Published February 27, 2015

Predicting the digestible energy of corn determined with growing swine from nutrient composition and cross-species measurements

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ABSTRACT: The DE values of corn grain for pigs will differ among corn sources. More accurate prediction of DE may improve diet formulation and reduce diet cost. Corn grain sources ($n = 83$) were assayed with growing swine (20 kg) in DE experiments with total collection of feces, with 3-wk-old broiler chick in nitrogen-corrected apparent ME (AME_N) trials and with cecectomized adult roosters in nitrogen-corrected true ME (TME_N) studies. Additional AME_N data for the corn grain source set was generated based on an existing near-infrared transmittance prediction model (near-infrared transmittance-predicted AME_N [NIT-AME_N]). Corn source nutrient composition was determined by wet chemistry methods. These data were then used to 1) test the accuracy of predicting swine DE of individual corn sources based on available literature equations and nutrient composition and 2) develop models for predicting DE of sources from nutrient composition and the cross-species information gathered above (AME_N, NIT-AME_N, and TME_N). The overall measured DE, AME_N, NIT-AME_N, and TME_N values were 4,105 ± 11, 4,006 ± 10, 4,004 ± 10, and 4,086 ± 12 kcal/kg DM, respectively. Prediction models were developed using 80% of the corn grain sources; the remaining 20% was reserved for validation of the developed prediction equation. Literature equations based on nutrient composition proved imprecise for predicting corn DE; the root mean square error of prediction ranged from 105 to 331 kcal/kg, an equivalent of 2.6 to 8.8% error. Yet among the corn composition traits, 4-variable models developed in the current study provided adequate prediction of DE (model R^2 ranging from 0.76 to 0.79 and root mean square error [RMSE] of 50 kcal/kg). When prediction equations were tested using the validation set, these models had a 1 to 1.2% error of prediction. Simple linear equations from AME_N, NIT-AME_N, or TME_N provided an accurate prediction of DE for individual sources (R^2 ranged from 0.65 to 0.73 and RMSE ranged from 50 to 61 kcal/kg). Percentage error of prediction based on the validation data set was greater (1.4%) for the TME_N model than for the NIT-AME_N or AME_N models (1 and 1.2%, respectively), indicating that swine DE values could be accurately predicted by using AME_N or NIT-AME_N. In conclusion, regression equations developed from broiler measurements or from analyzed nutrient composition proved adequate to reliably predict the DE of commercially available corn hybrids for growing pigs.

Key words: broilers, corn grain, digestible energy, pigs, prediction modeling, roosters

J. Anim. Sci. 2015.93
doi:10.2527/jas2014-7807

INTRODUCTION

Forty-four percent of the United States corn crop is fed to livestock (USDA Economic Research Service, 2013); energy is the most costly component of most diets. Corn grain swine DE has been measured numerous times and mean values have been published (3,908 kcal/kg DM; NRC, 2012). Individual corn grain sources can be expected to differ in DE value for swine considering ranges in assayed nutrient content: NDF, 7 to 13% of DM; ash, 0.3 to 3% of DM; starch, 64 to 75% of DM; and ether extract (**EE**), 2.9 to 5.5% of DM (DairyOne, 2014). Indeed, up to 8% variation in swine DE has been observed for corn grain (Kim et al., 1999; Anderson et al., 2012). Accurate prediction of DE for specific

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Received March 3, 2014.
Accepted December 5, 2014.

corn grain sources would allow more precise formulation of diets than use of tabular means.

Determining DE with swine requires more than 150 kg of corn grain per source (Sauber et al., 2005). In addition, the high cost and extensive labor involved with metabolism trials justify a search for other methods to predict DE of a corn grain sample. Existing prediction models developed from indirect predictions may be imprecise for individual feed ingredients as the models were derived using mixed diets (Morgan et al., 1987; Noblet and Perez, 1993). Previous studies (Campbell et al., 1983; Sibbald et al., 1983; Smith et al., 1987, 1988) have demonstrated that data from rats and roosters can be used to predict DE and apparent ME (**AME**) for swine across a variety of feedstuffs and mixed diets, but cross-species comparisons with a single feedstuff are limited (Charmley and Greenhalgh, 1987; Zijlstra et al., 2011). Predicting DE values for swine from measurements with broilers or roosters could reduce both grain quantity and assay time required. Our objectives were to 1) determine the accuracy of predicting swine DE of corn grain using existing literature equations based on nutrient composition and 2) to develop new DE prediction models based either on nutrient composition or on energy measurements with broilers or roosters.

MATERIALS AND METHODS

All animal handling and care procedures in these studies followed specifications outlined by the *Guide for the Care and Use of Agricultural Animals in Research and Teaching* (FASS, 2010) and were approved by the DuPont Pioneer internal animal care and use committee and by the animal care committees established at each of the testing facilities. Corn grain sources were produced by DuPont Pioneer (Johnston, IA) over a period of 7 yr (2000 through 2007) from field plots located in the Midwest (Iowa, Illinois, and Minnesota) and Great Plains (Kansas and Nebraska) states; identity-preservation procedures were followed with the harvest of each corn grain source. The sources included commercially grown hybrids yielding grain that represented the full range in energy content available from commercially produced hybrids. Prospective corn grain sources (>1,000 individual sources) were initially screened based on compositional and spectral diversity using whole-grain subsamples. Corn grain sources (including subsamples submitted for initial screening) were cleaned to meet at a minimum the number 2 grade standard (USDA Grain Inspection, Packers and Stockyards Administration, 1996). Additional corn grain sources were generated by blending commercial hybrids with corn grain with modified-oil-content corns (such as high-oil corn) following cleaning. The 83 grain sources selected for study were predicted to range from 3,900 to 4,300 kcal/kg DM in swine DE. These 83 sources were further tested with in vivo energy digestibility studies with swine, growing broiler chickens, and adult roosters. All corn sources were ground at the DuPont Pioneer Livestock Nutrition Center Feed Mill (Polk City, IA) using a hammer mill (Bliss Industries, LLC, Ponca City, OK). Corn grain sources were ground to a target mean particle size of 450 to 550 μm for the swine DE assay or to 650 to 750 μm for both nitrogen-corrected apparent ME (**AME_N**) and nitrogen-corrected true ME (**TME_N**) assays. Subsamples of the ground corn sources were evaluated for particle size (American Society of Agricultural Engineers method S319; ASAE, 1993).

