Development and Evaluation of Equations for Prediction of Feed Intake for Lactating Holstein Dairy Cows

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ABSTRACT

Improved prediction equations for dry matter intake (DMI) of Holstein cows that consume high energy diets were developed using regression techniques applied to a comprehensive database. The equations for predicting DMI, which were dependent on parity, accounted for the effects of milk yield, milk protein, body weight (BW), BW change, days pregnant, ambient temperature, relative humidity, and night cooling. A simplified prediction equation of DMI for farm application was developed and based on milk protein yield and BW at calving. An ambient temperature and a lag adjustment factor for early lactation were developed to improve accuracy of prediction of DMI of dairy cows in early lactation. The developed equations for DMI were evaluated against six independent data files. These equations accounted for 55 to 98% of the variation of the weekly group DMI of the independent validation data. The remainder of the variation in intake was attributed to diet, management, and undescribed animal factors. The equations developed in this study had a mean proportional bias of 5.6% and a mean square prediction error of 5.45 kg^2/d. Predicted intake using the new equations was within 3 to 8% of actual intake. The new equations must be applied to situations in which Holstein dairy cows are fed highly digestible diets because dietary fill effects are not considered in these equations. The relationship of milk protein yield and DMI warrants further investigation.

(**Key words**: feed intake, prediction equations, environment, milk protein)

Abbreviation key: **BCS** = body condition score, **MSPE** = mean square prediction error.

INTRODUCTION

Accurate measurement or prediction of DMI is essential for the formulation of balanced, economical diets and for the diagnosis of milk yield losses. Current equations for DMI (13, 20, 26, 30, 39) account for about 40% of the variation in the prediction of weekly DMI (32). These equations have been developed from historical databases that have been incomplete in their descriptions of diet, cow, management, and environmental factors, which are known to affect DMI. For dairy cows, high energy diets have led to the need to characterize the metabolic factors that affect DMI. Similarly, the effects of climate, body condition score [**BCS**; five-point scale where 1 = thin to 5 = fat as described by Garnsworthy and Topps (15)], and gestation have not been quantified and thus have not been used to estimate DMI. Controlled experiments are useful for identifying the effects of a single variable on DMI; however, a large database with several variables measured simultaneously is needed to quantify the effects on DMI that occur for cows managed under typical farm settings.

The purpose of this study was to develop improved prediction equations for DMI of lactating dairy cows fed highly digestible, high energy diets. The developmental focus was on the application of a system that could be utilized on the farm to improve the prediction of weekly DMI of relatively homogenous groups of lactating Holstein cows.

MATERIALS AND METHODS

Developmental Database

A database was assembled from four different regions of the US (Arizona, Florida, New York, and Utah) that contained high yielding Holstein cows fed and managed according to typical practices in each region. All cows were housed in free stalls and were managed using Calan door feeders (American Calan, Inc., Northwood, NH), except for cows at the New York location where tie stalls were used. Cow management, dietary ingredients, ration composition, and experimental protocols have been described previously (17, 32). Practices for the feeding and

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management of dry cows and the housing and feeding were established according to the usual management at each location. The developmental database was assembled from several studies of dose titration bST (17) and consisted of complete lactation records for each of the 241 Holstein dairy cows. The entire database represented 11,755 individual weekly observations of cows; a similar number of observations was performed across all four locations. For this study, the cows treated with bST and the excipient control cows were separated; the results and discussion presented in this study are primarily focused on the control cows. The measured and calculated variables from the developmental database and the frequency of measurement of these variables are summarized in Table 1.

Variables of the Cows

Daily milk yield and triweekly analyses of fat, protein, and lactose in milk were used to calculate weekly measurements of milk yield, 4% FCM, energy-corrected milk, milk protein yield, and milk fat yield for individual cows (Table 1). Weekly BW measurements were smoothed using a median smoothing routine (38), and the smoothed BW were utilized in all analyses. Weekly changes in BW were calculated as the smoothed BW of the current week minus the smoothed BW of the previous week (28). Weekly BCS were measured for each cow, and weekly changes in BCS were calculated as the BCS of the current week minus the BCS of the previous week. The effect of days pregnant during lactation on current DMI was evaluated as a linear relationship with days pregnant as well as a logarithmic function of fetal energy demand as described by Moe and Tyrrell (23).

TMR

Ingredients of the TMR were sampled weekly, composited monthly, and analyzed for CP, ADF, and

TABLE 1. Description of observed (O) and calculated (C) variables used in the database to predict DMI of lactating Holstein dairy cows

Variable	Variable type	Description
Milk	O	Weekly milk yield calculated from daily yield.
Milk fat percentage	O	Weekly milk fat percentage calculated from triweekly milk sampling.
Milk protein percentage	O	Weekly milk total protein percentage calculated from triweekly milk sampling.
Milk lactose percentage	O	Weekly milk lactose percentage calculated from triweekly milk sampling.
FCM	C	4% FCM calculated from mean weekly milk yield and milk fat percentage. FCM (kilograms per day) = (15 × kilograms of milk fat per day) + (0.4 × milk) (kilograms per day).
ECM[1]	C	Energy-corrected milk calculated from mean weekly milk yield, milk fat percentage, milk protein percentage, and milk lactose percentage. ECM (kilograms per day) = [(41.63 × milk fat percentage + 24.13 × milk protein percentage + 21.60 × milk lactose percentage − 11.72) × milk (kilograms per day)]/340.
MPRYD	C	Milk protein yield (kilograms per day) calculated from mean weekly milk yield and mean weekly milk protein percentage.
FATKG	C	Milk fat yield (kilograms per day) calculated from mean weekly milk yield and mean weekly milk fat percentage.
BW	O	BW measurements were taken weekly on individual cows at a common time within each site.
SMBW	C	Smooth BW was calculated as the mean of three consecutive weekly BW measurements adjusted with a median smoothing algorithm.
BWC	C	BW change per week per cow was calculated as smooth BW of the current week minus smooth BW of the previous week.
BCS	O	Body condition score (BCS) values were taken weekly on individual cows at a common time within each site.
BCSCH	C	BCS change was calculated as BCS of the current week minus BCS of the previous week divided by 2.
Conception date	O	Date of confirmed pregnancy.
DPREG	C	Days pregnant was calculated as current date minus the conception date. If days pregnant was 0, then days pregnant was set to 0.
Temperature minimum	O	Daily temperature minimum values were recorded at each site. Weekly temperature minimum values were calculated from the daily values of 7 consecutive d.
Temperature maximum	O	Daily temperature maximum values were recorded at each site. Weekly temperature maximum values were calculated from the daily values of 7 consecutive d.
Temperature mean	C	Calculated as the mean of the weekly temperature minimum and weekly temperature maximum values.
Relative humidity	O	Daily relative humidity values were recorded at a common time daily within each site.

[1] Equation from Tyrrell and Reid (36).

TABLE 2. Description of the four temperature-humidity indexes (THI) evaluated to define the relationship between DMI and climate.

Variable[1]	Calculation
THI 1	= 41.2 + dry bulb temperature (°C) + 0.36 × dew point temperature (°C)
THI 2	= 40.6 + 0.72 × [dry bulb temperature (°C) + wet bulb temperature (°C)]
THI 3	= 5.17 + 0.75 × dry bulb temperature (°C) + 0.15 × mean relative humidity
THI 4	= 0.65 × wet bulb temperature (°C) + 0.35 × dry bulb temperature (°C)

[1] Reference sources: THI 1 (19), THI 2 (18), THI 3 (13), and THI 4 (24).

NDF. Fat and ash values were assigned to individual dietary ingredients according to Van Soest and Fox (37). The TMR were formulated to meet or to exceed NRC (26) requirements. Ingredients of the TMR were different at each location, thus improving the potential for prediction of DMI across the various TMR.

