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Integration of the effects of animal and dietary factors on total dry matter intake of dairy cows fed silage-based diets

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An empirical regression model for the prediction of total dry matter intake (DMI) of dairy cows was developed and compared with four published intake models. The model was constructed to include both animal and dietary factors, which are known to affect DMI. For model development, a data set based on individual cow data from 10 change-over and four continuous milk production studies was collected ($n = 1554$*). Relevant animal (live weight (LW), days in milk (DIM), parity and breed) and dietary (total and concentrate DMI, concentrate composition, forage digestibility and fermentation quality) data were collected. The model factors were limited to those that are available before the diets are fed to animals, that is, standardized energy corrected milk (sECM) yield, LW, DIM and diet quality (total diet DMI index (TDMI index)). As observed ECM yield is a function of both the production potential of the cow and diet quality, ECM yield standardized for DIM, TDMI index and metabolizable protein concentration was used in modelling. In the individual data set, correlation coefficients between sECM and TDMI index or DIM were much weaker (0.16 and 0.03) than corresponding coefficients with observed ECM (0.65 and 0.46), respectively. The model was constructed with a mixed model regression analysis using cow within trial as a random factor. The following mixed model was estimated for DMI prediction: DMI (kg DM/day)* $= -2.9\ (\pm 0.56) + 0.258\ (\pm 0.011) \times$ *sECM (kg/day)* $+ 0.0148\ (\pm 0.0009) \times$ *LW (kg)* $-0.0175\ (\pm 0.001) \times$ *DIM* $-5.85\ (\pm 0.41) \times \exp(-0.03 \times \text{DIM}) + 0.09\ (\pm 0.002) \times$ *TDMI index. The mixed DMI model was evaluated with a treatment mean data set (207 studies, 992 diets), and the following relationship was found: Observed DMI (kg DM/day)* $= -0.10\ (\pm 0.33) + 1.004\ (\pm 0.019) \times$ *Predicted DMI (kg DM/day) with an adjusted residual mean square error of 0.362 kg/day. Evaluation of the residuals did not result in a significant mean bias or linear slope bias, and random error accounted for proportionally* >0.99 *of the error. In conclusion, the DMI model developed is considered robust because of low mean prediction error, accurate and precise validation, and numerically small differences in the parameter values of model variables when estimated with mixed or simple regression models. The Cornell Net Carbohydrate and Protein System was the most accurate of the four other published DMI models evaluated using individual or treatment mean data, but in most cases mean and linear slope biases were relatively high, and, interestingly, there were large differences in both mean and linear slope biases between the two data sets.*

Keywords: intake, dairy cow, modeling, animal factors, diet factors

Implications

Effects of standardized milk yield, live weight and stage of lactation on voluntary feed intake of dairy cows were determined based on data from 14 experiments. Effects of forage quality and amount and composition of concentrates on intake have been modelled previously. The current model separates animal and diet effects on intake so that intake can be predicted precisely and accurately using parameters available at the time of feeding. The model will improve current ration formulation systems by enabling the prediction of actual intake and intake responses, which are prerequisites for any economical model in optimizing milk production in various farming systems.

Introduction

Accurate prediction of dry matter intake (DMI) is important for the formulation of economical dairy cow diets. Regulation of feed intake in ruminants involves multiple mechanisms related to dietary and animal factors that are poorly

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understood (Mertens, 1994). Despite extensive research efforts over the past 30 to 40 years, no intake model that can be used generally has been developed. Limited success in this field is at least partly due to complicated interactions between the animal and feed characteristics, and difficulties in distinguishing and quantifying these factors. Many intake models use milk yield (MY) as an input variable (Vadiveloo and Holmes, 1979; Dulphy *et al*., 1989; National Research Council (NRC), 2001; Keady *et al*., 2004a), but the usefulness of such models in ration formulation may be questioned, as the final output (MY) is used to predict input (feed intake). These models are primarily useful in predicting intake required to sustain a given level of MY, as stated by Keady *et al*. (2004b). It should be remembered that MY is not known at the time of prediction (Ingvartsen, 1994).

Observed MY is a function of a cow's genetic potential, stage of lactation, diet characteristics and management factors. Intake potential of the diet was strongly correlated with observed milk energy output (Huhtanen *et al*., 2008) that can result in biased parameter values for both animal and diet factors in DMI prediction models. To overcome the problems resulting from variation in animal and environmental factors in estimating the effects of feed factors on DMI, we developed a relative silage DMI index (SDMI) using treatment mean data from milk production studies and mixed model regression analysis (Huhtanen *et al*., 2007). The model was extended to also include concentrate factors in predicting total DMI (Huhtanen *et al*., 2008). The model (total diet DMI index (TDMI index)) accurately predicted the differences in DMI within a study (prediction error within study 0.37 kg DM/day). However, to be useful in practical ration formulation, the intake prediction model should also take into account animal factors such as MY potential, live weight (LW) and stage of lactation.

The objective of this study was to develop a DMI prediction model based on TDMI index (Huhtanen *et al*., 2008) by including animal factors in the model. The aim was to estimate the true effects of animal and feed factors on intake by taking these factors into account independently. The model factors were restricted to those that would be available at the time of ration formulation; for example, excluding observed MY and LW change.

Material and methods

Data

A data set based on individual observations from 10 change-over studies ($n = 887$) and four continuous studies ($n = 667$) with a total of 1554 observations was used for model development (Appendix 1). The studies included 106 diets. The forages consisted of grass silages differing in chemical composition, digestibility and harvest (primary *v.* regrowth), and whole-crop silages. The concentrate feeds consisted of cereal grains (barley, oats), fibrous by-products and various protein supplements. Forages and concentrates were fed either separately or as a total mixed ration (TMR). The studies were conducted either in tie stalls or a loose housing system with mainly Finnish Ayrshire and Holstein–Friesian cows. The data before 30 days in milk (DIM) were excluded from the analysis, as the objective was to develop an intake model for established lactation. In change-over trials, one observation was based on the data from the last one or 2 weeks of each experimental period, and continuous trials were divided into 3-week periods. In change-over studies, the experimental design was either complete four-period Latin Squares or cyclic-change-over designs including four periods. The studies were conducted in four different barns (three tie stalls and one loose house), and the diets were fed as TMR (four studies) or forages and concentrates separately.

Another data set based on mean treatment values from 207 dairy cow studies (992 diets) using *ad libitum* feeding of grass silage, or grass silage partly replaced with legume or whole-crop cereal silages and supplemented with concentrates differing in the amount and composition values was used for model validation. Within each study, the concentrates were fed with the same silage, which was offered *ad libitum.* More details of the data are described in previous papers (Huhtanen *et al*., 2007 and 2008).