Digestible Energy Evaluation with Growing Pigs

The 83 corn grain sources were evaluated in 24 different swine DE trials conducted at the DuPont Pioneer Livestock Nutrition Center (Polk City, IA) over 5 yr. Each DE trial included 12 corn sources plus 1 check corn source common to all trials; 7 sources were present in more than 1 trial, providing across-experiment measurements, and some DE trials included sources that were not part of this project. Sources present in more than 1 trial were evaluated as unique entries to evaluate variability in mean DE values due to environmental variation over time. A uniform set of 42 barrows (mean initial BW 16 to 18 kg) of similar genetic background (PIC Line 1055 females × Line TR4 boars) were obtained from a single source (Swine Graphics Enterprises, LP, Webster City, IA) for each trial. The 36 pigs most uniform in weight (17.5 to 22.5 kg with a targeted weight of 20 kg) were selected for each DE trial with the remaining 6 pigs held as replacements. Selected pigs were placed in metabolism pens measuring 0.71 by 1.63 by 0.91 m fitted with adjustable rear and top panels and individual feeders (0.61 by 0.23 m) and water nipples. Eighteen pens were located in each of 2 similar environmentally controlled rooms. Pigs had free access to water only from 0730 to 0900 h and 1400 to 1530 h daily to minimize water waste. Pigs were weighed weekly during each trial. Test diets contained 89.5% ground corn supplemented with 2.5% minerals and vitamins (Swine Grower-Finisher VTM Premix; ADM, Des Moines, IA) to provide sufficient nutrients to support pig growth; sodium caseinate (8.0% of the diet; Erie Foods International, Inc., Erie, IL) supplied dietary AA and was assumed to be 100% digested. Fresh feed was supplied twice daily (0730 and 1400 h) but feed supply was limited to ensure that GE intake per unit of metabolic BW was constant and to reduce feed refusal; orts were rare. Feed supply was targeted at

3 times the estimated maintenance ME (approximately 80% of free choice feed intake) based on the assumption that energy digestibility at this intake level should be similar to that of pigs given free choice access to feed. Pigs within each room were allocated randomly to corn sources with 2 pigs in each room fed the check corn sample, and each source appeared at least once in each room and experimental period. Each trial included 3 separate 7-d experimental periods using a single set of pigs. During each experimental period, pigs within each room were rerandomized among the test corn sources. Therefore, individual pigs may have been used to test up to 3 different sources in a given trial. At the end of the 3 experimental periods within a trial, 8 observations per corn source and 12 observations for the check corn had been obtained. Each experimental period included 4 d for adaptation followed by 3 d for quantitative collection of feces. Ferric oxide (0.30%) was used as the start/stop marker (Adeola, 2001) for fecal collection. Feces were collected from each pig twice daily. Weighed fecal samples were dried in a 62°C forced-air oven until no additional weight was lost and uniform drying was achieved (7 d). The dried feces from each pig were weighed, pooled, and ground through a 6-mm screen (Thomas-Wiley Model 4 Laboratory Mill; Thomas Scientific, Swedesboro, NJ).

Nitrogen-Corrected Apparent ME Evaluation with Growing Chicks

These same 83 corn grain sources that were evaluated in the DE trials were evaluated for AME_N in 9 trials over 4 yr at AHPharma, Inc. (Salisbury, MD). Each AME_N trial included the same check corn that was used for DE evaluation and 13 corn sources, with 2 exceptions: 1 trial included 11 corn sources and a second trial included 17 corn sources. Twelve of the 83 corn sources were present in more than 1 trial and some trials included corn sources that were not part of this project. Broiler chicks (Ross 708) were obtained (from Mountaire Farms, Princess Anne, MD) on the day of hatch in sufficient numbers to ensure availability of the required number of healthy chicks for evaluating each corn source. Broilers were weighed, wing-banded on receipt (d 0), and fed a standard starter mash diet (3,135 kcal ME/kg diet) from d 0 to 21. This diet, formulated using a commercially available corn grain source, met or exceeded nutrient requirements suggested by NRC (1994) with consideration for commercial practice. The energy value of the starter diet was formulated to be similar to that of corn grain so that broilers would be acclimated to that energy level when grain sources were evaluated. Broilers, reared to 19 d of age in pens (0.914 by 1.219 m) on raised wire floors, were placed into battery cages (45.7 by 61.0 cm) on d 19 for a 2-d acclimation period. All trials were conducted in a single room that contained several battery units, each holding an equal number of cages; these battery units were used as blocking factors for randomization. Broilers were allocated randomly to cages with an equal number of males and females in each cage. Trials 1 through 7 used 6 birds per cage with 12 cages per corn source. The number of chicks in trials 8 and 9 was increased to 8 birds per cage with 10 cages per corn source to increase the quantity of fecal material collected. Cages within each block were assigned randomly and independently to corn sources. The energy assay was performed on d 21 immediately after weighing of birds. On d 21, broilers were fasted for 6 h, after which they were fed only their respective corn source for 6 h. Prior work at this facility had determined that a 6-h fasting period was sufficient time to clear fecal material from the gastrointestinal tract. A quantitative collection of excreta was made from each cage during the 6-h feeding period plus the 12 h after the corn supply was removed; no feed (corn source or starter mash diet) was provided to the broilers after the corn source was removed, but water was available. Fecal samples collected from each cage were oven-dried for approximately 24 h so samples contained less than 12% moisture and were ground with a mortar and pestle.

Nitrogen-Corrected True ME Evaluation with Cecectomized Roosters

Forty-four of the 83 corn grain sources evaluated for DE and AME_N were evaluated for TME_N at the University of Illinois (Urbana, IL) in 6 trials over 3 yr. Corn sources were selected to cover the full range of the near-infrared transmittance (**NIT**)-predicted DE from the initial screening (3,900 to 4,300 kcal/kg DM). Each trial evaluated 10 corn sources plus the same check corn source that was fed in the DE and AME_N evaluations; 4 corn sources were present in more than 1 trial. A total of 55 cecectomized adult White Leghorn roosters were fed in each trial in a modification (Parsons et al., 1992) of the true ME (**TME**) procedure by Sibbald (1986) to determine TME_N value. The birds were housed in an environmentally controlled room in individual cages (30.5 by 50.8 cm) with raised wire floors. Each trial consisted of 2 consecutive feeding periods that were separated by 1 mo to allow the roosters time for recovery from gavaging. Birds were assigned randomly to each corn source (5 per corn) in the first period; the same set of 55 birds was rerandomized for the succeeding feeding period, resulting in 10 observations for each corn grain source. Roosters received 30 g of corn grain via gavage into the crop immediately after a 24-h fasting period; feces were collected for 48 h postgavage. Fecal

Table 1. Methods of analysis

Analyte[1]	Sample type and method
DM	Corn and fecal. AOAC International method 930.15[2] (AOAC, 1995), AOAC International method 930.15[3] (AOAC, 2000), and AOAC International method 930.15 (AOAC, 2000; modification: 0.25-g sample dried for 2 h)[4]
GE	Corn and fecal. Bomb calorimetry (Parr Instruments model 1271; Parr Instruments, Moline, IL)[4]
EE fat	Corn. AOAC International method 920.39[2] (AOAC, 1995) and Association of Official Analytical Chemists method 920.39[3] (AOAC, 1990)
AH fat	Corn. AOAC International method 954.02/4.5.02[2] (AOAC, 1995)
Starch	Corn. CRA G-28 (Corn Refiners Association, Washington, DC),[2] Holm et al. (1986) with modification (Hall, 2000),[3] and AOAC International method 996.11[2] (AOAC, 1995)
CP	Corn and fecal. AOAC International method 990.03[2] (AOAC, 1995), AOAC International method 990.03[3] (AOAC, 2000), and Thermo Electron Corporation FlashEA 1112 Combustion Analyzer (Thermo Electron Corporation, Waltham, MA)[4]
NDF	Corn. Ankom 05/03 method (ANKOM Technology, Macedon, NY),[2] Van Soest et al. (1991) with modification (Whatman 934-AH glass microfiber filters with 1.5 µm particle retention; GE Healthcare Bio-Sciences Corp., Piscataway, NJ),[3] and Goering and Van Soest (1970)[5]
ADF	Corn. Ankom 05/03 method (ANKOM Technology, Macedon, NY)[2] and AOAC International method 973.18[3] (AOAC, 2000; modified to use Whatman 934-AH glass microfiber filters with 1.5-µm particle retention in place of fritted glass crucibles)
CF	Corn. American Oil Chemists' Society method Ba 6a-05[2] (Firestone, 1997) and AOAC International method 973.10[3] (AOAC, 2000)
Ash	Corn. AOAC International method 942.05[2] (AOAC, 1995) and AOAC International method 942.05[3] (AOAC, 2000; modification using 1.5-g sample weight, 4-h ashing time, and hot weighing)

[1]EE = ether extract; AH = acid hydrolyzed; CF = crude fiber.

