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Estimating the Energy Value of Dairy Feeds:
Evaluating UC DAVIS and NRC (2001) Equations

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The California dairy industry continues to expand at a rapid rate. Since 1997, the number of lactating dairy cows has increased approximately 50%, to about 1.5 million, and there seems little doubt that this increase will continue for some time. Such expansion has put pressure on all potential animal feed resources as dairy producers look to alternate feeds in order to keep dairy ration prices as low as possible. A list of feeds found in rations of dairy cows in California quickly reaches into the 100's and ranges, pretty much literally, from soup to nuts. The feeds listed in Table 1 are only those feeds that the author has come across in the past few years and for which feed assays were arranged.

The fundamental characteristic of formulated rations for dairy cattle, around which all other nutrients are structured, is its energy content. Expressed variably as ME (metabolizable energy) or NE_l (net energy for lactation; Figure 1), the level of energy in a formulated ration is the sum of the energies in its component feeds. And therein lies the rub since, unlike chemical components such as protein or fiber, the energy content of a feedstuff cannot be analyzed as it represents the potential of a feed, and its components, to do work as biological products, such as meat or milk, or as heat. Nevertheless an accurate knowledge of the energy content of feeds is central to formulation of rations, which will maximize animal output of usable products, and minimize output of unused nutrients (i.e., wastes).

The purpose of this article is to discuss currently available NRC and UCD approaches to estimate the energy value of commercial feedstuffs, and assess their accuracy.

THE SPECIAL CASE OF ALFALFA HAY

Alfalfa hay continues to be an important forage for dairy cattle in California. It is prized by dairy nutritionists and dairy ranchers for its slowly rumen degraded protein, rapidly rumen fermented non-structural carbohydrates, as well as its high energy value for lactating dairy cows. This latter characteristic is a result of its relatively, for a forage, low levels of structural carbohydrate (i.e., neutral detergent fiber or NDF) that is relatively, for a forage fiber, rapidly degraded by microbes in the rumen of dairy cows.

The current method to predict the energy (as total digestible nutrients; TDN) content of alfalfa hay is based upon a publication of Dr.'s Don Bath and Vern Marble of UC Davis (Testing Alfalfa for its Feeding Value, Leaflet 21457 – WREP 109, 1989; available through any UCCE Office). Bath and Marble noted, as had others before them, that because ADF contained a high proportion of the indigestible fiber components lignin and cutin, that there was a good relationship between the ADF level of a hay and its TDN value. Combined with the speed and low cost of the ADF assay, Bath and Marble felt

Table 1. A listing of some California Dairy Feeds.

Alfalfa (green chop -> summer)
Alfalfa (green chop - fall)
Alfalfa (cubes, dehy)
Alfalfa (cubes, sun-dried)
Alfalfa (hay)
Alfalfa (silage)
Alfalfa/Grass (hay)
Almond Hulls
Almond Meal
Almond skins (fresh)
Almond skins (ensiled)
Bakery Waste
Barley (grain)
Beet pulp (pellets, dehy)
Beet pulp (shreds, dehy)
Bermuda grass (hay)
Bermuda grass (seed screenings)
Brewers Grains (wet)
Canola Pellets (38% CP, solvent)
Carrots (fresh, tubers)
Charcoal (filtration, wine)
Citrus Pulp (wet)
Citrus Pulp (dehy pellets)
Corn (earlage)
Corn (gluten feed pellets)
Corn (gluten feed, dehy)
Corn (gluten feed, wet)
Corn (grain, flaked)
Corn (hominy feed)
Corn (silage)
Cotton (hulls, seed)
Cotton (meal, solvent)
Cotton (seed, upland with lint)
Cotton (seed, pima with lint)
Distillers Grains (dehy/corn/w sol)
Distillers Grains (dehy/wht/w sol)
Fescue (hay)
Grape (pomace)
Grass (fresh, spring)
Grass (undefined, silage)
Grass (Kleingrass)
Jojoba (meal)
Oat (hay)
Oat (straw)
Oat (whole crop, silage)
Palm Kernal Meal
Poultry (litter, dehy)
Prunes (flesh)
Prunes (pits)
Rice (bran)
Rice (hulls)
Rice (polishings)
Rice straw (hay)
Rice straw (silage)
Rye (whole crop, silage)
Ryegrass (pellets, screenings)
Ryegrass (silage)
Safflower (meal, solvent)
Soy (hulls, pellets)
Soy (meal, solvent)
Soy (waste, tofu)
Sudan grass (chaff)
Tomato Paste
Tomato Pomace (silage)
Walnut (meal)
Wheat (millrun/midds)
Wheat (whole crop, silage)
Wheat (straw)

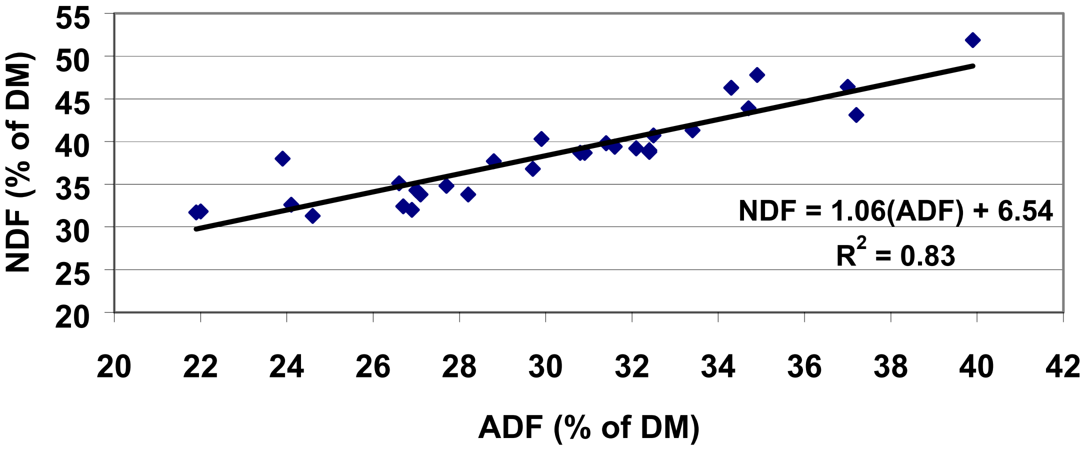
that ADF was an excellent assay to choose as a predictor of the TDN value of alfalfa hay. In their work, the best ADF based equation to predict the TDN value of alfalfa hay was:

