SYMPOSIUM: ENERGY AVAILABILITY

Estimating the Available Energy Content of Feeds for Dairy Cattle

W. P. WEISS
Department of Animal Sciences,
Ohio Agricultural Research and Development Center,
The Ohio State University, Wooster 44691

ABSTRACT

The available energy content of feeds must be known before diets can be formulated, but the difficulty in measuring energy availability requires that estimated values be used. Based on production data, the current system using net energy for lactation (NEL) or total digestible nutrients (TDN) overvalued the energy in feeds by 7 to 8%. A standard discount of 8 TDN units was used for both NEL and TDN. When the discount was calculated from actual intake (4 units per increment of maintenance), feed values for NEL and TDN were overestimated by 5 to 6%. Most feed values for NEL and TDN are estimated from acid detergent fiber. These models do not account for all sources of variation in digestibility, do not allow for variable discounts based on intake and associative effects, and are specific for a given population. Mechanistic models account for many sources of variation and can be modified to include variable discounts based on digestion and passage kinetics. The equation used to convert TDN to NEL does not consider the source of the digestible energy. The NEL of the fat that is contained within feeds is undervalued, and fiber is probably overvalued. Single-component equations are not adequate to describe the complex processes that determine energy availability. The current NEL and TDN systems overvalue the energy in feeds, but both systems still work remarkably well. These systems need to be modified to improve accuracy, but they should not be discarded. (Key words: net energy, digestibility, energy models)

Abbreviation key: CNCPS = Cornell Net Carbohydrate and Protein System, DE = digestible energy, ME = metabolizable energy.
of the TDN system were that TDN concentrations of feeds could be measured, and a large database of TDN values exists (47). Overall, the TDN system has worked well; however, TDN does not account for all energy losses. Gaseous and urinary energy losses, heat increment, and the work necessary to digest and move digesta through the gastrointestinal tract are not considered in the TDN system, and these losses are variable among different feedstuffs. The TDN system overvalues low digestibility feeds and undervalues high digestibility feeds. The biological flaws in the TDN system (or any system based predominantly on fecal losses) have been known since the late 1800s when Kellner and Armsby conducted their calorimetry work (27). Early editions by the NRC and many early textbooks stated that net energy values were more accurate than TDN, but TDN remained the standard because net energy values were so difficult to obtain.

Large-scale calorimetry work conducted at Beltsville in the 1960s allowed the widespread application of the net energy system to the nutrition of dairy cows (32, 33). Equations were developed from more than 500 energy balance studies to convert TDN or digestible energy (DE) values into net energy values. In 1971, the NRC (37) presented values for net energy (designated NE\textsubscript{Lactating cows}) for requirements and feedstuffs. Although the terminology has been changed, NE\textsubscript{L} requirements for maintenance, gestation, and milk production have not changed during the last 25 yr (38). The NE\textsubscript{L} values of feeds, however, have changed. In the 1971 NRC publication (37), NE\textsubscript{L} values were calculated from DE values. Since 1979, the NRC has calculated NE\textsubscript{L} from TDN using an equation that incorporates an 8% decrease in digestibility when cows are fed at productive levels of DMI (3 × maintenance). The current equation for converting TDN to NE\textsubscript{L} (35) is

\[
NE\textsubscript{L} \text{ (megacalories per kilogram)} = 0.0245 \times TDN \text{ (percentage)} - 0.12.
\]

Although the NE\textsubscript{L} system has theoretical advantages over TDN, it is still based on TDN. Because TDN is more commonly measured than NE\textsubscript{L}, most equations that are used to estimate NE\textsubscript{L} were actually derived from TDN data.

**Accuracy of energy systems.** For this review, I compiled literature data to compute the accuracy of the current (38) NE\textsubscript{L} and TDN systems. Lactation studies (11, 21, 22, 23, 26, 29, 50, 51, 58, 61) published in the *Journal of Dairy Science* over the last 5 yr and two unpublished studies from the author were compiled to compare current energy requirements with estimated energy contents of the diets. Donker (14) conducted a similar study using metabolizable energy (ME) values, but data from his study was published earlier than the data used in the present compilation. Lactation studies had to have lasted at least 7 wk (most experiments lasted 12 to 16 wk) to be included, and adequate data had to have been provided on nutrient composition (NDF for forages), feed descriptions, BW, milk production, and BW change. All studies meeting those criteria were used. The papers included studies on protein supplements, forage types, fat supplementation, and by-product feeds. No extremely poor quality forage was fed; the lowest estimated NE\textsubscript{L} of any forage was 1.25 Mcal/kg of DM. A total of 30 different diets from 12 experiments were used in the analysis.