Cows were fed TMR to allow 5% orts. Orts and DMI were measured daily. Weekly DMI was calculated, and weeks with <7 observations were weighted according to the actual number of observations conducted during that week. The criterion used to move cows from one TMR to another within each location was based on days of lactation, milk yield, and BCS. The TMR composition and criterion for change in TMR at each location has been described (17, 32).

Ambient Temperature and Humidity

Daily minimum and maximum temperatures and relative humidity values were recorded at each site for the Arizona, Utah, and Florida locations. Minimum and maximum daily temperatures and relative humidity for the New York location were obtained from the Northeast Regional Climate Center (Cornell University, Ithaca, NY) where data were gathered from a weather station 8 km from the open air research barn. Weekly minimum and maximum temperatures for use in the weekly prediction of DMI were calculated from daily values. Weekly mean temperature was calculated from weekly minimum and maximum temperatures.

Weekly mean temperature and humidity values were used to model the effects of environment on long-term or seasonal adaptations of DMI that occurred in dairy cattle. Four temperature-humidity indexes (Table 2) were selected from the literature (13, 18, 19, 24) to assist in defining the best relationship between climate and DMI. Night cooling was not accounted for in any temperature-humidity index calculation. Night cooling was considered to have occurred if two or more consecutive daily minimum temperatures were <10°C or if a weekly mean temperature was <10°C (24).

Three temperature classifications were identified according to the NRC (24): cold, <10°C; thermoneutral, 10 to 18°C; and hot, >18°C. Within each of the three temperature classifications, the effect of ambient temperature, night cooling, and relative humidity were quantified using multiple regression.

Statistical Procedures

Principal component analysis, a discriminant technique designed to identify independent associations among several variables, was utilized in PROC PRINCOMP of SAS (34) to identify categories of measurable variables that affected DMI for use in initial model development. The interactions of specific variables were also identified. Pearson correlation coefficients were calculated for a series of several experimental measurements both within and across parities and treatments. The stepwise and maximum R^2 selection methods of PROC REG of SAS (34) were used to identify several improved models to predict DMI. Three prediction models for primiparous cows and three prediction models for multiparous cows, were identified for further testing; all models contained continuous and categorical variables. Two comprehensive models, which consisted of either continuous (model 1) or continuous and categorical variables (model 2), were selected for overall accuracy of prediction of DMI. A simplified model (model 3) was selected because of the ease of measurement and application on the farm. The initial models are described subsequently. The yield and temperature variables contained alternative units of measure from which only the unit with the best fit was selected for application in the final models. The models were

Model 1 (a comprehensive model with continuous variables):

$$\begin{aligned} y_{ijklmnpqrs} = {} & U + b_1BW_{1i} + b_2YLD_{2j} + b_3TEMP_{3k} \\ & + b_4BCS_{4l} + b_5WOL_{5m} + b_6DPREG_{6n} \\ & + b_7BCSCH_{7q} + b_8BWC_{8r} + b_9LOC_{9s} \\ & + b_{10}DPREG \times WOL + b_{11}BCS \\ & \times WOL, \end{aligned}$$

Model 2 (a comprehensive model with continuous and categorical variables):

$$\begin{aligned} y_{ijklmnpqrs} = {} & U + b_1BWgp_{1i} + b_2YLD_{2j} \\ & + b_3TEMPgp_{3k} \\ & + b_4BCSgp_{4l} + b_5WOLgp_{5m} \\ & + b_6DPREGgp_{6n} + b_7BCSCHgp_{7q} \\ & + b_8BWCgp_{8r} + b_9LOC_{9s}, \text{ and} \end{aligned}$$

Model 3 (a simplified model with continuous and categorical variables):

$$\begin{aligned} y_{ijklm} = {} & b_1BW_{1i} + b_2YLD_{2j} + b_3TEMP_{3k} \\ & + b_5DPREG_{5l} + b_6BCS_{6m} \end{aligned}$$

where

U = mean intake (kilograms per day);
BCSgp = categories of BCS at calving (<2.0, 2.00 to 2.49, 2.50 to 2.99, 3.00 to 3.49, 3.50 to 4.00, and >4.00);
BCSCH = change in BCS (units per week);
BCSCHgp = categories of change in BCS (<–0.3, –0.2 to 0, 0, 0 to 0.2, and >0.3);
BW = weekly BW (kilograms per cow), calving BW (kilograms per cow);
BWC = change in BW (kilograms per week per cow);
BWCgp = categories of change in BW [<–7.0, –6.9 to –3.0, –2.9 to –0.8, –0.7 to 0.7, 0.8 to 2.9, 3.0 to 6.9, and >7 (kilograms per week)];
BWgp = categories of BW [400 to 449, 450 to 499, 500 to 549, 550 to 599, 600 to 649, 650 to 699, 700 to 749, and >750 (kilograms per cow)];
DPREG = days pregnant (n = 1, 2, . . ., 222);
DPREGgp = categories of days pregnant (<60, 61 to 120, 121 to 180, and >181);
TEMP = mean temperature, temperature minimum, temperature maximum, relative humidity, or temperature-humidity index;
TEMPgp = temperature categories (<10°C, 10 to 18°C, or >18°C);
WOL = week of lactation and log base e of week of lactation;
WOLgp = categories of week of lactation (1 to 9, 10 to 24, 25 to 36, 37 to 48, and 49 to 60);
YLD = milk yield (kilograms per day), log e milk yield (kilograms per day), FCM yield (kilograms per day), energy-corrected milk yield (kilograms per day), milk protein yield (kilograms per day), or milk protein percentage; and
LOC = experimental location (n = 1, 2, 3, 4).

Multiple regression using the PROC AUTOREG procedure of SAS (33) with a second-order, autoregressive error term was used to parameterize model variables for the effects of DMI across lactations. Parameterization was conducted separately for cows treated with bST and for the excipient control cows. Cows that were not administered bST in early lactation were in the control group. Variance inflation factors for any individual variable with a value >30 were evaluated (28). According to residual analysis, only 127 observations of individual weekly DMI from the total of 3252 observations of excipient control cows had high (>4 SD) residuals. Four residuals indicated a high, inconsistent concentration of milk protein and were corrected to correspond with values within the same week. Fifty-two of the high residuals were associated with climate change or a change in the TMR. The other high residuals were not related to any specific event. All residuals were maintained in the developmental database because parameter estimates were not greatly altered by the removal of these residuals. The database contained cows that had been selected for good health and udder conformation. The Durbin-Watson statistic was calculated as described by the SAS users manual (34).

Validation Data

Three data files that were completely independent from the developmental database were used to test the accuracy of the equations for prediction of DMI developed in this study. The first validation data file consisted of multiparous control cows from a bST study by Lefebre and Block (22) conducted at McGill University; this data file is referred to as the McGill data. Table 3 describes the diets fed during the McGill trial. The second validation data file was obtained from the University of Pennsylvania (P. Pitcher, 1992, personal communication); these data are referred to as the Pennsylvania validation data. The data were collected during five different university trials (2, 8, 10, 11, 29) in which the effect of

TABLE 3. Description of TMR and feeding management practices[1] for University validation data reported by Lefebre and Block (22).

	TMR		
Ingredient	A	B	C
	(% of DM)		
Alfalfa silage	45.0	60.0	61.0
Ear corn, high moisture	35.0	30.0	34.0
Soybeans, micronized	15.0	8.0	3.0
Fat	3.0	. . .	. . .
Mineral and vitamin mix	2.0	2.0	2.0

[1] Cows were housed in tie stalls with exercise once daily. Cows were milked at 0530 and 1530 h.

several fat sources was evaluated. Table 4 describes the composition and formula of the diets fed at each of the five locations in the Pennsylvania validation data. Temperature and humidity values were not available in these validation data files. The validation data were summarized to weekly means within each location, and each equation was used to predict the mean weekly group DMI. The weekly means represent parity groups of approximately 30 to 55 cows.