$$\text{TDN (\% of hay DM)} = 82.38 - (.7515 \times \text{ADF \%})$$

This equation, referred to as the 'Western States Equation' (WSE), has been adopted by virtually all California hay testing laboratories, and has served the industry well over the years as a quick, inexpensive, precise and robust method to predict the TDN of alfalfa hays.

The strength of the WSE is that increases in the ADF content of alfalfa hay are associated with changes in other nutrients in the hay, and all of them are negative relative to the overall energy value of the hay. The most obvious change is that as the ADF level increases, so does the NDF (neutral detergent fiber) level. NDF captures all of the structural fiber (unlike ADF that only captures about 70 to 85% of it in alfalfa hay) and since NDF is the slowest digesting portion of the plant that is in fact digestible, its increase will reduce the energy level of the hay. Figure 1 reflects this relationship in a set of California alfalfa hays analyzed by the author.

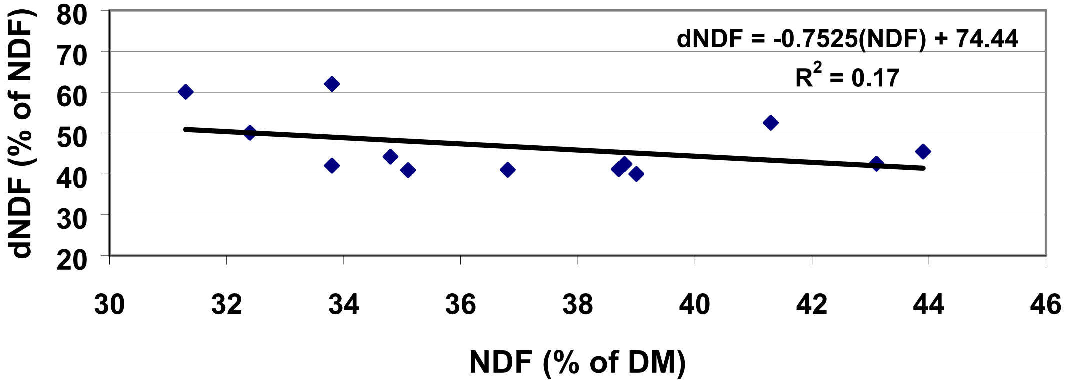
Figure 1. Relationship between ADF and NDF in California Alfalfa Hays.



However as ADF increases it is not just the NDF that is increasing, the digestibility of that NDF is decreasing as well (Figure 2), which means that on a unit NDF basis, there is less energy from the NDF that is in the hay. Thus the double negative whammy on TDN – more slowly digestible NDF in the hay and more of the NDF is not digested.

The relationship of NDF and dNDF (Figure 2) is certainly not as strong as that between ADF and NDF, reflecting the biological reality that there a numerous agronomic factors that impact the resistance of NDF to digestion by cows, but the relationship is clear.

Figure 2. Relationship of NDF and digestible NDF (dNDF) in California Alfalfa Hays.



Another negative associated with increasing ADF levels in alfalfa hay is that the crude protein (CP) level of the hay declines. CP is required in relatively high quantities by dairy cows and, if not supplied in hay, it must be purchased in high cost protein meals such as soybean or canola. This strong relationship, also noted by others, is in Figure 3.

Figure 3. Relationship of ADF and CP in California Alfalfa Hays.

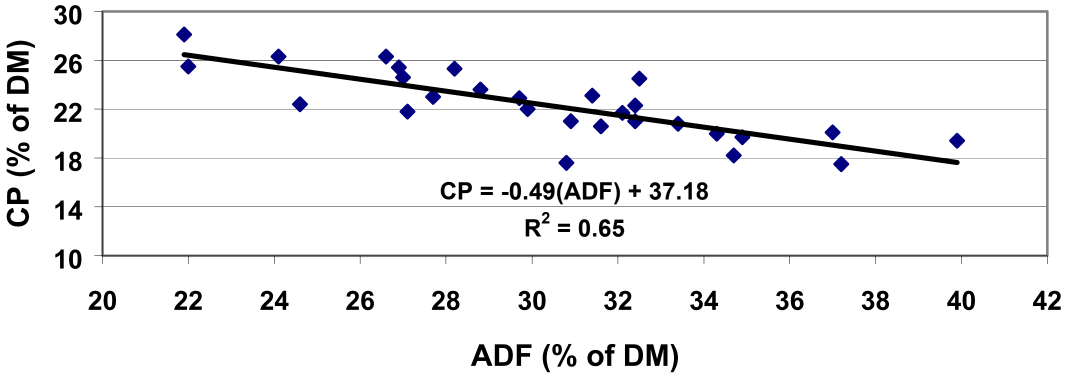
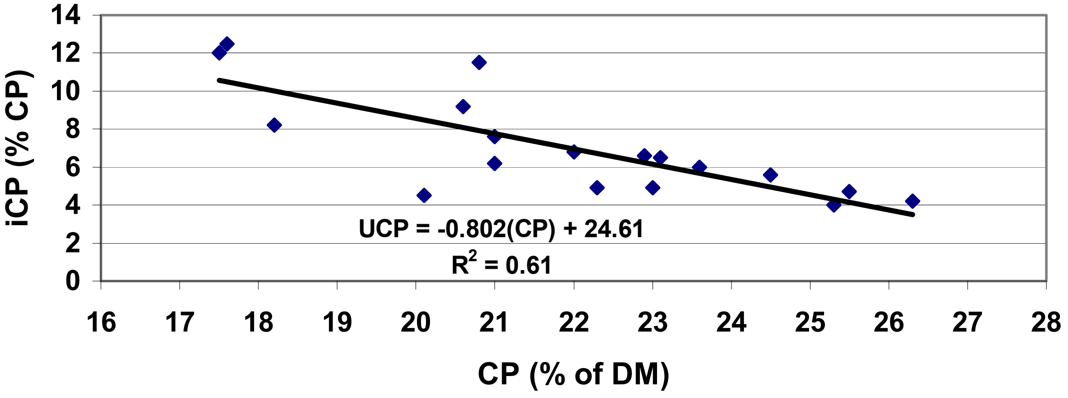