[2]Analyzed by Eurofins Laboratories, Des Moines, IA.

[3]Analyzed by Cumberland Valley Analytical Services, Hagerstown, MD.

[4]Analyzed by DuPont Pioneer Grain and Forage Analytical Laboratory, Urbandale, IA.

[5]Analyzed by Dairyland Laboratories, Arcadia, WI.

samples collected from each bird were freeze-dried and ground using a high-speed mill (Braun Aromatic KSM 2; Gillette, Boston, MA); the ground fecal samples from individual birds were not pooled within a corn source.

Chemical Analyses and Energy Calculations

Corn grain samples and fecal samples from all trials were ground before chemical analysis (KnifeTec 1095 Sample Mill; Foss Tecator AB, Hoganas Sweden) and analyzed at various laboratories as described in Table 1. Different laboratories were used over the years the trials were conducted; however, the check sample was included in each study sample set and the nutrient composition was similar across the laboratories. Intakes and the analyzed nutrient content of feed and excreta were converted to a DM basis for all energy calculations. Swine DE (kcal/kg DM) was calculated as

$$\text{DE} = (\text{intake GE} - \text{fecal GE})/\text{DM intake}.$$

Broiler AME (kcal/kg DM) and AME_N (kcal/kg DM) were calculated as

$$\text{AME} = (\text{intake GE} - \text{fecal GE})/\text{DM intake and}$$

$$\text{AME}_N = \text{AME} - \{[8.730 \times (\text{intake N} - \text{fecal N})]/\text{DM intake}\},$$

in which 8.730 is the nitrogen correction factor recommended by Titus et al. (1959). Rooster TME (kcal/kg DM) and TME_N (kcal/kg DM) were calculated as

$$\text{TME} = (\text{intake GE} - \text{fecal GE} + \text{endogenous energy})/\text{DM intake and}$$

$$\text{TME}_N = \text{TME} - \{[8.22 \times (\text{intake GE} - \text{fecal GE} + \text{endogenous energy})]/\text{DM intake}\},$$

in which 8.22 is the retained nitrogen correction factor recommended by Hill and Anderson (1958).

Historical estimates of endogenous excreta weight and nitrogen and energy concentrations generated in previous trials unrelated to this study were provided by the University of Illinois Animal Sciences Laboratory (Urbana, IL).

Near-Infrared Transmittance-Predicted Nitrogen-Corrected Apparent ME Data Set Generation

A near-infrared transmittance-predicted AME_N (NIT-AME_N) data set was generated using an Infratec 1241 Grain Analyzer (FOSS Analytical, Hillerød, Denmark) and an accompanying NIT prediction model. Near-infrared transmittance absorbance spectra (850 to 1,050 nm) collected on the instrument for 64 of the 83 corn sources were used with the respective AME_N animal trial data to develop a model and predict NIT-AME_N on all sources. The development of the partial least squares regression model involved pretreating the raw absorbance values with standard normal variate scatter correction followed by second derivative mathematical transformation (Williams and Norris, 1987). Data analysis, including random group cross-validation, was performed using the InfraSoft International chemometrics software WinISI II version 1.50e (NIRSystems Inc., Silver Spring, MD). The resulting 6-variable model rendered a strong R^2 (0.94) and relatively low SE (23 kcal/kg) of cross-validation for the calibration set. Model validation using 17 of the 83 corn sources showed a SE of prediction of 22 kcal/kg between in vivo broiler AME_N and NIT-AME_N predicted values.

Statistical Analysis of Data

Initial Data Evaluation. All energy data were analyzed using the MIXED procedure of SAS (SAS Inst. Inc., Cary, NC) to generate least squares means for use in model development. The check corn grain source was used as a covariate in each data set to improve precision and to calculate least squares means of all corn sources across studies at the overall mean DE of the check corn. The swine DE data set was analyzed with a model that included fixed effects of trial and corn source within trial; random effects of experimental period within trial, room within trial and experimental period, and pig within trial and room; and an error term. The model for AME_N data analysis included the same fixed effects as for DE, random effect of blocks within trial, and an error term. The model for TME_N analysis included fixed effects of trial, period within a trial, and corn source within a trial; random effect of cage within trial; and an error term. For those corn sources evaluated in more than 1 trial, there were no consistent differences between the within–corn source least squares means; therefore, the least squares means were averaged to provide a single value for each respective corn source.

A separate and independent source of data is the preferable strategy for model validation. However, in the absence of an independent data set, models are commonly evaluated by dividing the full data set into 2 equal portions, with 1 set being used for model development and the other set being used for model validation (Rawlings, 1988; Kutner et al., 2004). However, with a relatively small data set, a larger portion of data should be allocated to model development (Kutner et al., 2004). Within the current data set, 80% of the corn grain sources was used to develop models (training data set) to predict swine DE from the various information sources; the remaining 20% of corn grain sources was reserved for model validation. Sources reserved for validation were selected using a stratified random sampling scheme after sorting and grouping corn grain sources into 4 categories by a class interval of 1 SD from the overall DE mean.

Testing of Literature Equations and Development of DE Models. Because subsamples of a single large batch of each corn grain were used in both the poultry and the swine studies, nutrient compositional data of corn sources used in the poultry studies were found to be nearly identical to those of corn sources analyzed from the swine trials. Consequently, data from the swine set were used for modeling and validation of DE predicted from nutrient analyses. Five equations from published literature were evaluated in the initial assessment of nutrient composition values as predictors of corn DE. The first equation was from Ewan (1989) whereas the remaining 4 equations were developed by Noblet and Perez (1993; Eq. [22], [23], [27], and [28]). The availability of the respective compositional traits from the swine DE trials served as the basis for selecting these equations.