A farm evaluation of the simplified equation from this study was conducted using the DMI of four separate groups of dairy cows, housed in separate pens, from a commercial dairy farm with 250 cows in central New York. Mean DMI per pen for the four production groups of this commercial dairy herd ranged from 21.8 to 24.5 kg/d per cow. These intakes were measured for 2 consecutive d per mo for each pen for a period of 12 mo starting July 1992 and ending July 1993. The milk yield on this commercial farm was 11,230 kg of milk/yr per cow. The basal diet (DM basis), which was constant across DMI measurements, consisted of 35% corn silage, 15% haycrop

TABLE 4. Description of diets for the validation data of studies conducted in Pennsylvania.

	Reference[1]					
	(2)	(8)	(10)	(11)	(29)	(29)
Primiparous cows, no.	0	6	0	0	24	0
Multiparous cows, no.	24	6	40	40	0	21
TMR Composition, % of DM						
Corn silage	26.1	25.0	10.0	22.0	26.0	18.0
Alfalfa silage	18.5	. . .	. . .	. . .	. . .	41.0
Alfalfa hay	. . .	25.0	35.0	16.0	22.5	. . .
Corn	28.0[2]	20.7[3]	35.5[4]	42.0[2]	19.0[3]	17.0[3]
Soybean meal	7.2[5]	11.1[5]	14.0[5]	10.0[5]	6.5[6]	9.1[5]
Mineral and vitamin[7]	1.9	2.0	2.5	2.4	2.0	1.4
Concentrate[7]	18.3[8]	16.2[9]	3.0[10]	7.6[11]	24.0[12]	13.5[13]
TMR Analysis[14]						
DM, % of DM	61.7	59.0	71.0	50.2	59.3	70.6
CP, % of DM	17.3–18.5	17.7–18.0	18.4	16.5–17.1	16.5–17.1	17.5
NE_L, Mcal/kg of DM	1.75–1.87	1.61–1.74	1.71–1.86	1.67–1.78	1.59–1.80	1.55–1.66
NDF, % of DM	24.7–28.4	36.5–37.4	26.4	26.5–27.1	35.3–36.7	41.0–42.3
Fat, % of DM	3.12–6.95	3.09–5.30	3.30–5.80	3.07–4.94	3.34–6.78	2.89–4.73
NSC,[15] % of DM	39.5–46.5	32.8–34.3	41.4–43.9	44.9–45.9	32.0–35.1	28.1–30.4

[1] References for experiment.

[2] Cracked shelled corn.

[3] Ground ear corn.

[4] High moisture shelled corn.

[5] 48% CP Soybean meal.

[6] 44% CP Soybean meal.

[7] Minerals, vitamins, and concentrates were different at each site. Concentrates consisted of various treatment ingredients.

[8] 2.9–9.0% Corn, 0.5–10.0% soybean meal, 0–2.3% Megalac® (Church & Dwight, Co., Princeton, NJ), 0–9.5% whole cottonseed, 0–10.4% raw soybeans (six treatment rations).

[9] 0–3.0% Corn, 6.2% oats, 2.0% alfalfa meal, 2.1% dried brewers grains, 0 or 2.7% Megalac® (Church & Dwight, Co.), 2.0% linseed meal, 1.1% dry cane molasses, and 0.2% urea (two treatment rations).

[10] 3% Corn, and 0 or 3% Megalac® (Church & Dwight, Co.).

[11] 0 or 2% Megalac® (Church & Dwight, Co.), 5.0% soybean meal or 1.5% fish meal, and 1.5% blood meal (two treatment rations).

[12] 4.0% Corn or 4.0% Megalac® (Church & Dwight, Co.) (two treatment rations).

[13] 0 or 2.0% Corn, 5.1% oats, 1.6% alfalfa meal, 1.7% dried brewers grains, 1.6% linseed meal, 0.9% dry cane molasses, 0 or 2.1% isoacids, 0 or 0.2% urea, and 0 or 2.2% Megalac® (Church & Dwight, Co.) (four treatment rations).

[13] 0 or 0.8% Corn, 3.8% oats, 1.2% alfalfa meal, 1.2% dried brewers grains, 3.8% distillers dried grains, 1.2% linseed meal, 0.6% dry cane molasses, 0.1% urea, and 0 or 4% Megalac® (Church & Dwight, Co.).

[14] Values represent ranges of diet composition when more than one treatment was present per site.

[15] Nonstructural carbohydrates calculated as 100 – (NDF + CP + fat + ash).

silage, and 50% grain concentrate. Mean group milk yield, milk fat, milk protein, BW by hearth girth measurement, age, indoor barn temperature, and regional humidity values were monitored monthly for this commercial farm. These variables were used to test the field accuracy of the simplified equation from this study and a modified prediction equation of the NRC (26).

Three previously published models for the prediction of DMI (20, 26, 39) also were evaluated against the independent validation data at McGill University (22) and The Pennsylvania State University (2, 8, 10, 11, 29). The modified NRC (26) equation for DMI, as described by Rayburn and Fox (30), was evaluated for accuracy against the simplified equation. Measures of accuracy of the validation data were based on the mean square prediction errors (**MSPE**) overall and of each lactation period. The MSPE has been described previously (4) and has been used in other validation systems (31, 32). Simple linear regression of the predicted value against the actual value was conducted, and the corresponding R^2 and MSPE provided goodness of fit measures. Linear regression of predicted values on observed values with a zero intercept and the corresponding parameter estimate of the actual intake value provided a measure of bias for the overall range of actual and predicted values (28).

RESULTS

BW and BCS

Weekly BW accounted for ≤17% of the variation in DMI as determined by principal component analysis (Figure 3). The correlation of BW and BCS with DMI was different for each parity group (Table 5). The correlation between DMI and weekly BW was higher for primiparous (0.37 to 0.45) than for multiparous (−0.05 to 0.16) cows (Table 5). The BW and BW change (kilograms per cow) each week reflected the growth of primiparous cows and thus showed a higher correlation with DMI than did the correlation between BW and BW change and DMI for multiparous cows. Calving BW was correlated positively with DMI for both parity groups (Table 5). Change in BW over the lactation period (ending BW minus calving BW) for multiparous cows was negatively correlated with DMI (Table 5).

The BCS and weekly change in BCS accounted for ≤6% of the variation in DMI (Figure 3). The BCS was correlated more highly (negatively) with DMI for multiparous cows than for primiparous cows (Table 5). Calving BCS was not highly correlated with the DMI of cows in early lactation; however, BCS at calving was associated negatively with DMI over the entire lactation, except for first lactation cows treated with bST. Calving BCS for cows in this study ranged from 2.0 to 4.0 and did not include extremely obese cows (>4.0) that were associated with depressed DMI during early lactation (15). The lack of independence between BCS and BW make understanding the relationships among BCS, BW, and DMI difficult.

Yield Variables

The yield variables had the highest correlation with DMI and accounted for ≤45% of the variation in DMI during early lactation (Figure 3). Fat-corrected milk is a variable used in several prediction equations for DMI (20, 26, 39). However, actual milk yield had a slightly more positive correlation with DMI than did FCM for all parities and treatments in this study (Table 6). The correlations between energy-corrected milk and DMI were similar to those between actual milk yield and DMI. Total milk protein yield had the highest correlation with DMI among the milk yield parameters that were evaluated (Table 6). Milk lactose percentage had a higher correlation with DMI than did milk fat or milk protein percentage, except for primiparous cows treated with bST (Table 6).

