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Prediction of phosphorus output in manure and milk by lactating dairy cows

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ABSTRACT

Mathematical models for predicting P excretions play a key role in evaluating P use efficiency and monitoring the environmental impact of dairy cows. However, the majority of extant models require feed intake as predictor variable, which is not routinely available at farm level. The objectives of the study were to (1) explore factors explaining heterogeneity in P output; (2) develop a set of empirical models for predicting P output in feces (P_f), manure (P_{Ma}), and milk (P_m, all in g/cow per day) with and without dry matter intake (DMI) using literature data; and (3) evaluate new and extant P models using an independent data set. Random effect meta-regression analyses were conducted using 190 P_f, 97 P_{Ma}, and 118 P_m or milk P concentration (P_{MilkC}) treatment means from 38 studies. Dietary nutrient composition, milk yield and composition, and days in milk were used as potential covariates to the models with and without DMI. Dietary phosphorus intake (P_i) was the major determinant of P_f and P_{Ma}. Milk yield negatively affected P_i partitioning to P_f or P_{Ma}. In the absence of DMI, milk yield, body weight, and dietary P content became the major determinants of P_f and P_{Ma}. Milk P concentration (P_{MilkC}) was heterogeneous across the treatment groups, with a mean of 0.92 g/kg of milk. Milk yield, days in milk, and dietary Ca-to-ash ratio were negatively correlated with P_{MilkC} and explained 42% of the heterogeneity. The new models predicted P_f and P_{Ma} with root mean square prediction error as a percentage of observed mean (RMSPE%) of 18.3 and 19.2%, respectively, using DMI when evaluated with an independent data set. Some of the extant models also predicted P_f and P_{Ma} well (RMSPE% = 19.3 to 20.0%) using DMI. The new models without DMI as a variable predicted P_f and P_{Ma} with RMSPE% of 22.3 and 19.6%, respectively, which can be used in monitoring P excretions at farm level. When evaluated with an independent data set, the new model and extant models based on milk protein content predicted P_{MilkC} with RMSPE% of 12.7 to 19.6%. Although models using P intake information gave better predictions, P output from lactating dairy cows can also be predicted well without intake using milk yield, milk protein content, body weight, and dietary P, Ca, and total ash contents.
Key words: modeling, phosphorus, lactating cow, manure

INTRODUCTION

Phosphorus is an essential element for dairy cows with well-documented functions. A primary role of P is development and maintenance of the skeletal system. Phosphorus is also involved in cellular energy transfer through ADP and ATP. Phosphorus is intimately involved in acid-base buffer systems of blood, a part of casein, and associated with a small fraction of milk fat. It is also involved in enzyme systems and a constituent of saliva, and thereby assists in digestive functions (NRC, 2001; Vitti and Kebreab, 2010). Increased environmental concerns and regulations have drawn attention to P amounts in dairy rations. A major source of environmental pollution has been overfeeding P to dairy cows, caused by the safety margins added to diets to ensure that health and production of animals is not compromised (Kebreab et al., 2008). Although several studies have demonstrated no effect of feeding P above NRC (2001) recommended levels on production and health (Wu et al., 2001; Dou et al., 2003; Reid et al., 2015), the average dietary P concentration is still about 30% greater than NRC (2001) recommendations (Dou et al., 2003). Excess P is excreted by dairy cattle and contributes to eutrophication of water bodies (Smith et al., 2001). In the United States, the livestock sector is responsible for about 33% of P load into freshwater resources (FAO, 2006). Moreover, P overfeeding primarily using inorganic supplements could result in economic losses (Knowlton and Herbein, 2002) because P accounts for more than 50% of the cost of typical vitamin-mineral mixes used in dairy farms (Chandler, 1996).

In dairy cattle, P is primarily excreted in feces and secreted in milk. Urinary P excretion ($\mathbf{P_u}$) is negligible under practical feeding conditions; therefore, P balance

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of lactating dairy cows is determined primarily by P intake (**P_i**) with feed, P excreted in feces (**P_f**), and P secreted in milk (**P_m**; Valk et al., 2002). Measuring daily P_f can be laborious and expensive; therefore, several mathematical models have been developed for predicting P_f or P excreted in both feces and urine (**P_{Ma}**). The majority of the extant models (e.g., Van Horn et al., 1994; Wu et al., 2001; Weiss and Wyatt, 2004a; Nennich et al., 2005) require DMI of individual cows as an input, which may not be routinely available in dairy farms. Phosphorus secretion in milk is generally predicted assuming P concentration in milk (**P_{MilkC}**) is constant at 0.90 g/kg (NRC, 2001). However, Klop et al. (2014) reported that P_{MilkC} is variable and it is affected by differences in milk protein and lactose contents, which in turn is a function of nutrient composition in the diet.

