Animal Feed Science and Technology, 39 (1992) 95–110
Elsevier Science Publishers B.V., Amsterdam

A theoretically-based model for predicting total digestible nutrient values of forages and concentrates

W.P. Weiss[a], H.R. Conrad[a] and N.R. St. Pierre[b]
[a]*Department of Dairy Science, Ohio Agricultural Research and Development Center, Ohio State University, Wooster, OH 44691, USA*
[b]*Papillon Agricultural Products, Easton, MD 21601, USA*
(Received 23 May 1990, accepted 18 March 1992)

ABSTRACT

Weiss, W.P., Conrad, H.R. and St. Pierre, N.R., 1992. A theoretically-based model for predicting total digestible nutrient values of forages and concentrates. *Anim. Feed Sci. Technol.*, 39: 95–110.

A model using concentrations of neutral detergent fiber (NDF), lignin, crude protein (CP), ash, fatty acids or ether extract, and acid and neutral detergent insoluble crude protein, was developed for predicting total digestible nutrients (TDN) of feeds. The model incorporates theoretical digestion coefficients for CP, lipid, and non-fiber carbohydrate. Digestibility of NDF was estimated using a surface area model based on the lignin encrustation theory. The digestible amount of each nutrient was summed and then a term describing metabolic fecal TDN was subtracted. The model was tested on an independent set of 248 feeds (including forages and concentrates). The mean square error for all feeds was 61 g TDN kg^{-1} dry matter which is comparable with the error term for in vivo digestion data. The model was equally accurate and precise for forages and concentrate feeds.

INTRODUCTION

Feed energy, unlike many other nutrients, cannot be determined using standard analytical techniques. Therefore, most commercial laboratories provide users with estimated energy values. Estimating available energy with equations is probably the most common method used by commercial laboratories. Most equations are based on the negative relationship between fiber concentration and available energy, and have been derived by regression methods (Fonnesbeck et al., 1984; Minson, 1982). Regression equations have several limitations. First, the prediction error can be high (Abrams, 1988). Secondly the equation is population specific. The equations should not be used on samples outside the population that was used to derive the equation. Thirdly,

Correspondence to: W.P. Weiss, Department of Dairy Science, 1680 Madison Ave, Wooster, OH 44691, USA.

most equations have been derived using forage data; few equations are available for estimating energy values of concentrates.

A model based on the principles outlined by Goering and Van Soest (1970) and Osbourn (1978) was derived by Conrad et al. (1984). The Conrad et al. model uses the concentrations of neutral detergent fiber (NDF), lignin, ash, fat, and crude protein (CP) to estimate available energy (TDN or net energy-lactation (NE_l)). The equation had a high r^2 and low prediction error for the test population which included forages, grains, and some byproduct feeds.

Girard and Dupuis (1988) pointed out that the model of Conrad et al. (1984)had a theoretical flaw. The 1984 model was based on true digestion coefficients, but TDN is based on apparent digestion coefficients. Apparent digestibility is equal to true digestibility corrected for metabolic fecal losses. Girard and Dupuis (1988) modified the Conrad et al. equation to include a metabolic fraction (-142 g kg^{-1}).

The objective of this research was to improve and expand the prediction equation developed by Conrad et al. (1984) so that it would be theoretically sound and accurate for most feeds.

MATERIALS AND METHODS

Model derivation

The model is based on a summative approach for calculating the TDN value of feeds. Total digestible nutrients was chosen as the term for available energy because a large data base is available for TDN, and TDN can be transformed into other expressions of feed energy using standard equations (National Research Council (NRC), 1982). To use our equations, feeds are fractionated into potentially available NDF, ether extract (EE), CP, and non-fiber carbohydrate. These fractions are multiplied by their true digestibilities and then summed. An estimate of metabolic fecal TDN is subtracted from the total leaving an estimate of TDN. Theoretical values were used when available, otherwise empirical coefficients were derived from available data. These empirical values should be replaced by theoretical values when adequate data become available.

Energy from crude protein

The true digestibility of any uniform feed fraction can be determined using the Lucas test (Van Soest, 1982), i.e. regressing concentration of the nutrient on concentration of the digestible nutrient. Using the Lucas test, the true digestibility of CP from most forages is approximately 0.9 (Holter and Reid, 1959), and 1.0 for diets of predominantly concentrates (Arroyo-Aguilu and Evans, 1972; Fonnesbeck et al., 1984). True digestibility of CP in feeds can be reduced by heat treatment. The concentration of acid detergent insoluble CP (ADICP) when expressed as a proportion of total CP is correlated highly with digestibility of forage protein (Thomas et al., 1982) and can be used to estimate the true digestibility of forage CP (Eqn. (1); Weiss et al., 1983). Concentration of ADICP in concentrate feeds, however, is not as strongly correlated with protein digestibility as in forages (Cleale et al., 1987). Nakamura et al. (1989) and Van Soest (1989) reported that true or adjusted protein digestibility decreased about 0.004 units for every unit increase in ADICP as described in eqn. (2)

$$k_{dCP\text{-}F} = \exp(-0.0012\,\mathrm{ADICP}) \tag{1}$$

$$k_{dCP\text{-}C} = 1 - 0.0004^{*}\mathrm{ADICP} \tag{2}$$

where; $k_{dCP\text{-}F}$ is true digestibility of forage CP, $k_{dCP\text{-}C}$ is true digestibility of concentrate CP, and ADICP is expressed as g kg^{-1} total CP. The TDN from the CP fraction (E_{CP}) is determined using equation (3)

$$E_{CP} = k_{dCP} \times \mathrm{CP} \tag{3}$$

Energy for nutrient fractions are expressed on a TDN equivalent basis, i.e. carbohydrate and protein energy = 4 Mcal kg^{-1} and fat = 9 Mcal kg^{-1}. Atwater gave digestible protein a value of 5.2 Mcal kg^{-1}; which is theoretically correct (Maynard et al., 1979). However, most published TDN values give protein a value of 4.

