MATHEMATICAL METHODS TO ESTIMATE FEED ENERGY

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Energy is often the most limiting nutrient for high producing dairy cows. In the short term milk production is reduced when cows do not consume adequate energy. The long term effects of inadequate energy intake include poor reproductive performance and increased prevalence of metabolic and other diseases. Cows that consume excess energy also are more prone to many metabolic disorders. Balancing diets accurately for energy will prevent these problems, however, one must have accurate feed energy values to do this. The total amount of energy in a feed (**TE**) can be measured easily in a laboratory or calculated accurately based on routine lab measures. Total energy content, however, is poorly correlated with the amount of energy in a feed that is available to the cow. For example, corn grain and straw have similar concentrations of TE but their ability to support milk production differ significantly. Currently we do not have any laboratory procedures that can measure directly the available energy content of a feed. Because of this limitation, indirect methods to estimate available energy content of feeds are used. The most common method probably is to measure acid detergent fiber (**ADF**) and use a linear regression equation to estimate available energy content. The use of summative equations that require more analytical information is becoming more common.

Expressions of Feed Energy

The classical energy system for feeds describes energy in terms of where energetic losses occur. Digestible energy (**DE**) is equal to TE minus energy lost in feces. Metabolizable energy (**ME**) is equal to DE minus energy lost in urine and as methane from ruminal fermentation. Net energy is equal to the amount of energy actually used by the animal for productive purposes (e.g., milk production, growth, maintenance) which is equal to ME minus metabolic heat production. In dairy cattle nutrition, the energy values of diets and energy requirements are expressed relative to the energy value of milk, i.e., net energy for lactation (**NEL**). On average, the efficiency of converting TE to DE is about 0.7, the efficiency of converting DE to ME is about 0.85, and the efficiency of converting ME to NEL is about 0.6. Overall efficiency averages about 0.35 (only about onethird of the total energy in a diet is used for maintenance, growth, and milk production). Average efficiencies should not be used because of the substantial variation in efficiencies among feeds (Table 1).

Table 1. Efficiencies of energy conversions by ruminants.

	Range in Efficiencies	
Energy transformation[1]	All feeds	Common feeds
TE to DE	0.10 to 0.95	0.50 to 0.95
DE to ME	0.15 to 1.00	0.45 to 1.00
ME to NEL	0.00 to 0.90	0.58 to 0.90
TE to NEL	0.00 to 0.78	0.13 to 0.78

[1] TE = total energy, DE = digestible energy, ME = metabolizable energy, NEL = net energy for lactation.

Total digestible nutrients (**TDN**), because it is easier to measure than NEL is the most frequently measured form of available feed energy. The TDN value accounts for both fecal and urinary losses of energy and thus is not equivalent to either DE or ME. Although TDN does not cleanly fit the classical energy scheme, it still has value in applied nutrition; however, the direct use of TDN to balance diets is generally less accurate than balancing diets for NEL.

Energy Systems

An energy system consists of two parts; feed values and requirements of the cow. A good system should accurately reflect the ability of a diet to support a certain amount of work (maintain the animal, support a certain milk yield and/or growth rate, etc.). By comparing energy intake with energy expenditures the overall accuracy of the system can be determined. For example, if a diet is formulated to support 70 lbs. of milk/day without any change in body condition but body condition decreases when the diet is fed, the energy system is not in balance. In this example, feed energy values are overestimated, energy requirements are underestimated, or some combination of both. The energy system in common use in the U.S. is the NRC (1989) NEL system. Equations are available to estimate the NEL required for maintenance, for milk production, and for tissue reserves and growth (Table 2). In general, these equations work well but the energy required for milk production would be more accurately estimated using concentrations of milk fat, milk protein, and lactose rather than just fat as in the current equations. In addition, the maintenance equation will underestimate requirements for grazing cattle but we are currently unable to estimate grazing requirements accurately.

Table 2. Equations to estimate NEL requirements of dairy cows (Mcal/day).

Activity	Equation[1]
NRC (1989) Equations	
Maintenance	$0.08 \times BW^{0.75}$
Milk production	0.74 x FCM
Body weight change	5 x BW change
Recommended equation for milk production (Mertens and Dado, 1993)	
Lactose content known	Milk yield (kg/d) x (0.0395 x lactose + 0.092 x fat + 0.057 x protein)
Lactose not known	Milk yield (kg/d) x (0.19 + 0.092 x fat + 0.057 x protein)

[1] Where BW = body weight in kilograms; FCM = 4% fat-corrected milk in kilograms/day; BW change in kilogram/day; lactose, fat, and protein as percents.

The NRC does not present equations to estimate NEL of feeds, but it does contain a table with estimated NEL values for most common feeds. In practice, those table values plus estimated NEL values for forages and other feeds that were submitted for analysis often are used to formulate diets.

