Short communication: Prediction of intake in dairy cows under tropical conditions

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ABSTRACT

A meta-analysis was conducted to develop a model for predicting dry matter intake (DMI) in dairy cows under the tropical conditions of Brazil and to assess its adequacy compared with 5 currently available DMI prediction models: Agricultural and Food Research Council (AFRC); National Research Council (NRC); Cornell Net Carbohydrate and Protein System (CNCPS; version 6); and 2 other Brazilian models. The data set was created using 457 observations ($n = 1,655$ cows) from 100 studies, and it was randomly divided into 2 subsets for statistical analysis. The first subset was used to develop a DMI prediction equation (60 studies; 309 treatment means) and the second subset was used to assess the adequacy of DMI predictive models (40 studies; 148 treatment means). The DMI prediction model proposed in the current study was developed using a nonlinear mixed model analysis after reparameterizing the NRC equation but including study as a random effect in the model. Body weight (mean = 540 ± 57.6 kg), 4% fat-corrected milk (mean = 21.3 ± 7.7 kg/d), and days in milk (mean = 110 ± 62 d) were used as independent variables in the model. The adequacy of the DMI prediction models was evaluated based on coefficient of determination, mean square prediction error (MSPE), root MSPE (RMSPE), and concordance correlation coefficient (CCC). The observed DMI obtained from the data set used to evaluate the prediction models averaged 17.6 ± 3.2 kg/d. The following model was proposed: $\text{DMI (kg/d)} = [0.4762 (\pm 0.0358) \times 4\% \text{ fat-corrected milk} + 0.07219 (\pm 0.00605) \times \text{body weight}^{0.75}] \times (1 - e^{-0.03202 (\pm 0.00615) \times [\text{days in milk} + 24.9576 (\pm 5.909)]})$. This model explained 93.0% of the variation in DMI, predicting it with the lowest mean bias (0.11 kg/d) and RMSPE (4.9% of the observed DMI) and the highest precision [correlation coefficient estimate (ρ) = 0.97]

and accuracy [bias correction factor (C_b) = 0.99]. The NRC model prediction equation explained 92.0% of the variation in DMI and had the second lowest mean bias (0.42 kg/d) and RMSPE (5.8% of the observed DMI), as well as the second highest precision ($\rho = 0.94$) and accuracy ($C_b = 0.98$). The CNCPS and AFRC DMI prediction models explained 93.0 and 85.0% of the variation in DMI but underpredicted DMI by 1.8 and 1.4 kg/d, respectively. These 2 models (CNCPS and AFRC) resulted, respectively, in RMSPE of 11.3 and 10.7% of the observed DMI, with moderate to high precision ($\rho = 0.81$ and 0.82) and accuracy ($C_b = 0.84$ and 0.89). The remaining 2 models resulted in the poorest results, underpredicting DMI by 2.3 and 1.9 kg/d, with RMSPE of 22.8 and 14.9% of the observed DMI and moderate to low precision ($\rho = 0.49$ and 0.76) and accuracy ($C_b = 0.81$ and 0.86). The new model derived from the current meta-analytical approach provided the best accuracy and precision for predicting DMI in lactating dairy cows under Brazilian conditions.

Key words: meta-analysis, modeling, prediction of feed intake

Short Communication

Accurate prediction of feed intake by dairy cows is essential for optimizing nutrient utilization in dairy diets, which can potentially increase the productive, economic, and environmental performance of dairy systems. Despite the complexity of the mechanisms regulating feed intake, several currently available models [e.g., Agricultural and Food Research Council (AFRC, 1993); NRC, 2001; Freitas et al., 2006; Cornell Net Carbohydrate and Protein System (CNCPS, version 6.0; Tylutki et al., 2008); Santos et al., 2009] use empirical approaches to predict DMI with animal-related variables such as BW, milk production and composition, and DIM as fixed effects in the models. It is important to note, however, that application of empirical models is population-dependent, thus restricting their use to specific environmental and geographical conditions.