For commercial applications, estimating ADICP at about 85 g kg^{-1} CP to obtain a $k_{dCP\text{-}F}$ of 0.9 probably would be adequate for unheated forages. Forage that are heat damaged should be analyzed for ADICP and the data applied to eqn. (1). Most concentrates are not heat damaged, and do not have to be analyzed for ADICP. Since the true digestibility of CP in concentrates is approximately 1.0, a value of 0 for ADICP can be used in eqn. (2) for unheated concentrates. In concentrates that have undergone heating, e.g. dried distillers grains, analyze for ADICP and use eqn. (2).

Energy from NDF

The NDF term in the Conrad et al. (1984) model has been modified to account for neutral detergent insoluble CP (NDICP). Most, if not all feedstuffs, contain some NDICP, but the proportion of NDF that is NDICP varies among feedstuffs. For many forages that have not undergone heating, NDICP comprises less than 100 g kg^{-1} NDF (Mertens, 1973; Weiss et al., 1986). For many concentrates, however, NDICP can account for a substantial proportion of total NDF. The proportion of NDF that is NDICP was approximately 200 g kg^{-1} NDF for dried brewers grains and 400 g kg^{-1} NDF for dried distillers grains (Krishnamoorthy et al., 1982).

The presence of NDICP creates two problems for the original equations of

Conrad et al. (1984). The energy from non-fiber carbohydrate fraction (discussed below) is calculated by difference. Because total CP and NDF are subtracted from unity, NDICP is subtracted twice. The other problem with NDICP is that the lignin/NDF surface area model derived by Conrad et al. (1984) is based on the premise that NDF is comprised of carbohydrates (cellulose and hemicellulose) and lignin. There is no evidence that lignin interferes directly with CP digestion; therefore, the surface area model should include only carbohydrate and lignin. Furthermore, the true digestibility of NDICP is considerably higher than most reported digestion coefficients for NDF (Arroyo-Aguilu and Evans, 1972; Colburn et al., 1968).

Some, but not all, NDICP is associated with the lignin fraction and should not be considered a contaminant of NDF (Van Soest, 1965; Mertens, 1973). Measurement of lignin CP is laborious and error-prone because of the small amounts of material being analyzed. For practical applications, a relatively simple assay is needed to estimate lignin CP. Mertens (1973) suggested that ADICP can be used as an estimate of lignin associated CP for forages. However, ADICP in forages is partially digestible (averages 0.34 SE=0.11; Yu, 1974), but lignin is assumed to be indigestible. The partial digestibility of ADICP for concentrate feeds averages 0.66 (SE=0.04; Van Soest, 1989). Based on eqns. (1) and (2), ADICP has a digestibility of 0.3 and 0.6 for forages and concentrates. These values are similar to empirical data. Indigestible ADICP (IADICP) was chosen to estimate lignin-bound CP, and is estimated using eqns. (4) and (5)

$$\text{Forages: IADICP} = 0.7 \times \text{ADICP} \tag{4}$$

$$\text{Concentrates: IADICP} = 0.4 \times \text{ADICP} \tag{5}$$

where IADICP and ADICP are expressed as g kg^{-1} DM. Nitrogen-adjusted NDF (NDF_N) for forages is calculated as

$$NDF_N = NDF - NDICP + IADICP \tag{6}$$

where NDF, NDICP, and IADICP are expressed as g kg^{-1} DM.

For accurate prediction of energy from NDF, NDF_N should be used. This suggests that feeds should be analyzed for NDICP which will increase the cost and time of analyzing feed samples. For unheated forages, NDICP can be predicted from CP and NDF concentrations. An empirical eqn. (7) was derived by regressing NDICP on concentration of CP and NDF from a variety of legumes and grasses (Colburn et al., 1968; Mertens, 1973; Weiss et al., 1986).

$$NDICP = -87.7 + 0.33 \times CP + 0.143 \times NDF \; (R^2 = 0.77; s_{yx} = 8.0) \tag{7}$$

where NDICP, CP, and NDF are expressed as g kg^{-1} DM. Concentrates that have relatively high concentrations of NDF and CP should be analyzed for

NDICP. This includes distillers and brewers grains, and corn gluten feed. The term to estimate TDN from NDF (E_{NDF}) is

$$E_{NDF} = 0.75\ (NDF_N - LIG) \times [1 - (LIG/NDF_N)^{0.667}] \tag{8}$$

where LIG = acid detergent-sulfuric acid lignin and NDF_N and LIG are expressed as g kg^{-1} DM. The digestion coefficient ($k_{dNDF}=0.75$), is empirical and was derived from the data base used to develop the model. This is considerably less than the 0.96 derived by Girard and Dupuis (1988). There are two reasons for this difference. First, we have removed NDICP from NDF. The digestibility of NDICP is greater than that for NDF; therefore, the digestibility of NDF_N would be less than that for NDF. Secondly, k_{dNDF} corrects for passage of undigested potentially digestible cell wall. Some potentially digestible cell wall flows out of the gastro-intestinal tract before it can be digested. Other experimental data support the value of $k_{dNDF}=0.75$. Particulate turnover rates (k_p) at maintenance levels of feeding range between 0.02 and 0.04 h^{-1} (Colucci et al., 1982). The average in situ digestion rate (k_d) of NDF from a diverse population of feeds forages and concentrates) was 0.08 h^{-1} (Varga and Hoover, 1983) and for forages it was 0.076 h^{-1}. Waldo and Smith (1972) developed a model that incorporates digestion and passage to estimate digestibility (D)