Energy requirements (NE\textsubscript{L} and TDN) for maintenance, FCM production, and BW change were calculated from NRC (38) equations. The daily maintenance requirement for NE\textsubscript{L} (megacalories) or TDN (kilograms) was calculated as 0.08 × BW\textsuperscript{0.75} or 0.0352 × BW\textsuperscript{0.75}, respectively. The mean BW (in kilograms) for each treatment was used. The daily energy required for FCM production was calculated as 0.74 × FCM for NE\textsubscript{L} and 0.322 × FCM for TDN. Mean daily production of FCM (kilograms) was used. The daily energy required for BW gain was calculated as 5.12 Mcal of NE\textsubscript{L}/kg of BW or as 2.26 kg of TDN/kg of BW. The energy obtained from BW loss was calculated as 4.92 Mcal of NE\textsubscript{L}/kg of BW or as 2.17 kg of TDN/kg of BW. The mean BW change (gain or loss) was used. The total amount of energy required was summed and divided by DMI. The value obtained (either NE\textsubscript{L}, as megacalories per kilogram of DM, or TDN, as a percentage of DM) was considered the energy content of the diet based on requirements.

The energy values calculated from feed data were determined by using the NE\textsubscript{L} or TDN values for feedstuffs that have been published by NRC (38). For forages, NDF concentrations were used to match the forage fed to the appropriate feed in the NRC table. Interpolation was used when necessary. The energy values for the individual feedstuffs were summed to produce the energy value (NE\textsubscript{L}, expressed as megacalories per kilogram of DM, or TDN expressed as a percentage of DM) of the diet based on feed values. Most of the NE\textsubscript{L} values in the NRC tables were calculated from TDN values obtained at maintenance, but the conversion equation includes an adjustment for depressed digestibility at 3 × maintenance feeding. The TDN values in the tables are for maintenance feeding. The NRC (38) increased the requirements for TDN for maintenance and milk production instead of decreasing the TDN concentra-
tion in feedstuffs. The actual adjustments in TDN requirements are not given by NRC (38), but presumably they increased requirements about 8% to account for depressed digestibility at productive levels of DMI.

The energy value of diets based on energy requirements were compared with the energy values of diets based on feed composition. This type of comparison cannot determine whether the energy requirements or the feed values are correct but can determine whether feed values and energy requirement values can be used together to predict animal performance, assuming energy is the limiting nutrient. The validity of using production data to obtain NE\(_L\) values of diets is supported by the results of Saama et al. (45), who compared energy utilization obtained by calorimetry to that obtained by measuring milk and BW under field conditions. Although the field data underestimated maintenance energy by 3.5 Mcal and overestimated milk energy by 2.1 Mcal compared with calorimetry data, the sum of milk and maintenance energy obtained from field values was within 5% of the value obtained from calorimetry (36.4 Mcal vs. 37.8 Mcal). Those researchers (45) did not calculate energy for BW change.

The mean NE\(_L\) calculated from requirements was 1.55 and 1.65 Mcal/kg when calculated from feed data. The mean NE\(_L\) calculated from feed values was approximately 7% greater than the NE\(_L\) content of the diet based on energy requirements (Figure 1).

This mean bias would result in a typical cow (assumed DMI of 20 kg/d) consuming about 2 Mcal/d less NE\(_L\) than was required (approximately equivalent to 2.7 kg/d of 4% FCM or 0.4 kg/d of BW change). The regression of NE\(_L\) values based on requirements (Y) on NE\(_L\) values based on feed composition (X) was Y = -0.02 + 0.96X (r\(^2\) = 0.32; P < 0.01). The slope was not different from 1 (P < 0.25), and the intercept was not different from 0 (P < 0.25). Because the regression line was not different from the ideal relationship (Y = X), bias was essentially constant across the range in NE\(_L\) values. The NE\(_L\) calculated from feed data was more than 10% higher than the values calculated from requirements in 23% of the diets. Thirty-three percent of the diets had NE\(_L\) values based on feed data within ±5% of NE\(_L\) values based on requirements.

