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# Prediction of drinking water intake by dairy cows

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## ABSTRACT

Mathematical models that predict water intake by drinking, also known as free water intake (FWI), are useful in understanding water supply needed by animals on dairy farms. The majority of extant mathematical models for predicting FWI of dairy cows have been developed with data sets representing similar experimental conditions, not evaluated with modern cows, and often require dry matter intake (DMI) data, which may not be routinely available. The objectives of the study were to (1) develop a set of new empirical models for predicting FWI of lactating and dry cows with and without DMI using literature data, and (2) evaluate the new and the extant models using an independent set of FWI measurements made on modern cows. Random effect meta-regression analyses were conducted using 72 and 188 FWI treatment means with and without dietary electrolyte and daily mean ambient temperature (TMP) records, respectively, for lactating cows, and 19 FWI treatment means for dry cows. Milk yield, DMI, body weight, days in milk, dietary macro-nutrient contents, an aggregate milliequivalent concentration of dietary sodium and potassium (NaK), and TMP were used as potential covariates to the models. A model having positive relationships of DMI, dietary dry matter (DM%), and CP (CP%) contents, NaK, and TMP explained 76% of variability in FWI treatment means of lactating cows. When challenged on an independent data set (n = 261), the model more accurately predicted FWI [root mean square prediction error as a percentage of average observed value (RMSPE%) = 14.4%] compared with a model developed without NaK and TMP (RMSPE% = 17.3%), and all extant models (RMSPE% ≥ 15.7%). A model without DMI included positive relationships of milk yield, DM%, NaK, TMP, and days in milk, and explained 63% of variability in the FWI treatment means and performed well (RMSPE% = 17.9%), when challenged on the independent data. New models for dry cows included positive relationships of DM% and TMP along with DMI or body weight. The new models with and without DMI explained 75 and 54% of the variability in FWI treatment means of dry cows and had RMSPE% of 12.8 and 15.2%, respectively, when evaluated with the literature data. The study offers a set of empirical models that can assist in determining drinking water needs of dairy farms.
**Key words:** dairy cow, empirical model, water intake, sodium, potassium

## INTRODUCTION

The World Economic Forum lists water crisis among the top 10 likely global risks. Currently, agriculture accounts for approximately 70% of the world's total water consumption and this use is likely to increase to meet the growing demand for food (Schulte et al., 2014). It has been estimated that dairy cattle account for approximately 19% of the total global water footprint related to animal production, and of the total amount of water used to produce all animal food products, 98% is used to produce feed, whereas 1% is used for drinking (Hoekstra, 2012). Despite accounting for only a small proportion of the total amount of water needed to produce milk, water acquired through drinking is vital for production. This is illustrated by the fact that restriction of water has been shown to result in rapid, but usually reversible, reductions in feed intake and milk yield (Steiger Burgos et al., 2001). Lactating dairy cows have the highest free water intake (**FWI**) and also experience the largest flux of water of any domesticated ruminant (Woodford et al., 1984). Interestingly, the nutritional requirements for water vary by as much as a factor of 10 (Lassiter and Edwards, 1982), whereas the daily body water flux of a lactating dairy cow may be as high as 30% of its total body water (Beede, 2012).

Accurately quantifying FWI may be needed for a variety of purposes including understanding water intake requirements of animals in dairy farms. Estimates of FWI may also be useful when attempting to match available resources to newly constructed facilities. To do so, several mathematical models have been published

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and may be used to predict FWI in dairy cattle (e.g., Castle and Thomas, 1975; Little and Shaw, 1978; Murphy et al., 1983; Stockdale and King, 1983; Holter and Urban, 1992; Dahlborn et al., 1998; Meyer et al., 2004; Cardot et al., 2008; Khelil-Arfa et al., 2012; Appuhamy et al., 2014b). The majority of extant models require DMI of individual cows as an input, which may not be routinely available in commercial dairy farms. A few extant models (Castle and Thomas, 1975; Dahlborn et al., 1998; Khelil-Arfa et al., 2012) allow for predicting FWI without using DMI. Nonetheless, the performance of some of these equations has not been evaluated using independent FWI measurements, particularly from modern cows under current management. Additionally, the majority of the extant equations have been developed using data from feeding studies sharing similar experimental contexts and facilities. Therefore, successful extrapolation of these models to diverse commercial dairy herds might be limited. On the other hand, meta-analytic approaches can be applied to derive new equations presumably with greater extrapolation capacity using literature data covering different experimental contexts, diets, and animal characteristics. Particularly, the random-effect meta-analytic approaches support extrapolation as they assume data used for model development to be a random sample of the total population (Viechtbauer, 2010). The objectives of the present study were to (1) explore factors significantly associated with FWI and develop a set of empirical models for predicting FWI of lactating and dry cows using random-effect meta-analyses of literature data, and (2) evaluate extrapolation capacity of the new and extant models using an independent data set including FWI measurements made on modern cows.

## MATERIALS AND METHODS

### Data Sources

An extensive literature search was conducted for in vivo studies reporting measured FWI of lactating and dry dairy cows along with related information on DMI, dietary nutrient composition, milk yield, DIM, and BW. For lactating cows, 239 treatment means of FWI were retrieved originally from 69 research articles (Table 1). After excluding treatment means without corresponding measures of uncertainty (e.g., SD or SEM), sample size (N), treatment means of restricted water intake, and treatment means related to water treatments having significant effects on FWI, the final data set for lactating dairy cows included 188 FWI records published in 55 articles. Forty-three out of the 55 articles, or 78% of the studies, provided multiple FWI treatment means. Ninety-three percent of the FWI records were related to Holstein cows (81%) and their crosses (12%). Experiments conducted with dairy cows in North America (47%), Europe (25%), and Australia (8%) provided the majority of the records. Ten percent of the records were related to pasture-based diets, whereas the rest were from cows offered rations in the form of a TMR. Corn silage (13.0 to 74.5% of DM), grass or legume hay (4.0 to 81% of DM), alfalfa silage (7.7 to 83.8% of DM), and grass silage (17.4 to 63.5% of DM) were the major forage sources, whereas ground corn (2.6 to 46.3% of DM), barley grain (7.2 to 30.8% of DM), and soybean meal (1.0 to 24.0% of DM) were the major concentrate ingredients in TMR diets. Only 72 FWI measurements from 16 studies had information on both dietary Na and K, and ambient temperature (**TMP**). Dietary Na content (% of DM) in studies using salt blocks (e.g., Andersson et al., 1984; Bahman et al., 1993) included Na intake from salt blocks expressed relative to the DMI. A summary of the complete and subset data with dietary Na and K, and TMP records is given in Table 1. For dry cows, 19 treatment means of FWI and the other information were retrieved from 10 studies. A summary of dry cow data is given in Table 2.

### Model Development and Evaluation

***Lactating Cows.*** Three-level (cow → treatment group → study) random-effect model analyses were conducted first to quantify variability or heterogeneity of FWI across treatment groups within individual studies ($\boldsymbol{\tau_T^2}$) and among studies ($\boldsymbol{\tau_S^2}$). Summation of $\tau_T^2$ and $\tau_S^2$ gave the total heterogeneity of FWI measurements ($\boldsymbol{\tau^2}$). The 3-level random-effect model (Konstantopoulos, 2011) is given by

$$Y_{ij} = \mu + \eta(S)_j + \nu(T)_{ij} + \varepsilon_{ij},$$

where $Y_{ij}$ = mean FWI of the $i$th treatment group in the $j$th study, $\mu$ = overall mean, $\eta(S)_j$ = $j$th study-specific random deviation of FWI, which is assumed to be normally distributed with a mean 0 and variance of $\tau_S^2$, $\nu(T)_{ij}$ = random deviation of FWI specific to the $i$th treatment in the $j$th study, which is assumed to be normally distributed with a mean 0 and variance of $\tau_T^2$, and $\varepsilon_{ij}$ = sampling error or random variability of FWI among cows in the $i$th treatment of the $j$th study. Variance of $\varepsilon_{ij}$ is assumed to be known and calculated using standard deviation of the treatment means. When standard deviation was not reported, it was estimated with other uncertainty measures reported (e.g., SEM) and N as described in Alvarez-Fuentes et al. (2016).