Efficient use of dietary P by dairy cows has considerable economic and environmental implications, and developing and evaluating mathematical models that predict P balance are needed. A body of literature has been building that encompasses studies with wide range of P sources, intake, nutrient concentrations, milk production potentials, and stages of lactation. Potentially, the data can be used to identify variables that are required to predict P_f or P_{Ma} and P_m. The objectives of the current study were to (1) explore factors explaining heterogeneity in P_f, P_u, P_{Ma}, and P_m of modern lactating dairy cows using literature data published after 2000, (2) develop a set of empirical models for predicting P_f, P_{Ma}, and P_m using those factors, and (3) evaluate the new and extant models for predicting P output by dairy cows using an independent data set.

MATERIALS AND METHODS

Data Sources

Literature searches of the ScienceDirect (http://www.sciencedirect.com/) and *Journal of Dairy Science* (http://www.journalofdairyscience.org/) online databases were conducted using the combination of search terms "phosphorus excretion," "fecal phosphorus," "urinary phosphorus," and "dairy cows." The period covered was from 2000 to 2015. The searches were refined to include only scientific research published in journal articles in English. The searches resulted in 357 articles: 199 from ScienceDirect and 158 from *Journal of Dairy Science*. Abstracts of the 357 articles were examined for 2 major inclusion criteria: (1) studies should be in vivo involving lactating dairy cows, and (2) availability of information on measured P_f, P_u, or P_m. A further screening was carried out based on (1) availability of information on sample size (**N**) and information on uncertainty of the P excretion measures, such as standard deviation (**SD**), standard error of the mean (**SEM**), or standard error of the difference (**SED**); and (2) availability of description on diet composition, milk yield and composition, DIM, and BW. The second screening resulted in 38 articles meeting the criteria including 190 P_f, 118 P_m, and 97 P_u treatment means (g/d). Descriptions and summary statistics of relevant measured dietary and animal variables are provided in Table 1. The mean and variances of variables in the complete and reduced data sets containing means of P_f, P_m, and P_u were similar. Therefore, summary statistics of only the complete data set is given in the Table 1.

Treatment means and associated SD and N were of primary interest for the analysis. Additionally, ingredient and nutrient composition of experimental diets, including DM, CP, NDF, ADF, starch, gross energy (**GE**), ether extract (**EE**) contents (% of DM), DMI (kg/d), milk yield (kg/d), milk composition, BW (kg), and DIM were also retrieved. Any missing nutrient composition values of the experimental diet were calculated using the ingredient composition and nutritive value tables in NRC (2001). For studies only reporting SEM, SD was calculated as $SD = SEM\sqrt{N}$. For studies only reporting SED, SD was calculated as $SD = \left(SED/\sqrt{2}\right)/\sqrt{N}$. Phosphorus concentration in milk (g/kg of milk) was calculated by dividing P_m by milk yield. The SD for P_{MilkC} was calculated with the SD of P_m and milk yield using the online error propagation calculator (http://laffers.net; Stella et al., 2013). Phosphorus output in manure was calculated by adding P_f and P_u. The corresponding SD were calculated as for $P_{MilkC.}$

Statistical Analysis

A meta-regression analysis was conducted to construct a set of empirical equations to predict P excretions in manure and milk from dairy cows using R statistical software (version 2.12.2, R Foundation for Statistical Computing, Vienna, Austria). Random effect models were first used to estimate heterogeneity of the treatment means and extended to mixed effect meta-regression models, potentially explaining much of the heterogeneity as described in Viechtbauer (2010). Random effect models are given by

$$y_i = \mu + u_i + e_i,$$

where y_i = mean P_f, P_u, P_{Ma}, P_m, or P_{MilkC} of lactating cows in ith treatment group; μ = overall mean P_f, P_u, P_{Ma}, P_m, or P_{MilkC} of lactating cow; u_i = random deviation of the mean response (e.g., P_f) of cows in the ith