The mean TDN value calculated from feed data (assumed 3\(\times\) maintenance level) was 72.0% compared with 66.9% when calculated from requirement data for an average bias of 8% (Figure 2). The regression of TDN from requirements (Y) on TDN from feed data (X) was Y = -10.9 + 1.08X (r\(^2\) = 0.36; P < 0.01). The slope and intercept were not different (P < 0.25) from 1 and 0, respectively. The TDN values calculated from feed composition were more than 10% greater than the TDN values calculated from requirements in 27% of the diets and were within ±5% of actual TDN in 30% of the diets.

The NE\(_L\) equation used by NRC assumes intake at 3\(\times\) maintenance (reduces TDN 4% for every incre-
The average DMI by cows in this group of experiments was 3.25× maintenance. The NE_L values calculated from feed data were recalculated using actual DMI relative to maintenance. The adjusted values for NE_L calculated from feed data averaged 0.06 Mcal/kg (5%) higher than NE_L values obtained from requirements. The regression of adjusted NE_L values obtained from feed data (Y) on NE_L from requirements (X) was essentially the same as that for unadjusted NE_L (Y = –0.02 + .97X; r² = .28; P < 0.1). The adjustment for actual intake slightly reduced the statistical relationship (Figure 1 and 3) between NE_L values obtained from feed data and values obtained from requirements (r² decreased from 0.32 to 0.28 and the root mean square error increased from 0.103 to 0.104). When TDN values based on feed data were adjusted for actual intake (4% decline per increment above maintenance), TDN values were 3.7 units (6%) higher than the TDN values based on requirements (Figure 4). The adjustment for intake reduced the statistical relationship (Figures 2 and 4) between calculated and actual TDN values (r² decreased from 0.36 to 0.29, and the mean square error increased from 4.16 to 4.39).

Based on this analysis of a limited number of diets, essentially no difference in accuracy was observed between TDN and NE_L. When all potential sources of variation were considered, both systems did remarkably well. Much of the scatter (not the bias) could be explained by normal variations in energy utilization by cows (44), differences among experiments caused by experimental design, cow factors (e.g., DIM and parity), other dietary factors (e.g., source and amount of CP), and analytical errors (e.g., measurement of BW change). On average, current feed tables overestimated NE_L of diets by about 7% relative to energy requirements. Adjustment for actual DMI reduced the bias to about 5%. The TDN values of feeds (assumed 3× maintenance) were overestimated by about 8% compared with energy requirements. When TDN values based on feed data were adjusted for actual intake, TDN was overestimated by 6% compared with energy requirements. For both NE_L and TDN, the adjustment for actual DMI reduced the overestimation of feed energy values by about 25%.

These data suggest that feed energy values (NE_L or TDN) should be adjusted for actual intake. Furthermore, these data suggested that an additional 5 to 6% discount should be applied to current feed NE_L and TDN values.

Feed Factors that Affect TDN

Feed can be described in chemical, biological, and physical terms. Many chemical fractions are readily measured by both research and commercial laboratories. Biological measurements of feeds (e.g., enzymatic or in vitro digestibility) can often be made only in research labs. Physical measurements of feeds have not been widely adopted in the US except for
particle size measurements. The analytical methodologies for most of these measurements were reviewed recently (60).

The analytical system used to describe ruminant feed is a composite of the proximate and the detergent fiber systems. Commonly measured feed components include ash, CP, NDF, ADF, ether extract, fatty acids, lignin, starch, and many different N fractions. Ash has no energy and dilutes digestible OM. In theory, lignin also has no DE. The digestibility of lignin measured using the ADF and sulfuric acid method is usually not statistically different from 0 (55). The concentration of fatty acids is related positively with TDN values. When fat is supplemented properly, the digestibility of fatty acids is constant and very high (41). Ether extract, however, does not have constant digestibility and may not be related strongly to TDN values. The concentration of CP is positively related to TDN, but the relationship is indirect. Overall, fiber concentrations (ADF and NDF) are negatively related to TDN because fiber, on average, is less digestible than nonfiber.