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Table 1. Selected models for predicting DMI (kg/d) in lactating dairy cows

Model ¹	Equation ²
NRC (2001)	$DMI = (0.372 \times 4\% \text{ FCM} + 0.0968 \times BW^{0.75}) \times (1 - e^{[-0.192 \times (WOL + 3.67)])}$
CNCPS (Tylutki et al., 2008)	$DMI = (0.0185 \times BW \times 0.95 + 0.305 \times 4\% \text{ FCM}) \times (1 - e^{[-(0.564 - 0.124 \times 2) \times (WOL + 2)]})$
Vadivello and Holmes (1979); AFRC (1993)	$DMI = 0.076 + 0.404 \times CI + 0.013 \times BW - 0.129 \times WOL + 4.12 \times \text{Log}_{10}(WOL) + 0.14 \times MY$
Freitas et al. (2006)	$DMI = -100 + 0.116 \times BW + 2.91 \times MY + 22.8 \times MF - 2.6 \times MF^2 - 0.00483 \times BW \times MY$
Santos et al. (2009)	$DMI = (0.6089 \times 4\% \text{ FCM} + 0.0244 \times BW^{0.75}) \times (1 - e^{[-0.2919 \times (DIM + 5.5772)])}$

¹CNCPS = Cornell Net Carbohydrate and Protein System; AFRC = Agriculture and Food Research Council.

²WOL = week of lactation; CI = concentrate intake (kg of DM/d); MY = milk yield (kg/d); MF = milk fat (%).

Therefore, we hypothesized that models constructed with observations obtained under conditions different from those commonly found in tropical environments may lack the accuracy and precision to predict DMI.

The objectives of the current study were (1) to develop a model to predict DMI in lactating dairy cows under Brazilian conditions with BW, milk production and composition, and DIM as independent variables in the model, and (2) to evaluate and compare the adequacy of the proposed model with 5 currently available DMI prediction models: 2 American-based: NRC (2001) and Cornell Net Carbohydrate and Protein System (CNCPS, version 6.0; Tylutki et al., 2008); 1 British-based: AFRC (1993); and 2 Brazilian-based: Freitas et al. (2006) and Santos et al. (2009), using an independent data set.

The data set used in the current study was built from observations reported in 100 studies (457 treatments means; 1,655 cows) published in Brazilian journals from 1991 to 2013 (76 studies) or reported in graduate student theses (24 studies). The criteria adopted for data inclusion in the data set were as follows: (1) experiment conducted under the tropical conditions of Brazil; (2) cows under different feeding management systems and production levels; (3) individual measurements of DMI; (4) estimation of pasture intake using external and internal markers to determine fecal output of DM; and (5) adequate description of cows (e.g., BW, DIM, milk yield, and composition) and experimental diets (e.g., ingredient and chemical composition). Specifically, the data set was composed of Holstein cows (72.6%) and Holstein $\times$ Zebu crosses (27.4%) fed either TMR (86%) or pasture (14%). Forages used by TMR-fed cows included corn silage (75.5%), sugarcane (12.7%), spineless cactus (*Opuntia ficus indica* Mill.) or spineless cactus plus corn silage (6.3%), sugarcane silage (1.4%), sorghum and sunflower silages (2.4%), and alfalfa silage or hay (1.7%). Forages grazed by pasture-fed cows included *Pennisetum purpureum* Schum. (35.3%), *Brachiaria* spp. (29.4%), *Panicum maximum* (21.6%), and *Cynodon* spp. (13.7%).

For statistical analysis, the data set was randomly divided into 2 subsets, with the first subset (60 stud-

ies; 309 treatments means; Appendix 1; development) used to develop a DMI prediction model and the second subset (40 studies; 148 treatments means; Appendix 2; evaluation) used to assess the adequacy of the new developed DMI prediction model compared with 5 currently available models (Table 1).

