inclusion of DIM into the modeling process (model 5) produced a better fit than the AC model (model 4) with a decreased BIC value (by 163 units) and improved relationship between observed and predicted values and residual plot (Figure 2B). Ruminally undegradable protein supply and the interaction with BW showed significantly different coefficients for each DIM class. The significant random component for RUP indicated an interaction of RUP with the random effect of study. Compared with the CPM models, the best NRC model (model 5) produced a lower BIC (by 81 units compared with the CPM-DIM model, model 3).

Milk Protein Yield Models

Estimated MPY model results are shown in Table 5. Similar to the CPM-MY models, incorporation of intake variables significantly improved model BIC (by 245 and 256 units in models 7 and 8, respectively), the residual mean square error, and the residual structures (Figures 1B and 3A) compared with the DMI model (model 6). Intakes of NE_L , fermentable NDF, CHO fraction A, and protein fractions B1 and B2 were significant factors in the CPM models. In addition, the models contained quadratic terms for CHO fraction A and protein fraction B2. Intake of fermentable NDF and protein fraction B1 and some of the quadratic terms had a negative influence in the models. Incorporation of DIM (model 8) into the CPM model (model 7) indicated moderate improvement in the model fit as measured by the 11-unit decrease in BIC (and Figure 3A). Net energy of lactation and protein fraction B2 intakes and the quadratic term for protein fraction B2 intake had significantly different coefficients for the DIM1 and DIM2 classes. In both the full and reduced models, CHO fraction A and protein fraction B2 showed significant interactions with the random effects of study.

The NRC-MPY models were identical for both AC and DIM categories (model 9) and included intakes of NFC, RDP, RUP, BW, quadratic terms for RDP and BW, and an RDP by BW interaction. Incorporation of intake variables instead of DMI (model 6) improved the model fit as measured by the 144-unit decrease in the BIC value and the relationship between observed and predicted values and overall residual structure (Figures 1B and 3B). Intake of RDP and the quadratic terms for RDP and BW had a negative influence in the model. Intake of RDP significantly interacted with the random effects of study.

DISCUSSION

The diets included in this study encompassed a large variety of feeds (a total of 88), but the main ingredients were typical for North American dairy diets (Mowrey and Spain, 1999; Kellogg et al., 2001). Therefore, the results from this meta-analysis will be most applicable to Holstein cows fed alfalfa/corn/soybean meal-based diets.

A close relationship between DMI and milk production of dairy cows has been established (Roseler et al., 1997a; Martin and Sauvant, 2002; Voelker et al., 2002) and is confirmed in this analysis. Dry matter, however, is composed of various nutrients, some of which (individually or included in a comprehensive model) may have a stronger impact on production variables than DMI alone. Indeed, based on BIC values and a tighter

Table 4. Estimates (regressor variables), standard errors, and significance for the fixed and random components of the final candidate models for milk yield (response in kg/d; n = 563).

Lactation stage	Regressor variables ¹	Estimate	SE	F value	Pr > t or Pr > z ²
DMI model (model 1)					
(BIC ³ = 2931) (RMSE ⁴ = 2.78)	Intercept	8.661	1.3406	42.3	<0.001
	DMI	1.076	0.0604	316.8	<0.001
<i>Model variance components</i>					
	Intercept	6.645	2.8498		0.010
	DMI	0.019	0.0059		<0.001
CPM Dairy models					
All cows (Model 2) (BIC = 2902) (RMSE = 2.66)	Intercept	13.924	1.4146	96.0	<0.001
	NE _L	0.663	0.0509	153.8	<0.001
	FCHO	-0.829	0.2076	-16.0	<0.001
	ProtB2	1.131	0.4103	7.8	0.007
<i>Model variance components</i>					
	Intercept	7.864	1.9647		<0.001
	ProtB2	2.254	0.5705		<0.001
DIM model (Model 3) (BIC = 2793) (RMSE = 2.38)	Intercept	15.929	1.3074	148.8	<0.001
	NE _L	0.584	0.0460	161.3	<0.001
	FCHO	-0.839	0.1866	-20.3	<0.001
	ProtB2 (DIM 1)	1.803	0.3813	22.1	<0.001
	ProtB2 (DIM 2)	-0.324	0.4248	-0.6	0.446
<i>Model variance components</i>					
	Intercept	7.138	1.5855		<0.001
	ProtB2*DIM	1.709	0.4150		<0.001
NRC 2001 models					
All cows (Model 4) (BIC = 2875) (RMSE = 2.52)	Intercept	-16.475	6.6290	-6.3	0.014
	NE _L	0.645	0.0443	213.2	<0.001
	RUP	16.297	5.5310	9.0	0.004
	BW	0.040	0.0112	13.0	<0.001
	RUP*BW	-0.025	0.0090	-7.3	0.007
<i>Model variance components</i>					
	Intercept	6.472	1.8120		<0.001
	RUP	5.679	1.2843		<0.001
DIM model (Model 5) (BIC = 2712) (RMSE = 2.05)	Intercept	-14.289	5.6118	-6.8	0.012
	NE _L	0.608	0.0377	259.2	<0.001
	RUP (DIM 1)	4.982	4.8530	1.0	0.306
	RUP (DIM 2)	29.714	4.9890	36.0	<0.001
	BW	0.039	0.0094	17.6	<0.001
	RUP*BW	-0.005	0.0079	-0.4	0.542
	RUP*BW	-0.050	0.0081	-38.4	<0.001
<i>Model variance components</i>					
	Intercept	7.066	1.6263		<0.001
	RUP*DIM	3.641	0.9892		<0.001