Calculations

Relative silage intake potential (Huhtanen *et al*., 2007) is computed as:

$$\begin{aligned}\text{SDMI index} = 100 + 10 \times [&(D\text{-value} - 680) \times 0.0170 \\ &- (\text{TA} - 80) \times 0.0128 + (0.0198 \\ &\times (\text{DM} - 250) - 0.00002364 \times (\text{DM}^2 - 250^2)) \\ &- 0.44 \times a + 4.13 \times b - 2.58 \times b^2 + 5.90 \\ &\times c - 6.14 \times c^2 - 0.0023 \times (\text{NDF} - 550)], \quad (1)\end{aligned}$$

where D-value = concentration of digestible organic matter (OM; g/kg DM), TA = total acid (lactic acid + volatile fatty acids) concentration (g/kg DM), DM = DM concentration (g/kg), NDF = NDF concentration (g/kg DM), and a, b and c represent the proportions (0 to 1) of regrowth, legume and whole-crop cereal silages in total silage DM.

The relative effect of concentrate supplementation on intake potential was calculated as described by Huhtanen *et al*. (2008):

$$\begin{aligned}\text{CDMI index} = 100 + 10 \times [&(\text{CDMI} - 0.1629 \times \text{CDMI} \\ &- 0.018823 \times \text{CDMI}^2 - 5.49) + ((0.9474 \\ &\times \text{CCPI} - 0.4965 \times \text{CCPI}^2) - 2.02 \\ &\times (\text{CEPD} - 0.74)) + 0.00225 \times (\text{CNDF} - 250) \\ &- 0.0103 \times (\text{Cfat} - 40) - 0.0058 \\ &\times (\text{CDMI} - 8.0) \times (\text{SDMI index} - 100)], \quad (2)\end{aligned}$$

where CDMI = concentrate DMI (kg/day), CCPI = supplementary concentrate CP intake (kg/day; CP $>$170 g/kg DM), CEPD = concentrate protein degradability (g/g) according to MTT (2006), CNDF = concentrate NDF concentration (g/kg DM) and Cfat = concentrate fat concentration (g/kg DM).

Total diet DMI index was calculated as SDMI index + CDMI index−100. One unit in SDMI, CDMI or TDMI index corresponds to a difference of 0.10 kg/day in DMI as a default value.

On account of differences in the intake potential and nutritive value of the diets, as well as stage of lactation, observed yield does not directly describe the production potential of a cow or a group of cows. Therefore, the observed energy corrected milk yield (ECM) was adjusted to correspond to a standard diet fed at 150 DIM (sECM, standardized ECM yield). The standard diet was defined as a diet with an intake potential of 100 TDMI index points (Huhtanen *et al.*, 2008) and 90 g/kg DM metabolizable protein (MP). The ECM yield was calculated using the equation by Sjaunja *et al.* (1991):

$$\begin{aligned}\mathrm{ECM\,(kg/day)} = {} & \mathrm{Milk\,(kg/day)} \times (38.3 \times \mathrm{Fat\,(g/kg)} + 24.2 \\ & \times \mathrm{Protein\,(g/kg)} + 16.54 \times \mathrm{Lactose\,(g/kg)} \\ & + 20.7)/3140. \qquad (3)\end{aligned}$$

The concentration of MP was calculated according to the Finnish protein value system (Tuori *et al.*, 1998; MTT, 2006) with minor modifications. Standardized ECM was calculated as:

$$\begin{aligned}\mathrm{sECM\,(kg/day)} = {} & \mathrm{Observed\ ECM\,(kg/day)} \\ & + a \times (100 - \mathrm{TDMI\ index}) \\ & + b \times [90 - \mathrm{MP\ (g/kg\,DM)}] \\ & + c \times (150 - \mathrm{DIM}). \qquad (4)\end{aligned}$$

The DIM component (effect of the stage of lactation) in model (4) was estimated using the principles of the Wilmink (1987) equation:

$$\begin{aligned}\mathrm{ECM\ (kg/day)} = {} & a + b \times \mathrm{DIM} + c \times \exp(-0.05 \times \mathrm{DIM}) \\ & + d \times \mathrm{DIM}^2. \qquad (5)\end{aligned}$$

Only statistically significant ($P < 0.10$) parameters of the DIM component of model (5) were included in the model. The parameter values for *a*, *b*, *c* and *d* (for simplicity, *c* includes all the components of model (5)) of the model (4) were estimated using a mixed regression model from the individual cow data set as described later in detail. Standardized ECM yield should not be interpreted as a maximal potential yield of the cow, but rather a yield at a fixed stage of lactation when fed a standard diet.

Model comparisons

Four published intake prediction models were evaluated using both individual and treatment mean data sets. Two of the selected models (NRC, 2001; Cornell Net Carbohydrate and Protein System (CNCPS; Fox *et al.*, 2004)) included only animal factors, whereas the other two models (Vadiveloo and Holmes, 1979; Lewis, 1981) also included feed factors. The objective was not to conduct a comprehensive model comparison, but rather to evaluate models that differed in the extent to which animal and feed factors were present and to which necessary parameter values were available.

The NRC (2001) model use only animal variables to predict total DMI (TDMI):

$$\begin{aligned}\mathrm{TDMI} = {} & [(0.372 \times \mathrm{FCM} + 0.09968 \times \mathrm{LW}^{0.75}) \\ & \times (1 - \exp(-0.192 \times (\mathrm{WL} + 3.37)))], \qquad (6)\end{aligned}$$

where FCM = 4% fat corrected milk (kg/day), LW = live weight (kg) and WL = week of lactation. The exponential term adjusts for reduced intake during early lactation.

The CNCPS (Fox *et al.*, 2004) predicts intake from MY, LW and stage of lactation:

$$\begin{aligned}& \mathrm{TDMI\,(kg/day)} = (0.0185 \times \mathrm{LW} + 0.305 \times \mathrm{FCM}) \times \mathrm{Lag}; \\ & \mathrm{Lag} = 1 - \exp[(0.564 - 0.124 \times \mathrm{PMY}) \times (\mathrm{WL} + P)], \quad (7)\end{aligned}$$

where PMY = month of post-calving when peak milk yield occurred (1, 2 or 3) and $P = 2.36$ for PMY = 1 and 2, and $P = 3.67$ for PMY = 3. As the exact date of PMY was not recorded, a default value of 1.5 was used (in the individual cow data set, PMY was attained at 40 DIM). This parameter value (1 or 2) has very little effect on the predicted DMI after 30 DIM. The model also has temperature and mud adjustment factors, but all the studies were conducted in a temperate climate and within experimental dairy barns, and therefore no temperature or mud factors were needed.