The DMI prediction model proposed herein was developed using a nonlinear mixed-model analysis of the reparameterized NRC (2001) model but including study as a random effect in the model. Specifically, the proposed nonlinear model was adjusted using metabolic BW ($BW^{0.75}$), 4% FCM, and DIM as fixed effects. Because the data set was built using observations from 60 studies with different breeds, feeding systems, environmental conditions, and experimental methodologies, it was necessary to quantify the variance associated with study, as well as to predict fixed effects adjusted for study effect. Therefore, each study in the data set was treated as a random sample from a larger population of studies (St-Pierre, 2001; Sauvant et al., 2008). Inclusion of study effects required estimation of both the fixed effects associated with the nonlinear model parameters and the random effects of study, similar to the approach described in Vyas and Erdman (2009). The nonlinear mixed (NLMIXED) procedure (Littell et al., 2006) of SAS (version 9.1; SAS Institute Inc., Cary, NC) was used to fit the model:

$$Y_{ij} = (\beta_1 \times BW_{ij}^{0.75} + \beta_2 \times 4\% \text{ FCM}_{ij}) \times \left(1 - e^{[-\beta_3 \times (DIM_{ij} + \beta_4)]}\right) + exp_j + e_{ij},$$

where Y_{ij} = DMI of the i th DMI at the j th study with i ranging from 1 to 309, and j ranging from 1 to 60, $(\beta_1 \times BW_{ij}^{0.75} + \beta_2 \times 4\% \text{ FCM}_{ij}) \times \left(1 - e^{[-\beta_3 \times (DIM_{ij} + \beta_4)]}\right)$ = fixed effect of model; β_1 and β_2 = coefficients representing the DMI per kilogram of $BW^{0.75}$ and per kilogram of 4% FCM, respectively; β_3 and β_4 = coefficients representing the adjustment for DIM; exp_j = random effect of study assuming a normal distribution; and e_{ij} = random error associated with each observation assuming a normal distribution. Data points were removed if the studentized residual was outside the range of -2.5

Table 2. Descriptive statistics of the data set used to develop and evaluate models to predict DMI on dairy cows

Item	Mean	Median	Maximum	Minimum	SD
Development (n = 309) ¹					
Forage diet (% of DM)	59.4	60.0	100.0	35.0	13.6
NDF diet (% of DM)	41.1	40.4	78.8	26.9	10.3
CP diet (% of DM)	15.1	14.6	19.6	8.0	2.4
Ether extract (% of DM)	3.1	3.1	7.3	0.8	1.6
DMI (kg/d)	16.3	15.8	25.3	3.2	3.7
Milk yield (kg/d)	21.3	15.3	37.3	3.4	7.7
Milk fat (%)	3.71	3.55	5.56	2.20	0.58
4% FCM (kg/d)	20.1	15.5	37.3	3.1	6.8
BW (kg)	540.4	516.0	675.4	409.2	57.6
DIM	110	140	304	7	62
Evaluation (n = 148) ²					
Forage diet (% of DM)	60.0	59.4	100.0	40.0	13.2
NDF diet (% of DM)	40.0	37.4	72.8	25.5	8.1
CP diet (% of DM)	15.6	16.0	19.6	8.5	2.5
Ether extract (% of DM)	3.5	2.8	7.5	1.3	1.6
DMI (kg/d)	17.6	17.8	24.3	10.1	3.2
Milk yield (kg/d)	23.1	24.5	35.6	8.4	7.3
Milk fat (%)	3.46	3.50	4.58	2.25	0.50
4% FCM (kg/d)	21.0	22.7	31.3	7.9	6.3
BW (kg)	551.8	558.8	663.1	394.4	60.9
DIM	121	120	230	7	55

¹Appendix 1.²Appendix 2.

to 2.5 (Neter et al., 1996). The critical level of probability for type I error was set at $\alpha = 0.05$.

The adequacy of the DMI predictive model developed in the present study and that of currently available models (Table 1) were assessed for precision and accuracy using graphic analysis, coefficient of determination, mean square prediction error (**MSPE**), root MSPE (**RMSPE**), and concordance correlation coefficient (**CCC**) analyses using the Model Evaluation System (College Station, TX; <http://nutritionmodels.tamu.edu/mes.html>) as described by Tedeschi (2006).