The random-effect models were extended to mixed-effect models or meta-regression models including fixed

**Table 1**. A summary of full data set including 188 treatment means of FWI of lactating dairy cows from 55 studies and a subset with only 72 FWI treatment means from 16 studies having dietary sodium and potassium, and ambient temperature records

| | Full data set (n = 188)[2] | | | | Data subset (n = 72)[3] | | | |
|---|---|---|---|---|---|---|---|---|
| Variable[1] | Mean | SD | Minimum | Maximum | Mean | SD | Minimum | Maximum |
| FWI (kg/d) | 75.2 | 24.1 | 10.8 | 122 | 75.4 | 27.8 | 14.6 | 122 |
| DMI (kg/d) | 18.3 | 4.6 | 6.3 | 32.5 | 16.0 | 4.3 | 6.3 | 23.0 |
| Milk yield (kg/d) | 28.1 | 9.2 | 8.2 | 47.0 | 23.5 | 9.7 | 8.2 | 47.0 |
| Diet composition | | | | | | | | |
| DM (%) | 53.3 | 16.0 | 17.3 | 89.6 | 55.3 | 16.8 | 20.0 | 89.6 |
| CP (% of DM) | 15.3 | 3.1 | 4.3 | 23.9 | 14.6 | 3.3 | 9.4 | 21.4 |
| NDF (% of DM) | 33.7 | 9.7 | 9.5 | 55.9 | 31.6 | 10.3 | 9.5 | 55.1 |
| Ash (% of DM) | 7.0 | 1.4 | 3.6 | 11.3 | 7.4 | 2.2 | 3.6 | 11.3 |
| K (% of DM) | 1.62 | 0.60 | 0.86 | 3.22 | 1.65 | 0.62 | 0.95 | 1.65 |
| Na (% of DM) | 0.38 | 0.32 | 0.02 | 1.93 | 0.39 | 0.35 | 0.02 | 1.93 |
| NaK (mEq/kg of DM) | 578 | 137 | 353 | 1,162 | 595 | 136 | 370 | 1,162 |
| BW (kg) | 582 | 110 | 337 | 853 | 533 | 125 | 337 | 767 |
| DIM | 105 | 51 | 7 | 225 | 124 | 51 | 14 | 225 |
| TMP (°C) | 18.1 | 7.4 | 8.0 | 32.5 | 18.1 | 7.4 | 8.0 | 32.5 |

[1]FWI = drinking water intake, DM = dietary dry matter, CP and NDF = dietary CP and NDF contents, respectively; ash = total ash content; NaK = aggregated Na and K; and TMP = daily mean ambient temperature.

[2]Castle and Watson, 1973; Castle and Thomas, 1975; Little et al., 1976; Holter et al., 1982; Murphy et al., 1983; Stockdale and King, 1983; Andersson et al., 1984; Woodford et al., 1984; Andersson, 1985; Janicki et al., 1985; Nocek and Braund, 1985; Richards, 1985; Anderson, 1987; Gorewit et al., 1989; Holter et al., 1990, 1992; Shalit et al., 1991; Holter and Urban, 1992; Bahman et al., 1993; Dado and Allen, 1993, 1994, 1995, 1996; Silanikove et al., 1997; Dahlborn et al., 1998; Dewhurst et al., 1998; Muller et al., 1994; Mooney and Allen, 1997; Burgos et al., 2001; Osborne et al., 2002a, 2009; Voelker and Allen, 2003; Cottee et al., 2004; Meyer et al., 2004; Taylor and Allen, 2005; Harvatine and Allen, 2006; Chaiyabutr et al., 2007, 2008; Thomas et al., 2007; Cardot et al., 2008; Kume et al., 2008, 2010; Longuski et al., 2009; Kramer et al., 2009; Shapasand et al., 2010; Khelil-Arfa et al., 2012, 2014; Spek et al., 2012; Stocks and Allen, 2012; Brown and Allen, 2013; Genther and Beede, 2013; McBeth et al., 2013; Appuhamy et al., 2014b; Eriksson and Rustas, 2014; Reith et al., 2014.

[3]Holter et al., 1982, 1990; Stockdale and King, 1983; Andersson et al., 1984; Shalit et al., 1991; Bahman et al., 1993; Silanikove et al., 1997; Osborne et al., 2002b; Cottee et al., 2004; Meyer et al., 2004; Chaiyabutr et al., 2007, 2008; Spek et al., 2012; Genther and Beede, 2013; Eriksson and Rustas, 2014; Khelil-Arfa et al., 2014.

effects of explanatory variables. The mixed effect models are given by

$$Y_{ij} = \beta_0 + \beta_1 X_{ij1} + ... + \beta_p X_{ijp} + \eta(S)_j + \nu(T)_{ij} + \varepsilon_{ij},$$

where $X_{ij1}$ and $X_{ijp}$ = value of the first and the last explanatory variables related to FWI in the $i$th treatment group of the $j$th study, respectively; $\beta_0$ = intercept; $\beta_1$ and $\beta_p$ = regression coefficients of first and last explanatory variables, respectively; and $\nu(T)_{ij}$ and $\eta(S)_j$ = residual treatment and study-specific random deviations, respectively. Based on availability of data, 2 levels of explanatory variables were considered. Level 1 included DMI, milk yield, BW, DIM, and DM and dietary nutrient composition (n = 188). Level 2 included Level 1 plus joint milliequivalent concentration of Na and K in diet [**NaK**, NaK = dietary Na concentration (mmol/kg of DM) + dietary K concentration (mmol/kg of DM)], and TMP (n = 72). Mixed-effect models with and without DMI were developed in each level of the explanatory variables. Individual explanatory variables were first tested by regressing separately on FWI. Models including multiple explanatory variables were then formed with all possible combination of variables having notable effects ($P < 0.10$), when fitted individually. However, highly correlated variables (|r| > 0.5) were not included together to minimize multicollinearity issues (Appuhamy et al., 2014a). For example, DMI and milk yield were regressed separately (r = 0.67, Table 3). Success of model fitting was primarily ranked using log-likelihood ratio test. When multiple models had similar likelihood values, the model associated with the least Bayesian information criteria was chosen as the best prediction model. All the meta-analyses were

**Table 2**. A summary of dry cow data[1]

| Variable[2] | Mean | Minimum | Maximum |
|---|---|---|---|
| FWI (kg/d) | 35.0 | 16.0 | 66.5 |
| DMI (kg/d) | 11.4 | 6.7 | 21.8 |
| Diet composition | | | |
| DM (%) | 47.8 | 37.9 | 83.2 |
| CP (% of DM) | 14.7 | 9.9 | 16.6 |
| NDF (% of DM) | 42.4 | 34.1 | 65.8 |
| BW (kg) | 700 | 605 | 786 |
| TMP (°C) | 16.4 | 1.0 | 32.0 |

[1]Seif et al., 1973; Woodford et al., 1984; Holter and Urban, 1992; Silanikove et al., 1997; Osborne et al., 2002b, 2009; Kojima et al., 2005; Kume et al., 2010; Khelil-Arfa et al., 2014; Lamp et al., 2015.