In the model by Vadiveloo and Holmes (1979), concentrate intake was included as a diet factor in addition to LW, MY and stage of lactation parameters:

$$\begin{aligned}\mathrm{TDMI} = {} & 0.076 + 0.404 \times \mathrm{CDMI} + 0.013 \times \mathrm{LW} - 0.129 \\ & \times \mathrm{WL} + 4.12 \times \mathrm{Log(WL)} + 0.14 \times \mathrm{MY}, \qquad (8)\end{aligned}$$

where CDMI = concentrate DMI (kg/day) and MY = milk yield (kg/day).

Lewis (1981) developed a more complicated model including several silage characteristics and an interaction between silage intake potential and concentrate intake, whereas the model lacks the stage of lactation effects:

$$\begin{aligned}& \mathrm{SIP} = 0.103 \times \mathrm{DM} + 0.0516 \times \mathrm{D} - 0.05 \times \mathrm{NH_3\text{-}N} + 45 \\ & \mathrm{SDMI} = 1.068 \times \mathrm{SIP} - 0.00247 \times \mathrm{C} \times \mathrm{SIP} - 0.00337 \\ & \qquad \times \mathrm{C}^2 - 10.9 \\ & \mathrm{TDMI} = \mathrm{SDMI} \times (\mathrm{LW}^{0.75})/1000 + \mathrm{CDMI} \\ & \qquad + 0.00175 \times \mathrm{MY}^2, \qquad (9)\end{aligned}$$

where SIP = silage DMI potential (g/kg $\mathrm{LW}^{0.75}$) when silage is fed as the sole feed, DM = silage DM concentration (g/kg), D = silage concentration of digestible OM (g/kg DM), $\mathrm{NH_3}$-N = silage ammonia N concentration (g/kg total N), C = concentrate DMI (g/kg $\mathrm{LW}^{0.75}$) and SDMI = silage DMI (g/kg $\mathrm{LW}^{0.75}$) when silage is fed with concentrates. Models (6) and (7) were developed from data sets using predominantly maize-based rations, whereas models (8) and (9) were developed using mainly European grass silage-based rations.

Unfortunately, the recent comprehensive model by Keady *et al*. (2004a), which included several animal and feed factors and interaction between silage intake potential and concentrate supplementation, could not be evaluated as it included factors (silage intake potential determined by near infrared spectroscopy and body condition score (BCS)) that were not available in the present data set.

Statistical analysis

The following basal MIXED regression model of SAS (Littell *et al*., 1996) was used to develop the intake prediction models:

$$Y = B_0 + B_1X_{1ij} + b_0 + b_1X_{1ij} + B_2X_{2ij} + B_3X_{3ij} + e_{ij}, \tag{10}$$

where $B_0 + B_1X_{1ij} + B_2X_{2ij} + B_3X_{3ij}$ are the fixed effects and b_0, b_1 and e_{ij} are the random experiment effects (intercept, slope and error), i = number of subjects (cows within study (353), or studies (207)), and $j = 1 \ldots n_i$ values within a subject. The goodness of fit of the models was evaluated using residual mean square error (RMSE), which was calculated as a square root of the residual variance. Akaike's information criterion was used to evaluate the variance–covariance structure (the smaller the better). Adjusted values were calculated for the figures by adding the residual from each individual observation to the predicted value of the study regression (St-Pierre, 2001). The data were also analyzed with simple model regression without random study effect to evaluate the difference in RMSE that can partly be attributed to systematic differences between studies, for example, in the determination of forage *D*-value, DM concentration and feeding method.

For both sECM yield and total DMI models, all four parameters related to the stage of lactation (Wilmink, 1987) were first included in the model, but if the parameter was non-significant ($P < 0.10$) it was excluded from the model. If the exponential term of the Wilmink (1987) equation was significant, the value of the coefficient (−0.05) was adjusted until the best fit was obtained according to RMSE adjusted for random study effect.

The DMI model was generated using individual cow data and tested with treatment mean data. In practice, the diets are formulated for groups of cows rather than individual cows, justifying the use of treatment mean data in model evaluation. In the individual cow data set there was a much wider range in DIM within subject (cow (study)) than in treatment mean data (diet (study)), allowing a better estimation of the lactation stage effects on TDMI. Root mean squared prediction error (RMSPE) was calculated as RMSPE = square root (Σ (observed−predicted)$^2/n$). The models were evaluated by regressing residual (observed−predicted) values on the predicted values (St-Pierre, 2003). Predicted values were centered by subtracting the mean of all predicted values from each prediction. This makes the slope and intercept estimates in the regression orthogonal, and thus independent. Mean biases were assessed using the intercepts of the regression equations. The slopes of the regression equations were used to determine the presence of linear biases.

Results

Data

The description of the data based on individual cow observations and treatment mean data used for developing and evaluating intake prediction models, respectively, is shown in Table 1. On average, intake and MY were higher in the individual cow data set. Variation in production parameters was greater in the individual cow data set, but DMI displayed similar variation in both data sets. Both intake potential of silage and TDMI were more variable in the treatment mean data set.

sECM yield

The effects of the stage of lactation, dietary intake potential and MP concentration on ECM yield are shown in Table 2. The model was slightly improved when the coefficient of the exponential DIM parameter that describes the deviation from the linear decline in ECM yield was reduced from −0.05 to −0.07. The following equation was developed from regression coefficients in Table 2 to calculate sECM:

$$\begin{aligned}\text{sECM (kg/day)} = {} & \text{Observed ECM (kg/day)} + 0.131 \\ & \times (100 - \text{TDMI index}) + 0.142 \\ & \times (90 - \text{MP}) - 0.0481 \times (150 - \text{DIM}) \\ & + 6.96 \times \exp(-0.07 \times \text{DIM}).\end{aligned} \tag{11}$$

The quadratic effect of DIM and the interaction between the DIM and TDMI index were not significant ($P = 0.27$ and 0.54, respectively) and were therefore excluded from the model. Correlation coefficients between sECM and TDMI index or DIM were much weaker ($r = 0.16$ and 0.03) than corresponding coefficients with observed ECM ($r = 0.65$ and 0.46), respectively.