Biological characterization of feeds includes in vitro, enzymatic, and in situ digestibility of the total feed or of individual nutrients. Digestion kinetics such as rates and extents of digestion can be determined using these methods. Overall, the extents of digestibility that were determined using biological methods are positively correlated to TDN (60). Rates of digestion are not necessarily highly correlated to TDN. Biological methods usually have been applied to fibrous feeds and have been used extensively to characterize fiber digestion. Most methods are not well-suited to study the digestion kinetics of soluble or rapidly digesting nutrients. In vitro gas production has recently been employed to study the digestion kinetics of nonfiber nutrients (48).

Physical characteristics of feeds have not been used extensively to estimate TDN. The particle size of feeds can affect both digestibility and metabolizability. A reduction in the particle size of fibrous feeds generally decreases digestibility, gaseous energy losses, and the energy needed to digest the feed (39); a reduction in the particle size of nonfibrous feeds generally increases digestibility (7). The rate of hydration and specific gravity of feeds are related to ruminal retention time and can affect rate and extent of digestion, especially for fibrous feeds (6). Milling resistance (i.e., the energy required to grind a specific amount of sample) is correlated negatively to digestibility (31).

Estimation of Digestibility

Models based on feed composition. Historically, equations based on a single nutrient (e.g., ADF) have been the most common means used to estimate the energy content of feeds. These equations rely on a statistical relationship between digestibility and some characteristic, usually a chemical characteristic, of the feed (16, 30). These models do not consider the variable effect of DMI on digestibility (34). A feed fed to a lactating cow at 3× maintenance will have the same energy value as that feed when fed to a dry cow at 1.5× maintenance. Some equations incorporate a constant depression in digestibility for a given level of DMI (e.g., the equation used by NRC to convert TDN to NE₄). The problem with this technique is that all feeds are discounted similarly. As DMI changes, digestibility does not change equally for all nutrients or for all feeds (8, 15). Feed composition models do not adjust for negative or positive associative effects, both of which can affect digestibility (9). The estimated energy content of a feed is the same whether a feed is the only component of the diet or an ingredient in a mixed diet.

Many studies have shown that the concentration of ADF in forages is correlated negatively with digestibility (18, 30). This relationship has been the basis of most energy prediction models used by commercial testing laboratories. The statistical problems associated with this approach have been discussed (59). Another major limitation of the use of ADF (or any other single measure) to estimate energy is that a single measure is insensitive to changes in the concentrations of other nutrients. Two alfalfa samples that have the same ADF concentration have the same estimated energy, although they may differ in ash, lignin, or NDF. An underlying assumption for single-component equations is either that the nutrient in the model is the only factor affecting digestibility or that all other factors affecting digestibility are strongly (i.e., perfectly) correlated with the nutrient measured, but such an assumption is very tenuous (Table 1). Most single-component equations are valid only within a feedstuff class (e.g., alfalfa) and probably are not valid across geographic areas or climatic conditions. Few equations based on ADF are available for concentrate feeds. Many concentrate feeds contain low concentrations of ADF, and the variability in ADF concentrations is low. These conditions reduce the statistical precision of models based on ADF and can make equations extremely sensitive to analytical error.

Other single-component models use in vitro DM or OM disappearance or enzymatic digestion. Many experiments have shown that the in vivo digestibility of haycrop forages fed at maintenance can be estimated accurately from in vitro digestibility (60). In vivo digestibility of protein feeds (36) and energy concentrates (13) fed at maintenance to sheep could be
estimated by a single-component model based on either enzyme or in vitro digestibility. Errors from lack of fit were in the range of 4 to 6%. The estimation of digestibility of forages with enzymatic methods generally has greater error than that for concentrates (60). Most equations based on enzymes or in vitro digestibility consider only digestibility, not ME or net energy. Deaville et al. (13), however, reported that ME concentrations of many different concentrate feeds could be estimated accurately using an enzymatic procedure.

