APPLICATION OF THE CORNELL NET CARBOHYDRATE AND PROTEIN SYSTEM FOR FEEDING DAIRY CATTLE

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INTRODUCTION

Further improvements in ration formulation accuracy will likely come with use of models to account for more of the variation by accurately predicting requirements and feed utilization in each unique production setting. These models must allow inputs from each situation to be adjusted in a logical way until the cattle and feeds are accurately described. The final test is when predicted and observed performance (daily gain, milk amount and composition, and body condition score changes) agree, and observed responses to changes in management and feeds can be explained by predicted effects on ruminal fermentation, intestinal digestion, metabolizability of energy and amino acids, and product amount and composition. Then improved feeding programs can be accurately formulated for that unique situation where nutritional safety factor and nutrient excretion are minimized. This becomes imperative as we attempt to minimize the effects of cattle production on resource use, water quality and other environmental concerns. This requires nutritional accounting systems based on our understanding of the biological responses to variables influencing animal performance, yet driven by inputs available at the farm level, with an acceptable risk of use, considering information available and knowledge of the user.

PREDICTING REQUIREMENTS AND SUPPLY OF NUTRIENTS FOR EACH UNIQUE FARM

To predict requirements and feed utilization in each unique production setting, models which integrate our knowledge of feed, intake, and digestion and passage rates upon feed energy values, escape of dietary protein and microbial growth efficiency must be used. The Cornell Net Carbohydrate and Protein System for Evaluating Cattle Diets (**CNCPS**) is a biologically based structure and hierarchy for evaluating all classes of cattle diets with the purpose of adjusting nutrient requirements and feed utilization over wide variations in cattle, feed, management and environmental conditions. The CNCPS has been described and validated by Russell et al. (1992), Sniffen et al. (1992), Fox et al. (1992), O'Connor et al. (1993), Ainslie et al. (1993), Pitt et al. (1993), Tylutki et al. (1994) and Fox et al. (1995). The approach taken and level of aggregation of variables is based on the experience of the authors in working with farmers and consultants in attempting to apply accumulated knowledge to diagnose problems with performance and develop more accurate feeding programs. The CNCPS was developed over a period of 15 years, based on research that has accumulated on factors influencing cattle requirements and feed utilization. Separate submodels were developed by primary physiological function categories (feed intake and composition, rumen fermentation, intestinal digestion, metabolism, maintenance, growth, pregnancy, lactation and reserves) so that new information can be incorporated into the submodels affected. The CNCPS uses information and codes that can be universally obtained, understood and applied to describe cattle, and can be easily used in program formulas to calculate responses. Although not universally implemented, all of the critical carbohydrate and protein fractions can be routinely determined by feed testing laboratories. The user must have some nutritional knowledge to use the model because of the risks associated with not knowing how to choose inputs. However, with experience it can be used to evaluate the interactions of animal type and production level, environment, feed composition and management factors. Changes in the ration needed to meet animal and rumen fermentation requirements under widely varying conditions can also be identified.

The following summarizes primary components in the CNCPS for purposes of this discussion. We have found that our ability to predict requirements and supply of nutrients needed in the diet to meet them depends upon the accuracy with which these components are predicted. For more details, the reader is referred to the journal articles referenced above.

1. **Maintenance requirement for energy and amino acids.** The maintenance energy requirement is determined by metabolic body size and rate and adjustments reflecting breed type, physiological state, previous nutritional treatment, activity, environment (temperature, wind velocity, and animal surface area and insulation) and heat gain or loss required to maintain normal body temperature. The proportion of the energy and protein intake and its composition needed for productive functions cannot be accurately determined until the proportion needed for maintenance is determined. The combined animal and diet heat production must thus be determined to assess energy balance in a particular environment, requiring the prediction of both ME and NE. The amino acid requirements for maintenance depend on the prediction of sloughed protein and net tissue turnover losses, as predicted from metabolic fecal nitrogen, urinary nitrogen loss, and scurf protein.

2. **Energy and amino acid requirements for tissue deposition and milk synthesis.** Growth requirements are based on empty body tissue composition of the gain expected, based on expected mature size for breeding herd replacements or expected weight at a particular final composition, considering body size, effect of dietary ingredients, and anabolic implants. Prediction of amino acid requirements will not be accurate without accurate predictions of empty body gain or milk composition. Pregnancy requirements are predicted from uterine and conceptus demand with varying expected birth weights and day of gestation. These become critical in accuracy of ration formulation during the last 60 days of pregnancy. Lactation requirements are computed for varying day of lactation, levels and composition of milk.

Reserves are used to meet requirements when nutrient intake is inadequate. Reserves must be taken into account when evaluating ability to meet requirements, especially under environmental stress, feed shortage or early lactation conditions. Visual appraisal is used to assign a body condition score, which in turn is used to predict body fat and energy reserves. The cycle of reserve depletion and replenishment during lactation and the dry period is reflected by predicted condition score change.