Model development

Mixed (12) and simple (13) regression models predicting DMI for individual cow data are shown in Table 3. The parameter values were similar between the models, indicating that the effects of independent variables on DMI were consistent between the studies. The models were slightly improved when −0.03 rather than −0.07 was used as a coefficient for the exponential term of DIM, probably reflecting delayed maximum in feed intake compared with MY. Interaction between sECM and TDMI index was not significant ($P = 0.57$). Similarly, DIM or LW did not influence observed DMI response to TDMI index (interaction $P = 0.32$ and 0.80, respectively). Milk protein-to-fat ratio had a strong positive ($P < 0.001$) effect on DMI, when it was included as an additional independent variable to the mixed model shown in Table 3 (regression coefficient 2.68 ± 0.37). When data for primiparous and multiparous cows were analyzed

Table 1 *Statistical description of the variables used in the data files for development and validation of feed intake models in dairy cows*

	Individual cow data, $n = 1554$				Treatment mean data, $n = 998$			
	Mean	s.d.	Minimum	Maximum	Mean	s.d.	Minimum	Maximum
DM intake (kg/day)								
Silage	11.2	2.15	3.9	20.3	10.5	1.94	4.6	17.4
Concentrate	9.4	2.44	2.5	16.8	7.4	2.33	0	18.4
Total	20.6	3	10.8	29.3	17.9	2.82	9.9	25.2
NDF	8.4	1.33	3.4	12.8	7.3	1.35	3.6	11.1
CP	3.3	0.61	1.5	4.8	3.0	0.59	1.3	5.0
Relative intake potential								
Silage DM	103	7.3	83	120	97	11.4	60	136
Concentrate DM	104	11.6	58	128	95	14.1	41	152
Total DM	107	16.2	42	137	92	20.9	17	144
Silage composition								
DM (g/kg)	277	63.5	213	500	254	56.8	151	500
CP (g/kg DM)	147	18.7	102	194	155	24.9	88	272
D-value[a] (g/kg DM)	685	39.5	590	744	677	39.9	495	763
Total acids (g/kg DM)	75	28.6	0	149	82	35.9	7	218
Concentration in total diet (g/kg DM)								
CP	161	15	111	199	165	21	101	252
NDF	412	51	311	563	407	50	195	571
Metabolizable protein	92.1	6.1	75	103	90.0	5.5	74	114
Production parameters								
Days in milk	114	48	30	286	103	30	38	226
Milk (kg/day)	30.4	7.1	8.4	52.8	25.4	5.05	13	45.8
ECM (kg/day)	31.5	6.42	10.1	55.4	26.1	5.14	12.8	42.1
Milk fat (g/kg)	43.2	6.5	24.2	66.6	42.8	3.96	31.9	55
Milk protein (g/kg)	33.5	2.97	22.9	44.2	32.1	1.7	25.9	37.8
Live weight (kg)	599	66	443	802	564	41	440	673

DM = dry matter; ECM = energy corrected milk.

[a] *D*-value = concentration of digestible organic matter in DM.

Table 2 *Parameters for predicting ECM yield from the stage of lactation, dietary MP concentration and TDMI index (RMSE adjusted for random cow effect 1.57 kg/day)*

Item	Unit	Estimate	s.e.	*P*-value
Intercept		10.0	2.7	0.64
DIM	Days	−0.0481	0.002	<0.001
Exp (−0.07 × DIM)	Days	−6.96	2.86	0.015
TDMI index		0.131	0.037	<0.001
MP	g/kg DM	0.142	0.009	<0.001

ECM = energy corrected milk; MP = metabolizable protein; TDMI index = total diet dry matter intake index; RMSE = residual mean square error; DIM = days in milk.

separately, the total DMI was 0.50 ± 0.056 kg/day lower ($P < 0.001$) for the first lactation cows compared with the older cows when the effects of other factors (sECM, DIM, LW and TDMI index) were taken into account.

Mixed model regression equations predicting DMI using observed ECM yield (ECM model (14)) rather than standardized yield or only animal-related parameters (15) as independent variables are shown in Table 4. Intercept values increased significantly compared with the mixed DMI model (12). The effect of ECM yield was much greater (0.326 *v.* 0.258; $P < 0.001$) in the animal model (15) compared with the mixed DMI model (12). The linear DIM effect was markedly smaller ($P < 0.001$) in the ECM model (14) and animal model (15) compared with the DMI model (12). The effect of intake potential described as relative TDMI index became much smaller ($P < 0.001$) when observed rather than sECM yield was used in the prediction model. Although the residual was not greater for model (14) compared with model (12), it should be noted that the data needed for model (14) are only available retrospectively.

The parameter values of intake model (16) developed from the treatment mean data set are shown in Table 5. sECM yield and LW had greater effects on TDMI when estimated from treatment mean rather than from individual cow data set (model (12)). The effect of diet intake potential did not differ ($P = 0.25$) between the two data sets. The mean difference between the predictions was small (−0.03 kg/day) and the predictions were strongly correlated ($R^2 = 0.998$; mean prediction error 0.16 kg/day). Adjusted RMSE decreased from 0.36 to 0.32 when the parameters were estimated directly from treatment mean data set compared with the prediction model developed from the individual cow data set (12). Consistent with the individual cow data set, there was no interaction between sECM and TDMI index ($P = 0.49$) or DIM and TDMI index ($P = 0.39$).

Table 3 *Mixed and simple regression models predicting DMI (kg/day) from the animal characteristics, stage of lactation and intake potential of the diet (*n *= 1544; adjusted RMSE for mixed model 0.52 kg/day; RMSE of simple model 1.27 kg/day)*

		Mixed DMI model (12)			Simple DMI model (13)		
Item	Unit	Estimate	s.e.	*P*-value	Estimate	s.e.	*P*-value
Intercept		−2.9	0.56	0.001	−2.4	0.41	<0.001
sECM[a]	kg/day	0.258	0.011	<0.001	0.275	0.007	<0.001
LW	kg/day	0.0148	0.0009	<0.001	0.0136	0.0005	<0.001
DIM	Days	−0.0175	0.001	<0.001	−0.0171	0.001	<0.001
Exp (−0.03 × DIM)	Days	−5.85	0.41	<0.001	−6.53	0.58	<0.001
TDMI index		0.090	0.002	<0.001	0.089	0.002	<0.001

DMI = dry matter intake; RMSE = residual mean square error; sECM = standardized ECM yield; LW = live weight; DIM = days in milk; TDMI index = total diet dry matter intake index.

[a] Estimated using parameters from model (11).