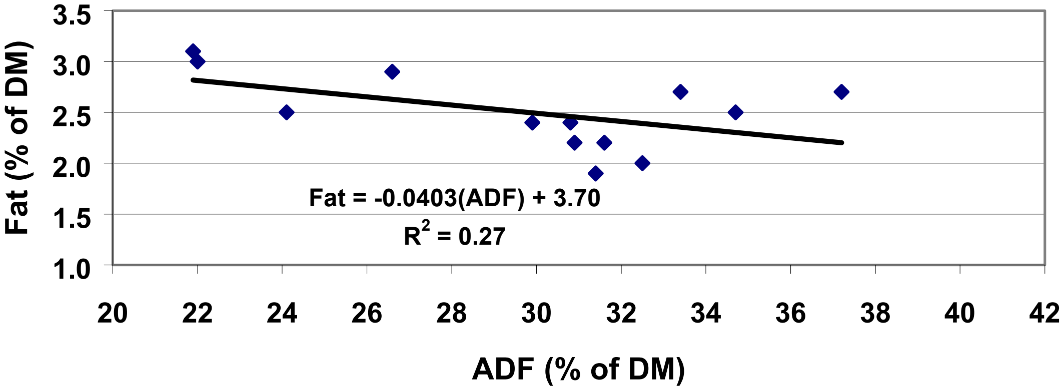
Figure 4. Relationship of CP and iCP in California Alfalfa Hays.



However, as with NDF, it is not just that CP is declining as ADF increases, but that the indigestibility of the CP is increasing as well (Figure 4), which means that on a unit CP basis, there is less digestible CP in the CP that is actually in the hay.

Finally, the fat level of alfalfa hay also declines as the level of ADF increases. Although fat levels of alfalfa hay are rather low, generally in the range of 2 to 3% of DM, fat is an energy dense component packing, on a weight basis, about twice as much energy as digested protein or carbohydrate. So even small declines (Figure 5) can be important.

Figure 5. Relationship of ADF and fat as ether extract (EE) in California Alfalfa Hays.



Overall it is clear that as the ADF level of hay increases, a number of other components change and that all of these changes will depress the energy (i.e., TDN) level of the hay. Clearly this is one of the major strengths of the WSE, as it is not increasing ADF *per se* which drives down the TDN of hay, but that ADF levels are tightly correlated to a number of other hay components that actually impact the energy level of the hay. So in a sense the WSE equation is an energy shortcut, since it is not necessary to examine the other characteristics since they are so tightly correlated to ADF.

But these correlations between ADF and the chemical characteristics of feeds that actually impact their energy levels do not hold *among* feeds because of agronomic differences among feed fibers. Thus it is necessary to use more complicated approaches to accurately estimate the energy values of the range of feeds in, for example, Table 1.

UCD FACTORIAL APPROACH TO ESTIMATE FEED ENERGY LEVELS

It has long been recognized that the two key factors that determine the energy value of a feedstuff for dairy cattle are its content of fat, due to its high energy value, and the digestibility of its structural fiber (i.e., NDF), due to its generally high content in forages. The former can be dealt with by chemical analysis, although the latter has proven to be more difficult. In North America, the tendency has been to rely upon the basic similarity of fiber, within a forage type, to develop unique energy prediction equations for each forage type (this is also the logic behind the WSE). This approach has also been used by the National Forage Testing Association (NFTA), which lists numerous equations at its web site to predict the total digestible nutrient (TDN) value of specific forages.

The big problem with this approach is that the botanical description of the feeds, and time of year that it was harvested for forages, must be known in order to decide which equation to use. This provides intractable problems for unknown and mixed forages as well as high fiber by-product feeds. In addition, these equations tend to be region specific. This can be a problem for forages, such as alfalfa hay, that are transported to markets outside their region of origin and forages, such as corn silage, that are grown from numerous cultivars selected for different agronomic characteristics. In contrast, European countries have tended towards use of *in vitro* fiber digestibility (i.e., small samples of the forage are 'digested' in a small container with rumen fluid from a cow or sheep) to estimate actual fiber digestibility. This approach eliminates concerns about accurate botanical description of the test feedstuff, but introduces the complexity, cost and uncertainty of the *in vitro* procedure itself. However new *in vitro* procedures, and their wide commercial availability in the USA, have overcome many concerns about its use to estimate the energy value of forages for cattle.