[2]FWI = drinking water intake, DM = dietary dry matter, CP and NDF = dietary CP and NDF contents, respectively, and TMP = daily mean ambient temperature.

**Table 3**. Pearson correlation coefficients for the relationships among explanatory variables[1] in the full data set (n = 188)

| Item | Milk | DM | CP | NDF | Ash | BW | DIM | NaK | TMP |
|---|---|---|---|---|---|---|---|---|---|
| DMI | 0.67 | –0.24 | 0.24 | –0.10 | –0.01 | 0.55 | –0.17 | –0.32 | –0.48 |
| Milk | | –0.35 | 0.44 | –0.08 | –0.07 | 0.46 | –0.43 | –0.47 | –0.37 |
| DM | | | –0.37 | 0.23 | –0.02 | –0.22 | –0.23 | –0.36 | 0.40 |
| CP | | | | 0.06 | 0.39 | 0.46 | –0.23 | –0.27 | 0.13 |
| NDF | | | | | 0.44 | 0.39 | –0.02 | –0.17 | –0.19 |
| Ash | | | | | | 0.31 | 0.03 | 0.32 | –0.25 |
| BW | | | | | | | –0.15 | –0.16 | –0.13 |
| DIM | | | | | | | | 0.38 | 0.04 |
| NaK | | | | | | | | | –0.21 |

[1]Milk = milk yield; DM = dietary dry matter; CP, NDF, ash, Na, and K = dietary CP, NDF, total ash, sodium, and potassium contents; NaK = dietary sodium and potassium milliequivalent content; and TMP = daily mean ambient temperature.

carried out using *metafor* package (Viechtbauer, 2010) in R (version 2.12.2, R Foundation for Statistical Computing, Vienna, Austria).

New models with and without DMI were evaluated with a separate data set including 261 FWI measurements (kg/cow per d) made recently on lactating dairy cows in 3 independent studies. Two experiments conducted at the University of California–Davis provided 236 FWI measurements. In one experiment, 12 Holstein cows with an average milk production of 39.3 ± 4.4 kg/d and an average BW of 667 ± 29 kg at the beginning of the study (157 ± 31 DIM) were randomly assigned to 2 dietary forage contents [37 vs. 53% of DM] and 2 dietary CP concentrations (16.2 vs. 19.7% of DM) over 4 periods, each providing repeated measures of FWI (Niu et al., 2016). In the other experiment, 12 Holstein cows with an average BW of 696 ± 47 kg, and an average milk yield of 45.5 ± 6.6 kg/d at the beginning of the experiment (130 ± 20 DIM), were assigned to 2 doses of a fibrolytic enzyme (plus control) over 3 periods, where repeated measures of FWI were taken. The fibrolytic enzyme supplementation did not affect FWI (unpublished data). The Institutional Animal Care and Use Committee at the University of California–Davis approved all the animal procedures in the experiment. The rest of the FWI measurements were obtained from the experiments published in Fraley et al. (2015). The FWI measurements were related to considerably variable DMI (14.7 to 30.0 with a mean of 21.3 kg/d), milk yield (16.8 to 45.8 with a mean of 32.1 kg/d), DM% (44.2 to 87.9 with a mean of 78.1%), CP% (14.4 to 18.8 with a mean of 16.6% of DM), NDF% (28.0 to 42.7 with a mean of 35.4% of DM), dietary Na content (0.16 to 0.40 with a mean of 0.24% of DM), dietary K content (1.03 to 3.35 with a mean of 1.34% of DM), NaK (347 to 1013 with a mean of 450 mEq/DM of kg), BW (518 to 807 with a mean of 664 kg), DIM (121 to 262 with a mean of 193), and TMP (9.7 to 29.4 with a mean of 21.4°C).

The overall agreement between model predictions and the data were determined by calculating the mean square prediction error (**MSPE**):

$$\text{MSPE} = \frac{1}{n} \cdot \sum_{i=1}^{n} \left(O_i - P_i\right)^2,$$

where $n$ = number of FWI observations, $O_i$ = $i$th observed value, $P_i$ = corresponding predicted value. As the square root of MSPE (**RMSPE**) carries the same unit of observed values, RMSPE was used to assess performance and was expressed as a percentage of average observed value (**RMSPE%**). The RMSPE% quantifies overall agreement between predicted and observed values but does not explain consistency of this agreement throughout the data range in question. Therefore, MSPE was decomposed into mean bias, slope bias, and bias due to random variability of data. Furthermore, agreement between predicted and observed values and presence of any bias were visually assessed with observed values versus predicted values plots and residual plots where prediction error (observed value − predicted value) was regressed against predicted values centered on their mean. Prediction error regression line intersecting the zero error line (horizontal) in residual plots indicates the presence of slope bias. The intersection moving away from the intersection between the zero error line and zero centered-prediction value line (vertical) indicates the presence of mean bias. New and extant models for predicting FWI of lactating cows by Castle and Thomas (1975), Little and Shaw (1978), Murphy et al. (1983), Stockdale and King (1983), Dahlborn et al. (1998), Holter and Urban (1992), Khelil-Arfa et al. (2012), Appuhamy et al. (2014b), and Meyer et al. (2004) were evaluated.

***Dry Cows.*** Two models were developed with and without DMI with the same meta-analytical approaches used for lactating cows. However, a quadratic relationship of TMP was tested by including squared TMP, which was centered on the mean TMP of 16.4°C (**$TMPC^2$**) in mixed-effect models. Centering on mean negated collinearity between TMP and $TMPC^2$ (R = 0.004, data not shown), when included in the same model. Due to paucity of data, the final dry cow models were evaluated only using the literature data themselves (internal evaluation) based on the same model evaluation criteria described above.

## RESULTS AND DISCUSSION

The main goal of the study was to develop a set of empirical models to predict FWI by dairy cows over a wide range of feed intake, diet composition, milk production, and ambient temperatures, which have been previously shown to be significantly associated with FWI. The literature data assembled in this study included wide ranges of those variables that allow for the development of models, which are able to capture the true associations and have a sound extrapolation capacity. The random-effect meta-analytic approach used to construct the models also support extrapolation as it assumes the data to be a random sample of the total population. Eighty percent of the data used to develop the models was related to Holstein cows in North America, Europe, and Australia. However, only 10% of the data were from grazing cows. Therefore, the models could be more representative of cows in confinement dairy farms. Random-effect meta-analysis approaches also allow for estimating heterogeneity or variability of the response (e.g., FWI) across studies, and also examining what proportion of the heterogeneity could be explained with the factors of interest (e.g., DMI, diet composition, and ambient temperature). Given the significant link between FWI and DMI of dairy cows (Appuhamy et al., 2014b), the majority of extant models for predicting the FWI include DMI as an explanatory variable. On the other hand, accurately measuring DMI of individual cows in commercial dairy farms is challenging (Vallimont et al., 2010). Therefore, in this study 2 sets of models were developed for estimating FWI of lactating cows or dry cows with and without DMI as a predictor variable. Moreover, the models developed including and excluding the NaK and TMP effects allowed for examining significance of those effects on FWI, independent of feed intake, milk production, and dietary DM and other nutrient contents.