Multiple-component models based on feed composition can be empirical or mechanistic. Empirical equations are derived by regression of numerous feed characteristics (e.g., ADF, CP, and enzymatic digestion) on digestibility. These equations are specific to a given population. Mechanistic models are based on nutritionally uniform (i.e., constant digestibility) fractions and should be independent of population (59). The statistical precision of most empirical multicomponent models is slightly better than that for single-component models (59). Multicomponent empirical models are less sensitive to analytical error than are single-component models, but, because of potential colinearity among independent variables, population specificity may be greater for empirical multicomponent models.

The detergent system of feed analysis is well-suited to mechanistic models. Extraction of a feed with neutral detergent solution produces one uniform fraction (cell solubles) and one nonuniform fraction (NDF). The cell-soluble fraction can be partitioned into ash (no energy), fatty acids (uniform fraction), CP (usually a uniform fraction), and nonfiber carbohydrate (usually a uniform fraction). Conrad et al. (10) derived a mathematical model based on surface relationships between NDF and lignin that can be used to estimate potentially digestible NDF. The calculated potentially digestible NDF was a uniform fraction (17).

Conrad et al. (10) developed a model, subsequently revised by Weiss et al. (62), that estimated TDN based on the uniform feed fractions just mentioned. When the revised model was tested on an independent data file that included roughages, forages, grains, and by-products, the mean square error between estimated and experimentally determined TDN was about 6% (62). Torrent et al. (53) compared experimentally determined TDN (cattle were fed slightly above maintenance) of alfalfa, brewers grains, beet pulp, and cottonseed hulls to estimated (62) values. For all feeds except cottonseed hulls, estimated values were within 3 percentage units of experimentally determined values. The TDN of cottonseed hulls was overestimated by 5 percentage units. Torrent et al. (53) measured ether extract and estimated the concentration of fatty acids. When that specific feed was analyzed for fatty acids (unpublished data) and the actual fatty acid value was used, the estimated TDN was within 3 units of actual TDN. Estimated (62) NE_L values have not been compared with experimentally determined NE_L.

Mechanistic models account for substantially more sources of variation than single-component models do. The potential influence of changes in nutrient fractions other than ADF is shown in Table 2. Compositional data for alfalfa (28) were used to generate regression equations to estimate NDF, lignin, and ash from ADF. Concentrations of NDF, lignin, and ash were estimated at the mean ADF concentration (35%). The estimated mean concentrations and mean concentrations ±1 standard prediction error were then used to estimate NE_L (62). The concentration of NE_L also was estimated with equations based on ADF. Because ADF was constant, the NE_L estimated from ADF equations was constant. The NE_L estimated using the model of Weiss et al. (62) varied from 1.3 to 1.5 Mcal/kg (approximately 13%). Results were similar for cool season grasses (data not shown).

Energy prediction equations for different feedstuffs that were grown in specific regions of the US have been compiled by Undersander et al. (54). All of the equations were based on ADF. The vast majority of these equations have never been tested on an independent data file (i.e., the accuracy of estimating in vivo digestibility or TDN from data not used to derive the equation). A very limited number of TDN values that were estimated from ADF were compared with actual TDN values; ADF equations were found to have slightly overestimated TDN in alfalfa with a low

### TABLE 1. Simple correlation coefficients between ADF and other nutrient fractions for different types of forages.

<table>
<thead>
<tr>
<th>Forage type</th>
<th>NDF</th>
<th>Lignin</th>
<th>Ether extract</th>
</tr>
</thead>
<tbody>
<tr>
<td>Legumes</td>
<td>0.896</td>
<td>0.830</td>
<td>-0.536</td>
</tr>
<tr>
<td>Cool season grasses</td>
<td>0.852</td>
<td>0.742</td>
<td>-0.348</td>
</tr>
<tr>
<td>Warm season grasses</td>
<td>0.480</td>
<td>0.740</td>
<td>0.789</td>
</tr>
<tr>
<td>Corn silage</td>
<td>0.970</td>
<td>0.601</td>
<td>ND</td>
</tr>
</tbody>
</table>

1Data for corn silage are from Weiss (unpublished), all other data are from Mertens (28).
2Sulfuric acid lignin.
3Not determined.
concentration of ADF (29%) but to have accurately estimated TDN for samples with higher amounts of ADF (59). The same result was found for cool season grasses. The concentrations of TDN of grass and legume mixtures and corn silage were not accurately estimated by an ADF equation. The model of Weiss et al. (62) also was used to estimate TDN: the highest error between estimated and actual TDN was 5%. The only published data found regarding the accuracy of estimates of the energy content of concentrate feeds was given by Weiss et al. (62). The TDN of grains and high protein feedstuffs were estimated within 5% of experimentally measured TDN values. Most estimated TDN concentration for high fiber by-products were within 7% of in vivo data, but the error was 10% for about 10% of the feeds.