The traditional, and still most common, approach to estimating the energy value of feedstuffs has been to calculate its total digestible nutrient (TDN) level using a factorial equation based upon analyzable components of feedstuffs. Although the exact TDN equation has changed over the past 100 years, as feedstuff analyses have improved, the principles have remained unchanged. Many equations calculate TDN as the sum of digestible crude protein (CP), digestible fat (multiplied by 2.25), digestible neutral detergent fiber (NDF), and digestible non-structural carbohydrate (NSC) all corrected for a metabolic cost of digestion by the animal. The TDN value, calculated in this manner, can then be used to estimate the digestible energy (DE), metabolizable energy (ME), and/or NE_l values of individual feedstuffs.

The following equations define estimates of the TDN and NE_l values of feedstuffs for cattle fed at a low level of intake (i.e., a level of intake sufficient only to maintain the body weight of the animal, referred to as the maintenance level of intake, or 1xM), as well as how to modify the energy value for animals fed at higher or lower intake levels.

Estimation of the TDN and NE_l (1xM) in Mcal/kg of Dry Matter

$$\begin{aligned}\text{TDN (1xM)} &= ((\text{CP}-\text{SCP}-\text{ADICP})*.98) + (\text{SCP}*.80) + ((\text{EE}-1)*.98*2.25)\\ &\quad + (\text{NDF}*\text{dNDF}) + (.98*(100-\text{ASH}-\text{EE}-\text{NDF}-\text{CP})))\end{aligned}$$

$$\text{ME (1xM)} = ((\text{TDN(1xM)})*1.01) - .45$$

Where: CP = crude protein (% of DM)
SCP = soluble CP (% of DM)
ADICP = acid detergent insoluble CP (% of DM)
EE = ether extract (% of DM)
NDF = ash-free NDF assayed with sodium sulfite & amylase (% of DM)
dNDF = *in vitro* NDF digestibility at 30 hrs (% of NDF)
ASH = ash (% of DM)

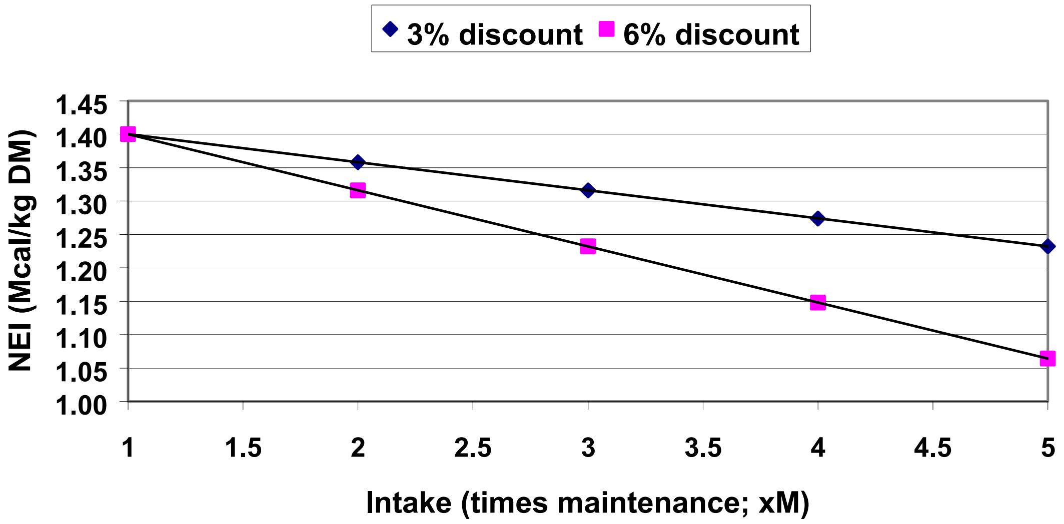
However, the energy content of a feedstuff is not a constant value. As its intake by the animal increases, its energy content tends to decline, since it passes through the intestine faster allowing rumen microorganisms and intestinal enzymes less time to digest available nutrients. The extent of the change, referred to as the energy discount or simply discount, quantifies the extent of this change. The discount is a reflection of the NDF and NSC content of the feedstuff, and it can be calculated as '% per unit of energy intake' (as a % of maintenance energy requirements of the ruminant in question) as:

$$\text{Discount} = ((.033 + (.132*\text{NDF}_{(\%\ \text{DM})})) - (.033*\text{NE}_{l\ (1\text{xM, Mcal/kg})})) + (\text{NSC}_{(\%\ \text{DM})}*.05)$$

where: NDF = ash-free NDF assayed with sodium sulfite & amylase (% of DM)
NE_l = energy value at 1xM intake
NSC = non-fiber carbohydrate calculated as: 100-ASH-EE-NDF-CP

The energy discount is important as it defines the rate of change in the energy value of a feedstuff as the energy intake of the target ruminant changes relative to its energy requirements for maintenance (Figure 6).

Figure 6. Reduction in NE_l of a feedstuff as the diet in which it is included is consumed at higher levels.



The equations outlined in the previous section, while descriptive of an approach to estimating the energy value of virtually any potential feed for ruminants, are rather complicated, and so a spreadsheet is available to make the calculations (Table 2) which can be downloaded from the author's website.

Table 2. A program to predict the energy value of any feedstuff.