Temperature Variables

Ambient temperature accounted for ≤10% of the variation in DMI as identified by principal component analysis (Figure 3). The correlation between temperature and weekly DMI during the previous months was similar to the correlation between current temperature and current weekly DMI (Table 7). Monthly mean temperature values can be used to adjust the prediction of DMI for lactating dairy cows. Relative humidity had a lower correlation with DMI than did temperature (Table 7). None of the temperature-humidity indexes (Table 2) evaluated in this study had a significant correlation with weekly DMI. Regression analysis did not show any significant relationships of temperature variables in predicting DMI. A categorical adjustment for DMI based on the three climate categories of the NRC (24) for the effects of humidity and night cooling improved the prediction of DMI (Table 8). Heat stress with high humidity without night cooling had the most detrimental effect on DMI. The depression of DMI associated with heat stress was lower for primiparous cows than for multiparous cows (Table 8).

TABLE 5. Correlation[1] of weekly DMI with BW, BW change, body condition score (BCS), and change in BCS by parity group and treatment.

Parity group	Treatment	BW[2]				BCS		
		Weekly	At calving	Weekly change	Lactation change[3]	Weekly	At calving	Weekly change
		(kg)						
Primiparous	Control	0.37	0.38	0.17	0.02[4]	–0.15	–0.11	–0.02[4]
Multiparous	Control	–0.05	0.27	0.07	–0.41	–0.35	–0.14	<0.01[4]
Primiparous	bST	0.45	0.31	0.17	0.24	–0.02	0.09	0.04
Multiparous	bST	0.16	0.28	0.05	–0.18	–0.31	–0.10	<0.01[4]

[1] All correlation coefficients are significant ($P < 0.10$) unless otherwise noted.

[2] All BW measurements are based on smoothed BW values.

[3] Lactation BW change is defined as BW at the end of lactation minus BW at calving.

[4] Not significant.

Lag Function During Early Lactation

A lag function was developed to improve the prediction of DMI during the first 16 wk postcalving. Cows were stratified by month of peak milk yield, and the intake delay or lag per week (percentage of maximum intake) was calculated. Cows that had a peak milk yield sooner in lactation (during the 1st mo) had a shorter lag or more rapid rise in DMI than did cows that reached peak milk yield during the 3rd mo of lactation (Table 9). The lag value (LAG) was calculated as an exponential function of the current week postcalving (WOL) and the month postcalving (1, 2, or >3) when peak milk yield occurred. The equation to calculate the lag was

$$\mathrm{LAG} = 1 - e^{-[(0.564 - 0.124 \times \mathrm{PKMK}) \times (\mathrm{WOL} + \mathrm{P})]}$$

where PKMK = month postcalving when peak milk yield occurred (1, 2, or >3) and P = 2.36 for PKMK = 1 and 2, or P = 3.67 for PKMK = 3. The lag value is used as a multiplier to the base equation for DMI when week of lactation is ≤16. The delay function values from the lag equation are listed in Table 9.

Equations for DMI

Several prediction equations for DMI that were dependent on parity were developed (Tables 10 and 11). A comprehensive and simplified model was selected for each parity group for further evaluation. Selection of the comprehensive model (Equation [D], Table 10; Equation [B], Table 11) was based on accuracy and precision as measured by R^2, bias, MSPE, and regression mean square. A simplified model (Equation [E], Table 10; Equation [F], Table 11) was selected primarily for ease of variable measurement at the farm. The comprehensive and simplified equations for improved prediction of DMI are listed in Equations [1] through [4]. Standard errors of partial regression coefficients are listed in parentheses.

TABLE 6. Correlation[1] of weekly DMI with actual milk, FCM, and energy-corrected milk (ECM) yield by parity and treatment.

Parity group	Treatment	Milk yield			Milk component				
		Milk	FCM[2]	ECM	Total milk protein	Milk fat	Total milk protein	Milk fat	Milk lactose
		(kg/d)					(%)		
Primiparous	Control	0.61	0.58	0.62	0.69	0.51	0.03	–0.04	0.43
Multiparous	Control	0.67	0.65	0.67	0.69	0.59	–0.26	–0.18	0.32
Primiparous	bST	0.55	0.48	0.51	0.61	0.40	0.12	–0.07	0.05
Multiparous	bST	0.61	0.60	0.61	0.64	0.55	–0.08	0.03	0.31

[1] All correlation coefficients are significant at $P < 0.10$.

[2] 4% FCM.

TABLE 7. Correlation of current weekly ambient temperature, ambient temperature of the previous month, and relative humidity with weekly DMI.

	Climate measurement period	Temperature			
		Minimum temperature	Maximum temperature	Mean temperature	Relative humidity
DMI, kg per cow	Current week[1]	–0.24	–0.20	–0.20	–0.10
DMI, kg per cow	Previous month[2]	–0.22	–0.16	–0.21	–0.11

[1] Correlations in this row are the association of DMI of the current week with climate values of the current week.

[2] Correlations in this row are the association of DMI of the current week with mean climate values of the previous month.

A comprehensive model for primiparous cows:

$$\begin{aligned}\text{DMI (kilograms per day)} = {} & [3.7_{(1.1)} + 0.012_{(0.001)} \times \text{BW (kilograms)} \\ & + 0.12_{(0.02)} \times \text{BW change (kilograms per week)} \\ & + 12.2_{(0.49)} \times \text{MPRYD (kilograms per day)} \\ & - 0.011_{(0.003)} \times \text{DPREG}] \times \text{LAG}.\end{aligned} \quad [1]$$

A simple model for primiparous cows:

$$\begin{aligned}\text{DMI (kilograms per day)} = {} & [4.6_{(0.9)} + 0.011_{(0.001)} \times \text{BW at calving} \\ & \text{(kilograms)} + 12.4_{(0.42)} \times \text{MPRYD} \\ & \text{(kilograms per day)}] \times \text{LAG}.\end{aligned} \quad [2]$$

A comprehensive model for multiparous cows:

$$\begin{aligned}\text{DMI (kilograms per day)} = {} & 0.6_{(0.2)} + 0.005_{(0.0015)} \times \text{BW (kilograms)} \\ & + 0.11_{(0.02)} \times \text{BW change (kilograms per week)} \\ & + 10.4_{(0.45)} \times \text{MPRYD (kilograms per day)} \\ & - 0.013_{(0.004)} \times \text{DPREG} - 0.17_{(0.02)} \times \text{WOL} \\ & + 4.59_{(0.33)} \times \log \text{WOL}.\end{aligned} \quad [3]$$

A simple model for multiparous cows:

$$\begin{aligned}\text{DMI (kilograms per day)} = {} & [8.4_{(1.0)} + 0.006_{(0.001)} \times \text{BW at calving} \\ & \text{(kilograms)} + 12.2_{(0.45)} \times \text{MPRYD} \\ & \text{(kilograms per day)}] \times \text{LAG}.\end{aligned} \quad [4]$$

In these models,

MPRYD = daily milk total protein yield (kilograms per day),
DPREG = days pregnant,
LAG = lag adjustment value for week in lactation ≤16, and
WOL = week of lactation.

In this study, the equations that were developed to predict DMI explained 79 to 84% of the variation in DMI of the developmental data file. Previously published (32) equations for predicting DMI were able to account for only 26 to 77% of the variation in the same data.

Dietary Factors

Dietary concentrations of NDF, ADF, and NE_L, although variable across locations and weeks of lactation, were not significant in describing DMI in this study. These results coincide with the results of the NRC (25), which suggest that DMI is not limited by fill factors when cows are fed highly digestible, high energy diets. Dietary NDF accounted for <1% of the variation in DMI. The TMR that were fed to cows in early lactation in the developmental database contained 1.65 to 1.71 Mcal/kg of NE_L (DM basis). Total fat content of the TMR ranged from 3.3 to 5%. Intake did not appear to be limited by fill when these high energy diets were fed. Although not statistically significant, the DMI of cows at the New York site was 0.5 to 1.2 kg/d lower, depending on week of lactation, than the mean DMI of cows at the three other sites. Cows at the New York location were fed fermented silage and high moisture corn and were housed in tie stalls, unlike those at the other three locations. Moisture content of the TMR (6), silage acids (5), and housing have been identified as factors that may reduce DMI. These negative intake factors might explain some of the lower DMI of the cows at the New York site. The cows at the Arizona location had 0.5 to 2 kg/d higher DMI, depending on week of lactation, than did cows at the other three sites ($P < 0.10$). The elevated DMI of the cows at the Arizona location could not be explained by the measured variables; however, feeding management and strategy can influence DMI.