Because of population specificity, the estimation of TDN of mixed feeds is especially prone to errors using ADF equations. The statistical relationship between ADF and digestibility is different for different feeds. Most ADF equations for grasses have a larger intercept and a more negative slope than do equations for legumes (18, 30, 54), which makes estimation of TDN of mixed grass and legume forages difficult. Corn silage also should be considered a mixed feed (i.e., corn grain and corn stover).

Accurate estimation of the TDN of corn silage from chemical components has proved to be quite difficult. The TDN (determined using sheep fed at maintenance) of different hybrids of whole plant corn grown under different environmental conditions ranged from about 67 to 78% (5). Because corn silage can constitute a significant portion of a diet, that amount of variation can be important. The concentration of ADF generally accounts for less than 60% of the variation in in vitro digestibility of corn silage (3, 43) and less than 40% of the variation in in vivo digestibility (12). Changes in the amount of grain in the silage and differences in the amount of ADF in the stover fraction are largely responsible for changes in the concentration of ADF in corn silage (3, 20). Assuming the digestibility of the grain is constant, if ADF changed only in response to changes in the ratio of stover to grain, ADF could accurately estimate the energy content of corn silage. Because two processes affect ADF concentrations in corn silage, the ability of an equation based on ADF to estimate energy content is questionable. Furthermore, equations based on ADF or NDF and lignin do not consider variations in the digestibility of the starch component of corn silage. Few data are available on the digestibility of starch from corn silage when fed at high DMI.

Variable discount models. In the models of Conrad et al. (10) and Weiss et al. (62), the true digestibility coefficients for each fraction were constants. The estimated TDN (at maintenance) was converted to NE\textsubscript{L} (3× maintenance) using the standard NRC equation. The models do not adjust for variations in digestibility that are caused by associative effects. Sarwar et al. (46) found that estimated (10) NDF digestibility was similar to in vivo NDF digestibility when cows were fed a diet that maintained ruminal pH above about 6. For a diet that generally maintained ruminal pH below 5.8, estimated NDF digestibility was about 12 units higher than in vivo digestibility. Those models also do not allow variable discounts for intake; all nutrients are discounted similarly as intake increases. Models that incorporate

### TABLE 2. Effect of variations in the concentrations of NDF, lignin, and ash (DM basis) on estimated NE\textsubscript{L} values of alfalfa when ADF is constant.

<table>
<thead>
<tr>
<th>Condition(^1)</th>
<th>ADF</th>
<th>NDF</th>
<th>Lignin</th>
<th>Ash</th>
<th>Estimated NE\textsubscript{L}(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean values</td>
<td>35</td>
<td>46</td>
<td>7.2</td>
<td>8.5</td>
<td>1.24 1.38 1.25 1.36</td>
</tr>
<tr>
<td>Low NDF</td>
<td>35</td>
<td>44</td>
<td>7.2</td>
<td>8.5</td>
<td>1.24 1.38 1.25 1.38</td>
</tr>
<tr>
<td>High NDF</td>
<td>35</td>
<td>48</td>
<td>7.2</td>
<td>8.5</td>
<td>1.24 1.38 1.25 1.34</td>
</tr>
<tr>
<td>Low lignin</td>
<td>35</td>
<td>46</td>
<td>6.2</td>
<td>8.5</td>
<td>1.24 1.38 1.25 1.39</td>
</tr>
<tr>
<td>High lignin</td>
<td>35</td>
<td>46</td>
<td>8.2</td>
<td>8.5</td>
<td>1.24 1.38 1.25 1.33</td>
</tr>
<tr>
<td>Low ash</td>
<td>35</td>
<td>46</td>
<td>7.2</td>
<td>7.0</td>
<td>1.24 1.38 1.25 1.40</td>
</tr>
<tr>
<td>High ash</td>
<td>35</td>
<td>46</td>
<td>7.2</td>
<td>10.0</td>
<td>1.24 1.38 1.25 1.32</td>
</tr>
<tr>
<td>All low</td>
<td>35</td>
<td>44</td>
<td>6.2</td>
<td>7.0</td>
<td>1.24 1.38 1.25 1.44</td>
</tr>
<tr>
<td>All high</td>
<td>35</td>
<td>48</td>
<td>8.2</td>
<td>10.0</td>
<td>1.24 1.38 1.25 1.28</td>
</tr>
</tbody>
</table>