PREDICTING THE ENERGY VALUE OF FEEDSTUFFS FROM ANALYSES

	------ Required assays for Energy Calculations ------								--------- Energy Calculations (DM basis) --------					
Sample	**DM**	**OM**	**Fat**	**CP**	**SCP**	**ICP**	**NDF**	**dNDF**	**TDN (1XM)**	**DE (1XM)**	**ME (1XM)**	**NEl (1XM)**	**Energy Discount**	**NEl (3XM)**
Description	%	-------- % DM --------			% CP	% CP	% DM	% NDF	%	Mcal/kg	Mcal/kg	Mcal/kg	% unit M	Mcal/kg
Feed 1	**24.9**	**88.6**	**1.1**	**8.2**	**55.0**	**13.4**	**49.8**	**46.6**	58.27	2.57	2.14	1.43	8.03	1.20
Feed 2	**28.2**	**96.3**	**6.5**	**24.4**	**62.0**	**7.4**	**31.4**	**56.9**	83.02	3.66	3.25	2.09	5.81	1.85
Feed 3	**92.4**	**95.0**	**3.7**	**19.5**	**19.0**	**7.0**	**41.2**	**27.8**	63.86	2.82	2.39	1.58	6.95	1.36

http://animalscience.ucdavis.edu/faculty/robinson

Commercial laboratories, such as Dairy One, Ithaca (NY) and Cumberland Valley Laboratories, Maugensville (MD) provide these assays. The *in vitro* NDF assay that has essentially become an industry standard is the '30 h *in vitro* NDF', which simply means that the sample of feed was incubated with rumen fluid for 30 h. The 30 h period was selected since it best correlates to digestion of feeds in dairy cows fed at maintenance. Once in hand, this value can be entered into a simple spreadsheet to estimate the energy value of the feed. The user enters only the analytical information in bold and the program estimates the various energy values, which can then be used for feed evaluation, feed pricing and ration formulation.

One commercial California laboratory (JL Analytical, Modesto) provides this assay. Based on the same 30 h *in vitro* NDF assay, the JL analytical report lists several analyzed fractions and the various energy values, which can then be used for feed evaluation and ration formulation. Indeed the author's laboratory at UC Davis provides the assays dNDF value required in the energy calculation.

However feedback has been that the package is both two expensive and too time consuming, at about 14 days turnaround time.

UCD CORRELATIVE APPROACH TO ESTIMATE FEED ENERGY LEVELS

In vitro procedures have developed over the years and now fall into two basic types. The 'traditional' procedure incubates small amounts of a test forage with rumen fluid for a defined time period. The incubation is terminated, and the residual dry matter (DM) and/or NDF (i.e., dNDF by difference) is determined gravimetrically. An alternate *in vitro* procedure, widely used in Europe, also incubates small amounts of the test forage with rumen fluid. However in this procedure the amount of gas produced in the fermentation is cumulatively collected and recorded at defined time intervals. The advantage of this procedure is that the incubation need not be terminated to measure the extent of digestion, although the disadvantage is that the amount of gas collected is only an indicator of the amount of carbohydrate fermented, rather than a measurement *per se*. Thus the amount of gas produced must be related to the energy content of the forage.

Gas produced by fermentation arises largely from the carbohydrate fraction of the feed, since ash does not ferment, fat produces no gas, and protein produces very little gas. The energy value of a feed can be estimated from the amount of gas produced at 24 h of incubation with supplementary analyses of crude protein (CP), indigestible CP (iCP) and crude fat (CF). This approach was developed by the research group in at Hohenheim University (Germany) and is based upon extensive *in vitro* incubation of forages that had their actual energy value determined in ruminants. The original equation calculated the energy value as ME (metabolizable energy) in MJ/kg, although we have modified the equation slightly based upon on own findings in California. The equation utilized is:

$$\text{ME (Mcal/kg)} = ((1.25 + (.0292*\text{Gas24}) + (.246*\text{fat}) + (.00143*(\text{CP}-\text{iCP})))/4.1855$$

Where: Gas24 is 24 h net gas production (ml/g DM)
CP is crude protein (% of DM)
iCP is indigestible CP (% of DM)

The main advantage of this approach is that the equation is applicable to any feed, and the reduction of the incubation time from 30 to 24 speeds sample turnaround.

NRC FACTORIAL APPROACHS TO ESTIMATE FEED ENERGY LEVELS

While we were busy developing these energy prediction approaches at UC Davis, the National Research Council (NRC: 2001) Dairy Sub-Committee released a new version of its ongoing series that define nutrient requirements of dairy cattle. This release, for the first time, included factorial approaches to estimate the energy value of dairy feeds based upon either an all analytical approach (NRC_{lig}) or an approach which included a 48 h *in vitro* determination of NDF digestibility NRC_{48}).

The NRC (2001) summative approaches require estimates of a similar group of several chemical components. They differ only in that the first approach utilizes the lignin (sulphuric acid procedure) content of the feed to estimate the digestibility of NDF (NRC_{lig}) whereas the second specifies that a 48 h *in vitro* or *in sacco* estimate of NDF digestion can be substituted for the lignin based estimate (NRC_{48}). Within each general approach, two equations are provided to estimate the truly digested CP in forages vs. concentrates and, within concentrates, two different equations are listed to estimate the DE value of animal protein meals vs. all other feeds. The definitions of 'forage' vs. 'concentrate', and whether protein meals based upon marine and poultry by-products classify as animal protein meals, are not defined. These equations can be found on pages 14 (equations 2-4a to 2-4e) and 16 (equations 2-8a to 2-8d) of NRC (2001). The NRC (2001) processing adjustment factor (PAF) is estimated from information provided in NRC (2001).

ADAS CORRELATIVE APPROACHS TO ESTIMATE FEED ENERGY LEVELS

However the ADAS (Agricultural Development and Advisory Service) group in the UK also had two correlative predictive equations that they had developed, primarily based upon UK grass silages. The first was based on the assumption that *in vitro* organic matter (OM) digestibility (ivOMD) measured by the Tilley and Terry (1963) rumen fluid-based method is a good estimate of gross energy (GE) digestibility. ME was assumed to equal 0.82 of DE as:

$$\text{ME (MJ/kgDM)} = 0.82*(\text{GE}*\text{ivOMD})$$

where: GE (MJ/kgDM) was measured by bomb calorimetry.