Table 4 *Mixed regression models predicting DMI (kg/day) from the animal characteristics and intake potential of the diet or only from animal characteristics (*n *= 1544; adjusted RMSE 0.52 kg/day (model 14); 0.58 kg/day (model 15))*

		ECM model (14)[a]			Animal model (15)[b]			Significance*	
Item	Unit	Estimate	s.e.	*P*-value	Estimate	s.e.	*P*-value	A	B
Intercept		−0.6	0.56	0.31	0.6	0.66	0.40	<0.001	<0.001
ECM[c]	kg/day	0.238	0.011	<0.001	0.326	0.011	<0.001	0.06	<0.001
LW	kg/day	0.0155	0.0009	<0.001	0.0177	0.0011	<0.001	0.49	<0.001
DIM	Days	−0.0057	0.001	<0.001	−0.0030	0.001	0.03	<0.001	<0.001
Exp (−0.03 × DIM)	Days	−5.4	0.42	<0.001	−5.6	0.47	<0.001	0.32	0.08
TDMI index		0.052	0.003	<0.001				<0.001	

DMI = dry matter intake; RMSE = residual mean square error; ECM = energy corrected milk; LW = live weight; DIM = days in milk; TDMI index = total diet dry matter intake index.

[a] Instead of sECM observed ECM yield was used.

[b] No diet parameters in the model.

[c] ECM = Observed ECM.

*Significance of the difference in parameter values compared with the mixed DMI model (Table 3) (A, model (14) and B, model (15)).

Model evaluation

The treatment mean data set was used to evaluate the mixed (12) and simple model (13) prediction equations developed using the individual data set:

$$
\begin{aligned}
&\text{Mixed model : Observed DMI} \\
&\quad = -0.10\ (\pm 0.33) \\
&\qquad + 1.004\ (\pm 0.019) \\
&\qquad \times\ \text{Predicted DMI} \\
&\qquad (\text{adjusted RMSE} = 0.362\ \text{kg/day}), \qquad (17)
\end{aligned}
$$

$$
\begin{aligned}
&\text{Simple model : Observed DMI} \\
&\quad = 0.56\ (\pm 0.19) + 0.967\ (\pm 0.011) \\
&\qquad \times\ \text{Predicted DMI (RMSE} = 0.912\ \text{kg/day;} \\
&\quad R^2 = 0.895). \qquad (18)
\end{aligned}
$$

Evaluation of residuals of equation (17) did not result in mean or linear slope (Figure 1). With equation (18) there was no mean bias ($P = 0.20$), but a numerically small ($P < 0.01$) linear bias of −0.034 was detected. On account of the minimal mean and slope biases, random error accounted for 99.5% and 99.0% of the residual variance for models (17) and (18), respectively. Residuals of neither mixed ($P > 0.41$) nor simple ($P > 0.14$) model predictions were significantly related to TDMI index, observed ECM yield, LW or DIM.

Table 5 *Mixed regression model (16) predicting DMI for treatment mean data (*n *= 992)*

Item	Unit	Estimate	s.e.	*P*-value[a]	Significance*
Intercept		−5.2	0.91	0.31	0.002
sECM	kg/day	0.285	0.016	<0.001	0.06
LW	kg/day	0.0176	0.0015	<0.001	0.03
DIM	Days	−0.0153	0.0042	0.001	0.48
Exp(−0.03 × DIM)	Days	−3.55	1.89	0.06	0.09
TDMI index		0.088	0.002	<0.001	0.25

DMI = dry matter intake; sECM = standardized ECM yield; LW = live weight; DIM = days in milk; TDMI index = total diet dry matter intake index.

[a] *P*-value of parameter estimates.

*Significance of the difference in parameter estimates compared with those estimated from the individual cow data set model (12).

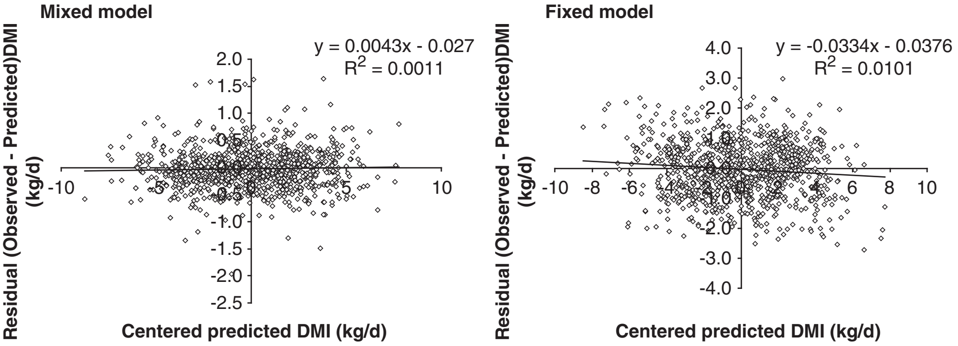

Figure 1 Plot of residuals (observed − predicted) *v.* predicted values of DMI (kg/day). Predicted values were centered by subtracting the mean predicted value from each predicted value; DMI = dry matter intake.

Table 6 *Comparison of accuracy and precision of intake prediction models with individual cow data set (*n *= 1554)*

Reference	Model	Mean bias (kg/day)	*P*-value	Linear bias	*P*-value	RMSPE (kg/day)	R^2	Random[a]
NRC (2001)	Mixed	−1.66	<0.001	−0.23	<0.001	1.94		0.163
	Simple	−1.73	<0.001	−0.05	0.001	2.35	0.726	0.448
CNCPS	Mixed	0.19	0.008	−0.01	0.33	0.78		0.938
(Fox *et al.*, 2004)	Simple	0.10	0.007	0.02	0.19	1.50	0.754	0.992
Vadiveloo and Holmes (1979)	Mixed	1.91	<0.001	0.18	<0.001	2.07		0.096
	Simple	1.84	<0.001	0.14	<0.001	2.39	0.753	0.390
Lewis (1981)	Mixed	2.37	<0.001	−0.07	<0.001	2.52		0.106
	Simple	2.22	<0.001	0.00	0.98	2.89	0.624	0.406

RMSPE=root mean squared prediction error; NRC = National Research Council; CNCPS = Cornell Net Carbohydrate and Protein System.
[a] Proportion of random error of total error variance.

In the treatment mean data set, the regression coefficient of milk protein-to-fat ratio was 2.04 (s.e. = 0.45; $P < 0.001$) when it was included as a second independent variable with predicted DMI (DMI = Predicted DMI + Protein/fat in milk).

Evaluation of the published models using the individual cow data set is shown in Table 6. The CNCPS (Fox *et al.*, 2004) model resulted in the most accurate (small mean bias) predictions of DMI with both mixed and simple model evaluations. It also had small mean and linear biases. The Vadiveloo and Holmes (1979) model was the most precise (low random error around regression line) in mixed model evaluation (adjusted RMSE = 0.64 kg/day), followed by the CNCPS (0.74 kg/day). The precision of models using FCM as the yield parameter was improved when ECM replaced FCM in the model. The NRC (2001) model clearly over-predicted DMI, whereas the models by Vadiveloo and Holmes (1979) and Lewis (1981) under-predicted it. The precision of models using only animal variables (NRC, CNCPS) was improved when TDMI index was included in the model as a second independent variable together with model-predicted DMI. Regression coefficients for TDMI index ranged from 0.05 to 0.07 per unit.