\(^1\)Mean values were calculated from Mertens (28). Low and high values are ±1 standard deviation, respectively, from the mean values.

\(^2\)The equation (18) used to generate values in column A was NE\textsubscript{L} = 2.208 − 0.0275 × ADF; the equation (54) for B was NE\textsubscript{L} = 2.30 − 0.0262 × ADF; the equation (54) for C was NE\textsubscript{L} = 1.89 − 0.0184 × ADF; the equation (62) for D was NE\textsubscript{L} = 0.0245 × (0.97 × (100 − NDF − Ash) + 0.75 × (NDF − lignin) × [1 − (lignin/NDF\(^{0.667}\))] − 4) − 0.12. Feed composition data are percentages.

---

rates of digestion and passage are needed for the calculation of variable discounts.

Variable discount models can be empirical, mechanistic, or, more commonly, a combination of both. The Cornell Net Carbohydrate and Protein System (CNCPS) is probably the variable discount model most in use today. With respect to energy, the model uses passage and digestion kinetics of various feed fractions to estimate the TDN content of the diet (49). Standard NRC equations are used to convert TDN to other expressions of energy. The CNCPS partitions feedstuffs into various protein fractions, digestible fiber fractions, nonfiber carbohydrate, and fat. In simplified terms, protein, fat, and nonfiber carbohydrate are assumed to be 90 to 100% potentially digestible. Potentially digestible NDF is calculated from lignin concentration. Rates of ruminal digestion obtained from in situ experiments and rates of passage obtained from marker studies are applied to the carbohydrate and protein fractions within each feedstuff. Passage and digestion are considered to be competitive events, and the digestibility of each fraction is calculated from the equation of Waldo et al. (57):

\[
digestibility = \frac{k_d}{k_d + k_p}
\]

where \( k_d \) = rate of digestion, and \( k_p \) = passage rate. Digestibility is then multiplied by the amount of potentially digestible nutrient in the feed. The authors of the CNCPS system (49) acknowledge the effects of particle size, density, and hydration rate on digestion and passage, but the specific equations used to adjust for these effects were not presented. Those authors (49) also acknowledged the importance of associative effects, but the 1992 version of the model had not incorporated associative effects into the energy prediction component.

Although one could argue about many empirical components of the model and the constants used for rates of digestion and passage, the basic principles of the model are sound. Models such as the CNCPS are a major advance in energy prediction because they provide variable discounts for feeds based on kinetics. To take full advantage of these types of models, better data for kinetics are needed. The problems that are associated with rate of passage measurements have been reviewed (40). The accuracy of the in situ method for estimating in vivo digestion rates also are questionable (2, 52).

**Estimation of NE\(_L\)**

Most current feed energy models are based on TDN. The conversion of TDN to NE\(_L\) is assumed to be constant. The equation (35) used to convert TDN to NE\(_L\) has a negative intercept; therefore, feeds with low TDN are discounted more than feeds with high TDN. Feeds with the same TDN, however, have the same NE\(_L\) regardless of which nutrients supply TDN. Data reported by Kellner in 1900 and cited by Kleiber (24) showed that the source of energy affected energetic efficiency. Relative to starch, fiber has a negative effect and fat has a positive effect on energetic efficiency.