This is a single unified equation for any potential ruminant feed, defined as ADASIVGE. Since the GE and ME values in the ADASIVGE procedure are not completely independent, the second approach replaced measured GE with GE predicted from the CP, ether extract (EE) and the rest of the OM (R) according to Graham (1983). This assumes GE values of 24.0, 39.0 and 18.0 MJ/kg for CP, EE and R respectively:

$$\text{ME (MJ/kgDM)} = 0.82*(((0.24*\text{CP})+(0.39*\text{EE})+(0.18*\text{R}))*\ \text{ivOMD})$$

Where: CP, EE and R are as % of DM.

This is also a single unified equation for any potential ruminant feedstuff and is defined as ADASIVPGE.

WHICH, IF ANY, APPROACH IS ACCEPTABLY ACCURATE ?

The obvious question was which, if any, of these four approaches were the most accurate in estimating the energy value of dairy feeds. In order to answer this question, a study was completed to evaluate the accuracy and precision of the six prediction approaches, two from NRC (2001), two from the University of California at Davis (UCD) and two from the Agricultural Development and Advisory Service (ADAS) in the UK, the source of the feeds where the ME values had actually been determined in sheep.

A total of 78 individual feeds representing 17 different forages, grains, protein meals and by-product feedstuffs were identified from a library of feeds for which the ME value had been determined at a maintenance energy intake in sheep, and that were maintained at the ADAS Nutritional Sciences Research Unit in Stratford-upon-Avon (UK). The individual feeds and their chemical analyses are in Table 3. These feeds represent a wide variety of ruminant feeds high in NDF, non-fiber carbohydrate and protein, but do not represent feeds with high levels of fat. The chemical assays and in vitro determinations required for each of the six predictive approaches are in Table 4.

Table 3. Chemical composition of the test feeds.

		Chemical components .						
		DM^2	OM	Fat	CP	ADICP	NDF	Lignin
	n	%	------	% DM	-------	% CP	--	% DM --
Alfalfa, cubes	5	91.3	89.3	2.8	19.8	10.7	45.3	8.1
Alfalfa, silage	5	89.4	89.4	2.3	20.4	8.7	40.2	7.8
Barley, grain	5	91.2	97.4	1.7	13.6	6.1	15.9	1.2
Corn, gluten feed	7	91.1	93.8	4.3	22.3	8.1	42.1	2.4
Corn, gluten meal	3	92.6	99.0	3.1	67.1	5.4	3.0	1.5
Corn, silage	6	90.0	91.7	1.8	10.1	11.6	49.4	3.5
Cotton, seed cake	4	92.0	94.0	6.5	36.9	8.3	42.1	11.1
Distillers, grains	5	89.2	94.7	7.8	30.0	25.9	35.3	13.0
Feather, meal	4	91.8	95.4	6.4	87.2	35.2	az[1]	az
Fish, meal	5	92.2	79.5	8.6	69.6	1.6	az	az
Grass, cubes	4	91.9	90.3	4.2	20.7	9.0	55.8	4.2
Grass, silage	6	87.1	91.2	3.6	18.7	8.1	53.8	3.4
Malt, culms	5	91.8	93.8	1.2	27.1	5.2	47.0	2.0
Palm, kernel meal	4	90.2	95.8	8.0	17.6	19.4	68.3	13.7
Wheat, grain	4	91.4	98.1	1.6	14.2	2.3	10.4	1.5
Wheat, silage	3	90.4	94.8	3.1	12.3	11.1	47.3	4.8
Wheat, silage (urea)	3	90.0	94.8	3.4	14.3	9.3	44.4	5.2

[1] - Assumed to be zero.

Average predicted ME values differed from those determined in sheep in several feeds (Fig 3). Of the 17 feeds, the NRC48 approach overpredicted 4 and underpredicted 4, the NRClig approach overpredicted 3 and underpredicted 4, the UCD30 overpredicted 3 and underpredicted 5, and the UCDgas overpredicted 4 and underpredicted 4. Of the 15 feeds examined by the ADAS approaches, the ADASIVGE overpredicted 2 and underpredicted 7 while the ADASIVPGE overpredicted 1 and underpredicted 6. Only two feeds (grass silage and malt culms) ME values were accurately predicted by all approaches, while one feed (corn silage) was underpredicted by all approaches.

Figure 7. Energy prediction errors of the six procedures.

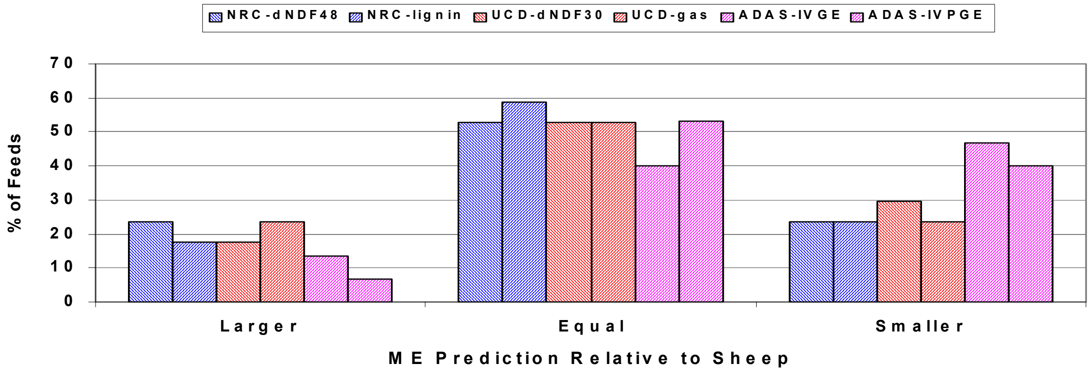


Table 4. Chemical component requirements, in vitro assay requirements and number of equations required for the six predictive approaches

	NRC(2001)		UC Davis		ADAS	
	dNDF48	lignin	dNDF30	gas	IVGE	IVPGE
Chemical assays						
gross energy					*	
ash	*	*	*		*	*
fat[1]	*	*	*	*		*
crude protein	*	*	*	*		*
soluble CP			*			
acid detergent insoluble CP	*	*	*	*		
neutral detergent fibre[2]	*	*	*			
lignin[3]		*				
In vitro assay	48h NDF		30h NDF	24h gas	IVOMD[4]	IVOMD[4]
Processing adj. factor[5]	*	*				
Equations[6]	3	3	1	1	1	1

[1] - as ether extract

[2] - neutral detergent fiber expressed ash-free with sodium sulfite and alpha-amylase.