3. **Prediction of intake and ruminal degradation of feed carbohydrate and protein fractions, and microbial growth.** The absorbed energy and amino acids available to meet requirements depend on accurate determination of dry matter intake, ingredient content of carbohydrate and protein fractions, microbial growth on the fiber and non fiber carbohydrates consumed, and the unique rates of digestion and passage of the individual feed carbohydrate and protein fractions that are being fed. First limiting in the CNCPS is accurate determination of DMI, and we typically insist on having actual DMI values to enter. Then we use predicted DMI as a benchmark for diagnostic purposes. The interactions of DMI, digestion and passage have several implications. First, the growth rate of each microbial pool that digests respective available carbohydrate fractions, and absorbable microbial amino acids produced, will depend on the special characteristics and intake of the feeds being fed, which in turn determines the demand for the nitrogen source required by each pool. Second, the percentage of cell wall that escapes digestion will change, depending on digestion and passage rates. Third, the site of digestion and, depending on the rate of whole tract passage, the extent of digestion will be altered. Variable rates of digestion and passage have similar implications for protein fractions in feeds. Those readily available will be degraded in the rumen, while those more slowly degraded will be partially degraded in the rumen and partially degraded postruminally, the proportion depending on rates of digestion and passage of the protein fractions in the feeds.

Rumen microorganisms can be categorized according to the types of carbohydrate they ferment. In the CNCPS, they are categorized into those that ferment structural carbohydrate (SC) and nonstructural carbohydrate (NSC), as described by Russell et al.(1992). Generally, SC microorganisms ferment cellulose and hemicellulose and grow more slowly, and utilize ammonia as their primary nitrogen source for microbial protein synthesis. NSC microorganisms in contrast ferment starch, pectin and sugars, grow more rapidly and can utilize ammonia and amino acids as nitrogen sources. The SC and NSC microorganisms have different maintenance requirements (the CNCPS uses .05 and .15 g of carbohydrate per g of microorganism per hour, respectively) and efficiency of growth of NSC digesting bacteria is optimized at 14% peptides as a percentage of NSC. These values are conservative and are based on the observations of Russell et al. (1992) that *Streptococcus bovis*, a primary starch fermenter, has about 6 times the maintenance cost of *Fibrobacter succinogenes*, a representative fiber digester. Thus the degradable protein requirement is for supporting optimal utilization of NSC and SC to meet respective microbial growth requirements. The rate of microbial growth of each category is directly proportional to the rate of carbohydrate digestion, so long as a suitable nitrogen source is available. The extent of digestion in the rumen depends on digestion of SC and NSC feed fractions and how rapidly the feed passes out of the rumen. The extent of digestion thus depends on factors such as level of intake, particle size, rate of hydration, lignification, and characteristics of each carbohydrate and protein fraction.

The ME and MP derived in each situation will primarily depend on the unique rates of digestion and passage of the individual feed carbohydrate and protein fractions that are being fed. Digestion rates are feed specific, and depend primarily on type of starch and protein, degree of lignification, and degree of processing. Extent of ruminal digestion is a function of competition between digestion and passage, and varies with feed type (forage vs grain) and particle size (effective NDF; **eNDF**). There are four nitrogen fraction requirements that must be met in evaluating a ration with the CNCPS; two microbial categories (ammonia for the SC and peptides and ammonia for the NSC microbial pools), and two animal pools (MP and essential amino acids). In evaluating a diet, one must be able to determine how well all four requirements are being met.

One of the critical factors affecting microbial growth is rumen pH. The CNCPS describes physical characteristics of feeds as related to their effectiveness in stimulating chewing, rumination and increased rumen motility based on their total cell wall content and particle size within classes of feeds (effective NDF; eNDF), based on Mertens (1988). The eNDF value in the CNCPS is defined as the percent of the NDF retained on a 1.18 mm screen. Factors other than particle size that influence the eNDF value are degree of lignification of the NDF, degree of hydration, and bulk density. Beauchemin (1991) published an excellent review of the factors influencing buffer production and rumen pH in cattle. Pitt et al. (1993) described the relationship between CNCPS eNDF values, rumen pH and SC digestion. Total microbial yield, and SC growth rate rapidly declines below a pH of 6.2, which relates to a diet eNDF content of 20%. The CNCPS reduces microbial yield 2.5 percentage units for each percentage drop in diet eNDF below 20%. Thus the diet eNDF must be accurately predicted to accurately predict microbial amino acid production and cell wall digestion.