To determine whether the current system is in balance, data from 30 studies published in the *Journal of Dairy Science* from 1991 through 1996 were compiled (Weiss, 1998). The experiments were designed to evaluate different forages, protein supplements, byproduct feeds and fat supplements. All experiments were continuous lactation trials lasting at least 12 wk. Total energy expenditure was estimated using NRC equations (Table 2) and then divided by dry matter intake to give estimated NEL content of the diet based on requirements. The NEL contents of the diets were also estimated using NEL values from the NRC feed composition table. If the system is in balance, the residuals (NEL from requirements - NEL from feed table) should be randomly scattered around zero.

However, with this data set, 24 of the 30 observations were less than zero (Figure 1). Mean NEL from requirements was lower ($P<0.05$) than mean NEL from feed tables (0.70 Mcal/lb. of DM vs. 0.75 Mcal/lb.). This means that on average, feed energy values are 7% too high, NEL requirements are 7% too low, or some combination of both. Vermorel and Coulon (1998) arrived at essentially the same conclusion using a different approach. Although 7% is not a large bias, it is not trivial either. For an average Holstein cow producing 70 lbs./d of 4% fat-corrected milk, a 7% bias is equal to about 2.3 Mcal of NEL/d (equivalent to the energy value of about 7 lbs. of milk/day). Data are available suggesting that much, but probably not all, of that bias is caused by overestimating feed NEL values.

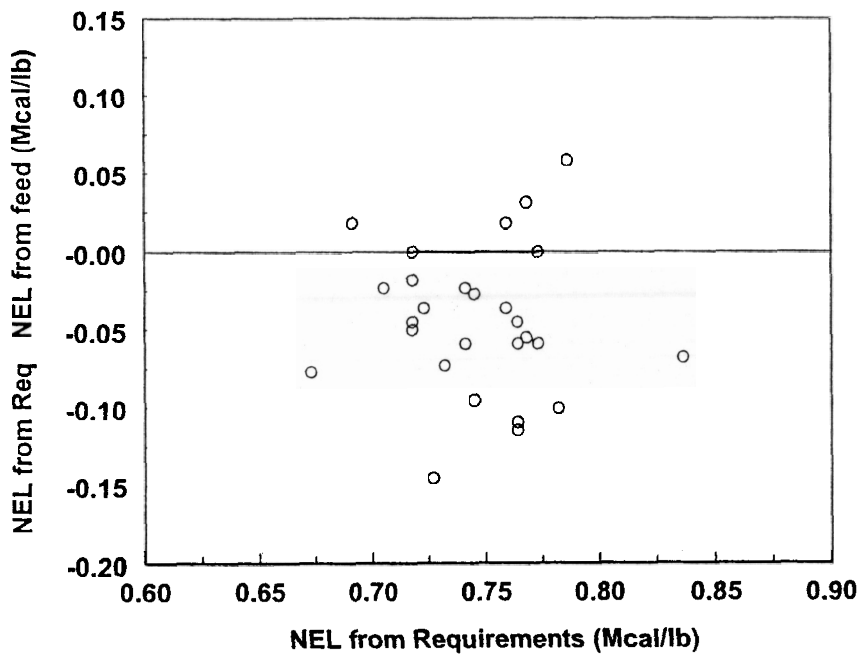

Figure 1. Comparison of NEL values estimated from requirements (NRC, 1989) and table NEL values (adopted from Weiss, 1998).

Estimating Feed Energy Values

ADF-based equations

Probably the most common method used by commercial feed labs to estimate the energy value of forages is to measure ADF and use a linear regression equation to obtain an estimate of NEL. These equations are based on the negative correlation between ADF concentration and digestibility of some forages. The two major problems associated with ADF-based equations are specificity and low sensitivity. Specificity is a problem inherent in all regression equations because regression reflects a statistical association, not necessarily a biological or chemical relationship. This means that the regression equation may be specific to the sample set used to derive the equation. Several different equations are available and estimated NEL values can vary appreciably between the different equations. For example, an ADF-based equation for alfalfa from Penn State (Undersander et al., 1993) yields NEL values that are 0.05 to 0.07 Mcal/lb. higher than an ADF-based equation for alfalfa developed at New Hampshire (Harlan et al., 1991). Does this mean that alfalfa grown in NH is less digestible than alfalfa grown in PA? Does it mean that the values for ADF are routinely higher from the NH lab than from the PA lab? Or does it mean something else? These questions cannot be answered, but illustrate the dependency of NEL estimates on the equation used to obtain the estimate. Specificity also means that an equation developed for one type of feeds (e.g., alfalfa) cannot be used for another type of feed (e.g., grass). Equations based on ADF are not available for many concentrate feeds which means nutritionists must use reference values such as those published in NRC.