TABLE 8. Relationship of weekly DMI with ambient temperature and adjustments for night cooling and relative humidity for lactating dairy cows.

Temperature, cooling, and humidity	Climate category				Feed intake adjustment	
	Basal temperature	Relative humidity	Minimum temperature[1]			
			Category	Night cooling[2]	Primiparous	Multiparous
	(°C/wk)	(%/wk)	(°C/wk)		(kg/d)	
Thermal neutral with night cooling	10–18	0–100	if <10	Yes	0	0
Thermal neutral without night cooling and low humidity	10–18	0–70	if ≥10	No	–0.2	–0.3
Thermal neutral without night cooling and high humidity	10–18	71–100	if ≥10	No	–0.6	–0.8
Cold	<10	0–100	NA[3]	NA[3]	0.02	0.03
Hot with night cooling and low humidity	>18	<65	if < 15	Yes	–0.2	–0.3
Hot without night cooling and low humidity	>18	<65	if ≥ 15	No	–0.05	–0.07
Hot with night cooling and high humidity	>18	≥65	if < 15	Yes	–0.8	–1.0
Hot without night cooling and high humidity	>18	≥65	if ≥ 15	No	–2.1	–3.2

[1] If minimum temperature was <10°C for a minimum of 2 consecutive d in 1 wk, then night cooling was determined to be prevalent.

[2] The presence of night cooling (yes or no) was defined by the frequency of daily minimum temperature within 1 wk.

[3] Not applicable, night cooling is not prevalent when temperatures are <10°C.

Equations for DMI for Cows Treated with bST

The DMI of lactating dairy cows treated biweekly with bST increased 2 to 10 wk after initiation of treatment (3). The intake lag period and DMI response were modified by milk yield response (17), frequency of bST injection, and management (3). Several equations for DMI that were sensitive to parity were developed for cows treated with bST (Table 12). The accuracy of prediction of DMI was lower for cows treated with bST than for controls as measured by MSPE (32). The application of these models were for cows that were >60 d postpartum and were receiving bST. The functional form of the models for DMI prediction was similar to equations developed for control cows; however, the regression coefficients for the independent variables were lower than those identified for control cows, which suggests that DMI is lower per unit of milk protein yield and BW change. This alteration in milk protein yield and BW change per unit of DMI may reflect the loss of BCS (3). The accuracy of these equations was lower than the accuracy of equations for control cows as was evidenced by a higher regression MSPE (Table 12). The cyclic 2-wk rise and decline in milk yield associated with biweekly bST injections (3) decreased the ability to account for variation in DMI.

Validation

The simplified equations developed in this study were functionally similar to the modified equation of the NRC (26) and provided a good basis for validation comparison. The comprehensive equations that were developed in this study were compared with the more complex equations of Weiss (39) and Kertz et

TABLE 9. Early lactation DMI adjustment values for DMI calculated by week of lactation as a function of month of peak milk yield.

Lactation	Peak milk month[1]		
	1[2]	2[3]	≥3[4]
(wk)			
1	0.77	0.65	0.59
2	0.85	0.75	0.66
3	0.90	0.81	0.72
4	0.94	0.87	0.77
5	0.96	0.90	0.81
6	0.97	0.92	0.84
7	0.99	0.95	0.87
8	0.99	0.96	0.89
9	0.99	0.97	0.91
10	0.99	0.98	0.93
11	0.99	0.98	0.94
12	0.99	0.99	0.95
13	0.99	0.99	0.96
14	0.99	0.99	0.97
15	0.99	0.99	0.98
16	0.99	0.99	0.99

[1] The default value was mo 2 if historical yield records were unavailable to determine the lag value.

[2] Lag values for mo 1 were calculated as $1 - \exp[-(0.564 - 0.124 \times 1) \times (\mathrm{WOL}) + 2.36)]$. WOL = Week of lactation.

[3] Lag values for mo 2 were calculated as $1 - \exp[-(0.564 - 0.124 \times 2) \times (\mathrm{WOL} + 2.36)]$.

[4] Lag values for mo ≥3 were calculated as $1 - \exp[-(0.564 - 0.124 \times 3)\ (\mathrm{WOL} + 3.67)]$.

al. (20). Values for MSPE are listed in kilograms squared per day and are measures of prediction accuracy (4).

Comprehensive equations. The comprehensive equation for primiparous cows described 70 and 77% of the variation of the data from Eastridge and Palmquist (8) and from Palmquist (29) with a bias of –6 and 4% and MSPE of 2.4 and 1.5 kg^2/d, respectively (Table 13). Prediction accuracy was much lower from the equations of Kertz et al. (20) and Weiss (39) (Table 13). The MSPE for those equations ranged from 11.8 to 37.4 kg^2/d with a bias of –21 to –34% (Table 13).

The comprehensive equation for multiparous cows that was developed in this study explained, on average, 94% of the variation in weekly group DMI from the Pennsylvania data (2, 8, 10, 11, 29) (Table 13). The same equation had a bias of –2 to 21% and an overall MSPE of 4.25 kg^2/d (Table 13). Using the equation of Weiss (39) and the same data, R^2 was 0.59, mean bias was –35 to –15%, and a mean MSPE was 45.26 kg^2/d (Table 13). The comprehensive multiparous equation applied to the validation data of Lefebre and Block (22) at McGill University had an R^2 of 0.84, a MSPE of 2.86 kg^2/d, and a bias of 6%. The Weiss (39) equation had a similar bias and MSPE but a lower R^2 of 0.21 for the data of Lefebre and Block. The equation of Kertz et al. (20) applied to wk 1 to 24 of lactation had a bias of 11% and a MSPE of 7.1 kg^2/d (Table 13). Figure 1A shows the relationship of the comprehensive multiparous equation, the equation of Kertz et al. (20), and the equation of Weiss (39) with actual DMI from the validation data of Lefebre and Block (22).

Simplified equations. The simplified equations for primiparous cows explained 55 to 73% of the variation of the data from Palmquist (29) and from Eastridge and Palmquist (8); bias was –1 and 7%, and MSPE was 2.1 and 3.0 kg^2/d, respectively. The modified equation of the NRC (30) had a much lower accuracy. The R^2 was 0.61 and 0.22, mean bias was –23.5%, and mean MSPE was 18.25 kg^2/d for the same data (Table 14).

The simplified equation for multiparous cows applied to the Pennsylvania data (2, 8, 10, 11, 29) had an overall R^2 of 0.93, a mean bias of 10%, and a mean MSPE of 5.5 kg^2/d (Table 14). Comparable validation measures for the modified NRC (26) equation were an R^2 of 0.18, bias of –23%, and an MSPE of 33.8 kg^2/d. The simplified equation predicted the weekly

TABLE 10. Parameter estimates of alternative prediction models for DMI of primiparous Holstein dairy cows.