Feed composition in the CNCPS is described by carbohydrate and protein fractions and is used to compute the amount of SC and NSC available for each of the two microbial pools. Digestion and passage rates have been developed for common feeds, based on data in the literature (Sniffen et al., 1992). Nearly all of the critical carbohydrate and protein fractions can be routinely determined by feed testing laboratories, using the Van Soest system (Van Soest et al., 1991) of feed analysis (NDF, CP, soluble protein, neutral and acid detergent insoluble protein). Table 1 shows, with a range of forages and concentrates, how feeds are described by chemical and physical characteristics in the CNCPS feed library. The first section shows the chemically determined fractions; the second section shows the digestion rates (kD) for carbohydrates (CHO) A (sugars), B1 (starch and pectin) and B2 (available NDF) and fast (B1), intermediate (B2) and slow (B3) protein. Total carbohydrates are computed as 100-(protein + fat + ash), using tabular or analytical values. Then carbohydrates are partitioned into structural (SC) and nonstructural (NSC) by subtracting NDF from total carbohydrates, with the available fiber being NDF-NDFprotein-(lignin x 2.4). Data from the literature is used to establish the distribution of sugars and starch in the NSC fraction. The growth of two microbial pools (SC and NSC) is then predicted, based on the integration of rates of digestion and passage, which in turn determines the nitrogen requirements of each pool, microbial protein (**MP**) produced and MP available from this source, carbohydrates escaping digestion and digested postruminally and ME derived from the diet. Passage rates are a function of level of intake, percent forage, and eNDF value.

Table 1. Describing feeds by chemical and physical characteristics

Item	Unit	Corn Sil 40% Grain	Brome Hay Mid Bloom	Alfalfa Hay Mid Bloom	Corn Dry Grain 720 g/L	Corn HM Grain 720 g/L	Soybean Meal - 49% CP	Soybean Whole	Soybean Whole Roasted
Concentrate	% DM	40.00	0.00	0.00	100.00	100.00	100.00	100.00	100.00
Forage	% DM	60.00	100.00	100.00	0.00		0.00	0.00	0.00
Dry Matter	% AF	33.00			88.00	0.00	90.00	90.00	90.00
NDF	% DM	45.00	88.00	91.00	9.00	72.00	8.00	13.00	13.40
Lignin	% NDF	8.89	66.00	46.00	2.22	9.00	2.50	1.54	10.00
CP	% DM	9.20	6.06	18.91	10.10	2.22	55.00	42.80	42.80
Solubility	% CP	50.00	14.60	17.00	11.00	10.60	20.00	44.00	5.70
NPN	% SOLP	100.00	25.00	28.00	73.00	40.00	55.00	22.73	100.00
NDFIP	% CP		96.00	93.00	15.00	100.00	5.00	4.00	23.60
ADFIP	% CP	16.00	31.00	25.00	5.00		2.00	3.00	7.29
Starch	% NSC	8.00	6.50	14.00	90.00	15.90	90.00	90.00	90.00
Fat	% DM	100.00	6.00	10.00	4.30	5.30	1.00	18.80	18.80
Ash	% DM		2.60	3.20	1.60	100.00	7.00	6.00	5.80
		3.10	10.00	9.00					
		4.00				4.30			
						1.60			
Effective NDF	% NDF	81.00	98.00	92.00	0.00	0.00	23.00	100.00	100.00
CHO-A kD	%/hr	275.00	250.00	250.00	150.00	300.00	300.00	300.00	300.00
CHO-B1 kD	%/hr				10.00		25.00	30.00	35.00
CHO-B2 kD	%/hr	30.00	30.00	30.00	5.00	35.00	6.00	5.00	5.00
Protein-B1 kD	%/hr	4.00	3.00	4.50	150.00	6.00	230.00	200.00	150.00
Protein-B2 kD	%/hr	300.00	135.00	150.00	5.00	135.00	11.00	10.00	5.00
Protein-B3 kD	%/hr				0.09		0.20	0.20	0.18
		10.00	11.00	9.00		10.00			
		0.20	0.09	1.25		0.15			
Methionine	%UIP	0.80	0.67	0.73	1.12	0.99	0.83	1.01	1.02
Lysine	%UIP	2.13	2.83	6.02	1.65	2.47	6.08	5.36	5.77
Arginine	%UIP	1.87	2.83	6.39	1.82	4.11	7.69	6.55	6.42
Threonine	%UIP	2.13	2.83	5.00	2.80	3.33	3.03	3.52	3.56
Leucine	%UIP	6.40	5.49	9.26	10.73	12.10	6.13	7.23	7.15
Isoleucine	%UIP	2.40	2.83	6.01	2.69	3.85	4.25	4.65	4.61
Valine	%UIP	3.20	3.83	7.14	3.75	4.78	3.79	5.09	4.91
Histidine	%UIP	1.07	1.00	2.62	2.06	2.70	2.27	2.82	2.96
Phenylalanine	%UIP	2.94	3.50	6.32	3.65	4.99	3.88	4.94	4.81
Tryptophan	%UIP	0.11	4.50	1.84	0.37	0.37	1.64	1.64	1.41

Simultaneously, the degraded and undegraded protein pools are predicted, which are used to determine nitrogen balance for each of the microbial pools, feed protein escaping undegraded and digested postruminally, and MP derived from undegraded feed protein. The protein fractions are expressed as a percentage of the CP. The "A" protein fraction is NPN and the "B1" fraction is true protein that is nearly all degraded in the rumen; these pools are measured as soluble protein. The "C" protein fraction is measured as acid detergent insoluble protein (ADIP) and is assumed to be unavailable. The "B3" or slowly degraded protein fraction can be determined by subtracting the value determined for ADIP from the value determined for neutral detergent insoluble protein (NDIP). The "B2" fraction, which is partly degraded in the rumen, depending on digestion and passage rates, can be then estimated as the difference between CP and the sum of soluble + B3 + C. Feed amino acid content is described by their concentration in the undegraded protein, as described by O'Connor et al. (1993). Intestinal digestibility of the amino acids (section 3, table 1) is assumed to be 100% in the B1 and B2 and 80% in the B3 protein escaping ruminal degradation.