### Lactating Cow Models

***Models Without Mineral and Temperature Variables.*** The models developed using the full data set (n = 188), that excluded NaK and TMP as candidate explanatory variables are listed in Table 4. The random-effect model analysis determined that the mean FWI of lactating cows was 78.4 ± 2.6 kg/d, which was related to average DMI, milk yield, and DM% of 18.3 kg/d, 28.1 kg/d, and 53.3%, respectively (Table 1). The analysis also revealed that total heterogeneity of FWI, which was the summation of variability of FWI within individual studies and variability of FWI among individual studies, was significant ($\tau^2 = 389 \pm 20$, $P < 0.001$). When the random-effect models were extended to mixed-effect meta-regression models, the final prediction model with DMI (Equation 1, Table 4) also included positive associations of dietary DM (DM%), CP (CP%), and ash (Ash%) concentrations. This model was associated with 51% less heterogeneity ($\tau^2 = 191$ vs. 389), indicating the variables explained more than half of total variability of FWI. When evaluated with the literature data used in model construction, the model had RMSPE% of 18.1% (Table 4), with minor mean and slope bias (Table 4 and Figure 1). When DMI was not used as an explanatory variable, milk yield and BW predominantly influenced FWI (Equation 2, Table 4) because of strong positive relationships with DMI (r = 0.67 and 0.55, respectively, Table 3). The associations of milk yield and BW appeared to be independent of each other given the correlation between them was not strong in the data (r = 0.46, Table 3). As observed in the model with DMI, DM%, and Ash% continued to have positive relationships with FWI independent of milk yield and BW. The relationship of CP% was not included in the model as it was confounded with milk yield and BW (Table 3). The model without DMI explained 46% of the heterogeneity ($\tau^2 = 210$ vs. 389), which was similar to the amount explained by the model using DMI (51%), indicating the possibility for predicting FWI of lactating cows successfully in the absence of feed intake records.

***Models With Mineral and Temperature Variables.*** The mean (82.2 ± 5.0 vs. 78.4 ± 2.6 kg/d) and heterogeneity ($\tau^2 = 425 \pm 21$ vs. $389 \pm 20$) of FWI measurements (n = 72) having NaK and TMP records were similar to those of full data set. The DMI, milk yield, DIM, and dietary nutrient composition ranges were similar between the 2 data sets. Moreover, the correlations of DMI and milk yield with FWI (kg/d) in the full and the reduced data sets were similar [r = 0.42 vs. 0.36, and r = 0.26 vs. 0.24, respectively (data not shown)]. Correlations of dietary DM (r = 0.36 vs. 0.35), CP (r = 0.11 vs. 0.14), and ash (r = 0.40 vs. 0.42) concentrations with FWI (per kg of DMI) were also similar (data not shown). Therefore, the subset with NaK and TMP records was a representative sample of the full data set. When NaK and TMP were considered as candidate explanatory variables, the final

**Table 4**. New models and associated heterogeneity estimates ($\tau^2$), heterogeneity changes ($\Delta\tau^2$), and root mean square prediction error (RMSPE, a percentage of the average observed value) and its decomposition to mean bias (MB), slope bias (SB), and random bias (RB, all as a percentage of RMSPE), when evaluated with data used for model development

| Equation | Variables and parameters involved in predicting drinking water intake[1] (kg/d) | $\tau^2$ [2] | $\Delta\tau^2$ | RMSPE | MB | SB | RB |
|---|---|---|---|---|---|---|---|
| Lactating cows | | | | | | | |
| Full data set (n = 188) | | | | | | | |
| | = 78.4 ± 2.6 | 389 | | | | | |
| 1 | = –68.8 ± 14.7 + 2.89 ± 0.30 × DMI + 0.44 ± 0.09 × DM% + 5.60 ± 1.52 × Ash% + 1.81 ± 0.54 × CP% | 191 | –51% | 18.1 | 0.1 | 2.1 | 97.8 |
| 2 | = –58.2 ± 13.7 + 0.96 ± 0.18 × Milk + 0.45 ± 0.09 × DM% + 6.21 ± 1.58 × Ash% + 0.067 ± 0.013 × BW | 210 | –46% | 20.3 | 0.0 | 1.1 | 98.9 |
| Data with NaK and TMP records (n = 72) | | | | | | | |
| | = 82.2 ± 5.0 | 425 | | | | | |
| 3 | = –91.1 ± 17.8 + 2.93 ± 0.53 × DMI + 0.61 ± 0.13 × DM% + 0.062 ± 0.009 × NaK + 2.49 ± 0.99 × CP% + 0.76 ± 0.29 × TMP | 101 | –76% | 13.8 | 0.3 | 2.6 | 97.1 |
| 4 | = –60.2 ± 17.1 + 1.43 ± 0.30 × Milk + 0.064 ± 0.011 × NaK + 0.83 ± 0.14 × DM% + 0.54 ± 0.31 × TMP + 0.08 ± 0.03 × DIM | 159 | –63% | 19.2 | 0.6 | 13.3 | 86.1 |
| Dry cows | | | | | | | |
| | = 34.0 ± 2.73 | 97 | | | | | |
| 5 | = 0.69 ± 0.48 × DMI + 0.28 ± 0.11 × DM% + 0.85 ± 0.17 × TMP | 57 | –41% | 20.7 | 0.1 | 0.1 | 99.8 |
| 6 | = 1.16 ± 0.38 × DMI + 0.23 ± 0.08 × DM% + 0.44 ± 0.16 × TMP + 0.061 ± 0.016 × $TMPC^2$ | 24 | –75% | 12.8 | 0.1 | 0.9 | 99.0 |
| 7 | = 0.010 ± 0.007 × BW + 0.32 ± 0.14 × DM% + 0.52 ± 0.21 × TMP + 0.053 ± 0.019 × $TMPC^2$ | 44 | –54% | 15.2 | 1.2 | 2.3 | 96.5 |

[1]DMI in kilograms per day, BW in kilograms, Milk = milk yield (kg/d), DM% = dietary DM%, CP% = dietary CP content (% of DM), TMP = daily mean ambient temperature (°C), $TMPC^2 = (TMP – 16.4)^2$, and NaK = joint concentration of Na and K in the diet (mEq/kg of DM).

[2]Heterogeneity of free water intake among treatment groups within individual studies plus heterogeneity among studies.

model with DMI included positive associations of NaK, TMP, DM%, and CP% with FWI (Equation 3, Table 4) and explained 76% of the heterogeneity. For each unit increase in DMI, FWI increased by 2.93 ± 0.53 kg/d. This estimate is within the range of estimates (2.38–3.22 kg/d) reported by Murphy et al. (1983), Holter and Urban (1992), Khelil-Arfa et al. (2012), and Appuhamy et al. (2014b). Regardless of DMI, FWI increased by 0.61 ± 0.13 kg/d for a unit increase in DM%. The effect size estimate of DM% was also within the range of estimates (0.27–0.83 kg/d) in extant models. Independent of DMI and DM%, FWI increased by 0.062 ± 0.009 for each unit increase in NaK (Equation 3, Table 4). The positive association of NaK is consistent with several extant models (Murphy et al., 1983; Meyer et al., 2004) representing a positive effect of dietary Na intake on FWI, and dietary K intake mediating variable FWI in Fraley et al. (2015) and St Omer and Roberts (1967). Nonetheless, NaK, the aggregated dietary Na and K concentrations (mEq/kg of DM), made the model simpler and tended to have a better model fit than a model including dietary Na and K concentrations as 2 separate variables (data not shown).