	Alternative equation[1]							
Variable	A	B	C	D	E	F	G	H
Constant	–6.5	9.3	5.1	3.7	4.6	4.6	0.8	–9.3
BW, kg	0.018	0.009	0.011	0.012	. . .	. . .	0.017	0.015
Calving BW, kg	. . .	. . .	. . .	. . .	0.011	0.011	. . .	. . .
BW Change, kg/wk	0.12	0.12	. . .	0.12	. . .	. . .	0.15	0.10
Milk, kg/d	0.46	. . .	. . .	. . .	. . .	. . .	. . .	0.43
4% FCM, kg/d	. . .	0.23	. . .	. . .	. . .	0.45	. . .	. . .
MPRYD,[2] kg/d	. . .	. . .	12.2	12.2	12.4	. . .	11.9	. . .
Milk total protein, %	1.57	. . .	. . .	. . .	. . .	. . .	. . .	1.31
Calving BCS[3]	. . .	. . .	. . .	. . .	. . .	. . .	–0.36	. . .
Days pregnant	. . .	0.005	–0.007	–0.011	. . .	. . .	. . .	. . .
WOL[4]	. . .	. . .	. . .	. . .	. . .	. . .	. . .	–0.079
$\log_e$ WOL	. . .	. . .	. . .	. . .	. . .	. . .	. . .	2.45
Temperature adjustment[5]	Yes	Yes	Yes	Yes	No	No	Yes	Yes
Early lactation lag[6]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Regression MSE[7]	2.37	2.89	2.39	2.43	2.46	2.80	2.48	2.19
Total R^2	0.83	0.79	0.82	0.84	0.79	0.78	0.83	0.83
Durbin-Watson[8]	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0

[1] All equations were developed in this study for evaluation.

[2] Milk protein yield.

[3] Body condition score.

[4] Week of lactation postcalving.

[5] Yes = Temperature adjustment was used to predict DMI; no = temperature adjustment was not used.

[6] Yes = Early lactation lag was used to predict DMI; no = early lactation lag was not used.

[7] Mean square error of regression output.

[8] Durbin-Watson test statistic for measure of autocorrelation.

intakes for data from Lefebre and Block (22); R^2 was 0.80, bias was 14%, and MSPE was 10.9 kg^2/d (Table 14). The modified NRC (26) equation explained a much lower proportion of variance; R^2 was 0.18, MSPE was 10.7 kg^2/d, and mean bias was 12%. Figure 1B shows the relationship of the simplified equation for multiparous cows and the modified NRC (26) equation for the McGill validation data of Lefebre and Block (22).

The simplified equation for multiparous cows applied to the DMI on the dairy farm had an overall R^2 of 0.51 with a 3% bias compared with data using the modified NRC (26) equation, which had an R^2 of 0.49 and a bias of 8% (Table 15). The prediction accuracy of the DMI was lowest for the multiparous cows in early lactation. The relationship of actual farm DMI by lactation group and predicted DMI as determined by the simple and modified NRC (26) equations are presented in Figure 2.

The prediction accuracy was better for the equations in this study that were sensitive to parity than for the prediction equations for DMI developed by Kertz et al. (20), Weiss (39), and the NRC (26). The variance accounted for from these previously published equations was as low as 4% with a range in bias from −35 to 12% (Tables 13 and 14). Except for the data of Erickson et al. (10), for multiparous cows, the accuracy of the equations developed in this study had improved accuracy; bias was <10%, MSPE was <8 kg^2/d, and R^2 was consistently >0.80 for the prediction of weekly group DMI (Tables 13 and 14).

DISCUSSION

This study identified four equations that were sensitive to parity and that improved the prediction of DMI for lactating dairy cows across an entire lactation. Quantitative factors for temperature adjustment, which accounted for the effects of night cooling and humidity, were developed. An adjustment for lag that was based on the month of peak milk yield improved the prediction of DMI for cows in early lactation. Calving BW and milk protein yield are easily measured variables that are highly correlated with DMI and that can be utilized to predict DMI of lactating Holstein dairy cows in farm situations.

TABLE 11. Parameter estimates of alternative prediction models for DMI of multiparous Holstein dairy cows.

	Alternative equation[1]							
Variable	A	B	C	D	E	F	G	H
Constant	−5.8	0.6	0.9	1.0	18.5	8.4	7.6	8.5
BW, kg	0.006	0.005	. . .	. . .	. . .	. . .	. . .	. . .
Calving BW, kg	. . .	. . .	0.005	0.009	. . .	0.006	0.005	0.012
BW Change, kg/wk	0.10	0.11	0.11	0.11	. . .	. . .	0.13	0.13
Milk, kg/d	0.36	. . .	. . .	0.35	0.35	. . .	. . .	0.33
4% FCM, kg/d	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
MPRYD,[2] kg/d	. . .	10.4	10.3	. . .	. . .	12.2	12.6	. . .
Milk protein, %	1.2	. . .	. . .	1.2	. . .	. . .	. . .	0.73
Milk lactose, %	0.5	. . .	. . .	. . .	. . .	. . .	. . .	0.61
Calving BCS[3]	. . .	. . .	. . .	−1.76	−1.2	. . .	. . .	−2.1
Days pregnant	−0.011	−0.013	−0.012	−0.009	−0.010	. . .	. . .	−0.007
WOL[4]	−0.125	−0.17	−0.16	−0.13	. . .	. . .	. . .	. . .
Log_e WOL	4.1	4.59	4.6	4.15	. . .	. . .	. . .	. . .
Temperature adjustment[5]	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Early lactation factor[6]	No	No	No	No	Yes	Yes	Yes	Yes
Regression MSE[7]	2.41	2.53	2.53	2.39	2.94	2.75	2.63	2.40
Total R^2	0.86	0.85	0.85	0.86	0.85	0.84	0.84	0.86
Durbin-Watson[8]	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.1

[1] All equations were developed in this study for evaluation.

[2] Milk protein yield.

[3] Body condition score.

[4] Weeks of lactation postcalving.

[5] Yes = Temperature adjustment was used to predict DMI; no = temperature adjustment was not used.

[6] Yes = Early lactation lag was used to predict DMI; no = early lactation lag was not used.

[7] Mean square error of regression output.

[8] Durbin-Watson test statistic for measure of autocorrelation.

BW and BCS

The comprehensive equations developed in this study contain weekly BW and BW change values that are not routinely available on the farm. Imprecise values increase the error associated with prediction of DMI. The simplified models developed in this study provide an improvement over current systems for predicting DMI with the use of BW at calving, a single BW measurement. This simplification reduces the time required to gather information on the dairy farm without sacrificing accuracy in the prediction of DMI. However, use of BW at calving has not always improved the prediction of DMI (27).

Garnsworthy and Topps (15) found that fat cows at parturition had a longer lag before peak DMI and a greater BW loss than those cows that were not overconditioned. High BCS at calving in observational studies versus controlled studies may be indicative of lower yielding cows that consume less DM. Thus, the negative coefficients associated with BCS at calving (Tables 5, 10, and 11) in some of the equations in this study might be correlated with low milk yield and not with excessive body fat. Therefore, the equations for predicting DMI that utilize BCS at calving (Tables 10 and 11) include an overall lactational adjustment for intake that is not specific for any period.

The weekly BW change in this study ranged from –18 to 23 kg/wk per cow and described 5 to 10% of the variation associated with DMI (Figure 3). Weekly BW changes are the result of changes in gut fill, body composition, skeletal growth, and fetal size (40). The use of BCS did not improve the prediction of DMI over the use of BW change, which might be related to the correlation of the two variables. Simultaneous alterations can occur in body fat, body protein, and gut fill, which can skew the usefulness of using only BW or only BCS to predict DMI. Body weight is utilized in many prediction equations for DMI and might reflect relative total BW changes throughout lactation and body maintenance. Body weight at calving, a static measurement, is useful in defining the relationship of DMI and body maintenance.

Dietary Characteristics

The lack of significant association between dietary fiber, energy density, or other nutrient components in this study was primarily due to the high energy concentration of the TMR fed to cows in the developmental data file. These TMR were representative in level of energy density of TMR fed to high yielding cows on commercial dairy farms in the US. Based on principal component analysis, BW accounted for 17% of the variation in DMI, BSC accounted for 6%, yield accounted for 45%, and climate accounted for 10%. The remaining variation (22%) was attributed to undescribed management and dietary factors (Figure 3).

TABLE 12. Parameter estimates of alternative prediction models for DMI of Holstein dairy cows treated with bST.