4. **Prediction of intestinal digestion.** Coefficients empirically derived are used to predict intestinal digestibilities and fecal losses based on summaries of data in the literature. A more mechanistic approach is needed that incorporates the integration of digestion and passage to predict intestinal digestion. However, the accuracy of prediction of pool sizes digested depends on the accuracy of prediction of ruminal flows, and therefore has second priority to prediction of ruminal fermentation, particularly since, with most feeds, over 75% is ruminally digested. Until routine predictions of feed content of carbohydrate and protein fractions are available and their digestion and passage rates can be accurately predicted, the use of a more complex intestinal submodel could result in a multiplication of errors.

5. **Prediction of metabolism of absorbed energy and amino acids**. A metabolic submodel needs to be able to predict heat increment and efficiency of use of absorbed carbohydrate, VFA's, lipid and amino acids for various physiological functions with changes in productive states. However, we are currently limited to the use of transfer coefficients derived from equations for an application level model because of the limitations in predicting end products of ruminal fermentation, absorbed carbohydrate and amino acids, and the infinite metabolic routes connecting the numerous tissue and metabolic compartments, the multiple nutrient interactions, and the sophisticated metabolic regulations which drive the partioning of absorbed nutrients in various productive states. Pitt et al. (1993) has described the prediction of ruminal fermentation end products within the CNCPS structure as a first step. The equations used to predict ME from DE reflect the variation in methane produced across a wide range in diets. The equations used for lactating dairy cows to predict NE_l from ME reflect the energetic efficiency associated with the typical mix of metabolites in the ME, based on respiration chamber data (Moe, 1981), and validated reasonably well on independent data (Roseler, 1993). The equations used for growing cattle to predict NE_m and NE_g reflect the wide variation in metabolites used in growing cattle and dry cows, and validated with little bias with our unpublished data across a wide range of ME contents.

6. **Prediction of feed biological values.** Table 2 shows feed biological values predicted for the feeds shown in table 1. The top section shows tabular DIP and UIP and 1xTDN values from our feed library. The 1xME and $3xNE_l$ values are predicted from the Dairy NRC (1989) equations. The ME equation gives a variable DE efficiency, ranging from 83% for the brome hay to 89% for the corn. The ME efficiency for NE_l ranges from 59% for the brome hay to 61% for the corn, based on the 1x ME and 3x NE_l. The efficiency of ME use for NE_g ranges from 27% for the brome hay to 47% for corn. The negative NE_g value for brome hay at a low pH shows the effect of extrapolating equations beyond the range of the data. Shown next are biological values generated by the CNCPS for 2, 4, 6 and 8%/h, the range in passage rates typical for the feeds at 1x to 4x level of intake. For a cow producing 50 kg milk, CNCPS predicted intake is 4x and passage rates are 4 to 6%/h for the forages and 8%/h for the concentrates. The passage rates would be about half these values at 1x level of intake, which is typical for dry cows. The passage rate can also vary, depending on feed eNDF value. Within each of these categories, feed TDN, ME, NE_l, NE_g and MP from microbial true protein (MTP) are predicted, and at 8%/hr are predicted for both the high (6.5) and low (5.7) ruminal pH that can occur. The first observation is that percent of protein escaping ruminal fermentation varies considerably depending on passage rate. It is of particular importance in those feeds high in B2 protein, such as soybean meal. Passage rate has little effect on escape protein in feeds (such as corn silage) with a high proportion of B1 and B3 protein. The adequacy of the tabular values for DIP and UIP depend on the level of intake of the cow. Passage rate had the greatest effect on feed energy values for forages, because of their lower intestinal digestibility. Rumen pH had a dramatic effect on both forage energy value and MTP. These values reflect a 0% digestion rate for the available NDF at the low pH and approximately 40% less MTP yield from A and B1 carbohydrates.