Subsequently, swine DE prediction models were developed using the nutrient composition of the sources analyzed. Selection of prediction models was first made using the RSQUARE option of the REG procedure of SAS to generate initial information on R^2 and root mean square error (**RMSE**) of models for each group of p-variable models using the training data set. Alternative models within each group were then scrutinized for statistical significance of coefficients and changes in model R^2, Akaike's information criterion (**AIC**), and Bayesian information criterion (**BIC**) values. Digestible energy prediction models using data from in vivo AME_N and TME_N trials and NIT evaluation (NIT-AME_N) were derived using simple regression procedures by including different levels of polynomials, starting with a simple linear effect and continuing until no further improvements in model R^2, RMSE, AIC, and BIC values were observed. Candidate models in all cases were validated based on the mean difference between predicted and actual observations (**DIF**), the mean absolute difference between predicted and actual observations (**ABS**), the root mean square error of prediction (**RMSEP**), the correlation between observed and predicted values (r), and the percentage of prediction error (**PE**):

$$\text{DIF} = \frac{\sum_{i=1}^{n}\left(\hat{Y}_i - Y_i\right)}{n},$$

$$\text{ABS} = \frac{\sum_{i=1}^{n}|\hat{Y}_i - Y_i|}{n}, \quad \text{and}$$

$$\text{RMSEP} = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{n}}$$

in which Y_i = observed DE for the i^{th} validation source, $\hat{Y}_i$ = predicted DE for the i^{th} validation source, and n = number of validation set sources, and

$$\%PE = \left(\frac{\text{RMSEP}}{\overline{\text{DE}}}\right)\times 100,$$

in which $\overline{\text{DE}}$ is the mean observed DE of validation sources used.

Bootstrapping and Cross-Validation of Prediction Models. The data set used in the current analysis is limited in size. Inefficient use of data due to splitting it into development and validation sets further exacerbates this situation. Therefore, the validity of variance estimates and normality assumptions as well as confidence interval (**CI**) estimates may be in question. Bootstrapping and cross-validation techniques are essential for testing assumptions concerning the distribution around parameter estimates and providing a more efficient validation process, respectively. A single most appropriate candidate model from each information source derived from the model development and validation steps were considered for further evaluation. In a preliminary evaluation, the general relationship between SE of slopes from a linear regression of DE on AME_N and number of bootstrap samples (***s***) were used to determine the optimum number of samples needed. In total, bootstrap replications ranging from 200 to 3,000, each with a sampling rate of 100%, were evaluated. The SE of slopes was stable after s = 1,000; however, 2,000 replications were used to allow for a better description of distribution properties. Bootstrap sampling was done with replacement using the SURVEYSELECT procedure of SAS as described by Becker and Powers (2001) and Cassell (2007). Predictor variables and DE from the 83 corn sources were used as original sources of data for resampling. Steps used for bootstrapping included the following (Efron, 1979): 1) generate large number of independent bootstrap samples (size = n) by resampling original data with replacement, 2) compute $\hat{\theta}^*(x)$ for each sample, and 3) calculate statistic for inference to θ: SEM and CI. For large samples, the (1 –α) percent CI for θ is

$$\theta = \hat{\theta} \pm Z_{\alpha/2}\text{SE}(\hat{\theta}^*)$$

in which $\text{SE}(\hat{\theta}^*) = \sqrt{\dfrac{\sum_i^s(\hat{\theta}_i^* - \overline{\theta}^*)^2}{s-1}}$, and

$$\overline{\theta}^* = \frac{\sum_i^s \hat{\theta}_i^*}{s},$$

in which $\hat{\theta}$ = parameter estimate from original sample, $\hat{\theta}_i^*$ = bootstrap estimate from the ith sample, and $\overline{\theta}^*$ = means of $\hat{\theta}_i^*$.

Histograms from sampling distribution of $\hat{\theta}^*$ were used to construct percentile CI. Percentage CI from a total of s independent bootstrap estimates that are ordered from smallest to the largest is

$$\left(s\times\frac{\alpha}{2}\right)^{th} \le \theta \le \left[s\times\left(1-\frac{\alpha}{2}\right)\right]^{th}$$

For studies with a small sample size (n), K-fold cross-validation provides a more efficient route to evaluate accuracy of prediction (Kutner et al., 2004). Due to the limitation in sample size in the current study, we considered the case of $K = n$, also known as leave-one-out (**LOO**) procedure. Candidate models from the previous step were evaluated for accuracy of prediction during each sampling; the $n - 1$ set of data was used as a learning set to estimate coefficients for the respective models, which were then validated based on the excluded sample. Hence, individual models were tested on all 83 sources (or 44 for TME_N) at the end of the analysis. Comparisons between models were based on DIF, ABS, RMSEP, and r.

RESULTS AND DISCUSSION

Particle size analysis revealed mean values of 516 (SD = 39), 682 (SD = 44), and 704 μm (SD = 34) for the DE, AME_N, and TME_N sets, respectively. Particle size determinations are necessary because the recommended particle size range differs between swine and broilers. The effects of particle size on nutrient digestibility in swine and broilers are well recognized (Wondra et al., 1995; Amerah et al., 2007). The overall mean DE determined from the swine DE assay was 4,105 kcal/kg, which was approximately 100 kcal/kg DM more than the mean AME_N or NIT-AME_N values but similar to the mean TME_N value of 4,086 kcal/kg (Table 2). Wiseman et al. (1998) similarly observed that AME values were lower for young than for adult broilers and lower than the DE values of growing pigs.

The range in energy values by the various methods for corn grain sources was 317 to 440 kcal/kg DM, which is similar to the within-source differences observed in kilocalories AME/kilogram DM of various cereal grains for broilers and layers (Black et al., 2005). The relative variability observed in energy values among corns as determined by the various methods was comparatively small as demonstrated by the small CV (2.3 to 2.4%). In contrast, the CV of analyzed nutrients in corn sources was much higher, ranging from approximately 10 to 40% for nutrients such as protein, fat, fiber, and ash. The nutrient value ranges and CV of the corn grain calibration set compiled by Pelizzeri et al. (2013) were similar to those observed in this study. Zhao et al. (2008) also observed similar ranges in nu-

Table 2. Calculated energy values and analyzed nutrient composition of corn grain sources fed in swine DE trials (all values except DM on a DM basis)

Item[1]	Mean[2]	Minimum	Maximum	SD	CV, %
Calculated energy values, kcal/kg DM					
DE	4,105	3,904	4,344	100	2.4
AME_N	4,006	3,865	4,269	94	2.3
TME_N	4,086	3,955	4,272	80	2.0
NIT-AME_N	4,004	3,877	4,283	92	2.3
Analyzed nutrients of corn grain samples[3]					
DM %	86.6	83.7	88.9	1.2	1.4
GE, kcal/kg	4,576	4,409	4,841	101	2.2
EE fat, %	5.57	3.11	10.8	1.96	35.1
SCHO,[4] %	72.8	63.6	79.9	3.7	5.1
Starch, %	68.5	58.3	74.2	3.4	4.9
Protein, %	9.54	7.89	12.3	0.98	10.3
NDF, %	10.7	6.66	15.4	2.14	20.0
ADF, %	4.54	1.92	7.99	1.80	39.6
Crude fiber, %	1.74	0.93	3.72	0.42	27.8
Ash, %	1.35	0.87	2.36	0.28	20.5

[1]AME_N = nitrogen-corrected apparent ME; TME_N = nitrogen-corrected true ME; NIT-AME_N = near-infrared transmittance-predicted AME_N; EE = ether extract; SCHO = soluble carbohydrates.

[2]Calculated energy mean values are based on least squares means of sources (n = 83 for DE, AME_N, and NIT-AME_N, and n = 44 for TME_N); analyzed nutrient mean values are simple means of raw data (n = 83).

[3]In-house DM values, GE values, and protein values (calculated from nitrogen) are calculated averages of a minimum of 2 assay replicates.

[4]Calculated from analyzed nutrient values as 100 – (protein + fat + ash + NDF).

trient values for a corn-based calibration set, and CV calculated from that set were also similar to those observed in this study. The nutrient ranges observed in those studies were deemed sufficient for developing ME prediction models.