The RMSPE value was expressed relative to the observed mean. The MSPE comprises 3 sources of error expressed as percentage of MSPE: (1) the error due to bias, (2) the error due to deviation of the regression slope from 1, and (3) the random error. The random error represents the error that is not explained by the model (Bibby and Toutenburg, 1977). The precision and accuracy of the DMI prediction models were assessed by estimating the CCC, as described by Lin (1989). The CCC was divided into correlation coefficient (ρ) or precision and bias correction factor (C_b) or accuracy. The ρ and C_b values ranges from 0 to 1, with values closer to 1 indicating more precision and accuracy (Lin, 1989; King and Chinchilli, 2001; Liao, 2003). In addition, the Kolmogoroff-Smirnov D-test (Kolmogoroff, 1933; Smirnov, 1933) was used to assess the probability of whether or not 2 data sets (e.g., observed and predicted values) have same distribution.

The subsets used for developing and evaluating the DMI prediction models represented a wide range of dairy cow and diets characteristics. The descriptive statistics of cows and diets used in both subsets of data were similar, indicating that they were adequately randomized (Table 2). Moreover, the data set was representative of the dairy cattle systems commonly used in Brazil (Oliveira et al., 2007; Stock et al., 2007).

The fit model to predict DMI included 4% FCM, BW, and DIM as independent variables:

$$\begin{aligned} \text{DMI (kg/d)} = & [0.4762 \pm 0.0358 \ (P < 0.001) \\ & \times 4\% \text{ FCM (kg/d)} + 0.07219 \pm 0.00605 \ (P < 0.001) \\ & \times \text{BW (kg)}^{0.75}] \times [1 - e^{-0.03202 \pm 0.00615 \ (P < 0.001)} \\ & \times [\text{DIM} + 24.9576 \pm 5.909 \ (P < 0.001)]]]. \end{aligned}$$

An adjustment factor for DIM $[1 - e^{-0.03202 \times (\text{DIM} + 24.9576)}]$ was included to improve the prediction of DMI during the first 120 DIM (Roseler et al., 1997). This adjustment was necessary during early lactation because the increase in DMI is slower than the increase in milk production in response to metabolic adaptations and gut fill in early lactation (Ingvarsen and Andersen, 2000). Based on the adjustment factor, it was estimated that DMI at the first week of lactation averaged 65% of that at 120 DIM when using fixed FCM and BW in the model predictions.

Table 3. Summary of statistical measures to assess adequacy of several models using regression between observed (Y) and model-predicted (X) DMI

Item ¹	Model					
	Proposed	NRC (2001)	Tylutki et al. (2008) ²	AFRC (1993)	Freitas et al. (2006)	Santos et al. (2009)
Y (kg)	17.61	17.61	17.61	17.61	17.61	17.61
X (kg)	17.72	18.02	15.84	16.20	15.30	15.73
Mean bias (Y – X) (kg)	–0.11	–0.42	1.77	1.40	2.31	1.88
Coefficient of determination (R ²)	0.93	0.92	0.93	0.85	0.37	0.78
MSPE (kg × kg)	0.73	1.04	3.98	3.52	16.04	6.83
Root MSPE (% of observed DMI)	4.85	5.80	11.34	10.66	22.75	14.85
Partition of MSPE (%)						
Error due to mean bias	1.64	16.63	78.50	55.98	33.31	51.91
Error due to slope not equal to 1	3.63	3.21	3.95	0.98	26.89	15.97
Random error	94.73	80.16	17.55	43.05	39.80	32.12
CCC (0 and 1)	0.964	0.930	0.674	0.733	0.400	0.656
ρ (0 and 1)	0.965	0.944	0.806	0.822	0.494	0.762
C_b (0 and 1)	0.999	0.985	0.836	0.891	0.810	0.861
Distribution comparison						
KS test ³ (<i>P</i> -value)	0.88	0.60	<0.001	<0.001	<0.001	<0.001

¹MSPE = mean squared prediction error; CCC = concordance correlation coefficient; ρ = correlation coefficient estimate (precision); C_b = bias correction factor (accuracy).