Using the treatment mean data set, our model (12) performed better compared with models (14) and (15), which used observed rather than standardized ECM yield, according to all criteria (RMSPE, mean bias, linear bias) of evaluation (Table 7). The CNCPS model was the most accurate of the four published models. It was also the most precise of the simple models, but the Vadiveloo and Holmes (1979) and Lewis (1981) models were more precise with mixed model evaluation (adjusted RMSE 0.47 *v.* 0.52 kg/day). Mean bias (observed−predicted) of DMI was on average 0.67 kg/day smaller in treatment mean data compared with individual cow data. In most cases, linear biases were also markedly different between the two data sets. For example, with the NRC (2001) model, linear bias was −0.23 kg/day with the individual data set and 0.14 kg/day with the treatment mean data set, that is, observed increases were smaller or greater than predicted in the two data sets (Figure 2). A corresponding change in linear bias was also observed when the animal model (15) from the present individual data set was evaluated with treatment mean data. Consistent with the individual cow data set, the precisions of the NRC and CNCPS models were improved by including TDMI index in the model with predicted DMI. Using mixed model regressions, the coefficients were 0.055 (NRC) and 0.052 (CNCPS), respectively.

Discussion

Model development and evaluation

Feed intake is the strongest single nutritive factor influencing performance of dairy cows, and therefore much attention has been focused on developing models predicting intake.

Table 7 *Comparison of accuracy and precision of intake prediction models with treatment mean data* (n = 992)

	Model	Mean bias (kg/day)	*P*-value	Linear bias	*P*-value	RMSPE (kg/day)	Random[a]	R^2
NRC (2001)	Mixed[c]	−2.31	<0.001	0.14	<0.001	2.39	0.047	
	Simple	−2.35	<0.001	0.06	<0.001	2.61	0.187	0.840
CNCPS	Mixed[c]	−0.53	<0.001	0.28	<0.001	0.96	0.293	
(Fox *et al*., 2004)	Simple	−0.44	<0.001	0.20	<0.001	1.20	0.705	0.873
Vadiveloo and Holmes (1979)	Mixed[c]	1.05	<0.001	0.32	<0.001	1.30	0.129	
	Simple	1.12	<0.001	0.30	<0.001	1.78	0.500	0.801
Lewis (1981)	Mixed[c]	1.49	<0.001	0.28	<0.001	1.65	0.079	
	Simple	1.57	<0.001	0.26	<0.001	2.03	0.345	0.821
Model (12)[b]	Mixed[c]	−0.03	0.59	0.00	0.84	0.36	0.995	
	Simple	−0.04	0.19	−0.03	0.002	0.92	0.990	0.895
Model (14)[b]	Mixed[c]	−0.34	<0.001	0.02	0.38	0.51	0.540	
	Simple	−0.27	<0.001	−0.02	0.14	1.02	0.929	0.878
Model (15)[b]	Mixed[c]	−0.50	<0.001	0.30	<0.001	0.94	0.251	
	Simple	−0.52	<0.001	0.18	<0.001	1.16	0.735	0.875

RMSPE = Root mean squared prediction error; NRC = National Research Council; CNCPS = Cornell Net Carbohydrate and Protein System.
[a] Proportion of random error of total error variance.
[b] Models predicted from the individual data set.
[c] Adjusted for the random study effect.

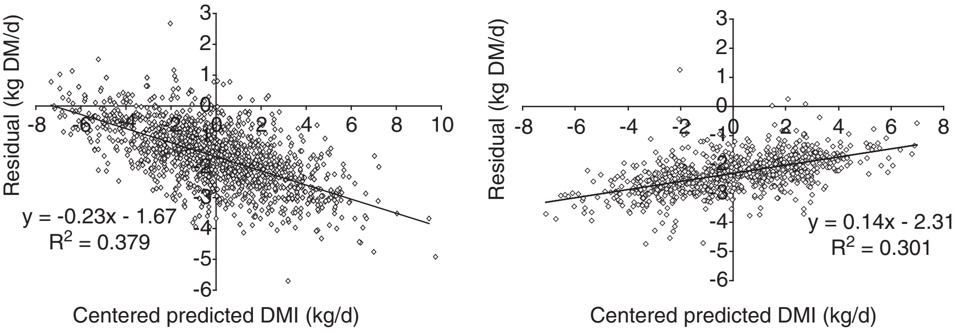

Figure 2 Plot of residuals (observed−predicted) *v.* predicted (NRC, 2001) values of DMI (kg/day) for the individual cow data (left) and treatment mean data (right). Predicted values were centered by subtracting the mean predicted value from each predicted value; DMI = dry matter intake.

The published prediction models are usually based on multiple regression equations, and vary in their complexity (see Ingvartsen, 1994). Although many of the models include animal, diet and sometimes management factors, in many cases the models are based entirely on animal factors (e.g. NRC, 2001; Fox *et al*., 2004) or feed factors predicting relative intake potential of the diet (Huhtanen *et al*., 2008). This study was designed to extend our previous models predicting relative DMI potential of silage and total DMI (Huhtanen *et al*., 2007 and 2008) for predicting actual DMI by including animal factors in the model.

The model (12) developed from individual cow data was both accurate and precise when validated using a large treatment mean data set. The model can be considered robust because of (i) a low mean prediction error, (ii) high accuracy and precision in validation (no mean and slope bias, random error >99% of total error), (iii) numerically small differences in the parameter values of model variables when estimated with mixed or simple regression models, and (iv) that the residuals in model validation were not correlated to animal (ECM, LW and DIM) or dietary factors (TDMI index). Our RMSE of 1.27 kg/day (12) compares well with the corresponding values of 1.47 and 1.55 kg/day for primiparous and multiparous cows, respectively, in the study by Roseler *et al*. (1997). When the treatment mean data were used for validation and split into two subsets according to mean yield in the study (< 25 *v.* >25 kg/day), DIM (<100 *v.* ⩾100 days) and experimental design (change-over *v.* continuous trials), the intercepts (0.12 *v.* −0.27, 0.06 *v.* −0.25 and 0.12 *v.* −0.47, respectively) and slopes (0.992 *v.* 1.015, 1.006 *v.* 1.012 and 0.992 *v.* 1.025, respectively) between predicted and observed DMI were similar, which also suggests that the model (12) was robust.