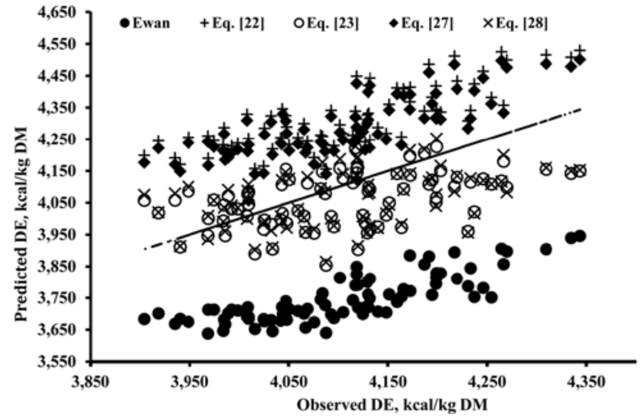

Figure 1. Relationships between observed DE and predicted DE calculated from literature equations (Ewan, 1989; Eq. [22], [23], [27], and [28] from Noblet and Perez, 1993) using nutrient composition of samples analyzed in swine DE trials (n = 83). The diagonal line represents predicted DE = observed DE.

Development and Testing of Wet Chemistry Models

The predicted mean DE determined from literature equations based on nutrient composition and using current wet chemistry data ranged from 3,779 to 4,309 kcal/kg (Table 3; Fig. 1). Whereas Eq. [22] and Eq. [27] often overpredicted DE, the equation derived by Ewan (1989) underpredicted DE. Both Eq. [22] and Eq. [27] are 4-variable models with 3 variables in common (ash, CP, and crude fiber) having reported values outside the observed corresponding ranges of corn sources in this study. Equations [23] and [28] showed the lowest ABS, RMSEP, and PE; however, these 2 equations underpredicted DE when the observed DE was above 4,200 kcal/kg. Generally, these equations were developed based on mixed diets so, in addition to being developed using predictor variables with values outside the observed ranges of corn sources in this study, the correlation structure between DE and predictor variables as well as between the predictors themselves would be expected to differ from those of

Table 3. Predicted DE values generated using literature equations and nutrient composition of corn grain sources fed in swine DE trials (n = 83)[1]

Equation source	Predicted DE, kcal/kg DM ± SE	DIF ± SE	ABS ± SE	RMSEP	r	PE, %
Ewan, 1989	3,779 ± 7	–326 ± 7	326 ± 7	331	0.80	8.8
Noblet and Perez, 1993[2]						
Equation [22][3]	4,307 ± 11	202 ± 7	202 ± 7	213	0.77	5.2
Equation [23][4]	4,059 ± 9	–46 ± 11	88 ± 7	107	0.45	2.6
Equation [27][5]	4,309 ± 10	205 ± 7	205 ± 7	215	0.36	5.2
Equation [28][6]	4,091 ± 9	–13 ± 12	88 ± 6	105	0.76	2.6

[1]DIF = difference between predicted and actual observations; ABS = absolute difference between predicted and actual observations; RMSEP = root mean square error of prediction; PE = prediction error.

[2]Units for GE are kilocalories/kilogram DM and units for all other nutrients are grams/kilogram DM.

[3]DE = 4,151 – 12.2 × ash + 2.3 × CP + 3.8 × ether extract – 6.4 × crude fiber.

[4]DE = 4,168 – 9.1 × ash + 1.9 × CP + 3.9 × ether extract – 3.6 × NDF.

[5]DE = 1,407 + 0.657 × GE – 9.0 × ash + 1.4 × CP – 6.7 × crude fiber.

[6]DE = 1,161 + 0.749 × GE – 4.3 × ash – 4.1 × NDF.

Table 4. Observed correlations between corn grain source nutrient compositions (n = 83)[1]

Nutrient	DE	GE	EE fat	Crude fiber	Protein	ADF	NDF	Ash	Starch	SCHO
DE	1.00									
GE	0.88**	1.00								
EE fat	0.86**	0.96**	1.00							
Crude fiber	–0.23*	–0.14	–0.070	1.00						
Protein	0.11	0.071	–0.088	–0.41**	1.00					
ADF	0.55**	0.60**	0.61**	–0.40**	0.015	1.00				
NDF	0.43**	0.56**	0.57**	–0.17	–0.087	0.82**	1.00			
Ash	–0.087	–0.16	–0.11	0.20	–0.088	–0.094	0.080	1.00		
Starch	–0.62**	–0.66**	–0.67**	0.28*	–0.11	–0.61**	–0.70**	0.041	1.00	
SCHO	–0.73**	–0.82**	–0.84**	0.23*	–0.16	–0.80**	–0.87**	–0.041	0.80**	1.00

[1]EE = ether extract; SCHO = soluble carbohydrates (calculated from analyzed nutrient values as 100 – [protein + fat + ash + NDF]).

*$P < 0.05$; **$P < 0.01$.

corn grain. Consequently, these equations would not be expected to perform as well for independent samples made up of a single ingredient. Considering current feed costs as well as the consequences of under- or overpredicting feed energy on animal performance, a 3 to 9% PE for corn grain would not be acceptable for precision formulation of diets.

Ether extract and GE showed a strong and positive correlation ($r > 0.85$) with DE (Table 4). Moderate levels of correlation to DE were detected for ADF (r = 0.55) and NDF (r = 0.43) values. Total starch and calculated soluble carbohydrates were negatively associated (–0.62 and –0.73, respectively) with DE. Predictor variables also showed a strong correlation with each other. This relationship caused the partial contribution of variables to the overall model R^2 to change depending on the presence or absence of other strongly correlated variables. For example, whenever EE or GE was included in a model, each accounted for 70% of the variation in DE. However, as a result of the strong correlation (r = 0.96) between EE and GE, including EE in the model along with GE resulted in only a small partial R^2 for EE. Lessire et al. (2003) also observed strong positive correlations between GE and ME with fat and negative correlation between GE and starch in their evaluation of corn grain samples for use in developing AME_N prediction equations. The correlation structure among variables in the current study is quite different from that reported for mixed diets. In contrast to current results, both Morgan et al. (1987) and Noblet and Perez (1993) reported strong negative correlations between DE and fiber measures (crude fiber, ADF, and NDF) ranging from –0.71 to –0.91 or between DE and ash (–0.64 and –0.65) but positive correlations between DE and starch (0.79 and 0.49). Diets in their studies were considerably higher (on average) in NDF (15%) and ADF (7.5%) but lower in starch (41%) than the corn sources tested in this study. Although the direction of the relationship with DE was similar to the current study, these studies reported much weaker correlations between DE and EE (0.12 to 0.30) or GE (0.28 to 0.30). Because of the difference in the relative relationship of predictor variables with DE as well as associations among predictor variables in feeds composed of a variety of ingredients and an individual feed ingredient such as corn, the relative weight of predictor variables as well as the combination of important variables in DE prediction models based on mixed diets may be different. Therefore, it is not appropriate to use models based on mixed diets for prediction of DE for corn-based diets.