$$D = k_d/(k_d + k_p) \tag{9}$$

Using average in situ k_d and an average k_p of 0.02, the average digestibility of potentially digestible NDF would equal about 0.8. Since the test data base was predominantly forage a value near 0.76 would be expected. The best solution, once accurate digestion rates for NDF_N are available is to replace a constant $k_{d\,NDF}$ with equation (9) which would account for variable rates of digestion and passage. This is discussed in more detail below.

Energy from ether extract

The ether extract (EE) fraction of feeds consists of a heterogeneous mixture of different lipids including compounds that are highly digestible (fatty acids) and compounds that contain almost no digestible energy (pigment and waxes). Composition of the ether extract fraction varies among feeds. The EE fraction of forages has a high concentration of non-nutritive compounds, whereas, EE of concentrate feeds tend to consist of a large proportion of fatty acids. The variability in digestibility within EE and the diverse composition of the fraction precludes the use of a single digestibility constant for EE in a broad spectrum equation.

Fatty acids (FA) provide the majority of digestible energy from the EE fraction. True digestibility of FA is dependent upon their concentration in the diet (Palmquist, 1991). In diets with 10 g FA kg^{-1} DM, true digestibility of

FA was 1.0, but decreased to 0.78 in diets with 80 g FA kg^{-1} DM (Palmquist, 1991). Typical diets contain approximately 30 g kg^{-1} DM of FA; therefore, true digestibility of FA fraction would be around 0.94. Fatty acids can be measured using a relatively simple and inexpensive method (Sukhija and Palmquist, 1988). When actual fatty acid data are available, TDN from the EE fraction (E_{EE}) can be calculated using eqn. (10)

$$E_{EE} = FA \times 2.25 \qquad (10)$$

The 2.25 is based on Atwater's constants for equating lipid to carbohydrate (Maynard et al., 1979). Concentration of fatty acids also can be estimated from EE. Based on limited data (analyses conducted by D. Palmquist, personal communication), non-fatty acid EE is equal to about 10 g kg^{-1} DM. Hence, E_{EE} can be determined using eqn. (11)

$$E_{EE} = 2.25 \times (EE - 10) \qquad (11)$$

Forages and many concentrates have low concentration of EE, and the added cost of EE or FA analysis probably is not justifiable. For feeds with high and variable amounts of lipid, e.g. oil seeds and many byproduct feedstuffs, the improved accuracy may justify the added analytical expense.

Energy from non-fiber carbohydrates (NFC)

Digestibility of plant material that is soluble in neutral detergent (cell solubles) is high and constant among feeds. Estimates of the true digestibility of cell solubles range from 0.85 to 1.2 (values obtained using the Lucas test) with an average of 0.98 for cattle and sheep fed at maintenance (Van Soest, 1982). The concentration of NFC is calculated by difference and its TDN (E_{NFC}) is determined using eqn. (12) when E_{EE} is determined using eqn. (10) and by eqn. (13) when E_{EE} is determined using equation (11)

$$E_{CS} = 0.98\ (1000 - NDF_N - CP - Ash - FA - 10 + IADICP) \qquad (12)$$

$$E_{CS} = 0.98\ (1000 - NDF_N - CP - Ash - EE + IADICP) \qquad (13)$$

where all vaiues are expressed a g kg^{-1} DM. The term, -10 is an estimate of indigestible EE.

Metabolic fecal energy

All the equations for estimating energy from feed components are based on true digestibility, but TDN is based on apparent digestibility. The model must include a term for metabolic fecal TDN. Girard and Dupuis (1988) used 142 g kg^{-1} DM intake as an estimate of metabolic fecal dry matter. The equations they developed were used to estimate digestible dry matter. The equations derived in this paper are to be used to estimate TDN. Van Soest (1982) summarized many experiments, and metabolic dry matter excreted by cattle and sheep averaged 130 g kg^{-1} DM intake. Composition of fecal cell solubles from sheep fed different forages averaged about 300 g ash, 300 g CP, 250 g water soluble, nitrogen-free material, and about 150 g EE kg^{-1} fecal cell soluble dry matter (Jarrige, 1965). Data on digestibility of fecal N is limited. Anthony (1970) reported that the apparent digestibility of N from cattle manure was about 0.5. This corresponds to a true digestibility of 0.7. The energy from CP in fecal cell solubles is 27 ($130\times0.3\times0.7$). Fecal EE is comprised of FA (usually quite low) and indigestible compounds such as waxes and pigments; the relative amounts will depend upon the diet. Based on average composition of the EE fraction of alfalfa (Palmquist and Jenkins, 1980) and digestibility data of FA (Palmquist, 1991), composition of fecal EE from forage fed animals would be about 830 g indigestible lipid, 110 g endogenous FA, and 60 g undigested FA kg^{-1} fecal EE. For a corn based diet, fecal EE would be comprised of 510 g indigestible lipid, 360 g endogenous FA, and 130 g undigested FA kg^{-1} fecal EE. Averaging the forage and corn data, fecal EE contains about 670 g indigestible lipid and 330 g FA kg^{-1}. Based on output of 130 g metabolic cell solubles, fecal E_{EE} would equal 14 ($130\times0.15\times0.32\times2.25$). The water soluble, N free material in feces would have 31 units of energy based on a digestibility of 0.98 ($130\times0.25\times0.98=31$). The estimated TDN value for metabolic fecal cell solubles (MF_{TDN}) is 72 g kg^{-1} (14+31+27) which was rounded to 70.