	Alternative equation[1]					
Variable	A	B	C	D	E	F
	Multiparous			Primiparous		
Constant	–0.6	5.4	12.4	1.7	8.7	–4.7
BW, kg	0.013	0.013	. . .	0.017	. . .	0.019
Calving BW, kg	. . .	. . .	0.005	. . .	0.005	. . .
BW Change, kg/wk	0.09	0.08	. . .	0.084	. . .	0.082
Milk, kg/d	0.37	. . .	. . .	. . .	. . .	0.33
MPRYD,[2] kg/d	. . .	10.1	9.2	9.9	9.5	. . .
Milk total protein, %	0.41	. . .	. . .	. . .	. . .	1.6
Milk fat, %	. . .	. . .	. . .	. . .	. . .	–0.25
Days pregnant	. . .	–0.003	. . .	. . .	0.011	. . .
Temperature adjustment[3]	Yes	Yes	Yes	Yes	Yes	Yes
Regression MSE[4]	3.30	3.50	3.90	2.90	3.10	2.80
Total R^2	0.82	0.80	0.77	0.77	0.76	0.79
Durbin-Watson[5]	2.0	2.0	2.0	2.1	2.0	2.0

[1] All equations were developed in this study for evaluation.

[2] Milk protein yield.

[3] Yes = Temperature adjustment was used to predict DMI.

[4] Mean square error of regression output.

[5] Durbin-Watson test statistic for measure of autocorrelation.

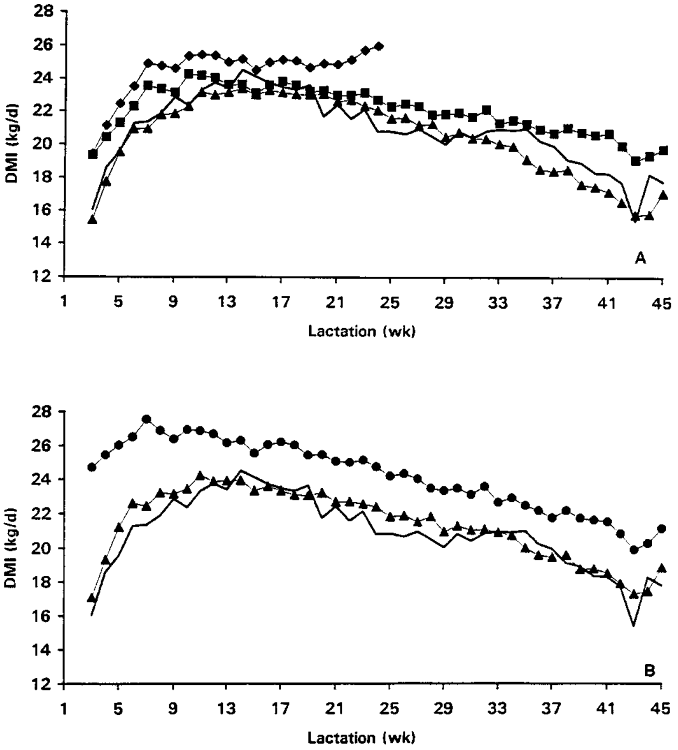

Figure 1. Relationship of actual DMI from the validation data of Lefebre and Block (22) (—) and the predicted DMI from the equations of Kertz et al. (20) (♦), Weiss (39) (■), and the comprehensive multiparous equation (▲) from this study (panel A). The actual DMI from the data of Lefebre and Block (22) (—) and the predicted DMI from the modified equation of the NRC (26) (●) and simplified multiparous equation (▲) from this study (panel B).

Early Lactation Lag

During early lactation, DMI increased more slowly than the increase in milk yield because of metabolic adaptations and gut fill. A systematic overprediction of DMI for cows in early lactation is characteristic of many prediction equations (13, 26, 39) because of the time lag between maximum daily milk output and maximum DMI. Early lactation adjustment factors (39) or segmented equations (30) are two methods used to reduce error in estimating the DMI of cows in early lactation. Weiss (39) used a logarithmic adjustment for lag to improve the prediction of DMI of cows in early lactation. The lag adjustment factor developed in the present study enhanced the prediction of DMI for cows in early lactation by using week of lactation and month of peak milk yield. The month of peak milk yield was used to calculate the lag because this value can be easily obtained from historical yield records at the farm. If previous yield records are not available, then the 2nd mo can be utilized as the default month for calculating the lag variable. The lag adjustment may assist in describing management situations that occur on some farms experiencing a rapid increase in milk yield (wk 1 to 4 of lactation) or extremely slow peak milk yield (wk 9 to 12 of lactation). A slow rise in DMI might be the result of metabolic or health problems.

Temperature

The adjustment factors for ambient temperature that were developed in this study were unique in

TABLE 13. Validation of the comprehensive equation[1] for DMI and the equations of Weiss (39) and Kertz et al. (20)[2] with independent research data.

Validation reference source and measurement	Intake equation		
	Comprehensive	Weiss	Kertz et al.
		Primiparous	
Palmquist (29)			
R^2	0.77	0.79	0.62
MSPE,[3] kg^2/d	2.4	37.4	22.0
Bias, %	−6	−34	−25
Eastridge and Palmquist (8)			
R^2	0.70	0.78	0.86
MSPE, kg^2/d	1.5	25.4	11.8
Bias, %	4	−29	−21
		Multiparous	
Ferguson et al. (11)			
R^2	0.95	0.74	0.95
MSPE, kg^2/d	4.8	40.0	36.1
Bias, %	9	−27	−26
Palmquist (29)			
R^2	0.98	0.92	0.97
MSPE, kg^2/d	0.38	41.3	25.1
Bias, %	1	−30	−26
Eastridge and Palmquist (8)			
R^2	0.84	0.10	0.86
MSPE, kg^2/d	0.70	63.0	48.6
Bias, %	0	−32	−29
Erickson et al. (10)			
R^2	0.95	0.48	0.97
MSPE, kg^2/d	15.0	7.9	12.0
Bias, %	21	−15	−11
Baker et al. (2)			
R^2	0.96	0.72	0.90
MSPE, kg^2/d	0.37	74.1	60.8
Bias, %	−2	−35	−32
Lefebre and Block (22)			
R^2	0.84	0.21	0.79
MSPE, kg^2/d	2.86	2.8	7.1
Bias, %	6	3	11

[1] Comprehensive equation for DMI (Table 10, Equation D for primiparous cows and Table 11, Equation B for multiparous cows) was developed in this study.

[2] Included only wk 1 to 24 of lactation.

[3] Mean square prediction error.

accounting for the effects of not only temperature, but also relative humidity and night cooling. Other research has quantified these environmental effects separately (7, 12) but not interactively. Environmental conditions that might alter or reduce the precision of these adjustments in DMI include intense radiant heat and the sudden exposure of cows to a change to extreme environmental conditions. Calving season and stage of lactation might alter the magnitude of the depression in DMI because of heat stress (7, 14). The developmental data in this study were from a single early fall calving season, so seasonal effects on heat stress could not be evaluated. Cows that had been adapted to heat showed less depression in DMI, possibly because of physiological adaptations (9). The environmental adaptation period for grazing beef cows ranges from 4 to 21 d (35), depending on induced stress. No reference for adaptation periods for lactating dairy cows was identified; therefore, weekly temperature and humidity values were used, and prediction of DMI was improved. The adjustment factors to intake for temperature that were developed in this study must be applied to dairy cows that have been adapted to the climate; prediction of DMI for dairy cows exposed to abrupt changes in temperature and humidity will not be improved. The temperature adjustments for DMI developed in this study could be utilized to calculate monthly guidelines for adjusting DMI by climate regions.