The collinearity among analytes observed for corn sources is assumed to apply to all corn diets. Therefore, under such circumstances, collinearity between predictor variables poses no prediction problem unless extrapolation is attempted (Rawlings, 1988). These associations among predictor variables led to several competing

Table 5. Equations[1] developed from training data set to predict DE (kcal/kg DM) from nutrient composition of corn grain sources (n = 66)

		Model statistics[2]			
Equation no.	Equation	RMSE	R^2	AIC	BIC
C1	DE = 1,092 + 11.1 × ADF – 14.4 × NDF – 6.74 × starch + 0.78 × GE	50	0.79	513	516
C2	DE = 3,752 + 44.0 × EE[3] fat + 18.0 × CP + 12.0 × ADF – 11.3 × NDF	50	0.76	520	523
C3	DE = 4,659 + 36.5 × EE fat + 15.0 × ADF – 20.0 × NDF – 8.95 × starch	50	0.76	522	532

[1]Units for GE are kilocalories/kilogram DM and units for all other nutrients are grams/100 grams DM.

[2]RMSE = root mean square error; AIC = Akaike's information criterion; BIC = Bayesian information criterion.

[3]EE = ether extract.

Table 6. Validation[1] of new equations using nutrient composition of corn grain sources (n = 17)

Equation no.[2]	DE, kcal/kg DM Actual ± SE	DE, kcal/kg DM Predicted ± SE	DIF ± SE	ABS ± SE	RMSEP	r	PE, %
C1	4,113 ± 26	4,107 ± 25	–6.2 ± 12	38 ± 7.0	47	0.94	1.2
C2	4,113 ± 26	4,106 ± 23	–7.6 ± 9.8	36 ± 4.5	40	0.93	1.0
C3	4,113 ± 26	4,108 ± 22	–5.0 ± 12	40 ± 6.6	48	0.93	1.2

[1]DIF = difference between predicted and actual observations; ABS = absolute difference between predicted and actual observations; RMSEP = root mean square error of prediction; PE = prediction error.

[2]See Table 5 for equations.

models that had similar prediction capability. Generally, models with 4 or 5 variables had better or similar R^2 and RMSE than models of other size. Differences between the 2 groups of models in R^2 and RMSE were small; therefore, further evaluation was performed on 4-variable models, including possible interactions between these variables. Model R^2 of equations based on data from the current study (Table 5) were similar, ranging from 0.76 to 0.79; RMSE was 50 kcal/kg for all; and AIC and BIC ranged from 513 to 522 and 516 to 532, respectively. In the current study, both ADF and NDF terms were included in each equation. This is in contrast to other single ingredient-type studies in which only a single estimate of fiber, either NDF (Anderson et al., 2012) or ADF (Fairbairn et al., 1999; Pedersen et al., 2007; Cozannet et al., 2010), was deemed important. Within the 17 validation sources, all equations exhibited similar prediction capabilities (Table 6), with ABS ranging from 36 to 40 kcal/kg, RMSEP ranging from 40 to 48 kcal/kg, and PE ranging from 1.0 to 1.2%. This decrease in PE was a marked improvement compared to errors observed when DE was estimated with the published literature equations (Table 3). Consequently, the DE of corn grain for swine for the sources tested was predicted with a reasonable degree of accuracy simply based on nutrient composition of corn grain using the equations that were developed. Because bomb calorimetry is required for DE prediction by Eq. [C1; Table 5] and is not commonly determined in feed analysis laboratories, Eq. [C2] and [C3] (Table 5) likely would be used more extensively for corn grain and would entail an analytical cost per sample of between US$25 and $35.

Digestible Energy Prediction Based on Nitrogen-Corrected Apparent ME, Near-Infrared Transmittance-Predicted Nitrogen-Corrected Apparent ME, and Nitrogen-Corrected True ME

Considering the close relationship between observed and predicted DE values (Fig. 2) as well as the strong linear association between AME_N and DE (r = 0.85), it would seem reasonable to apply a simple linear equation (model [I], Table 7) to the current data. However, the quadratic coefficient in model [II] (Table 7) was different from 0 ($P < 0.01$) and including a quadratic factor exhibited a minor improvement in R^2, RMSE, AIC, and BIC values as compared to model [I]. Both models often overpredicted DE of sources with observed DE of less than 4,000 kcal/kg but underpredicted the DE of sources with a very high observed DE (Fig. 2). However, a clear difference in the prediction behavior of models [I] and [II] was observed with the 3 sources with the highest DE where model [II] underpredicted DE values. A similar relationship between observed and predicted DE was noted when NIT-AME_N was used as a predictor variable (figure not shown). The TME_N model (model [V]; Table 7) included only a linear coefficient term; any additional level of polynomial components was not different ($P > 0.05$) from 0. Compared to models based on AMEN, NIT-AMEN, or wet chemistry, TMEN showed the lowest R^2 and highest RMSE values. Although the range of sources included was the same for both TME_N and DE studies, perhaps including more than 44 sources (53% of the available corn grains) in the TME_N evaluation would have improved the model R^2 and RMSE.

Predicted DE of the sources used for validation of models [I] to [V] ranged from 4,101 to 4,114 kcal/kg (Table 8). Generally, NIT-AME_N models (models [III] and [IV]; Table 7) showed a similar or improved predic-

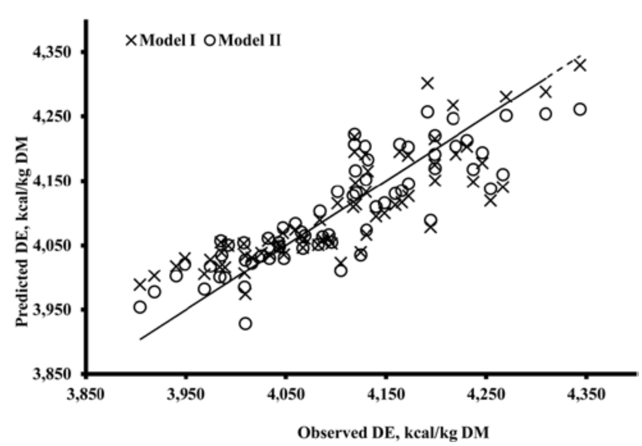

Figure 2. Relationship between observed DE and predicted DE generated using nitrogen-corrected apparent ME model [I] (linear) or model [II] (quadratic; Table 7) based on the training data set (n = 66). The diagonal line represents predicted DE = observed DE.

Table 7. Model development using training data set to predict DE from nitrogen-corrected apparent ME (AME_N; $n = 66$) and near-infrared transmittance-predicted AME_N (NIT-AME_N; $n = 66$) and nitrogen-corrected true ME (TME_N; $n = 35$)

		Coefficients			Model statistics[1]			
Predictor	Model	Intercept ± SE	Linear ± SE	Quadratic ± SE	RMSE	R^2	AIC	BIC
AME_N	I	415 ± 298	0.92 ± 0.074**		54	0.71	529	531
	II	–32,912 ± 11,356**	17.4 ± 5.6**	–0.00204 ± 0.00069**	51	0.74	522	525
NIT-AME_N	III	315 ± 291	0.95 ± 0.073**		52	0.73	524	526
	IV	–30,233 ± 11,772*	16.1 ± 5.8**	–0.00187 ± 0.00072*	50	0.75	519	522
TME_N	V	–210 ± 550	1.05 ± 0.13**		61	0.65	290	292

[1]RMSE = root mean square error; AIC = Akaike's information criterion; BIC = Bayesian information criterion.