Metabolic TDN is probably not constant; variations due to fiber content of the diet (Arroyo-Aguilu and Evans, 1972) and dry matter intake of the animal (Colburn et al., 1968) are likely. Additional data are needed to improve the estimate of MF_{TDN}.

The TDN of a feed can be estimated by summing the energy provided by each feed fraction and subtracting MF_{TDN}. Equation (14) is used to calculate TDN of feeds when EE values are known; equation (15) is used to calculate TDN of feeds when FA values are available

$$
\begin{aligned}
TDN_m = {} & 0.98\,(1000-NDF_N-CP-ASH+IADICP-EE) \\
& +k_{dCP}CP+2.25(EE-10) \qquad (14) \\
& +0.75(NDF_N-LIG)\,[1-(LIG/NDF_N)^{0.667}]-70
\end{aligned}
$$

$$
\begin{aligned}
TDN_m = {} & 0.98\,(1000-NDF_N-CP-ASH+IADICP-FA-10) \\
& +k_{dCP}CP+2.25FA \qquad (15) \\
& +0.75(NDF_N-LIG)\,[1-(LIG/NDF_N)^{0.667}]-70
\end{aligned}
$$

Data base

The data from Table 2 in Conrad et al. (1984) were used to derive the model. To test the model, data from NRC feed composition tables and from experiments published in major journals concerned with animal agriculture were compiled. Data from experiments that had adequate feed composition data [NDF, lignin (measured using sulfuric acid), CP, and ash] and in vivo digestibility (maintenance feeding-cattle and sheep) were used. In most experiments, EE was not measured; therefore, table values (NRC, 1982) were used. Very few data on NDICP content of feeds were available; therefore, NDICP was estimated for most of the forages using equation (7). The NDICP values used for byproduct feeds, grains, and protein feeds came from published reports (Krishnamoorthy et al., 1982) or from analyses conducted in our laboratory. Amount of ADICP in forages was estimated at 85 g kg^{-1} CP except for heated forages (Yu, 1974) in which case the actual ADICP values were used. Actual ADICP content of concentrates was used when available, otherwise data from published reports or our laboratory were used. In most experiments, TDN content of feeds was not determined, but digestible energy or digestible dry matter was reported. Digestible energy and digestible dry matter were converted to TDN using standard equations (Crampton et al., 1957; Lofgreen, 1953).

Statistical analysis

Analysis of variance, regression analysis and correlation analysis were used to test the precision and accuracy of the model. Feeds in the test database were divided into four categories: forages and roughages, high fiber concentrates, high starch concentrates, and high protein concentrates. Actual TDN values were regressed on estimated TDN values using the entire data base and within each feed category. An unbiased prediction would yield a *y*-intercept=0 and slope=1. Accuracy and bias of eqns. (14) and (15) were tested using the general linear model of Statistical Analysis System (SAS) (SAS, 1988). Main effects were method of determining TDN (actual or predicted), feed category, and the category by method interaction. A significant *F* test for method or method by category interaction would indicate that the prediction equation was not accurate for particular feed categories. Correlations between the deviations (predicted–actual) and various nutrient fractions were determined.

RESULTS AND DISCUSSION

Data from several studies were summarized by NRC (1985) and estimates of true digestibility of CP ranged from 0.84 to 0.95. Values produced from eqns. (1) and (2) fit well within this range. The effect ADICP has on true digestibility also has been well documented (Thomas et al., 1982; Weiss et al., 1983). Therefore, TDN from this fraction should be accurate. The energy from the NFC fraction also should be accurate. Several researchers have reported true digestibility coefficients for this fraction and it averages about 0.98 (Van Soest, 1982).

To confirm the E_{EE} values obtained from eqn. (11), those values were regressed on apparent digestible EE values published by Schneider (1947). The data base was a random sample of feeds including both concentrates and forages ($N=25$). The slope of the regression line was 0.99 with an intercept of -7.0 ($r^2=0.98$). Since the slope was not statistically different from 1, the two methods produced essentially equal results. The intercept (-7.0) is an estimate of metabolic fecal EE energy. This compares reasonably well with the estimated fecal EE energy discussed above.

The coefficient for digestibility of potentially available cell wall (0.75) is empirical. Girard and Dupuis (1988) reported an excellent relationship between NDF digestibility data from long term (>72 h) in vitro data to values calculated from the surface area model. For long term incubations, the digestibility coefficient for potentially digestible cell wall should be approximately 1.0. We used in vivo digestion data from cattle and sheep fed at near maintenance level. Additional proof of the accuracy of predicting energy from the cell wall fraction is the overall accuracy of eqns. (14) and (15).