Mean ambient temperature was positively and linearly associated with FWI within the range of 8.0 to 32.5°C. The increase in water consumption is largely believed to be triggered by the increased need to support evaporative and respiratory heat losses (Pereira

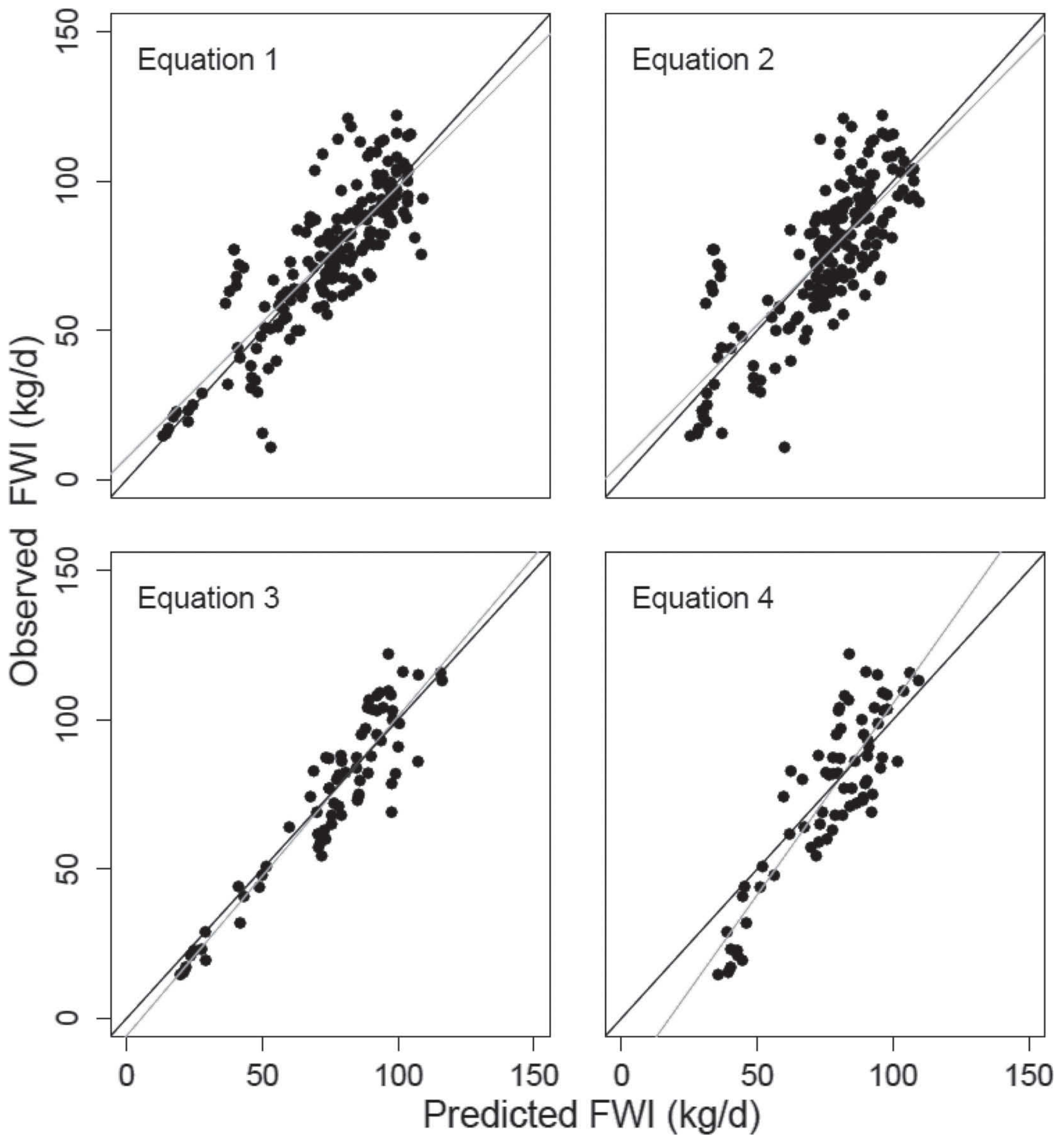


**Figure 1**. Observed versus predicted drinking water intake (FWI) of lactating dairy cows from new models, when evaluated with literature data used for model development. The black and gray lines represent, respectively, the unity line (y = x) and the scatter regression line.

et al., 2014). We also tested a quadratic term of TMP but did not observe significant improvement in model fit (data not shown) with lactating cow data. For each unit (°C) increase in TMP, FWI increased by 0.76 ± 0.29 kg/d. In contrast, Meyer et al. (2004) estimated FWI to increase by a greater amount of 1.52 kg/d. The low effect size estimate in the new model (Equation 3, Table 4) may be partly due to confounding of TMP with DMI because DMI was negatively correlated with TMP in the data (r = −0.48, Table 3). Such a confounding is less likely in the model of Meyer et al. (2004) as DMI was not a direct covariate to the model although it was required to calculate dietary Na intake (Table 5). The CP% had a positive association with FWI, independent of DMI and the other factors. For a unit increase in CP%, FWI increased by 2.49 ± 0.99 kg/d. Murphy et al. (1983) developed a model demonstrating FWI of dry cows to increase approximately 2.0 kg/d for each unit increasing in CP% within a CP% range similar to the present data range (Table 1). The final model with DMI (Equation 3) was related to minor systematic bias (<3.0% of total error, Table 4), suggesting that that model could successfully predict FWI over wide ranges of the explanatory variables (i.e., DMI or milk yield). Consistently, the model still performed well (RMSPE = 16.3% with negligible mean bias, data not shown), when challenged only on FWI measurements related to high milk yields (>35 kg/d).

Milk yield became a major driver of FWI in the absence of DMI in models owing to a strong positive relationship between DMI and milk yield (Equation 4, Table 4). Body weight was not included in the model without DMI as milk yield and BW had a stronger correlation than the correlation found in the full data set [r = 0.75 (data not shown) vs. 0.46 (Table 3)]. However, a positive association of DIM was included in the model, whereas DM%, NaK, and TMP continue to be positively related to FWI (Equation 4 in Table 4). The model without DMI explained 63% of heterogeneity in FWI and was associated with a RMSPE% of 19.2%, when evaluated internally. Water intake predictions from the model without DMI had a slope bias indicating over prediction at low FWI, and under prediction at high FWI of lactating cows (Equation 4 in Figure 1).