¹Intake and production data are in kilograms per day (megacalories per day for NE_L). FCHO = Fermentable carbohydrate intake; ProtB2 = protein fraction B2 intake; DIM1 = DIM < 100 d; DIM2 = DIM ≥ 100 d.

²For random effects.

³BIC = Bayesian information criterion; lower is better.

⁴RMSE = Root mean square error after adjusting for the random effect of experiment.

residual structure, MY and MPY prediction improved when intake of specific nutrients was included in the model. Therefore, this analysis suggests that MY and MPY in dairy cows can be better predicted based on intake of individual nutrients derived through the feeding programs used than on DMI alone.

With both the CPM and NRC datasets, NE_L intake was the strongest regressor variable influencing MY

(models 2 through 5), as suggested by the relatively larger *F* statistic. Diets for lactating dairy cows are formulated to be highly digestible and, in most situations, DMI is strongly related to intake of total digestible nutrients, or energy (NE_L, metabolizable energy) intake (Hristov et al., 2002); the Pearson correlation coefficient between NE_L intake and discounted total digestible nutrients intake was 98.7% in the NRC data

Table 5. Estimates (regressor variables), standard errors, and significance for the fixed and random components of the final candidate models for milk protein yield (response variable in kg/d; n = 549).

Lactation stage	Regressor variables ¹	Estimate	SE	F value	Pr > t or Pr > z ²
DMI model (model 6)					
(BIC ³ = 28) (RMSE ⁴ = 5.01)	Intercept	0.306	0.0464	43.6	<0.001
	DMI	0.031	0.0021	216.1	<0.001
<i>Model variance components</i>					
	Intercept	0	—		—
	DMI	1.40×10^{-5}	2.77×10^{-6}		<0.001
CPM Dairy models					
All cows (Model 7) (BIC = -217) (RMSE = 3.06)	Intercept	0.388	0.0635	41.0	<0.001
	NE _L	0.001	0.0007	3.2	0.074
	FNDF	-0.038	0.0083	-20.2	<0.001
	CHOA	0.345	0.0680	26.0	<0.001
	ProtB1	-0.155	0.0156	-100.0	<0.001
	ProtB2	0.403	0.0387	108.2	<0.001
	CHOA*CHOA	-0.114	0.0259	-19.4	<0.001
	ProtB2*ProtB2	-0.072	0.0110	-42.3	<0.001
<i>Model variance components</i>					
	Intercept	0.007	0.0021		<0.001
	CHOA	0.005	0.0013		<0.001
	ProtB2	0.003	0.0006		<0.001
DIM model (Model 8) (BIC = -228) (RMSE = 2.98)	Intercept	0.403	0.0621	42.3	<0.001
	NE _L (DIM 1)	0.001	0.0007	1.0	0.333
	NE _L (DIM 2)	0.011	0.0024	23.0	<0.001
	FNDF	-0.028	0.0084	-10.9	0.001
	CHOA	0.320	0.0659	24.0	<0.001
	ProtB1	-0.163	0.0153	-114.5	<0.001
	ProtB2 (DIM 1)	0.433	0.0380	130.0	<0.001
	ProtB2 (DIM 2)	-0.020	0.0939	-0.04	0.829
	CHOA*CHOA	-0.105	0.0248	-17.6	<0.001
	ProtB2*ProtB2 (DIM 1)	-0.078	0.0109	-50.4	<0.001
	ProtB2*ProtB2 (DIM 2)	0.022	0.0246	0.8	0.3787
<i>Model variance components</i>					
	Intercept	0.007	0.0019		<0.001
	CHOA	0.004	0.0011		<0.001
	ProtB2*DIM	0.002	0.0005		<0.001
NRC 2001 model ⁵ (model 9)					
(BIC = -116) (RMSE = 3.82)	Intercept	-0.062	0.5488	-0.01	0.910
	NFC	0.024	0.0028	67.2	<0.001
	RDP	-0.239	0.1132	-4.4	0.037
	RUP	0.098	0.0072	187.7	<0.001
	BW	0.003	0.0020	1.7	0.200
	RDP*RDP	-0.072	0.0135	-29.2	<0.001
	RDP*BW	0.001	0.0002	21.2	<0.001
	BW*BW	-3.94×10^{-6}	1.882×10^{-6}	-4.4	0.037
<i>Model variance components</i>					
	Intercept	0.001	0.0015		0.209
	RDP	0.001	0.0002		<0.001

¹Intake and production data are in kilograms per day (megacalories per day for NE_L). FNDF = fermentable NDF intake; CHOA = carbohydrate fraction A intake; ProtB1 = protein fraction B1 intake; Prot B2 = protein fraction B2 intake; DIM1 = DIM < 100 d; DIM2 = DIM ≥ 100 d.