The TDN values predicted using equations (14) or (15) agreed well with actual TDN for all feeds and within feedstuff categories (Figs. 1(a–e)). Regression statistics for the prediction model within feed categories and for all feeds are in Table 1. All slopes were statistically not different from 1 and all intercepts were statistically not different from 0. This indicates that the prediction model was not biased. Deviations were not correlated to any feed nutrient ($P<0.10$) for the entire population or within feed categories with one exception. Within forages, the deviation was negatively correlated with ash content ($r^2=0.03$, $P<0.03$). Analysis of variance revealed no difference ($P<0.50$) in method of determining TDN (actual or predicted) and the interaction between method and feed category was not significant ($P<0.35$). Mean square error (MSE) for all feeds was 61 g kg^{-1} DM. A collaborative study to determine the variation in measuring in vivo TDN (five laboratories) of a single source of alfalfa reported a MSE of 31 g kg^{-1} DM (Donnefer, 1966). Schneider and Lucas (1950) reported that between experiment MSE was about 50 g TDN kg^{-1} for feeds when fed alone and about 110 g TDN kg^{-1} when determined by the difference method. Therefore, the minimum error expected owing to variation in our test population would be about 30–50 g kg^{-1} DM. Distribution of deviations for all feedstuffs was: 109/248 (0.440) with deviations ± 30; 166/248 (0.669) with deviations ± 50; 30/248 (0.121) had deviations $\geqslant 90$. The lack of bias as revealed by regression

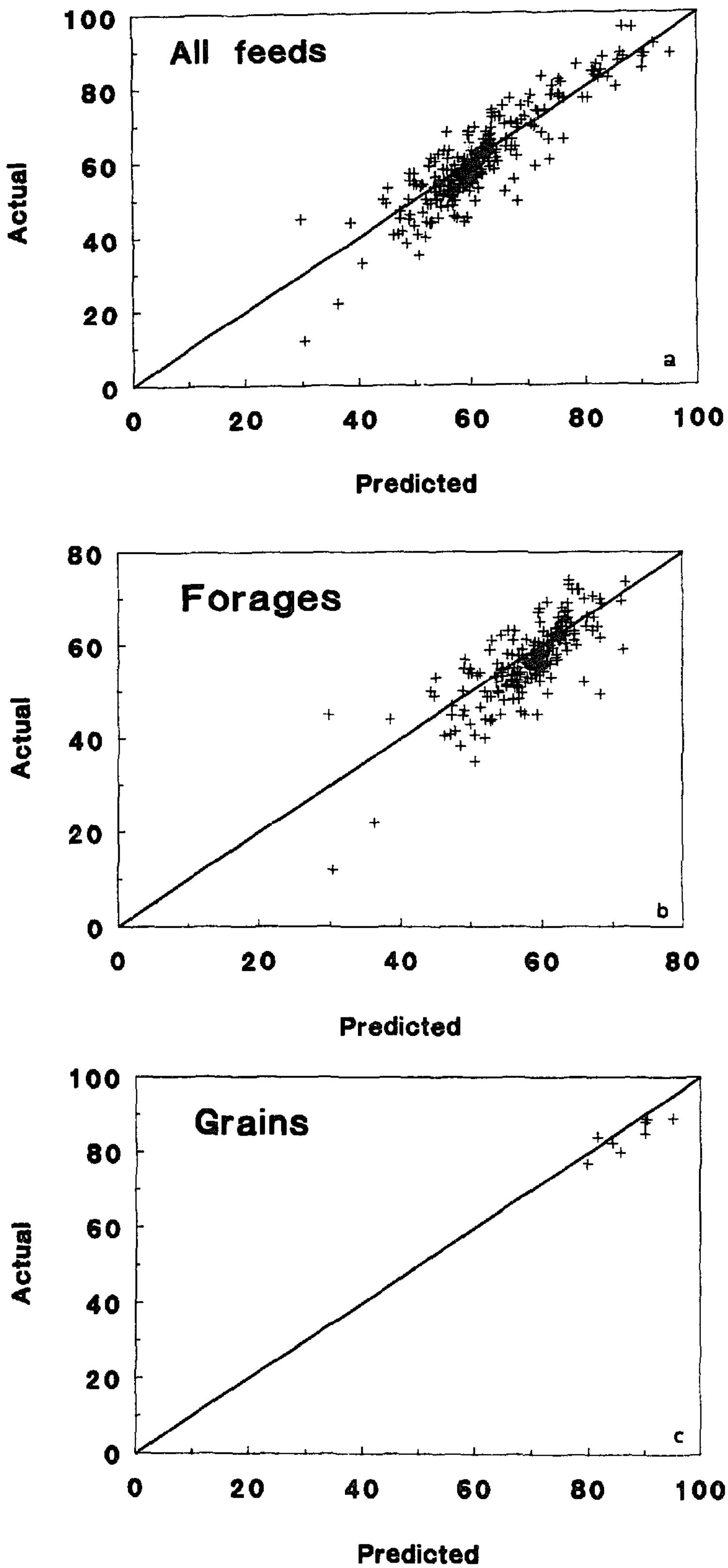
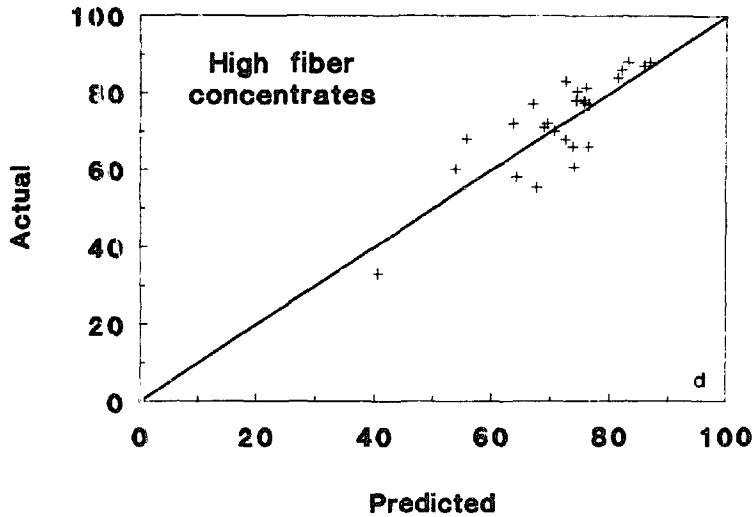


Fig. 1. Relationship between TDN predicted using eqns. (14) or (15) and actual TDN for different feed categories. The solid line represents the perfect relationship ($Y=1X+0$).