Milk Protein

The effect of milk protein yield as a significant variable in predicting DMI was unexpected. Milk lactose concentration is biologically associated with milk protein concentration through the α-LA subunit of lactose synthase (21). Because milk lactose is the major osmotic regulator of milk volume, a direct link to milk protein yield and energy demand for milk synthesis is possible. Similarly, the aminostatic intake theory of Harper et al. (16), which is supported by experiments in rats and poultry, suggests that a more ideal supply of protein to tissue might enhance performance and subsequent intake or directly mediate a hypothalamic effect on DMI (1). Analytical techniques for measuring ideal protein patterns for ruminants need to be advanced before Harper's aminostatic theory (16) can be evaluated for

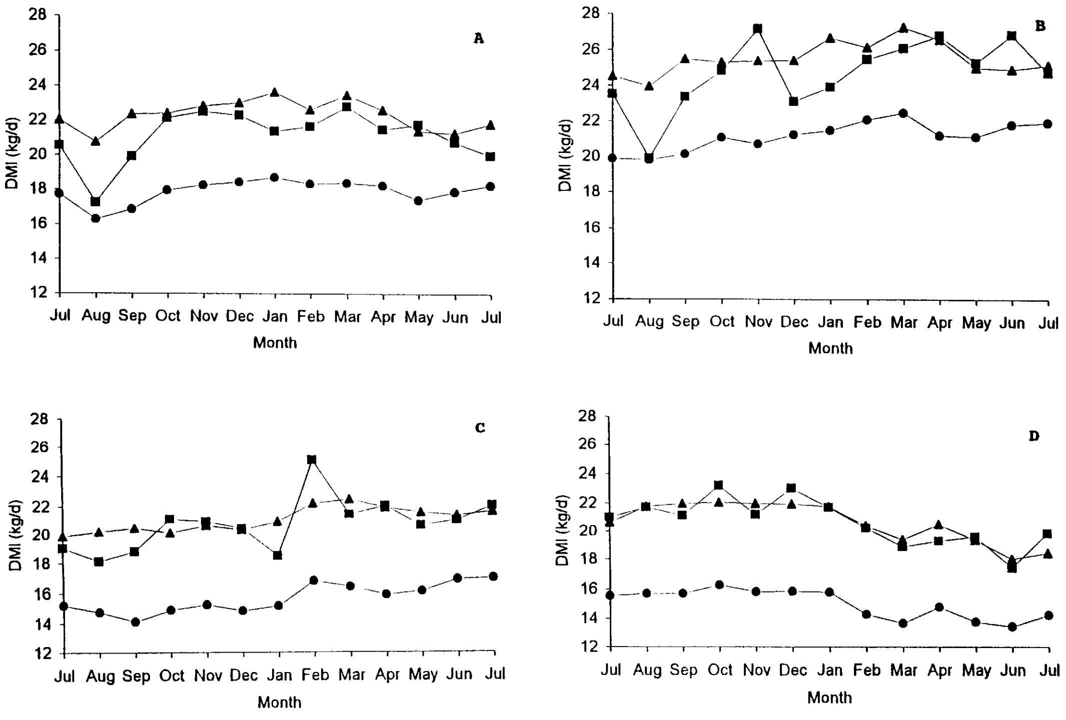

Figure 2. Relationship of the monthly group DMI from a commercial dairy farm of 250 cows (■) and the predicted DMI from the modified equation of the NRC (26) (●) and simple equation from this study (▲): panel A, primiparous cows in early lactation; panel B, multiparous cows in early lactation; panel C, multiparous cows in midlactation; and panel D, multiparous and primiparous cows in late lactation. The DMI of all cows on the farm was measured from each group on 2 consecutive d within each month starting July 1992 and ending July 1993.

ruminants. Adequate supply of amino nitrogen must be available to support milk protein synthesis. The relationship of milk protein yield and DMI to the supply of amino acids to the central nervous system for feedback control of DMI needs to be better characterized.

CONCLUSION

The equations developed in this study improved the prediction of DMI by using variables that were easily defined and measurable. Although a large amount of variation is unexplained by the current systems for prediction of DMI, the new equations developed in this study improved the precision of prediction of DMI by accounting for the intake lag effect in early lactation, environmental temperature, night cooling, relative humidity, milk protein yield, BW, and days pregnant. The equations must be applied to situations in which Holstein dairy cows are fed high energy diets. Further evaluation of the bio-

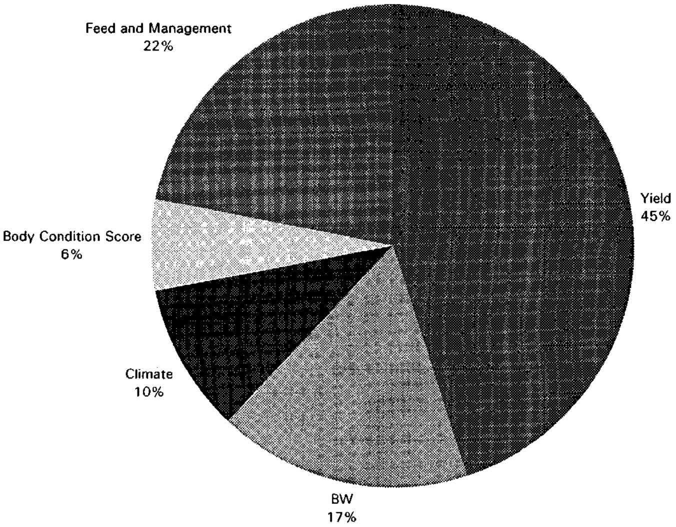

Figure 3. Description of factors that affect DMI in lactating dairy cows and the amount of variability explained by each factor calculated using principal component analysis of a large comprehensive database.

TABLE 14. Validation of the simple equation[1] for DMI and the modified equation developed by the NRC[2] with independent research data.

Validation reference source and measurement	Equation: Simple	Equation: Modified NRC
	Primiparous	
Palmquist (29)		
R^2	0.55	0.61
MSPE,[3] kg^2/d	2.1	18.5
Bias, %	–1	–24
Eastridge and Palmquist (8)		
R^2	0.73	0.22
MSPE, kg^2/d	3.0	18.0
Bias, %	7	–23
	Multiparous	
Ferguson et al. (11)		
R^2	0.87	0.27
MSPE, kg^2/d	8.2	32.1
Bias, %	12	–24
Palmquist (29)		
R^2	0.83	0.11
MSPE, kg^2/d	5.2	27.2
Bias, %	6	–23
Eastridge and Palmquist (8)		
R^2	0.84	0.02
MSPE, kg^2/d	3.4	42.9
Bias, %	6	–26
Erickson et al. (10)		
R^2	0.92	0.02
MSPE, kg^2/d	22.4	4.9
Bias, %	25	–9
Baker et al. (2)		
R^2	0.82	0.50
MSPE, kg^2/d	1.5	61.9
Bias, %	0	–32
Lefebre and Block (22)		
R^2	0.80	0.18
MSPE, kg^2/d	10.9	10.7
Bias, %	14	12

[1] Simplified equation for DMI (Table 10, Equation E for primiparous cows and Table 11, Equation F for multiparous cows) was developed in this study.

[2] Equation for DMI developed by the NRC (26) and modified by Rayburn and Fox (30).

[3] Mean square prediction error.

TABLE 15. Validation of the simple equation[1] for DMI prediction and the modified equation for the NRC[2] for predicting DMI with independent farm data.

Validation reference source and measurement	Equation: Simple	Equation: Modified NRC
	Primiparous	
Stone[3]		
R^2	0.52	0.47
Bias, %	+6	+13
	Multiparous	
Stone		
R^2	0.51	0.49
Bias, %	+4	+12

[1] Simplified equation for DMI prediction (Table 10, Equation E and Table 11, Equation F) was developed in this study.

[2] Equation for DMI developed by the NRC (26) and modified by Rayburn and Fox (30).

[3] Farm data from W. C. Stone (1992, personal communication).

logical relationship between milk protein yield and DMI might provide insights into methods to enhance the DMI of high yielding dairy cows fed energy dense diets.

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