Table 2. Predicted biological values of feeds (1,2,3)

Item	Unit	Corn Sil 40% GR	Brome Hay M. Bloom	Alfalfa Hay M. Bloom	Corn Dry Grain 56	Corn HM Grain 56	Soybean Meal - 49	Soybean Whole	Soybean Whl. Roast
			Tabular Values						
DIP	% CP	71	60	62	38	40	58	78	35
UIP	% CP	29	40	38	62	60	42	22	65
TDN	% DM	66	56	60	89	88	84	91	91
ME	Mcal/kg	2.49	2.04	2.22	3.49	3.47	3.29	3.60	3.60
NEl	Mcal/kg	1.50	1.25	1.35	2.05	2.04	1.94	2.11	2.11
			@ Passage Rate of 2%/h						
DIP	% CP	79	63	71	64	77	84	87	58
UIP	% CP	21	37	29	36	23	16	13	42
TDN	% DM	70	60	60	85	86	86	86	84
ME	Mcal/kg	2.66	2.24	2.22	3.31	3.38	3.36	3.39	3.28
NEl	Mcal/kg	1.72	1.44	1.43	2.13	2.18	2.17	2.18	2.12
NEg	Mcal/kg	1.13	0.79	0.78	1.59	1.63	1.62	1.64	1.57
MTP	g/kg	62	48	51	71	79	73	60	48
			@ Passage Rate of 4%/h						
DIP	% CP	75	58	63	52	72	75	81	46
UIP	% CP	25	42	37	48	28	25	19	54
TDN	% DM	65	53	57	82	85	85	85	84
ME	Mcal/kg	2.45	1.92	2.1	3.21	3.32	3.33	3.34	3.28
NEl	Mcal/kg	1.58	1.23	1.35	2.07	2.14	2.14	2.15	2.11
NEg	Mcal/kg	0.96	0.52	0.68	1.52	1.59	1.60	1.61	1.57
MTP	g/kg	55	36	46	61	74	66	55	43
			@ Passage Rate of 6%/h						
DIP	% CP	72	54	58	45	68	68	76	38
UIP	% CP	28	46	42	55	32	32	24	62
TDN	% DM	62	49	56	80	83	84	84	84
ME	Mcal/kg	2.32	1.74	2.02	3.13	3.27	3.3	3.3	3.28
NEl	Mcal/kg	1.5	1.12	1.3	2.02	2.1	2.13	2.13	2.11
NEg	Mcal/kg	0.86	0.36	0.61	1.46	1.58	1.58	1.58	1.57
MTP	g/kg	50	33	43	54	70	61	51	39
			@ Passage Rate of 8%/h						
DIP	% CP	69	51	54	39	65	63	72	33
UIP	% CP	31	49	46	61	35	37	28	67
@ pH = 6.5									
TDN	% DM	60	47	54	79	83	84	84	84
ME	Mcal/kg	2.23	1.63	1.97	3.07	3.22	3.28	3.28	3.27
NEl	Mcal/kg	1.44	1.05	1.27	1.98	2.08	2.12	2.11	2.11
NEg	Mcal/kg	0.79	0.26	0.57	1.42	1.53	1.57	1.57	1.56
MTP	g/kg	46	30	41	48	66	57	48	36
@ pH = 5.7									
TDN	% DM	52	36	49	78	82	83	82	84
ME	Mcal/kg	1.88	1.13	1.74	3.03	3.18	3.26	3.19	3.3
NEl	Mcal/kg	1.21	0.73	1.12	1.95	2.05	2.1	2.06	2.12
NEg	Mcal/kg	0.49	-0.25	0.36	1.39	1.50	1.55	1.51	1.58
MTP	g/kg	21	10	20	27	38	33	27	21

1. Tabular TDN Values are 1X maintenance from Van Soest, 1994.
2. Tabular ME and Tabular NEl are computed from 1989 dairy NRC equations; ME is 1X and NEl is 3X maintenance, all other values are predicted by the CNCPS.
3. MTP is microbial true protein yield, predicted as 15.4% of ruminally degraded organic matter. Microbial yield is reduced by 40% at pH = 5.7.

ADJUSTING ANIMAL AND DIETARY FACTORS TO PREDICT ACTUAL PERFORMANCE

The previous discussion indicates acccurate prediction of energy and amino acid supply depended on prediction of NDF, starch, CP and protein solubility pool sizes and their digestion and passage rates, and microbial amino acid composition. Prediction of absorbed energy and amino acid requirements depended on accurate prediction of protein retained, amino acid tissue composition, and efficiency of use of absorbed energy and protein. We believe that with adequate feed composition values and knowledge of how to use input values, models such as the CNCPS that have an appropriate structure for accounting for these variables can be used as a beginning point to predict ME, NE, and amino acid requirements and supply. First, the animal, environmental and feed compositional factors must be described as accurately and completely as possible. However, because many of the factors (body size, environmental conditions, feed digestion rates, particle size, etc.) depend on field observation, the input factors must be adjusted in a logical way until the model predicts the performance that is being observed before alternatives can accurately be evaluated. This approach allows requirements to be computed for the specific animal, environmental, DMI and feed compositional conditions.

We have developed the following sequence of steps in using the CNCPS to determine the first limiting nutrient (energy, absorbed protein, amino acids) for specific conditions, based on our use of the CNCPS in designing experiments and in conducting field case studies (Roseler, 1991; Fox et al., 1992; Stone et al., 1992). This hierarchy is necessary, beacuse of the "ripple effect" of all of the interactions in the model. When one factor is altered, several others will likely be affected. The hierarchy inherent in the CNCPS assumes energy is first limiting, and amino acid requirements are supplied to meet the energy requirement for maintenance, pregnancy, or daily gain or milk production from the energy intake over that needed for maintenance and pregnancy.