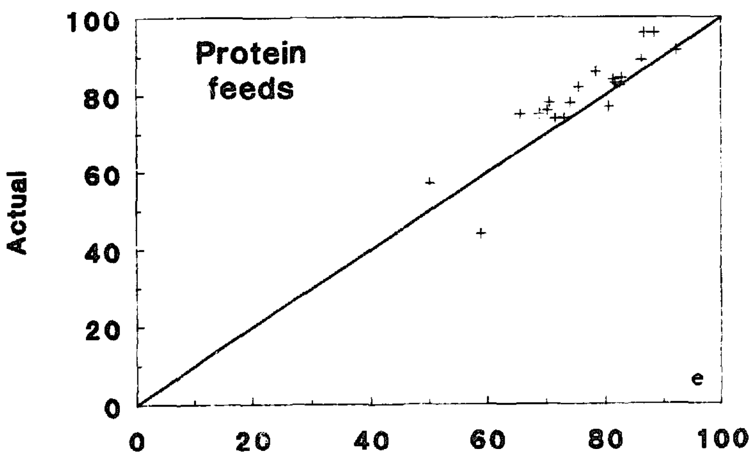


TABLE 1

Regression statistics and residual error for predicting TDN using eqns. (14) or (15)[1] in g kg^{-1} DM

Feed Group	N	Intercept		Slope		r^2	MSE[2]
		b_0	SE	b_1	SE		
All feeds	247	−39	23	1.05	0.04	0.78	61
Forages/roughages	191	−28	42	1.03	0.07	0.54	58
Fiber concentrations	26	43	84	0.96	0.11	0.73	65
Grains	7	71	187	0.88	0.21	0.74	23
Protein feeds	20	48	135	0.97	0.17	0.62	76

[1]Statistics based on the following regression model: actual TDN$=b_0+b_1$ predicted TDN.
[2]MSE, mean square error.

analysis, the lack of a significant difference owing to the method of determining TDN, and the lack of substantial correlations between deviations and feed components illustrate that eqns. (14) and (15) can be used to give accurate, precise and unbiased estimates of TDN for a diverse population of feeds.

In general, eqns. (14) and (15) produced accurate estimates of TDN; however, certain feeds produced large deviations. In many cases, composite data are questionable; in other instances, deficiencies in the model are evident. Most of the large deviations occurred with the NRC data. These data are averages from different experiments. Several contradictions occur within the NRC table when TDN values and feed composition are compared among similar feeds. In general, TDN values for protein feeds were underestimated when using eqns. (14) or (15). Based on comparison data; however, it appears the energy value of protein feeds given by NRC are overstated relative to soybean meal. For instance, cottonseed meal has twice as much NDF and four times as much lignin as does soybean meal yet its TDN value is only 40 g kg^{-1} less than that of soybean meal. Predicted TDN values for cottonseed meals were about 100 g kg^{-1} less than predicted TDN value for soybean meal. Coppock et al. (1987), in a review of cottonseed products, suggested that the TDN value for cottonseed given by NRC appeared high relative to soybean meal. This could be owing, in part, to the use of older data because cottonseed meal previously had relatively large amounts of EE (Schneider, 1947). A large deviation also occurred for sunflower meal, but the NRC TDN value appears extremely low relative to its composition.

Other relatively large deviations occurred for whole cottonseed and whole soybeans. The predicted TDN value was about 100 g kg^{-1} less than NRC for cottonseeds with lint but about 100 g kg^{-1} more for soybeans. Cottonseeds have about 100 g kg^{-1} more lignin, about 200 g kg^{-1} more NDF, about the same amount of oil, and half as much CP as does whole soybeans. Lignin is considered to be indigestible; therefore, if all else were equal cottonseed should have at least 100 g kg^{-1} less TDN than soybeans. Smith et al. (1981) reported that whole cottonseed with lint had a TDN of about 960 g kg^{-1}. Cottonseed in that experiment had 10 g less lignin and about 10 g kg^{-1} less ash per kg than the values presented in NRC. Smith et al. (1981) did not report NDF values, but when NDF was estimated at 390 g kg^{-1} and other values from Smith et al. were used, a TDN value of 880 g kg^{-1} was obtained using eqn. (14).

Deviations were large for many byproduct feeds when NRC data were used; however, when actual experimental data were used the deviations were much less. For example, using NRC composition of cottonseed hulls produced a large deviation (160 g kg^{-1}) but when actual composition data were used the deviation was 40 g kg^{-1}. Similar results were found for corn gluten feed, soyhulls, sunflower silage, and bahiagrass. Owing to the extreme variation in composition data of byproduct feeds (Belyea et al., 1989), differences between actual data and table values should be expected.