*$P < 0.05$; **$P < 0.01$.

tion capability compared to AME_N models (models [I] and [II]) for the 17 validation sources. However, there was no consistent advantage of quadratic equations (models [II] and [IV]) over simple linear equations (models [I] and [III]). Similarity in the prediction capability of AME_N and NIT-AME_N models is due partly to the fact that part of the sources used in the current study were used for development of NIT models. The parallel relationships among these corn sources imply that factors limiting energy availability were similar across species; this suggests that DE values for swine of these corn sources can be predicted from AME_N or NIT-AME_N measurements. In contrast, Zijlstra et al. (2011) were unable to model swine DE ($R^2 = 0.03$) based on the AME of barley measured in young broilers and growing pigs and concluded that broiler AME could not be used to predict swine DE. This likely was due to a difference among species in response to additional fiber or in their capacity to digest NDF components. Jorgensen et al. (1996) observed that fermentation of nonstarch polysaccharides, the major component of dietary fiber, was less extensive in broilers than in pigs. Barley DM typically contains 20% NDF, whereas the corn grain sources of this study averaged 10.7% NDF (Table 2). Validation tests with TME_N (model [V]) showed the lowest correlation ($r = 0.83$) and the highest ABS (44 kcal/kg), RMSEP (57 kcal/kg), and PE (1.4%) values. An r value of 0.86 for swine DE and corresponding rooster TME_N values was calculated from the triticale data set of Charmley and Greenhalgh (1987) and other studies have observed even stronger relationships ($r > 0.90$) between swine and rooster energy measurements (Campbell et al., 1983; Sibbald et al., 1983, 1990; Smith et al., 1988). However, in contrast to the current study, those studies had used a broad range of feedstuffs (oilseed meals, cereal grains and byproducts, and mixed diets) leading to a large spread in DE values for estimating the accuracy of predicting swine energy values (measured as DE, AME, or AME_N) from rooster TME or TME_N values.

Bootstrap Evaluation and Leave-One-Out Model Validations

Histograms and quantile–quantile plots of only model [I] are presented as parameter estimates from the various models that were developed, showed similar distributions, and revealed no additional information (Fig. 3). Under normality, data points are expected to lie along the diagonal line on the quantile–quantile plots. Both slopes and intercepts exhibited relatively normal distributions, and minor deviations at the extreme data points are suggestive of a slight skewness in the underlying distributions. Under such circumstances, it might be argued that the traditional CI with equal distances from the estimates, as in $\hat{b} \pm t_{\alpha/2}\mathrm{SE}(\hat{b})$, may lead to inac-

Table 8. Validation[1] of models developed to predict DE from nitrogen-corrected apparent ME (AME_N; $n = 17$) and near-infrared transmittance-predicted AME_N (NIT-AME_N; $n = 17$) and nitrogen-corrected true ME (TME_N; $n = 9$)

Information		DE, kcal/kg DM						
source	Model[2]	Actual ± SE	Predicted ± SE	DIF ± SE	ABS ± SE	RMSEP	r	PE, %
AME_N	I	4,113 ± 26	4,110 ± 24	–3.6 ± 13	41 ± 7.4	51	0.88	1.2
	II	4,113 ± 26	4,104 ± 23	–9.2 ± 13	42 ± 8.2	54	0.86	1.3
NIT-AME_N	III	4,113 ± 26	4,114 ± 24	0.05 ± 11	35 ± 6.0	43	0.91	1.0
	IV	4,113 ± 26	4,110 ± 22	–3.4 ± 10	32 ± 6.5	41	0.93	1.0
TME_N	V	4,100 ± 36	4,101 ± 33	0.88 ± 20	44 ± 13	57	0.83	1.4

[1]DIF = difference between predicted and actual observations; ABS = absolute difference between predicted and actual observations; RMSEP = root mean square error of prediction; PE = prediction error.

[2]Models refer to models in Table 7.

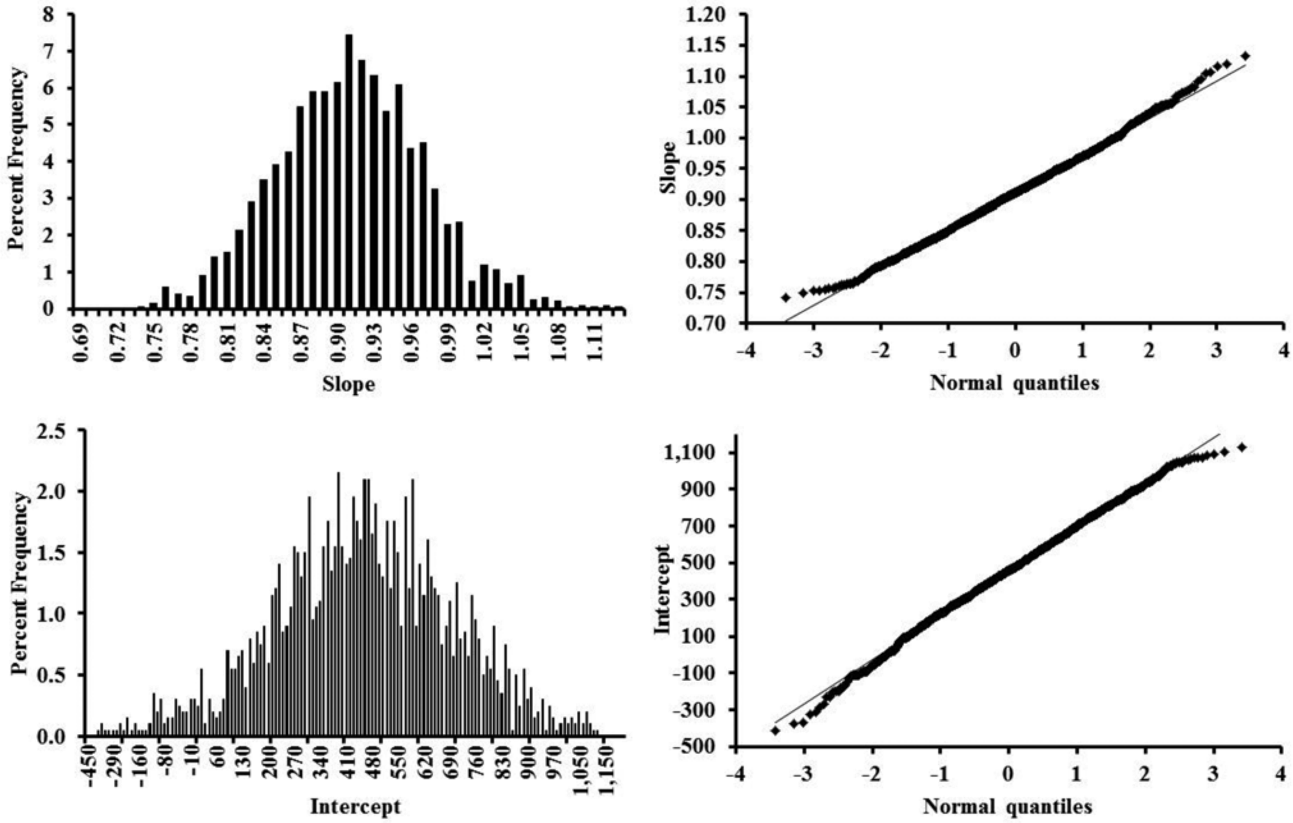

Figure 3. Histograms and quantile–quantile plots of bootstrap estimates for nitrogen-corrected apparent ME model [I] data (Table 7). Number of bootstrap samples = 2,000.