Many experiments have shown that fiber reduces the efficiency of converting DE to net energy. The starch equivalent system developed by Kellner (24) discounted the energy value of feeds as fiber increased, although digestibility may have been the same. Cattle fed a diet that contained 75% alfalfa were less efficient at converting ME to tissue energy than those fed a 75% concentrate diet at equal ME intakes (42). Metabolizable energy from orchardgrass (higher NDF) was used less efficiently for growth than was ME from alfalfa, even though DE contents were similar (56). Fiber alters energetic efficiency relative to starch because all DE from fiber comes from fermentation, but some starch can be digested in the small intestine. Fiber changes the nutrients absorbed (e.g., increased acetate), and fiber increases digesta in the gut, which increases the energy needed for digestion. Larson et al. (25) compiled calorimetry data and regressed values of net energy for gain on various nutrients. The concentration of NDF had a negative coefficient (i.e., as NDF, net energy for gain decreased). Part of this effect was due to the negative correlation between NDF and digestibility; however, when the ME content of the diet was included in the equation, NDF still had a significant negative effect (–0.01 Mcal/1% increase in NDF) on net energy for gain (25). The Agricultural and Food Research Council (1) has adopted a ME system based somewhat on variable energetic efficiencies of different nutrients. The ME concentration of some feeds is estimated by equations that include a measure of digestibility and fiber. Most of those equations discount the ME content of feeds between 0.03 and 0.06 Mcal for every 1% increase in the concentration of modified ADF. This adjustment is independent of the effect fiber has on digestibility. These types of equations need to validated on a wider array of feeds.

Digestible energy from fat is used more efficiently than is energy from carbohydrate. Dietary fat does not contribute to methane production or to urinary energy (4). Therefore, the DE and ME contents of fat are the same (38). The efficiency of converting ME from fat to NE\(_L\) also is higher than for carbohydrate. Calorimetry work from Beltsville (4) reported that
77% of the ME from fat was converted to NE\textsubscript{L}; the efficiency for most other feedstuffs is about 60%. The NRC (38) has adjusted for the increased efficiency and does not use the standard TDN equation to estimate NE\textsubscript{L} of pure fat. If the standard equation for NE\textsubscript{L} would have been used, fat would have an NE\textsubscript{L} of 4.2 Mcal/kg, but the value in the NRC table is 5.8 Mcal/kg. The table value is about the same as that obtained experimentally (4).

The NE\textsubscript{L} contents of essentially all feeds, except pure fat, are calculated with the same equation. No adjustment is made for increased energy efficiency for fat contained in feedstuffs, which causes an inconsistency in the energy values of feeds. The NE\textsubscript{L} value of whole soybeans is 2.18 Mcal/kg, but the NE\textsubscript{L} content of an equivalent mixture of soybean meal and fat has 2.64 Mcal/kg of NE\textsubscript{L}. The current NRC method underestimates the NE\textsubscript{L} of high fat feeds (but not pure fat) relative to that of low fat feeds.

Multiple-component models can be modified to adjust for various metabolic efficiencies. The models from Ohio State University (10, 62) partition TDN into digestible protein, nonfiber carbohydrate, fat, and fiber. These individual components could be multiplied by efficiency coefficients to produce NE\textsubscript{L}. Weiss et al. (62) applied this principle to digestible fat. Based on efficiency data from Andrews et al. (4), the standard coefficient of 2.25 that was used to convert digestible ether extract to TDN was changed to 2.8, which gave TDN from fat 24% more NE\textsubscript{L} than the standard TDN equation. The 24% is the difference between the efficiency of converting DE to NE\textsubscript{L} for carbohydrate and fat. Individual efficiency factors also could be applied to the fiber, nonfiber, and protein fractions.

**CONCLUSIONS**

Based on production data, mean NE\textsubscript{L} and TDN values for diets are overestimated by 7 to 8%. Part of the bias was caused by increased DMI, but, when actual DMI was used to adjust NE\textsubscript{L} and TDN values, the bias was still 5 to 6%. The current method of estimating energy from a single component should be reconsidered. Single-component equations should be applied only to samples that are similar to those used to derive the equation. Mechanistic models should be applicable to most feeds and should account for more sources of variation than do single-component models. To evaluate mechanistic models fully, comprehensive data are need on the composition of feeds and measures of available energy. Models that include variable discounts based on passage and digestion kinetics should improve the accuracy of estimating feed energy values, but more research is needed to develop accurate methods of measuring digestion and passage kinetics. Terms to adjust for differences in energetic efficiency among nutrients, especially fat and fiber, should be incorporated into energy models.

Physical characteristics of feeds can affect digestibility and passage, and their use in energy equations should be evaluated.

**REFERENCES**