***Model Evaluation With Independent Data.*** Although the new models were developed with heterogeneous literature data presumably allowing for a sound extrapolating capacity, determination of real capacity requires them to be evaluated with independent data. Only the models developed for lactating cows were evaluated this way as an adequately large and variable independent data set could be achieved only for these cows. The independent FWI measurements were obtained recently from high producing (average milk yields of 39 to 46 kg/d at 116 to 157 DIM) Holstein cows in the United States, and thus allowed for determining the relevance of new models to modern cows. The data covered reasonably wide ranges of DMI, milk yield, dietary DM, Na, and K contents, and TMP (CV = 16, 18, 16, 24, 28, and 14%, respectively). The K concentrations showed the greatest variability (1.03 to 3.35% of DM) and included 4 observations (2.0% of the data), which were greater than 3.0% of DM. Considering macrominerals are generally overfed (Castillo et al., 2013) and dietary K can increase up to 3.0% of DM in some US commercial dairy operations (Cela et al., 2014), those observations of high macromineral contents were included in the data set. The dietary Na concentrations were in line with the ranges of commercial farms (e.g., 0.25 and 0.58% of DM at the 10th and 90th percentiles; Castillo et al., 2013). The RMSPE and its components (mean, slope, and random bias) for new and extant models challenged on independent data are presented in Table 5. Consistent with the performances based on internal evaluation (Table 4), new models that used DMI as an explanatory variable had smaller prediction error compared with models without DMI. Moreover, new models including NaK and TMP predicted FWI more accurately than the models without those 2 factors (RMSPE% = 14.4 vs. 17.3%, Table 5). Compared with all new and extant models, Equation 3 using DMI, DM%, CP%, NaK, and TMP as explanatory variables best predicted FWI of lactating cows (RMSPE% = 14.4%). The mean predicted FWI of the model was very close to the mean observed FWI as indicated by the small mean bias estimate (0.1% of the total bias in Table 5). The model tended to overpredict at low FWI and under predict at high FWI (Figures 2 and 3), but this slope bias was small compared with the total prediction error (4.1%), the majority (95.8% in Table 5) of which was due the random variability of data. Overall, the presence of small mean and slope biases indicate the model parameters are fairly representative of the true relationships of DMI, DM%, CP%, NaK, and TMP to FWI in the lactating cow population. Among extant models, those by Murphy et al. (1983) and Meyer et al. (2004) requiring DMI data performed well with RMSPE% of 15.7%. On average, the Murphy et al. (1983) model underpredicted FWI (Figure 3), whereas the Meyer et al. (2004) model overpredicted FWI (data not shown) to a similar extent as indicated by similar mean bias estimates (5.7 and 5.2%, respectively, Table 5). Moreover, both extant models also overpredicted at low FWI and underpredicted at high FWI (Figures 2 and 3), but the slope biases were 2 to 3 times greater than that of the new model (8.3 and

**Table 5**. Performances of new and extant models for lactating cows evaluated with independent drinking water measurements (kg/d) made on individual cows (n = 261)[1]

| Reference | Models for predicting FWI[2] (kg/d) | RMSPE% | MB | SB | RB |
|---|---|---|---|---|---|
| New models | | | | | |
| With DMI | | | | | |
| Equation 1 | $= -68.8 + 2.89 \times DMI + 0.44 \times DM\% + 5.60 \times Ash\% + 1.81 \times CP\%$ | 17.3 | 29.0 | 2.4 | 68.6 |
| Equation 3 | $= -91.1 + 2.93 \times DMI + 0.61 \times DM\% + 0.062 \times NaK + 2.49 \times CP\% + 0.76 \times TMP$ | 14.4 | 0.1 | 4.1 | 95.8 |
| Without DMI | | | | | |
| Equation 2 | $= -58.2 + 0.96 \times Milk + 0.45 \times DM\% + 6.21 \times Ash\% + 0.067 \times BW$ | 19.8 | 29.9 | 12.8 | 57.3 |
| Equation 4 | $= -60.2 + 1.43 \times Milk + 0.064 \times NaK + 0.83 \times DM\% + 0.54 \times TMP + 0.08 \times DIM$ | 17.9 | 1.2 | 28.6 | 70.2 |
| Extant models | | | | | |
| With DMI | | | | | |
| Murphy et al. (1983) | $= 16.0 + 1.58 \times DMI + 0.90 \times Milk + 0.05 \times NaI + 1.20 \times mnTMP$ | 15.7 | 5.7 | 8.3 | 86.0 |
| Meyer et al. (2004) | $= -26.1 + 1.30 \times Milk + 0.406 \times NaI + 1.516 \times TMP + 0.058 \times BW$ | 15.7 | 5.2 | 12.3 | 82.5 |
| Murphy et al. (1983) | $= 23.0 + 2.38 \times DMI + 0.64 \times Milk$ | 17.3 | 29.0 | 5.2 | 65.8 |
| Holter and Urban (1992) | $= -32.4 + 2.47 \times DMI + 0.60 \times Milk + 0.62 \times DM\% + 0.091 \times JD - 0.00026 \times JD^2$ | 18.8 | 24.7 | 1.4 | 61.8 |
| Khelil-Arfa et al. (2012) | $= -77.6 + 3.22 \times DMI + 0.92 \times Milk - 0.28 \times CONC\% + 0.83 \times DM\% + 0.037 \times BW$ | 20.7 | 18.0 | 31.3 | 50.7 |
| Appuhamy et al. (2014b) | $= -34.6 + 2.75 \times DMI + 0.84 \times Milk + 2.32 \times Ash\% + 0.27 \times DM\%$ | 22.1 | 54.6 | 4.7 | 40.7 |
| Little and Shaw (1978) | $= 12.3 + 2.15 \times DMI + 0.73 \times Milk$ | 26.0 | 68.9 | 1.9 | 29.2 |
| Stockdale and King (1983) | $= -9.37 + 2.30 \times DMI + 0.53 \times DM\%$ | 27.8 | 67.7 | 3.4 | 28.9 |
| Without DMI | | | | | |
| Castle and Thomas (1975) | $= -15.3 + 2.53 \times Milk + 0.45 \times DM\%$ | 19.7 | 3.9 | 39.6 | 56.5 |
| Khelil-Arfa et al. (2012) | $= -41.1 + 1.54 \times Milk - 0.29 \times CONC\% + 0.97 \times DM\% + 0.039 \times BW$ | 22.6 | 17.6 | 37.8 | 44.6 |
| Dahlborn et al. (1998) | $= 14.3 + 1.28 \times Milk + 0.32 \times DM\%$ | 28.3 | 67.7 | 4.4 | 27.9 |

[1]RMSPE = root mean square prediction error as a percentage of average observed value; MB, SB, and RB = mean, slope, and random bias, respectively, as a percentage of mean square prediction error.

[2]FWI = free water intake; DMI (kg/d), BW (kg), Milk = milk yield (kg/d), DM% = dry matter percentage of the diet, CONC% = concentrate content of the diet (% of DM), CP% = dietary CP content (% of DM), Ash% = dietary total ash content, NaK = dietary sodium and potassium content (mEq/kg of DM), NaI = sodium intake (g/d), TMP = daily mean ambient temperature (°C), mnTMP = daily minimum ambient temperature (°C), and JD = Julian day.

12.3 vs. 4.1%, Table 5). Therefore, Equation 3 is recommended for predicting FWI of lactating dairy cows if DMI measurements of individual cows are available.

Although tie-stall or stanchion barns allow for measuring DMI of individual cows in some farms [e.g., in about 50% of US dairy farm operations (USDA, 2007)], accuracy of the measurements may be often challenged by wet feed refusals, an inability to individually weigh the feed delivered to each cow, and lack of feed dividers between cows (Vallimont et al., 2010). Therefore, a mathematical model not including DMI but based on reliable and routinely available information would benefit the majority of farms in determining FWI. Given the strong correlation of DMI with milk yield, reliable records of which are routinely available, a mathematical model including milk yield instead of DMI appears to be promising. Consistently, the new model (Equation 4) including milk yield, NaK, DM%, and DIM best predicted FWI of lactating dairy cows. The extant model in Castle and Thomas (1975) including only milk yield and DM% also performed well on independent data but had a larger RMSPE% (19.7%) than the RMSPE% of the new model (17.9%, Table 5). Predictions from the new model without DMI had small mean bias (1.2% of total bias, Table 5), although slope bias (28.6% of total bias) was quite notable (Figure 3). Nonetheless, both mean and slope bias of the Castle and Thomas (1975) model were greater than those of the new model (Table 5). Therefore, Equation 4 is recommended for predicting FWI of lactating cows if the DMI measurements are not available.