²Cornell Net Carbohydrate and Protein System (CNPCS) model.

³KS = Kolmogoroff-Smirnov D-test (Kolmogoroff, 1933; Smirnov, 1933), which assesses the probability that 2 data sets (observed and model-predicted values) have the same distribution.

The DMI prediction model proposed in the present study was also adjusted for the effect of study. Consequently, the potential effects of breed (i.e., Holstein vs. Holstein × Zebu cows) and feeding systems (i.e., TMR vs. pasture) on DMI among studies were accounted for in the model predictions (St-Pierre, 2001; Sauvante et al., 2008), thus explaining the selection of a single DMI prediction model. The chemical composition of diets was not included as an independent variable in the present model because, according to NRC (2001), the most common approach for formulating dairy cattle diets is to establish nutrient requirements first, followed by estimation of DMI, before considering the inclusion of dietary ingredients. Furthermore, equations containing dietary factors are best used to predict animal performance rather than feed intake (NRC, 2001).

It is well established that heat stress negatively affects the performance of lactating dairy cows (West, 2003). For instance, when environmental conditions are outside the thermal neutral zone due to increased air temperature and temperature-humidity index, DMI, milk yield, and feed efficiency all decrease substantially (West, 2003). Thus, adjustment for environmental conditions is needed to predict DMI (NRC, 2001). However, because of the insufficient environmental data reported in the studies selected for the current meta-analysis, climate variables (e.g., air temperature, temperature-humidity index) were not used as fixed effects in the model.

A positive relationship ($P < 0.001$) between DMI and FCM (0.476 ± 0.036 kg/kg of FCM) was observed (see proposed equation), due to increased energy demand for milk production. According to the NRC (2001), it is not conclusive whether milk production is driven by intake or whether intake is driven by milk production. Based on the energy intake regulation theory (Conrad et al., 1964; Mertens, 1987), intake is driven by milk production. For instance, the increase in DMI in cows treated with bST followed that of milk yield (Chalupa et al., 1986; Bauman, 1992), confirming that animals consume more OM to meet their energy requirements. A positive relationship ($P < 0.001$) was also observed between DMI and $BW^{0.75}$ (0.072 ± 0.006 kg of DMI/kg of $BW^{0.75}$), likely in response to enhanced energy needs for maintenance.

The new model provided the most accurate and precise prediction of DMI (Table 3; Figure 1) compared with the 5 currently available DMI prediction models (Table 1). In fact, the DMI prediction model developed in the present meta-analysis explained 93.0% of the variation in DMI and yielded the lowest bias (mean overprediction of DMI = 0.11 kg/d) and RMSPE (4.9% of observed DMI) and the largest proportion (95.0%) of the random error in the RMSPE, indicating that most of the model error was not associated with fixed variables. In addition, the proposed model resulted in the highest precision ($\rho = 0.97$) and accuracy ($C_b = 0.99$), reinforcing its robustness for predicting DMI of

Figure 1. Relationship between observed ($\square$) and residual (observed – predicted; $\circ$) DMI with predicted values for dairy cows using the proposed model, NRC (2001), Agriculture and Food Research Council (AFRC, 1993; Vadiveloo and Holmes, 1979), Cornell Net Carbohydrate and Protein System (CNCPS, version 6.0; Tylutki et al., 2008), Freitas et al. (2006), and Santos et al. (2009) models. Data set included 148 treatment means from 40 studies.

lactating dairy cows under the tropical conditions of Brazil.

The NRC (2001) model equation for predicting DMI explained 92.0% of the variation in DMI and overpredicted DMI by 0.41 kg/d. It also resulted in the second lowest RMSPE (5.8% of the observed DMI) and second best precision ($\rho = 0.94$) and accuracy ($C_b = 0.98$; Table 3; Figure 1). However, compared with the model proposed herein, the NRC (2001) equation resulted in greater dispersion of observed and residue values relative to the equality line ($Y = X$; Figure 1). In contrast, only the NRC (2001) model and the model developed herein showed the same distribution between predicted and observed DMI values.