Compared with the TDMI index model (Huhtanen *et al*., 2008), including the animal factors into the mixed (12) and simple (13) regression models reduced RMSE from 0.42 to 0.36 and 1.64 to 0.92 kg/day, respectively. The smaller decrease with mixed model analysis is related to the fact that within a study animal factors (sECM yield, LW and DIM) are constant between diets. However, in practice RMSE will be greater due to random errors in sECM when predicted from the current yield and diet parameters.

The developed model includes several feed factors integrated into a single parameter of diet-relative intake potential (TDMI index) and animal factors (sECM yield, LW and DIM). It would be possible to substitute equation (11) for (12), but then the model would include observed ECM, that is, it would invalidate the objective of developing an intake model based on parameters available before the diet is fed. The parameter value for the relative TDMI index was slightly smaller (0.090 kg per unit) than the default value (0.100). In the evaluation of the TDMI index, the observed increase per one TDMI index unit was 0.095 kg (Huhtanen *et al*., 2008), suggesting some interactions between the feed factors. The only interaction term in the TDMI index model is the negative relationship between silage intake potential and level of concentrate supplementation. This interaction was also incorporated into the models by Lewis (1981) and Keady *et al*. (2004a). The slightly lower value in this study may indicate some interactions between animal factors and intake potential, but interactions were not significant in model development or evaluation, and were therefore excluded.

Instead of using observed MY, we used ECM yield standardized for TDMI index, dietary MP concentration and DIM. This approach provides two advantages: (i) it can be estimated before the diet is fed to the cows, and (ii) it is markedly less correlated to diet characteristics than observed yield, allowing a more reliable separation of diet and animal effects on DMI. Consistent with individual cow data, TDMI index was much more strongly correlated to the observed compared with sECM yield ($r = 0.80$ *v.* 0.16). It should also be noted that although the regression coefficient for observed ECM yield was numerically even lower than for sECM in the DMI prediction model (0.238 *v.* 0.258), the effect of yield variable on predicted DMI was smaller when standardized rather than observed ECM was used as a model factor. Predicted DMI responses were 1.22 and 1.53 kg per one unit of standard deviation in standardized and observed ECM yield (4.7 *v.* 6.4 kg). In contrast, predicted DMI response per one s.d. unit of TDMI index (s.d. = 16.1) was greater when sECM rather than observed ECM yield was used in the model (1.45 *v.* 0.84 kg). Consequently, the true effects of dietary factors on DMI will be underestimated when observed yield is used as a model factor. This is mainly due to the strong correlation between diet intake potential and MY, that is, the dietary effects on DMI are to a large extent realized via increased MY. However, as discussed earlier by Ingvartsen (1994) and Keady *et al*. (2004b), the problem of using observed yield in predicting DMI is that it is not available at the time of feeding the diet, that is, system output (MY) is used to predict system input (intake). In contrast, sECM yield used in our model (Table 3) can be estimated before feeding from current yield, diet composition and DIM. According to our knowledge, only the Danish fill unit system (Kristensen and Ingvartsen, 2003) and INRA system (Faverdin *et al*., 2007) use potential rather than observed MY in estimating intake capacity. In the INRA system, potential MY is a function of peak yield, stage of lactation and gestation, but it does not take into account diet effects on the potential MY. The study by Friggens *et al*. (1998) demonstrated elegantly that using observed MY can be misleading in predicting intake potential. A 10 kg difference in MY between cows fed low and high concentrate diets during the first period would suggest a great difference in intake potential, but this was not realized when the diets were switched.

In the treatment mean data set, annual increases in ECM and sECM yields were 0.48 and 0.23 kg/day, respectively, corresponding to 146 and 70 kg per 305-day lactation, when regressed against the year of the study. These values correspond well to the phenotypic and genotypic increases in MY during the last decades (Faba, 2009), suggesting that sECM yield reflects the genetic potential of the cows.

Model comparison

The model (12) performed better according to all evaluation criteria (lower RMSPE, mean and linear bias and random error) than the published models evaluated. This could be related to accurate estimations of the intake potential of the diets using large treatment mean data sets (Huhtanen *et al*., 2007 and 2008) and separation of animal and diet effects on DMI by using standardized rather than observed ECM yield. The ranking of the CNCPS (Fox *et al*., 2004), Vadiveloo and Holmes (1979) and Lewis (1981) models on the basis of goodness of fit was similar for both the individual and treatment mean data sets, as found in the study by Keady *et al*. (2004b). The NRC (2001) and CNCPS (Fox *et al*., 2004) models predicted much higher DMI than the models by Vadiveloo and Holmes (1979) and Lewis (1981), probably because they were developed using data from diets largely based on maize and lucerne silages and maize grain. With all published models, the difference between observed and predicted DMI was greater for individual cow data than for treatment mean data. In the models that do not include any feed variables (NRC (2001) and CNCPS (Fox *et al*., 2004)), the difference can be attributed to the higher intake potential for the individual cow compared with the treatment mean data (TDMI index 107 *v.* 92). With the Vadiveloo and Holmes (1979) model, the difference can be related to the higher silage intake potential in the individual cow data set (103 *v.* 97), since their model includes CDMI, which is the most important concentrate factor influencing total DMI (Huhtanen *et al*., 2008). In the case of the Lewis (1981) model, which is derived predominantly from feed variables, a weak effect of MY (0.105 kg DMI/day/kg between 20 to 30 kg/day) and absence of LW effect in the model may explain different mean biases between the two data sets.

The precision of both the NRC (2001) and CNCPS (Fox *et al*., 2004) models improved when TDMI index was used as a second variable in the model in addition to predicted DMI, suggesting that animal factors cannot deal with all diet effects on intake despite the strong correlation between intake potential and observed ECM yield. In contrast, dietary concentrations of NDF, ADF and net energy were not significant in describing intake (Roseler *et al*., 1997). This could partly be because fill does not limit the intake of highly digestible high-energy diets, and partly because their data consisted of studies of dose titration of bovine somatotropin with small variation in diet composition within study location. In contrast to the model by Roseler *et al*. (1997), the meta-analysis by Hristov *et al*. (2004) demonstrated that several dietary factors influenced the DMI of cows fed North American diets.

In addition to changes in the mean bias, the linear slope biases were markedly different between the two data sets. This was the problem not only with published models, since the animal model (15) derived from the individual cow data presented the same problem when evaluated using treatment mean data set (linear bias 0 *v.* 0.28 with mixed models). One possible explanation is that variation in body mobilization between the cows is greater than between the diets, resulting in a biased relationship between the yield and intake. Residuals (observed − predicted) of DMI predictions were positively related to TDMI index, ECM yield and LW with the NRC (2001), CNCPS (Fox *et al*., 2004) and animal models (15), suggesting that the models derived using only animal variables from individual cow data underestimate intake responses of treatment mean data (positive linear bias).