Poor sensitivity means that ADF-equations do not account for all the factors that affect NEL concentrations. The concentrations of ash, lignin, and fat all effect NEL concentrations of feed but ADF is only correlated significantly with lignin concentrations. Two samples with the same ADF could have markedly different ash and fat concentrations. Within a feedstuff class, ADF and NDF are highly correlated ($r > 0.8$), however, significant variation still occurs. The NDF concentration of an alfalfa sample with a given ADF concentration could vary by as much as 10 percentage units. Would an alfalfa sample with 30% ADF and 37% NDF have the same NEL as an alfalfa sample with 30% ADF and 47% NDF? An ADF-equation would give the same NEL value even though the actual NEL content probably is lower for the high NDF sample. Van Soest et al. (1991) concisely summarized the above discussion by stating, "It [ADF] is not a valid fiber fraction for nutritional use or for the prediction of digestibility." The time has come to use a more rational, accurate, and robust method to estimate NEL values of feeds.

Ohio State Equations

A logical approach to estimating the NEL values of feeds is to partition feeds into fractions that are energetically uniform (i.e., fractions that contain the same amount of available energy regardless of feedstuff). This fractionation scheme should be based on fractions that can be measured routinely by commercial labs. Ash and lignin are uniform fractions because neither fraction provides any DE to cows. Crude protein approximates a uniform fraction because true digestibility is between 90 and 100% (when fed at maintenance intake) for all feeds except those that have been heat-damaged. Fatty acids, but not ether extract, also approximates a uniform fraction because true digestibility is about 90% (maintenance intake) for all feeds. Nonfiber carbohydrates (NFC) when calculated by difference (100-NDF-CP-ash) also is a uniform fraction for most feeds, but important exceptions exist. For most feeds, the true digestibility of NFC is >95% when intake is approximately at maintenance, but for some unprocessed or coarsely processed grains and for corn silage, NFC digestibility can be significantly less than 95%. The above fractions account for about 70% of most diets; NDF makes up the rest of the diet and it is not a uniform fraction. Digestibility of NDF can exceed 90% for some feeds (extremely immature grass) and can be less than 35% (very mature grass or roughage). No currently available method of fiber analysis produces a uniform fraction.

Conrad et al. (1984) developed a model to estimate TDN content of feeds based on the principles outlined by Osbourn (1978) and Goering and Van Soest (1970). The model was subsequently modified (Weiss et al., 1992; Weiss, 1993) and is now used by several commercial feed labs. The unique approach of Conrad et al. (1984) was to use the surface area law (i.e., surface area is proportional to mass raised to the two-thirds power) to explain the effect lignin has on NDF digestibility. Basically, the equation derived by Conrad et al. (1984) says that lignin and the amount of NDF covered by lignin are not digestible. The equation to estimate NDF digestibility plus the equations to estimate the energy provided by other feed fractions are shown in Table 3. The TDN values estimated using those equations were compared with measured TDN values for a diverse set of feeds (forages, byproducts, grains, protein meals); no bias was evident and the prediction error was similar to that associated with in vivo measurement of TDN.

<u>Needed changes in the OSU approach</u>

1. *Inaccuracies associated with converting from TDN to NEL.* A major problem with the OSU summative equation is that it is based on TDN, not NEL. The NRC (1989) system is also based on TDN; an equation (NEL, Mcal/lb. = 0.0111 x TDN - 0.0545) is used to convert TDN (measured at maintenance intake) into NEL (measured at approximately 3 x maintenance). This approach is flawed (Vermorel and Coulon, 1998). The NRC (1989) equation results in essentially equal efficiencies of converting TDN to NEL for all feeds. For example, wheat straw

with a TDN of 45% has a calculated NEL of 0.44 Mcal/lb (0.99 Mcal of NEL/lb. of TDN). Corn grain at 90% TDN has a calculated NEL of 0.94 Mcal/lb. (1.04 Mcal of NEL/lb. of TDN). Based on known energetic losses, substantially less NEL should be available from 1 lb. of TDN from straw than from 1 lb. of TDN from corn grain. To overcome this problem, we are developing a different approach but is based on the equations shown in Table 3. Rather than estimating TDN, we propose estimating DE by multiplying values obtained from equations in Table 3 by the appropriate heat of combustion. On average carbohydrate has 4.15 Mcal/kg, fat has 9.4 Mcal/kg and protein has 5.7 Mcal/kg therefore:

$$DE\ (Mcal/kg) = 0.0415 \times (dNFC + dNDF) + 0.094 \times dFat + 0.057 \times dCP - 0.3$$

Where dNDF, dNDF, dFat and dCP are calculated as in Table 3. The value, 0.3 is an estimate of 'metabolic fecal DE' and was calculated as 7 x 0.044. This estimated DE value is for cows fed at maintenance but digestibility decreases on average 4% per increment of maintenance. Based on a 4% average decrease per increment of maintenance, the discount can be calculated as:

{[NEL intake (i.e., dry matter intake x NEL concentration)/9.5] -1} x 4.