1. **Accurately determine DMI, and compare it to that expected.** The actual dry matter intake must be accurately determined, taking into account bunk clean out, moisture content of feeds and scale accuracy. The accuracy of any model prediction is highly dependent on the DMI used. Intake of each feed must be as uniform as possible over the day, because as far as we know all field application models assume a total mixed ration with steady state conditions.

2. **Compare energy allowable to observed milk production or daily gain.** The daily gain or milk production being obtained should agree with those predicted from the diet considering animal type, environmental conditions, feed intake and diet feedstuff carbohydrate composition. If not, the user should evaluate the following.

a. *Predicted change in body condition score, based on diet energy excess or deficiency.* In the case of lactating and dry cows, the predicted energy balance compared to observed days over which animal condition will change one score are excellent indicators of the diet energy balance being achieved. However, predicted and observed body condition scores should agree.

b. *Animal inputs.* Mistakes or incorrect judgements about inputs such as body size, milk production and its composition, environmental conditions or feed additives are often made.

c. *Feed factors that may be influencing energy derived from the diet* as the result of feed compositional changes, and possible effects on digestion and passage rates. The ME derived from forages are most sensitive to NDF amount and % of the NDF that is lignin, available NDF digestion rate, and eNDF value. After making sure the feed composition values are appropriate, the digestion rate is considered. Adjustments are made, using the ranges and descriptions in table 6 of Sniffen et al. (1992). If the rumen pH is below 6.2, the digestion rate should be reduced; we are in the process of automatically making that adjustment, based on pH predicted from eNDF. We next check the assignment of eNDF; it is used in computing passage rate. If too low, passage rate may be too high, reducing predicted ME value. The major factors influencing energy derived from feeds high in NSC are ruminal and intestinal starch digestion rate. This is mainly a concern when feeding corn and/or corn silage. We adjust this value based on appearance of corn in the manure, using the values in table 7 of Sniffen et al. (1992) as a guide.

3. **Make adjustments to insure effective fiber requirements are being met.** In high producing cows or high energy fed feedlot cattle, it is difficult to balance fiber requirements because of the increase in energy density needed to meet energy requirements for maximum production. Based on Pitt et al. (1993), we make adjustments to insure that diet eNDF is a minimum of 20% in lactating cows, or growing cattle where forage utilization is important. As much as 25% eNDF may be required to maintain an adequate pH, depending on feeding management. In beef cattle fed high concentrate diets, a minimum of 8% is required to keep cattle on feed under typical feedlot conditions; under these low pH conditions (pH below 6) microbial yield will be reduced at least a third by the CNCPS, and very little energy will be derived from the fiber in forages fed, and the SC digestion rate should be set at 0. The eNDF is that required to keep rumen pH averaging above 5.6 to 5.7, the threshold below which cattle stop eating (R. Britton, University of Nebraska, personal communication).

4. **Balance the rumen for nitrogen.** Feeds such as soybean meal that are high in degradable true protein are added until ruminal peptide needs are met if amino acids are expected to be deficient; they are required for optimal fermentation of nonstructural carbohydrates. Then adjust remaining ruminal nitrogen requirements with feeds high in NPN or soluble protein until ammonia needs are met. In addition to maximizing microbial amino acids supplied, the total tract digestion of both fiber (Sniffen et al., 1992) and starch (Sniffen et al., 1992; Theurer, 1991) are dependent on the extent of ruminal fermentation.

5. **Balance the animal's metabolizable protein (MP) requirements.** This component represents an aggregate of nonessential amino acids and essential amino acids. The MP requirement is determined by the animal type and the energy allowable gain or milk production. The adequacy of the diet to meet these requirements will depend on microbial protein produced from structural and nonstructural carbohydrate fermentation and feed protein escaping fermentation. If MP balance appears to be unreasonable, we check first the starch (Carbohydrate B1) digestion rates, using the ranges and descriptions in Sniffen et al. (1992) tables 4, 5 and 6 for Carbohydrate B1. Altering the amount of degradable starch will also alter the peptide and total rumen N balance, because of altered microbial growth. Often the most economical way to increase MP supply is to increase microbial protein production by adding highly degradable sources of starch, such as processed grains. Further adjustments are made with feeds high in slowly degraded or rumen escape (bypass) protein (low Protein B2 digestion rates; see tables 4, 5 and 6, Sniffen et al., 1992).

6. **Compare essential amino acids supplied to requirements.** This is last to be adjusted, because the amino acid balance is affected by changes made in all of the preceding. Essential amino acid balances can be estimated within the structure of the CNCPS because the effects of the interactions of intake, digestion and passage rates on microbial yield, available undegraded feed protein and estimates of their amino acid composition can be predicted along with microbial, body tissue and milk amino acid composition. However, the development of more accurate feed composition and digestion rates, and more mechanistic approaches to predict utilization of absorbed amino acids will result in improved predictability of diet amino acid adequacy for cattle. Sources of first limiting essential amino acids are adjusted where practical to improve the amino acid profile. In preliminary studies, energetic efficiency appeared to improve as essential amino acid profiles approached that of requirements (Fox et al., 1995).