Regardless of whether DMI is included or not, applicability of the new models can be limited in dairy farms using salt blocks [e.g., 15% of the farms in California (Castillo et al., 2013)] as determination of NaK is difficult. Alternatively, we re-evaluated the new models using NaK based on Na intake estimated according to NRC (2001) guidelines and found the models to perform well (RMSPE = 14.7 and 19.7% for Equations 3 and 4, respectively). This indicates a potential to predict FWI successfully, although determining the true mineral intake by animals is difficult. Another limitation of the model applicability would be unavailability of information on dietary macromineral content because some producers have financial limits for feed testing. Although, commercial mineral supplements will have a

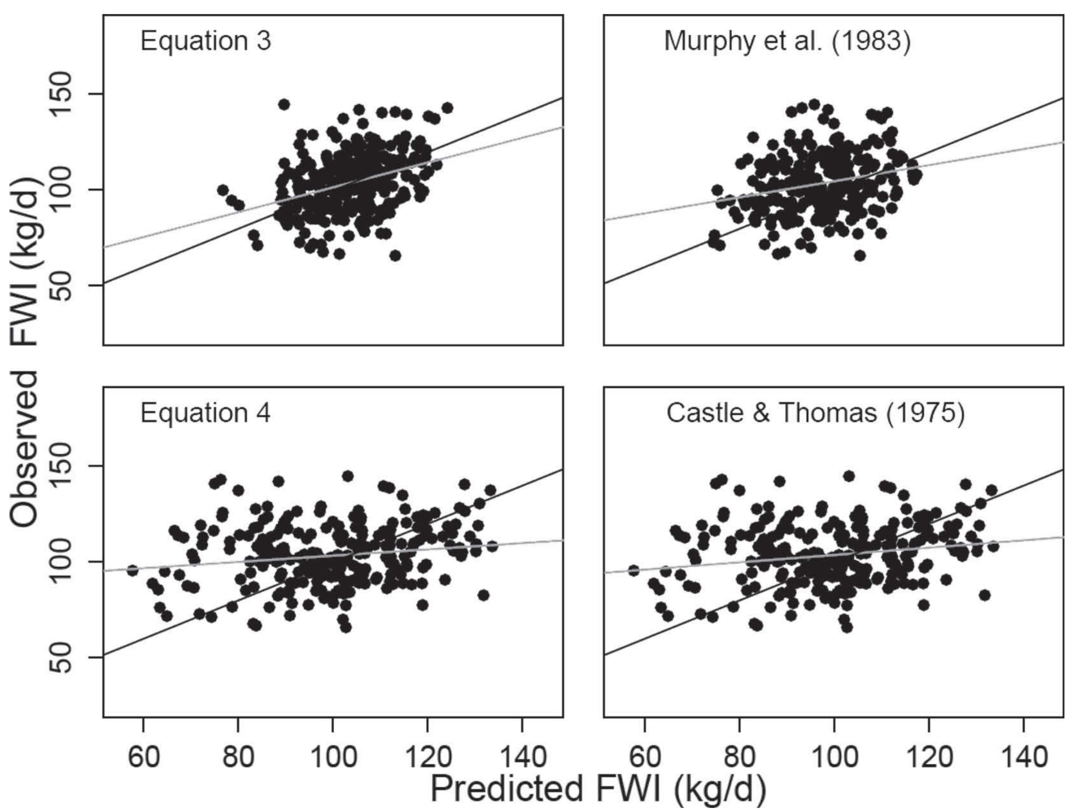


**Figure 2**. Observed versus predicted drinking water intake (FWI) of lactating cows from new models with (Equation 3) and without (Equation 4) DMI and extant models with [Murphy et al. (1983)] and without [Castle and Thomas (1975)] DMI, when evaluated with independent data. The black and gray lines represent, respectively, the unity line (y = x) and the scatter regression line.

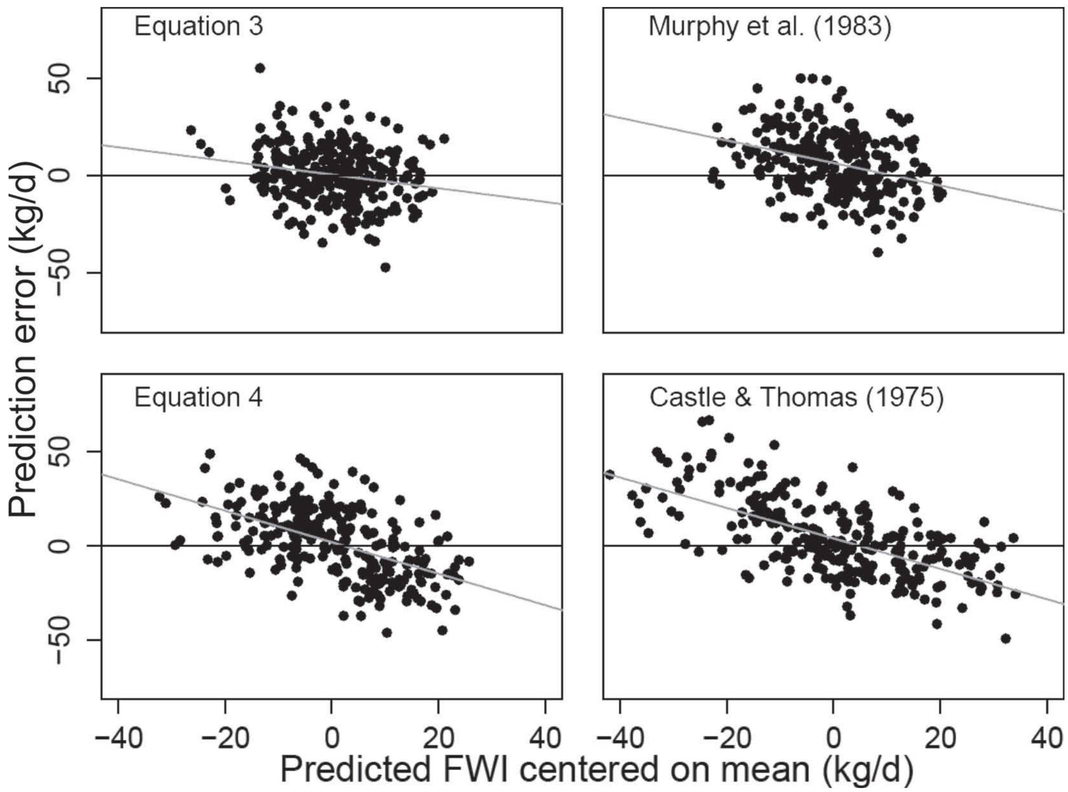


**Figure 3**. Prediction error (observed value – predicted value) versus predicted drinking water intake (FWI) of lactating cows from new models with (Equation 3) and without (Equation 4) DMI and extant models with [Murphy et al. (1983)] and without [Castle and Thomas (1975)] DMI, when evaluated with independent data. The black line represents the 0 error, whereas the gray line is the prediction error regression line.

guaranteed feed analysis and not require additional testing, forages are required to be tested for macrominerals as they are highly variable in mineral concentrations, particularly K (Norell and Chahine, 2014). Perhaps, as Norell and Chahine (2014) indicated, the table values of feed Na and K concentrations in NRC (2001) and a more recent analytical data set summarized by Beede (2005) might assist in determining FWI with reasonable accuracy.