The better accuracy and precision of the new equation compared that of the NRC (2001) model for predicting DMI in lactating dairy cows raised under tropical conditions is likely explained by 2 major factors: (1) the data used for developing the new DMI prediction model were obtained from cows raised in the tropics; and (2) the use of study as a random effect in the model, which is known to improve predictions in biological systems and to provide a more accurate description of prediction errors (St-Pierre, 2001).

The CNCPS model (Tylutki et al., 2008) explained 93.0% of the variation in DMI but underpredicted it by 1.8 kg/d, with RMSPE of 11.3% of the observed DMI (Table 3). In addition, the error due to mean bias was relatively high (79.0% of the MSPE). The CNCPS model uses the equation developed by Milligan et al. (1981) with adjustment for week of lactation (Roseler et al., 1997) for predicting DMI. Similar to the NRC (2001) model, the CNCPS model was developed using observations collected from US Holstein cows fed TMR, which could explain their higher biases compared with the proposed model. Thus, the differences in environmental and dietary conditions between Brazil and the United States limit the use of the NRC and CNCPS models to predict DMI under tropical conditions.

The AFRC (1993) model equation explained 85.0% of the variation in DMI but underpredicted it by 1.4 kg/d; it was the third most accurate equation for predicting DMI, with RMSPE of 10.7% of the observed DMI and ρ and C_b of 0.82 and 0.89, respectively (Table 3). The mean bias error was the major component of the MSPE, averaging 56%. The AFRC (1993) equation was based on Vadivello and Holmes (1979), who used 26 experiments with 385 cows fed grass silage-based diets in the United Kingdom. Thus, the differences in environmental and dietary conditions between Brazil and the United Kingdom limit the use of the AFRC equation to predict DMI under tropical conditions.

Although the models proposed by Freitas et al. (2006) and Santos et al. (2009) were developed using

observations from lactating dairy cows raised in Brazil, the quality of their DMI predictions was poor. For instance, their equations explained 37.0 and 78.0% of the variation in DMI and underpredicted it by 2.31 and 1.88 kg/d, with RMSPE of 22.9 and 14.9% of the observed DMI, respectively. In addition, the precision ($\rho = 0.49$ and 0.76) and accuracy ($C_b = 0.81$ and 0.86) were lowest (Table 3; Figure 1) among the DMI prediction equations evaluated in the present study.

The poor precision and accuracy to predict DMI with the models proposed by Freitas et al. (2006) and Santos et al. (2009) might be related to the small number of studies used to develop the data sets. Freitas et al. (2006) used 9 experiments to build their empirical model to predict DMI in Holstein and Holstein $\times$ Zebu cows. Santos et al. (2009) reparameterized the NRC (2001) DMI prediction equation with data obtained from only 1 experiment, in which 18 Holstein $\times$ Zebu cows (6 Holstein $\times$ Gir, 6 Holstein $\times$ Guzera, and 6 Holstein $\times$ Nelore) were fed pasture supplemented with concentrate. Santos et al. (2009) concluded that the reparameterization of the NRC (2001) equation was appropriate to estimate DMI, but the accuracy and precision were not evaluated with an independent data set.

In conclusion, the DMI prediction model proposed in the present study: $\text{DMI (kg/d)} = [0.4762 \times 4\% \text{ FCM (kg/d)} + 0.07219 \times \text{BW (kg)}^{0.75}] \times (1 - e^{-0.03202 \times (\text{DIM} + 24.9576 \pm 5.909)})$ provided the highest accuracy and precision for predicting DMI in lactating dairy cows raised in the tropical conditions of Brazil compared with 5 currently available models (e.g., NRC, 2001; CNCPS, Tylutki et al., 2008; AFRC, 1993; Freitas et al., 2006; and Santos et al., 2009).

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Appendix 1: List of Publications Describing the Experiments Used in the Development Model

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- ## Appendix 2: List of Publications Describing the Experiments Used in the Evaluation Models
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