Other deviations point out deficiencies in the model. The largest overestimations occurred with hulls (rice, oat, barley, peanut and almond). Part of the problem, especially for rice and oat hulls could be due to the high silica content of these feedstuffs (Van Soest and Jones, 1968). Another potential error with low energy feeds is that actual TDN were determined by the difference method which can greatly increase error (Schneider and Lucas, 1950).

Necessary improvements

Equations (14) and (15) can be used to estimate TDN for most feeds accurately and precisely. The model still must be improved when more data become available. A factor not incorporated into those equations is the effect of particle size and feed processing on TDN. Pelleted dehydrated alfalfa is consistently underestimated by eqns. (14) and (15). Ground corn, flaked corn and whole corn have the same TDN value according to eqns. (14) and (15), but flaking and grinding increase the energy value of the grain.

The two largest deficiencies in the model are the lack of adjustments for variable feed intake and associative effects. Digestibility decreases as animals consume more feed (Tyrrell and Moe, 1975). Equations (14) and (15) are appropriate only when animals are fed at maintenance. The NRC adjusts for reduced digestibility at higher levels of intake when TDN is converted to NE_l using eqn. (16)

$$NE_l \ (\mathrm{Mcal\ kg^{-1}}) = 0.00245 \times \mathrm{TDN} - 0.12 \tag{16}$$

where TDN is expressed as g kg^{-1}. That equation will work on TDN values predicted using eqns. (14) or (15). This approach, however, does not allow for variable depressions in digestibility among feedstuffs. Digestion of fiber generally is slower than digestion of cell solubles; therefore, as passage rate increases fiber should be affected more than cell solubles. Girard and Dupuis (1988) discounted fiber digestion by 0.17 but cell soluble digestion by only 0.07 when intake increased from maintenance to four times maintenance. We have been unable to develop a universal equation that predicts discount factors for all feedstuffs. As accurate rates of digestion and passage are generated the depression in digestibility can be calculated based on eqn. (10).

The other major deficiency in eqns. (14) and (15) is that associative effects are not considered. This could be one reason predicted TDN values deviate from actual values. For instance, if cottonseed replaced grain in a high grain diet, fiber digestion might be improved and this would be measured as TDN of cottonseed. As data become available, mathematical functions can be derived and added to eqns. (14) and (15) to account for associative effects.

CONCLUSIONS

A model using NDF, lignin (sulfuric acid method), ash, EE or FA, CP, NDICP and ADICP has been developed that can be used to accurately estimate TDN content of a diverse population of feeds. For commercial application, NDF, lignin, CP, and ash should be determined, but estimated values for EE, NDICP and ADICP can be used to determine an energy value of unheated forages. For heated forages, byproducts feeds, and most concentrates a complete analysis is needed for high accuracy. This model will provide a means to make accurate comparisons of the energy content of feeds and aid in accurate diet formulation.

ACKNOWLEDGMENTS

This research was sponsored in part by grants from the Ohio Dairy Farmers Federation Research Check-off Fund, Columbus, and Agway, Syracuse, NY, and by state and federal funds appropriated to the Ohio Agricultural Research and Development Center. The Ohio State University. Manuscript number 136-90.

REFERENCES

Abrams, S.M., 1988. Sources of error in predicting digestible dry matter from the acid-detergent fiber content of forages. Anim. Feed Sci. Technol., 21: 205–208.
Anthony, W.B., 1970. Feeding value of cattle manure for cattle. J. Anim. Sci., 30: 274–277.
Arroyo-Aguilu, J.A. and Evans, J.L., 1972. Nutrient digestibility of lower-fiber rations in the ruminant animal. J. Dairy Sci., 55: 1266–1274.
Belyea, R.L., Stevens, B.J., Restrepo, R.J. and Clubb, A.P., 1989. Variation in composition of byproduct feeds. J. Dairy Sci., 72: 2339–2345.
Cleale IV, R.M., Klopfenstein, T.J., Britton, R.A., Satterlee, L.D. and Lowry, R.S., 1987. Induced non-enzymatic browning of soybean meal. III. Digestibility and efficiency of protein utilization by ruminants of soybean meal treated with xylose or glucose. J. Anim. Sci., 65: 1327–1335.
Colburn, M.W., Evans, J.L. and Ramage, C.H., 1968. Apparent and true digestibility of forage nutrients by ruminant animals. J. Dairy Sci., 51: 1450–1457.
Colucci, P.E., Chase, L.E. and van Soest, P.J., 1982. Feed intake, apparent diet digestibility, and rate of particulate passage in dairy cattle. J. Dairy Sci., 65: 1445–1456.
Conrad, H.R., Weiss, W.P., Odwongo, W.O. and Shockey, W.L., 1984. Estimating net energy lactation from components of cell solubles and cell walls. J. Dairy Sci., 67: 427–436.
Coppock, C.E., Lanham, J.K. and Horner, J.I., 1987. A review of the nutritive value and utilization of whole cottonseed, cottonseed meal, and associated by-products by dairy cattle. Anim. Feed Sci. Technol., 18: 89–129.
Crampton, E.W., Lloyd, L.E. and MacKay, V.G., 1957. The calorie value of TDN. J. Anim. Sci., 16: 541–552.
Donnefer, E., 1966. Collaborative in vivo studies on alfalfa hay. J. Anim. Sci., 25: 1227–1231.