Regression coefficients for the milk fat-to-protein ratio when included as a second variable with predicted DMI were significantly higher in the NRC, CNCPS and the current (15) animal models (9.3, 8.2 and 4.8) compared with the current model (12) including both animal and feed factors (2.0). As the milk fat-to-protein ratio is related to the energy balance of cows (Heuer *et al*., 2001; Friggens *et al*., 2007), the above differences in regression coefficient indicate that mobilization/storage of body energy can result in biased parameter estimates when the intake prediction models are derived using only animal variables. In negative energy balance, body fat is mobilized, which increases milk fat concentration, whereas the supply of amino acid is reduced, resulting in lower milk protein concentration. Adjusting the observed ECM yield to the mean calculated energy balance reduced the linear bias from 0.30 to 0.15 in the present data, which also supports the view that energy balance is involved in biased estimates of intake prediction models based only on animal factors.

Management and environmental factors influencing intake

In addition to the animal and diet factors used in the present model (12), many environmental and management factors can have a substantial influence on DMI (Ingvartsen, 1994; Mertens, 1994), and can contribute to the greater RMSE with the simple compared with the mixed regression model (0.90 *v.* 0.36 kg/day). Although management factors were often reported, within a study these effects were typically constant (e.g. feeding time, TMR *v.* separate feeding) and are mainly accounted for by the random study effect, and therefore cannot reliably be estimated from the data.

BCS influenced by *pre-partum* management has a strong influence on DMI (Garnsworthy and Topps, 1982; Hayrli *et al*., 2003) or intake capacity (Faverdin *et al*., 2007), and could be one factor contributing to the greater RMSE with simple model analysis. Increased BCS at the same LW has reduced DMI, and therefore including BCS in the intake model could reduce intake prediction error associated with increased body tissue mobilization or fatness. The model by Keady *et al*. (2004a) predicts a decrease of 1.12 kg in daily DMI per one unit increase in BCS (scale 0 to 5). Similar or even greater negative BSC effects on DMI were reported by Roseler *et al*. (1997). Some models have used LW change as a model factor in predicting DMI (see Ingvartsen, 1994). In the models by Roseler *et al*. (1997), the regression coefficient of weekly LW change on DMI was 0.10 to 0.15 kg/kg. However, using LW change in the intake prediction model has the same disadvantage as observed MY, that is, it is available only retrospectively. The strong effects of BCS (Keady *et al*., 2004a) and energy balance on DMI, and consequently on residual DMI (observed−predicted), suggest that these factors can contribute to the between-study differences in DMI. Unfortunately, we did not have data to evaluate BCS effects on DMI.

The length of time the cows had access to feed varied from 6 to 24 h in the treatment mean data set, which can influence DMI and explain part of the random study effect. Increasing the time of access to feed from 8–20 to 24 h/day has increased the total DMI of grass silage-based diets by 0.6 to 1.0 kg/day (Martinsson and Burstedt, 1990; Martinsson, 1992; Heikkilä and Toivonen, 2005). These findings support the hypothesis that part of the between-study variation can be related to differences in the time of access to feed.

Generally, feeding forages and concentrates as TMR increases DMI when compared to feeding the same ingredients separately (Maltz *et al*., 1992). In our model, the effect of concentrate feeding is accounted for by the CDMI index, but the feeding technique (TMR *v.* separate) may contribute to the RMSE difference between the mixed and simple models.

Most published models are based on data from certain breed(s). However, breed can have a substantial effect on intake (Ingvartsen, 1994). In the present treatment mean data, DMI was 0.32 kg/day higher ($P < 0.001$) for Ayrshire cows, including Nordic Red breeds, compared with Holsteins and Friesians. However, including breed in the model only marginally reduced RMSE (0.920 *v.* 0.909). It should also be noted that there can be other systematic differences between studies conducted using different breeds. The proportion of heifers is another systematic factor between the studies that can cause differences between studies in DMI when other factors are constant. In the present individual cow data, DMI was 0.50 kg/day lower for first-lactation cows compared with older cows. However, in the analysis of the treatment mean data set, the proportion of first-lactation cows ($n = 796$) was not significant.

In addition, both Ingvartsen (1994) and Mertens (1994) listed a number of factors (e.g. feeding frequency, tie stalls *v.* loose housing, temperature, photoperiod) that can influence between study differences, but are constant within study. Therefore, it can be expected that the true prediction error in practical conditions (same animals, same environment and management, same feed analysis) are closer to the mixed model rather than the simple model mean prediction error.

Methodological effects

In addition to the management factors discussed above, some methodological differences between studies can also increase simple model prediction error. Silage digestibility has a strong influence on relative SIP (Huhtanen *et al*., 2007). In the treatment mean data set, silage digestibility was determined *in vivo* in sheep fed with maintenance, rumen fluid (Tilley and Terry, 1963) or pepsin-cellulase (Nousiainen *et al*., 2003) methods. Although each method can be precise within study in determining forage digestibility, there can be between-study differences (e.g. activity of rumen fluid) resulting in between-study bias in digestibility and intake potential estimates.

Silage DM concentration was determined using a range of techniques (oven drying, toluene distillation, toluene distillation + ethanol correction, or using equations to correct for volatile losses). For example, using the average silage composition of the treatment mean data set, the calculated difference in DM concentration between oven DM and corrected DM (Huida *et al*., 1986) was 12.0 g/kg, corresponding to a difference of 0.53 (range 0.08 to 1.18) kg DM in daily silage intake. The method used to determine silage DM concentration may increase prediction error with both mixed model (oven DM method for silages differing in concentration of volatiles) and simple model analysis (different DM method between trials).

Conclusions and implications

A model was developed to extend the relative TDMI index model to account for the animal effects (yield, LW and stage of lactation) on DMI. The model parameters were limited to those available at the time of ration formulation, that is, observed MY and LW change were excluded. Instead, sECM yield was used in order to be able to estimate animal and diet effects independently. The model developed from individual cow data performed well when validated against a large treatment mean data set. The model performed markedly better than any of the published models, partly because of negligible mean and linear biases and partly due to lower random error. An advantage of the model is that it separates animal and diet effects on intake so that intake can be predicted as precisely and accurately by using parameters available at the time of feeding as the models based on parameters that are available only retrospectively. The model will improve current ration formulation systems by enabling the prediction of actual intake and intake responses, and consequently responses to changes in the nutrient supply, which are prerequisites for any economical model in optimizing milk production in various farming systems.

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