[3] - 72% sulphuric acid method.

[4] - *in vitro* Tilley and Terry (1963).

[5] - an arbitrary adjustment factor that is not analyzable but must be estimated based upon unclear criteria.

[6] - there are five total equations required for each NRC approach if fat supplements are included, but no more equations for the UC Davis or ADAS equations**.**

The means of the ME values for each feedstuff determined in sheep were regressed against each set of ME values estimated from each of the six approaches (Table 5). The UCDgas and both ADAS approaches resulted in slopes and intercepts that differed from unity and zero, respectively. However the slopes and intercepts for the UCD30 and both NRC approaches did not differ from unity and zero respectively. However the r^2 increased numerically from the NRClig (0.61) to the NRC48 (0.74) to the UCD30 (0.84) reflecting a corresponding decrease in SEM.

When the regressions of these three approaches were completed without the statistically non-significant intercept, the resulting slopes did not differ from zero and showed an overall 1% overestimate for the NRC48 approach, a 3% underestimate for the UCD30 approach and no error for the NRClig, vs. the ME values determined *in vivo* with sheep. However the goodness of fit, and SEM, reflected the regressions with the intercept allowed to deviate from zero, suggesting the best fit was for the UCD30 (0.83), the lowest was for NRClig (0.61) and the intermediate was for NRC48 (0.72).

Table 5. Predicted versus estimated (with sheep) metabolizable energy (ME, MJ/kg DM) among test feedstuffs at maintenance energy intake.

	Value			*P*		
	Int	slope	SEM	Int[1]	slope[2]	r^2
Intercept not Fixed						
NRC (2001)						
dNDF48	-1.86	1.16	1.65	0.24	0.39	0.74
lignin	0.01	1.00	1.92	0.99	0.98	0.61
UC Davis						
dNDF30	-1.28	1.08	1.11	0.23	0.54	0.84
gas	4.37	0.63	0.92	<0.01	<0.01	0.73
ADAS						
IVGE	3.14	0.70	0.82	<0.01	<0.01	0.73
IVPGE	3.12	0.69	0.80	<0.01	<0.01	0.81
Intercept Fixed at Zero						
NRC (2001)						
dNDF48	-	1.01	1.63	-	0.97	0.72
lignin	-	1.00	1.85	-	0.98	0.61
UC Davis						
dNDF30	-	0.97	1.10	-	0.75	0.83
gas	-	0.99	1.21	-	0.89	0.50
ADAS						
IVGE	-	0.95	0.99	-	0.58	0.70
IVPGE	-	0.94	0.97	-	0.48	0.70

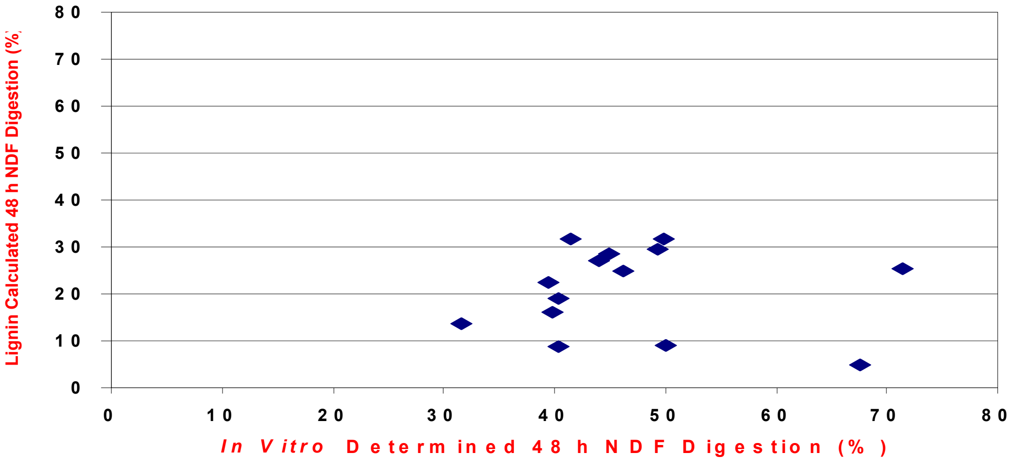
[1] - probability that the intercept (Int) differs from zero.
[2] - probability that the slope differs from unity.

SO WHICH IS BEST ?

The approach employed to evaluate the accuracy of these ME prediction equations presumes that the estimates determined *in vivo* with sheep are accurate and that errors in predictions are due to errors in the predictive equations. Clearly these assumptions cannot be absolutely correct and ultimately the extent of the resulting error cannot be determined

NRC (2001) approaches: It seems clear that the both NRC (2001) approaches were broadly accurate across the range of feeds examined (i.e., the slopes of the best fit equations forced through the intercept did not diverge meaningfully from unity). However the overall precision of the NRClig approach was substantively lower than the NRC48. Since the NRClig and NRC48 equations move to convergence as the NDF level of the feed declines to zero, and since 15% of the feed samples had less than 5% NDF in DM (27% of samples had less than 20% NDF of DM), the extent of the decline in precision of the NRClig equation relative to the NRC48 equation was more substantial than that suggested by the decline in the overall precision. The primary reason for this occurrence was the absolute failure of the lignin-based procedure to predict *in vitro* digestion of NDF at 48 h (Figure 8). The clear lack of a relationship between 48 h NDF digestion *in vitro* and that predicted from lignin, suggests that use of lignin to predict 48 h *in vitro* NDF digestion, and so ME content of feeds, is neither accurate nor precise.