### *Dry Cow Models*

The average FWI of dry cows was estimated to be 34.0 ± 2.73 kg/d taking into account the heterogeneity ($\tau^2$ = 98.2 ± 38.3) of the FWI treatment means from literature (Table 4). This was less than half (42%) of the FWI estimates for lactating cows. In addition to DMI, DM% and TMP were positively associated with FWI of dry cows (Equations 5 and 6, Table 4). This is consistent with the observations of Holter and Urban (1992) who demonstrated significant associations of DMI and DM% with FWI of dry cows under thermoneutral conditions. However, they also observed CP% to be associated with FWI. Cattle have limited capacity to produce concentrated urine; therefore, they drink more water to dilute urinary urea, if excessive amounts of CP were fed (Holter and Urban, 1992; Appuhamy et al., 2014b). The maximum CP% of diets in Holter and Urban (1992) was 23% of DM, suggesting that some cows entered a diuretic phase and consumed more water, allowing the link between CP% and FWI to be prominent. Such a relationship was not observed in this study as the maximum CP% of dry cows in our data was 16.6%. The model that included a quadratic relationship of TMP (Equation 6) explained more variability of FWI than the model including a linear (Equation 5) relationship ($\tau^2$ change = −75 vs. −41%, respectively). The link between FWI and TMP is consistent with the quadratic relationship of TMP (i.e., 10 to 36°C) and respiratory cutaneous water loses from Holstein cows (Campos Maia et al., 2005, 2008). When evaluated with data used for model development, predicted and observed FWI were in a close agreement (Figure 2B) and had RMSPE of 12.8% indicating the model parameters would be fairly representative of true relationship of FWI to DMI, DM%, and TMP. However, the model should be further evaluated using independent data when such data becomes available. Among extant mod-

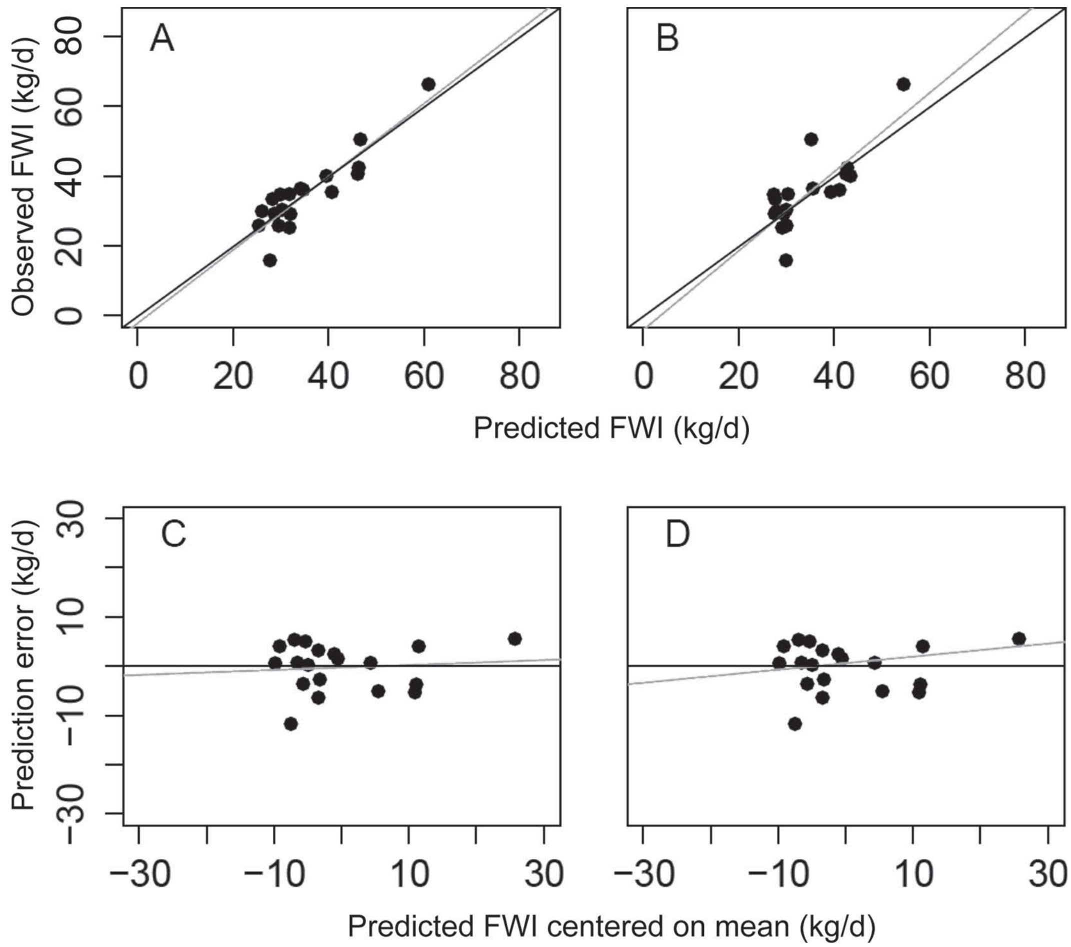


**Figure 4**. Observed versus predicted drinking water intake (FWI) from models with (A) and without (B) DMI, and prediction error versus predicted FWI centered on mean from models with (C) and without (D) DMI for dry cows. The black line represents the unity line (y = x) in A and B and the 0 error in C and D. The gray line is the scatter regression line.

els, only Holter and Urban (1992) offered a model to predict FWI of dry cows without requiring DMI data, which was solely based on CP%. Equation 7 (Table 4) was developed without including DMI as a predictor variable. The model used BW, DM%, and TMP variables and explained 54% of the heterogeneity of FWI (Table 4). Availability of DMI measurements appeared to be critical for predicting FWI of dry cows. However, the model without DMI had RMSPE% of 15.2% (Table 4) without notable mean or slope bias (Figure 4), and therefore, may be useful in predicting FWI of dry cows.

## CONCLUSIONS

When analyzed with data from 55 studies published in the literature, on average lactating cows consumed 78.4 ± 2.6 kg of water each day. Heterogeneity of FWI across the studies was significant. Dry matter intake, dietary DM, CP, Na and K concentrations, and daily mean ambient temperature were positively and independently related to FWI of lactating dairy cows and explained 76% of the heterogeneity. A new empirical model including these variables predicted FWI more accurately compared with extant models with DMI (RMSPE% = 14.4 vs. ≥15.7%). Therefore, the new model is recommended for predicting FWI of lactating dairy cows, if DMI records are available. In the absence of DMI records, milk yield, dietary DM, and Na and K contents, daily mean ambient temperature, and DIM were positively and independently related to FWI and explained 63% of the heterogeneity. A new empirical model including these variables predicted FWI more accurately compared with extant models that do not require DMI data (RMSPE% = 18.1 vs. ≥19.7%). Therefore, the new model is recommended for predicting FWI of the lactating dairy cows, if DMI records are not available. As observed with lactating cows, DMI, dietary DM content, and daily mean ambient temperature were significantly related to FWI of dry cows and explained 75% of heterogeneity in FWI across 10 studies. In the absence of DMI records, BW, dietary DM content, and daily mean ambient temperature were significantly related to FWI and explained 54% of the heterogeneity. Two new empirical models developed using these variables with and without DMI variable performed well (RMSPE% = 12.8 and 15.2%, respectively) and did not under- or overpredict FWI of dry cows over the data range (i.e., DMI varying from 6.7 to 21.8 kg/d). Overall, the present study offers a set of empirical models that can assist in estimating the drinking water intake by dairy cows in commercial dairy herds.

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