Estimated DE is then reduced by the discount: DE x [(100-discount)/100].

For example, a cow eating 35 Mcal of NEL/day will have a discount factor of [(35/9.5) - 1] x 4 = 10.7% which is equivalent to (100-10.7)/100 = 0.893

The discounted DE value is then converted to ME using the standard NRC equation:

$$ME\ (Mcal/kg) = 1.01 \times DE - 0.45$$

That ME value is then converted to NEL :

NEL (Mcal/kg) = 0.703 x ME - 0.19 (Moe et al., 1972).

Divide the result by 2.2 to obtain NEL in Mcal/lb. Using the approach outlined above, the 7% bias (Figure 1) was reduced to 1.2%.

Table 3. The Ohio State University summative equation (Conrad et al., 1984; Weiss et al., 1992) for estimating TDN content of feeds[1].

Feed Fraction	Equation for Estimating True Digestibility
[1a] CP from forages	$CP \times e^{-0.012 \times ADIN}$
[1b] CP from concentrates	$CP \times [1 - (0.004 \times ADIN)]$
[2] Nonfiber carbohydrate	$0.98 \times (100 - NDF_{CP} - CP - Ash - EE)$
[3a] Fat (FA analysis)	$FA \times 2.7$
[3b] Fat (EE analysis)	$(EE - 1) \times 2.7$
[4] NDF	$0.75 \times (NDF_{CP} - L) \times [1 - (L/NDF_{CP})^{0.667}]$
Total Feed	
TDN, %[2]	{[1a] or [1b]} + [2] + {[3a] or [3b]} + [4] - 7

[1] CP = crude protein; ADIN = acid detergent insoluble nitrogen (% of total N); NDF_{CP} = crude protein-free NDF; EE = ether extract; FA = fatty acids; L = lignin. All values except ADIN are expressed as a percent of dry matter.

[2] Values obtained from each equation, e.g., [1a] are summed and 7 is subtracted.

2. *Estimating NEL value of corn silage.* Accurately estimating the NEL of corn silage is extremely difficult. This is probably because corn silage is actually a mixture of two very different feeds (high moisture corn grain and mature stalks) and because the digestibility of the starch in corn silage is extremely variable. When fed at maintenance, variation in starch digestibility is much less and from limited data, the OSU equations work well at estimating TDN values of corn silage at low intakes. For lactating cows, NEL estimates obtained from the OSU equations are usually too high. We are attempting to develop a method based on particle size of the silage to improve our ability to estimate the NEL value of corn silage. At the present time, empirical adjustments based on published and unpublished starch digestibility data for corn silage have been developed and can be applied to the OSU equations. For normal corn silage, the 0.98 value in equation [2] in Table 3 should be replaced by 0.92. For mature corn silage (dry matter concentrations > 40%), the 0.98 in Equation [2] should be replaced with 0.85. These adjustments improve the accuracy of the equations for corn silage but a less empirical approach is needed.

3. *Grain processing.* Our equations are based on chemical composition only; no adjustments are made for particle size and other physical characteristics. Because of this limitation, steam-flaked corn will have the same estimated NEL as whole shelled corn which is definitely incorrect. Additional data such as particle size and density could be incorporated into the equation to adjust for processing. At the current time, we use an empirical adjustment based on published data regarding digestibility of starch from processed grains. In Equation [2] in Table 3, the 0.98 should be replaced with 1.02 for rolled barley, rolled wheat, steam-flaked sorghum, and steam-flaked corn. For cracked corn, the value should be 0.93 and for dry rolled sorghum the value is 0.90.

4. *Effect of intake.* Our equations use a very simplistic approach to discount feeds for increased feed intake (i.e., 4% per increment of maintenance). On average this is probably correct but for a specific diet it probably is not. More sophisticated models that include rates of passage and digestion are needed to account for variation in the effect of intake on digestibility. These models however are constrained by the lack of accurate rate data. More research is needed in this area.

5. *Associative effects.* High concentrate diets often depress fiber digestion so that the actual available energy content of the diet is less than would be expected (i.e., a negative associative effect). At the current time we do not know how to model these effects accurately. The practicing nutritionist must be aware of these effects and make the necessary adjustments. Estimated NEL values are usually overestimated with high grain diets.

Conclusions

- The current NRC system substantially overestimates feed energy relative to requirements. The bias is probably around 7%.
- ADF-equations to estimate feed energy should be abandoned but if they are used, they must be used cautiously. The sample being tested must be similar to samples used to derive the equation.
- The summative approach is robust (applicable to most feeds) and accurate.
- The summative approach does not account for differences in grain processing, tends to overestimate energy value of corn silage and needs to incorporate better discounting methods.

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