Fonnesbeck, P.V., Wardeh, M.F. and Harris, L.E., 1984. Mathematical models for estimating energy and protein utilization of feedstuffs. Utah Agric. Exp. Station, Bulletin 508.
Girard, V. and Dupuis, G., 1988. Effect of structural and chemical factors of forages on potentially digestible fiber, intake, and true digestibility by ruminants. Canadian J. Anim. Sci., 68: 787–799.
Goering, H.K. and van Soest, P.J., 1970. Forage Fiber Analysis. Agriculture Handbook 379, US dept. Agriculture, Washington DC, 20 pp.
Holter, J.B. and Reid, J.T., 1959. Relationship between the concentration of crude protein and apparently digestible protein in forages. J. Anim. Sci., 18: 1339–1349.
Jarrige, R., 1965. The composition of sheep faeces and its relation to forage digestibility. In: Proc. Int. Grassland Congress, Edicoes, Alarico, Sao Paulo, pp. 809–814.
Krishnamoorthy, U., Muscato, T.V., Sniffen, C.J. and van Soest, P.J., 1982. Nitrogen fractions in selected feedstuffs. J. Dairy Sci., 65: 217–225.
Lofgreen, G.P., 1953. The estimation of total digestible nutrients from digestible organic matter. J. Anim. Sci., 12: 359–365.
Maynard, L.A., Loosli, J.K., Hintz, H.F. and Warner, P.G., 1979. Animal Nutrition. McGraw-Hill, New York, 602 pp.
Mertens, D.R., 1973. Application of theoretical mathematical models to cell wall digestion and forage intake in ruminants. Ph.D. Dissertation, Cornell University, Ithaca, NY, 217 pp.
Minson, D.J., 1982. Effect of chemical composition on feed digestibility and metabolizable energy. Nutrition Abstracts and Reviews-Series B52 (10): 592–615.
Nakamura, T., Klopfenstein, T.J. and Britton, R.A., 1989. Digestibility of heated and unheated protein sources. Am. Soc. Anim. Sci. Midwest (Abstr.) p. 153.
National Research Council, 1982. United States-Canadian Tables of Feed Composition. National Academic, Washington, DC, 148 pp.
National Research Council, 1985. Ruminant nitrogen usage. National Academic, Washington, DC, 138 pp.
Osbourn, D.F., 1978. Principles governing the use of chemical methods for assessing the nutritive value of forages: A review. Anim. Feed Sci. Technol., 3: 265–275.
Palmquist, D.L., 1991. Influence of source and amount of dietary fat on digestibility in lactating cows. J. Dairy Sci., 74: 1354–1360.
Palmquist, D.L. and Jenkins, T.C., 1980. Fat in lactation: Review. J. Dairy Sci., 63: 1.
Statistical Analysis System, 1988. SAS/STAT User's Guide, Release 6.03, SAS Institute, Cary, NC, 1028 pp.
Schneider, B.H., 1947. Feeds of the World. Their Digestibility and Composition. West Virginia University, Morgantown, WV, 299 pp.
Schneider, B.H. and Lucas, H.L., 1950. The magnitude of certain sources of variability in digestibility data. J. Anim. Sci., 9: 504–512.
Smith, N.E., Collar, L.S., Bath, D.L., Dunkley, W.L. and Franke, A.A., 1981. Digestibility and effects of whole cottonseed fed to lactating cows. J. Dairy Sci., 64: 2209.
Sukhija, P.S. and Palmquist, D.L., 1988. Rapid method for determination of total fatty acid content and composition of feedstuffs and feces. J. Agric. Food Chem., 36: 1202–1206.
Thomas, J.W., Yu, Y., Middleton, T. and Stallings, C., 1982. Estimations of protein damage. In: F.N. Owens (Editor), Protein Requirements for Cattle: Symposium. Oklahoma State University, Stillwater, OK, pp. 81–98.
Tyrrell, H.F. and Moe, P.W., 1981. Effect of intake on digestive efficiency. J. Dairy Sci., 58: 1151–1163.
Van Soest, P.J., 1965. Use of detergents in analysis of fibrous feeds. III. Study of effects of heating and drying on yield of fiber and lignin in forages. J. AOAC, 48: 785–790.
Van Soest, P.J., 1982. Nutritional Ecology of the Ruminant. O & B Books, Corvallis, OR, 374 pp.

Van Soest, P.J., 1989. On the digestibility of bound N in distillers grains: a reanalysis. Cornell Nutr. Conf., 24–26 October 1989, Syracuse, NY. Cornell University, Ithaca, NY, pp. 127–135.
Van Soest, P.J. and Jones, L.H., 1968. Effect of silica in forages upon digestibility. J. Dairy Sci., 51: 1644–1648.
Varga, G.A. and Hoover, W.H., 1983. Rate and extent of neutral detergent fiber degradation of feedstuffs in situ. J. Dairy Sci., 66: 2109–2115.
Waldo, D.R. and Smith, L.W., 1972. Model of cellulose disappearance from the rumen. J. Dairy Sci., 55: 125–129.
Weiss, W.P., Conrad, H.R. and Shockey, W.L., 1983. Predicting digestible protein using acid detergent insoluble nitrogen. J. Dairy Sci., 66 (suppl. 1): 192 (abstract).
Weiss, W.P., Conrad, H.R. and Shockey, W.L., 1986. Digestibility of nitrogen in heat-damaged alfalfa. J. Dairy Sci., 69: 2658–2670.
Yu, Y., 1974. Comparisons of chemical, in vitro and in vivo methods for estimating nutritive values of normal and chemically treated haylages. Ph.D. Dissertation, Michigan State Univ., East Lansing, MI, 270 pp.