AN EXAMPLE APPLICATION IN A NEW YORK DAIRY HERD

The same CNCPS model is used for all classes of beef and dairy cattle. Data from an actual dairy herd where the CNCPS has been used for the past 2 years will be used as an example because it demonstrates the principles and procedures described previously. This case study has been described in detail by Stone et al. (1992). When we began using the CNCPS in this herd in June of 1992, the average milk production was 10,953 kg. The changes made by using the CNCPS were estimated to save $74,600 the first year. The herd average is now over 11,818 kg milk, and manure analysis indicate that nitrogen excretion has been reduced about a third. In a study in progress to evaluate plasma urea nitrogen levels relative to conception rates in 20 New York herds, PUN levels are about 20% lower in this herd than in

Table 3. Results of CNCPS in a field application (1) and sensitivity analysis in response to changes in selected inputs.

	Base June 1991	Re-Bal March 1992	Sensitivity Analysis				
			DMI (2)	NDF (3)	eNDF (4)	SolP (5)	Starch (6)
Diet, kg DM/d							
Corn Silage	5.76	7.58	6.81	7.58	7.58	7.58	7.58
Alfalfa Silage	2.40	2.95	2.65	2.95	2.95	2.95	2.95
HMEC	4.95	7.44	6.69	7.44	7.44	7.44	7.44
Treated SBM		3.27	2.94	3.27	3.27	3.27	3.27
SBM	4.72	1.32	1.18	1.32	1.32	1.32	1.32
WCS	2.54	2.63	2.36	2.63	2.63	2.63	2.63
Protein Mix	0.45						
Corn grain	2.09						
Tallow	0.23						
Minerals	0.32	0.91	0.82	0.91	0.91	0.91	0.91
Total DMI, kg	23.5	26.1	23.4	26.1	26.1	26.1	26.1
Predicted DMI,kg	23.7	25.5	25.5	25.5	25.5	25.5	25.5
Level of Intake, xM	3.6	4.0	3.6	4.2	4.0	4.0	3.9
Diet CP, % DM	20.2	18.2	18.2	18.2	18.2	18.2	18.2
DIP, % CP	61	56	57	56	56	54	56
NSC, % DM	40	44	44	49	44	44	44
NEl, Mcal/kg	1.76	1.72	1.72	1.79	1.72	1.72	1.69
Actual Milk, kg	43.4	49.1	49.1	49.1	49.1	49.1	49.1
ME Allowable Milk, kg	43.3	47.3	41.7	50.1	47.3	47.1	45.4
ME Balance, Mcal	-0.1	-2.0	-8.1	1.0	-2.0	-2.2	-4.0
MP Balance, g	186	266	-13	328	99	365	-209
MP from Bacteria, g	1501	1651	1516	1639	1465	1658	1203
MP from Feed, g	1454	1729	1501	1739	1746	1822	1729
Bact N Balance, g N	140	59	55	61	106	42	177
Peptide Balance, g N	79	-3	3	-13	23	17	74
Urea Cost, Mcal	0.96	0.48	0.00	0.59	0.49	0.66	1.11
Days to CS change	2253	141	35	284	146	129	71
eNDF Supplied, kg	4.9	5.0	4.5	4.2	3.8	5.0	5.0
eNDF Required, kg	4.7	5.2	4.7	5.2	5.2	5.2	5.2
Predicted ruminal pH	6.30	6.24	6.24	6.11	6.04	6.24	6.24
Predicted PUN, mg %	16.4	13.0	10.0	14.0	13.0	15.0	17.0
Limiting AA	MET	MET	MET	MET	MET	MET	MET
Limiting AA, % Req.	102	107	99	109	98	109	85

1. Diets and animal parameters specified as per Stone, et. al. ,1992
2. Dry Matter intake reduced in the rebalanced diet to the level of the base (June 1991).
3. NDF composition of feedstuffs were reduced by 1 SD as reported by the Northeast DHIA Forage Testing Laboratory.
4. Effective NDF values of all feedstuffs were reduced by 25%.
5. Protein solubility of feedstuffs were reduced by 1 SD as reported by the Northeast DHIA Forage Testing Laboratory.
6. Starch digestion rate of the HMEC was reduced to 5%/h and gross intestinal digestibility was reduced to 50%.

nearly all of the other herds. Initial data from the high producing mature cows will be used to demonstrate how the model was used to predict requirements and feed utilization, to formulate more efficent and cost effective rations, and to adjust for various conditions encountered during this time.