²For random effects.

³BIC = Bayesian information criterion; lower is better.

⁴RMSE = Root mean square error after adjusting for the random effect of experiment.

⁵NRC models, all cows and DIM, were identical.

set (over all observations). The strong presence of energy intake in the MY models in this analysis reflects the critical importance of available energy for MY in the dairy cow. Milk yield was also significantly influ-

enced by fermentable CHO and protein fraction B2 intakes in the CPM data set, although, based on the *F* statistic, the relative importance of this regressor was smaller compared with NE_L intake.

The CPM-MY models (models 2 and 3) indicated negative coefficient for fermentable CHO intake. This suggests that, provided all other model regressor variables are constant, fermentable CHO intake would have a negative influence on the model. Although less important than NE_L intake (based on the relative values of the F statistic), RUP intake was a significant factor in the NRC-MY models (models 4 and 5). This is in agreement with the NRC (2001) committee report, which, based on a large data set consisting of 206 treatment means, concluded that MY increased linearly with increasing RUP concentration of the diet at a rate of 1.85 kg of milk for each percentage unit increase in RUP. An earlier meta-analysis by Santos et al. (1998), however, did not find a significant relationship between MY and RUP content of the diet, except for treated soybean and fish meals.

Incorporating stage of lactation (DIM1 and DIM2) in both CPM and NRC milk yield models (models 3 and 5) improved model fits. From the relative BIC values, it appeared models based on NRC-estimated intakes (models 4 and 5) provided slightly better fits for MY than models based on CPM-derived estimates (models 2 and 3).

Intake of NE_L , fermentable NDF, CHO fraction A, and protein fractions B1 and B2 were important in predicting MPY in the CPM models (models 7 and 8) and intake of NFC, RDP, RUP, and BW were components of the NRC model (model 9). In general, the MPY models were not very parsimonious and should be considered less reliable than the MY models. Not a single intake variable was distinctly predominant, although protein fractions B1 and B2 (CPM, models 7 and 8) and RUP (NRC, model 9) intakes had relatively the largest influence in the model (F statistic). Intakes of CHO fraction A and protein fraction B2 and RDP (CPM, models 7 and 8 and NRC, model 9, respectively) were significant random components in the MPY models, indicating contributions of these regressor variables to MPY variability over the studies. Moloi (1998) reported that diet-related variables, such as RDP, NDF, and NFC concentration of the diet influenced MPY in dairy cows. In the Moloi (1998) study, however, no single variable was identified as having major influence on MPY. Smoler et al. (1998) indicated generally poor prediction of milk protein concentration when diet-related variables were used in the modeling process; models included both CHO and protein variables. They suggested that individual CHO fractions might be better predictors of MPY than total CHO. Our data suggest that intake of protein fractions B1 (soluble proteins, a negative coefficient) and B2 (insoluble, available proteins) as derived through CPM and RUP (NRC) can strongly influence MPY in Holstein cows. In a similar

analysis, Smoler et al. (1998) emphasized the importance of ruminally undegradable protein in predicting MPY in dairy cows. Based on a data set including 38 studies with 206 treatment means, the NRC (2001) Dairy Committee reported that MPY in dairy cows increased linearly with increasing dietary RUP concentration. Similar to the negative coefficient for fermentable CHO in the CPM-MY models, fermentable NDF and protein fraction B1 intakes had a negative coefficient in the CPM-MPY models (models 7 and 8). The coefficient for RDP in the NRC model (model 9) was also negative. Body weight was present in the NRC-MPY model (model 9). The importance of animal variables for predicting MPY was also emphasized by Smoler et al. (1998).

CONCLUSIONS

Models based on intake of nutrients improved prediction of MY and MPY in Holstein cows compared with DMI alone. Intake of NE_L was the dominant variable in MY prediction models derived from both CPM Dairy and NRC (2001) nutrient estimates. A variety of energy- or protein-related parameters were also important in modeling MY. Incorporating stage of lactation in the MY models improved the model fit. Milk protein yield models based on intake of individual nutrients were generally not very parsimonious, but did improve prediction over the DMI model. These models were dominated by RUP intake and included a number of energy-related intake variables. Incorporating stage of lactation into the CPM Dairy MPY model improved the model fit whereas it did not for the NRC model.

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