curate inferences. When assumptions on model statements hold true, variance estimates from the ordinary least squares (**OLS**) procedure are expected to be similar to bootstrap estimates (Freedman, 1981). Variances of OLS estimates were similar to or slightly higher than the bootstrap variances for the candidate model from each information source (Table 9). Although the OLS CI appeared similar to the percentile CI, the OLS intervals for model [I] slopes and intercepts were approximately 23 to 30% wider. Similarly, the model [III] OLS CI was approximately 20% wider. The 95% CI for parameter estimates for model [V] and Eq. [C1] also was 2 to 24% wider. The percentile CI values often were asymmetric. For example, the OLS 95% CI for the slope of model [I] was 0.921 ± 0.148; however, the percentile CI values ranged from 0.921 – 0.126 to 0.921 + 0.116. Considering the underlying distribution of these estimates, true values are more likely to be captured by the percentile CI. Although the current results are based on limited data and there was no perfect agreement with bootstrap estimates, the results in the current study should provide reasonable inferences of parameter estimates.

Predicted DE, and hence prediction accuracies, were similar when cross-validating models [I], [III], and [V] and Eq. [C1] using the LOO procedure (Table 10); as testing models [II] and [IV] and Eq. [C2] and [C3] did not improve validation statistics, those results are not shown. None of the observed DIF values were significantly ($P > 0.05$) different from 0. This lack of significance in the DIF values may not necessarily suggest a near-perfect agreement between observed and predicted values but rather nearly equal biases in both directions canceling one another to give an average value of 0. Relative to the mean observed DE, models showed a 1.2 to 1.5% PE. Generally, the TME_N model had the lowest prediction capability, with higher ABS (50 kcal/kg), RMSEP (62 kcal/kg), and PE (1.5%) than the other models. These LOO validation results generally agree with the earlier validations (Tables 6 and 8).

Although the range in energy value for most common corn hybrids was present in the corn sources assayed in the current study, adding data from more hybrids at both ends of the DE spectrum as well as including more data points within the current range to attain a nearly similar frequency across the DE spectrum could improve the accuracy of prediction. The DE value of improved (i.e., high available energy) corn hybrids is clustered within the current range but with a small between-hybrid variability. Blending commercial corn hybrids with a high-oil corn could provide more data points at the high extreme (>4,300 kcal/kg DM) and

Table 9. Summary of parameter estimates from models representing each information source using 2,000 bootstrap replications

	Information source[1]						
Estimate	AME_N Model [I][2]	NIT-AME_N Model [III][2]	TME_N Model [V][2]	Nutrient composition equation C1[3]			
Intercept							
Mean (SE)	455 (250)	301 (243)	–111 (459)	844 (455)			
Confidence intervals							
OLS[4]	–180 to 1,010	–267 to 896	–1,035 to 849	–56.3 to 1,748			
Large sample	–59.3 to 889	–162 to 791	–993 to 807	–45.5 to 1,738			
Percentile	–51.4 to 913	–199 to 760	–1,141 to 704	–120 to 1,690			
Linear coefficient							
				ADF	NDF	Starch	GE
Mean (SE)	0.91 (0.06)	0.95 (0.06)	1.03 (0.11)	9.92 (5.27)	–11.6 (4.9)	–4.60 (2.91)	0.80 (0.064)
Confidence intervals							
OLS	0.77 to 1.07	0.80 to 1.09	0.79 to 1.26	–0.73 to 20.7	–21.3 to –2.2	–9.60 to 0.30	0.65 to 0.94
Large sample	0.80 to 1.04	0.83 to 1.06	0.80 to 1.24	–0.34 to 20.3	–21.4 to –2.2	–10.4 to 1.05	0.67 to 0.92
Percentile	0.80 to 1.04	0.84 to 1.07	0.83 to 1.28	–0.59 to 20.1	–21.4 to –2.2	–9.91 to 1.58	0.77 to 0.93

[1]AME_N = nitrogen-corrected apparent ME; NIT-AME_N = near-infrared transmittance-predicted AME_N; TME_N = nitrogen-corrected true ME.

[2]These model types correspond to the models in Table 7, but parameter estimates are based on boot-strap data.

[3]See Table 5 for variables in equation C1.

[4]OLS = ordinary least squares.

less-improved or lower-nutritional-quality corn hybrids could be used to extend the lower extreme (<3,900 kcal/kg DM). However, effects of concocting such blended corn grain sources to obtain targeted DE levels at both extremes may alter the correlation structure between important variables, the physical associations among components within a grain particle, and the relative weight of variables in DE prediction.

Past research evaluating cross-species energy relationships has been based on diverse feedstuffs or mixed diets. This study, in contrast, was limited to a single feedstuff and therefore had a very limited range of values and much lower degree of variation among sources. The validation statistics show promise for using nutrient composition and measurements with broilers to predict DE of corn grain for swine. Prediction accuracy could be further refined through increasing the size and expanding the range of the data set. For selection of hybrids in plant breeding programs, predicting DE values for swine from measurements with broilers would reduce the labor and time required for analysis. On a commercial basis, because the DE value of individual corn grain sources varies, more precise prediction of the energy value (DE or AME_N) of corn grain based on nutrient composition should assist nonruminant nutritionists in formulating diets more precisely. A more precise diet formulation, in turn, should help optimize both feed efficiency and economics of production by avoiding the overfeeding of energy relative to the AA supply or, conversely, overfeeding AA relative to the energy supply (McCann et al., 2006). More accurate prediction of the energy value of the specific batch of corn grain being fed also should per-

Table 10. Cross-validation[1] of models using the leave-one-out procedure (n = 83 for nitrogen-corrected apparent ME [AME_N], near-infrared transmittance-predicted nitrogen-corrected apparent ME [NIT-AME_N], and nutrient composition and n = 44 for nitrogen-corrected true ME [TME_N])

Information source	Model or equation	DE, kcal/kg DM Actual ± SE	DE, kcal/kg DM Predicted ± SE	DIF ± SE	ABS ± SE	RMSEP	r	PE, %
AME_N	I[2]	4,105 ± 11	4,105 ± 9	–0.2 ± 6.0	43 ± 3.6	54	0.84	1.3
NIT-AME_N	III[2]	4,105 ± 11	4,105 ± 10	–0.2 ± 5.6	40 ± 3.4	51	0.84	1.2
TME_N	V[2]	4,094 ± 15	4,094 ± 12	–0.03 ± 9.4	50 ± 5.5	62	0.84	1.5
Nutrient composition	C1[3]	4,105 ± 11	4,104 ± 10	0.08 ± 5.3	39 ± 3.2	48	0.87	1.2

[1]DIF = difference between predicted and actual observations; ABS = absolute difference between predicted and actual observations; RMSEP = root mean square error of prediction; PE = prediction error.

[2]Models refer to models in Table 7.

[3]See Table 5 for variables in equation C1.

mit the relative need for, and benefit from, added fat sources to be determined with greater confidence.

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