Figure 8. The lignin problem –> lignin does not predict digestion of NDF.



UC Davis approaches: Both UC Davis approaches were broadly accurate among the range of feeds examined (i.e., the slopes of the best fit equations forced through the intercept did not diverge meaningfully from unity). However the UCDgas approach demonstrated bias, as evidenced by the substantial deviation of the intercept from zero.

ADAS approaches: The ADAS approaches were broadly accurate among the range of feeds examined (i.e., the slopes of the best fit equations forced through the intercept did not diverge meaningfully from unity). However the accuracy of these approaches were lower than the other methods examined, as evidenced by their relatively low r^2, compared to the other methods, if forced through the origin. Both ADAS procedures demonstrated bias, as evidenced by the deviation of the intercept from zero.

Overall: It is clear that the NRC (2001) calculation of NDF digestion based upon lignin was not an accurate predictor of *in vitro* NDF digestion at 48 h, and these approaches to estimate *in vivo* digestion of NDF cannot be considered interchangeable. The reasons for this deviation are not clear, but suggest differences in lignin chemistry among feedstuffs, although it demonstrates that lignin levels among feedstuffs are not related to rate of digestion as the 48 h digestion occurs prior to completion of digestion.

All of the ME predictions evaluated were similarly accurate (i.e., overall predictive errors ranged from –0.06 to +0.01 when forced through the intercept) and there was little to choose between them in this regard. However the precision of the prediction (i.e., r^2) ranged from a low of 0.50 to a high of 0.83, with the general order: UCDgas<NRClig<ADASIVGE=ADASIVPGE<NRC48<UCD30. Overall the NRClig and UCDgas approaches are not supported by these results due to poor precision among feeds, in spite of the high accuracy among feeds.

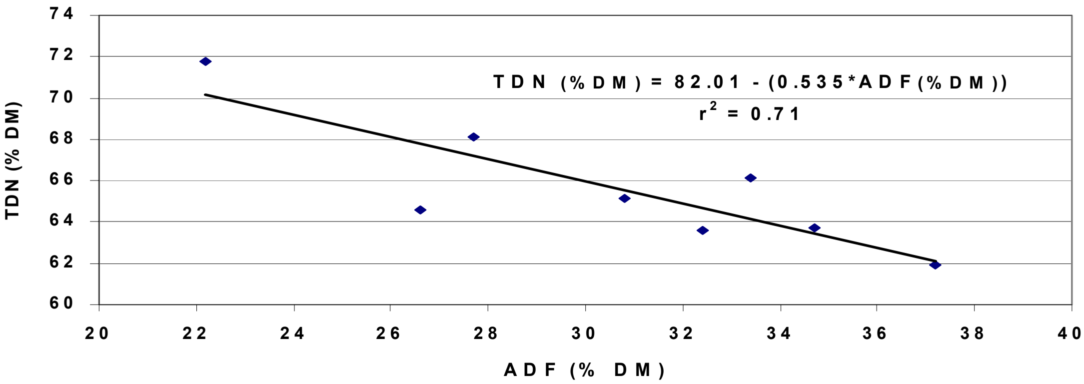
That the UCD30, UCDgas, ADASIVGE and ADASIVPGE approaches are single unified equations provides a substantial benefit over both NRC approaches which are actually three equations requiring categorical definition of feedstuffs. Clearly both NRC (2001) approaches have severe limitations for mixtures of feedstuffs, such as compound feeds and total mixed rations, where feeds from several NRC (2001) categories are combined and a single equation which, by NRC (2001) definition will be inappropriate for some of the feeds in the mixture, has to be chosen to estimate the ME content of the mixture. Nevertheless the NRC48 approach is judged to be better than the ADASIVGE and ADASIVPGE approaches as it has high accuracy (+1% ME overestimate) and an intermediate level of precision (r^2=0.70). The best procedure overall is the UCD30, as it is a single unified equation, has high accuracy (-3% ME underestimate) and has the highest precision (r^2=0.83).

However, these comments relate only to the accuracy and precision of the methods among feed groups and do not address the relative differences in cost, complexity or time requirements for the various approaches. Indeed the relative simplicity of the UCDgas and both ADAS approaches suggest that under many conditions they will be the method(s) of choice as the loss in accuracy and/or precision may be compensated by the reduced cost and complexity of the procedures.

BACK TO THE PAST – THE WESTERN STATES EQUATION REVISITED

The WSE was developed in the 1960’s and 1970’s based upon the alfalfa hays that were fed at that time. However since about 1980, alfalfa seed companies have been including dNDF values for potential cultivars in their selection criteria. If this has resulted in more digestible fiber, then the WSE may be underestimating the energy value of alfalfa hays. To examine this, a small set of California alfalfa hays had their TDN values estimated by the UCD30 procedure and these values were regressed against the ADF content to ‘re-create the WSE. Results, Figure 9, suggest that the intercept is unchanged from the WSE (i.e., the energy value of NSC and CP and fat is unchanged) but that the WSE is undervaluing the energy value of alfalfa hay.

Figure 9. Relationship between ADF and TDN in alfalfa using the UCD30 approach.



CONCLUSIONS

The energy content of feedstuffs is central to accurate feed formulation that both maximizes animal performance and minimizes environmental impact. California dairy nutritionists face challenges in accurate estimation of the energy value of feedstuffs due to the diverse array of feedstuffs available. However methods are available to estimate the energy value of feedstuffs, with acceptable accuracy, however it is not reasonable to expect that these methods will be without cost, both in terms of dollars and time.

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