These evaluations are summarized in table 3. The base ration and evaluation is the diet that was being fed to this group before applying the CNCPS. Predicted and measured DMI were within good agreement, and the CNCPS predicted that the cows were just in energy balance. The MP balance was within reason considering our recommendation of a 5% safety factor, and the requirement for the first limiting amino acid (methionine) was just being met. The effective NDF requirement was being met, giving a predicted rumen pH of 6.3, which would allow maximum microbial growth for the energy and protein ruminally available. Thus when inputs for the cows, environment and feeds were accurately described, the CNCPS predicted the observed response (43.5 kg milk). However, the excess of ammonia, peptides and MP resulted in a predicted plasma urea nitrogen of 16.4 mg%. The CNCPS rebalanced ration (Re-Bal) is for a period after the ration adjustments had stabilized and milk production had increased steadily to 49 kg. The diet protein had been decreased by two percentage units, with an improved overall balance of all 4 nitrogen pools (rumen ammonia and peptides, MP, and essential amino acids). Also the number of ingredients were decreased by balancing the 4 nitrogen pools rather than having to use complex mixtures to be sure all bases were covered. Primary changes were to increase microbial yield with more fermentable carbohydrates and to replace some of the soybean meal with less degradable soybean meal (treated SBM). Actual milk production now exceeded ME allowable milk even after adjusting maintenance requirements for energy cost to excrete the excess nitrogen (urea cost). Based on our data, we assume this to be due to improved EAA balance. Intake was also now exceeding predicted by .59 kg/d.

The next evaluation (2) shows what happened when intake dropped 2 kg during hot weather; ME allowable milk production declined 7.5 kg. When input temperature was changed to actual, the decline in intake was accurately predicted. One of the results of instituting the CNCPS was setting up a DMI monitoring program, and plotting predicted vs actual. This provided a tool for diagnosing problems, avoiding the usual trial and error approach to solving the decline in milk production.

In the next evaluation (3), forage NDF declined, which increased ME balance 3 Mcal and energy allowable milk 2.7 kg and increased MP and methionine balance because of increased microbial growth. However, effective NDF requirements are not being met, and pH is predicted to be borderline.

The next evaluation (4) represents a situation in which diet effective NDF declined. The MP from bacteria declined 186 g/d because eNDF requirement was not met and rumen pH dropped to 6.04 and methionine became deficient. In the next evaluation (5), protein solubility declined, increasing MP from feed by 93 g/d.

The last evaluation (6) shows what happened when the corn harvested had a high percentage of small, hard, whole kernels in the corn silage and ensiled high moisture corn and a lot of corn kernels were observed in the manure. Ruminal starch digestion rate was lowered to 5%/h and intestinal starch digestibility was lowered to 50% to adjust for this condition. The lower ruminal starch digestibility reduced MCP yield 448 g/d, resulting in a deficiency of MP and methionine. The effect of the combination of escaping more starch and a lowered intestinal digestibility resulted in 2 Mcal less ME/day, and lowered energy allowable milk 1.8 kg.

CONCLUSIONS

In the 21st century, producing meat and milk from cattle will become more efficient in the use of nutrients by using models to accurately predict requirements and feed utilization in each unique production setting. These models must allow inputs from each situation to be adjusted in a logical way until the cattle and feeds are accurately described. Then when predicted and observed performance (daily gain, milk amount and composition, and body condition score changes) agree, improved feeding programs can be accurately formulated for that unique situation where nutritional safety factor and nutrient excretion are minimized. The challenge will be to develop systems that are aggregated at a level that can accurately reflect our understanding of the underlying biology, yet be usable on farm considering information available, ability to monitor and quantify key input variables and animal responses, and knowledge and time available of the consultant using the models.

REFERENCES

Ainslie, S.J., Fox, D.G., Perry, T.C., Ketchen, D.J. and Barry, M.C. 1993. Predicting metabolizable protein and amino acid adequacy of diets fed to lightweight Holstein steers. J. Anim. Sci. 71:1312.

Beaucheamin, K.A. 1991. Ingestion and mastication of feed by dairy cattle. In Veterinary Clinics of North America: Food Animal Practice. Volume 7, No. 2, July 1991.

Fox, D.G., Sniffen, C.J., O'Connor, J.D., Van Soest, P.J. and Russell, J.B. 1992. A net carbohydrate and protein system for evaluating cattle diets. III. Cattle requirements and diet adequacy. J. Anim. Sci. 70:3578.

Fox, D.G., Barry, M.C., Pitt, R.E., Roseler, D.K. and Stone, W.C. 1995. Application of the Cornell net carbohydrate and protein model for cattle consuming forages. J. Anim. Sci. 73:267.

Mertens, D. 1988. Balancing carbohydrates in dairy rations. Proc. Large Dairy Herd Management Conference, Dept. of An. Sci., Cornell Univ. pg 150.

Moe, P.W. 1981. Energy metabolism of dairy cattle. J. Dairy Sci. 64:1120.

NRC. 1989. Nutrient Requirements of Dairy Cattle. National Academy Press, Washington, DC.

O'Connor, J.D., Sniffen, C.J., Fox, D.G. and Chalupa, W. 1993. A net carbohydrate and protein system for evaluating cattle diets. IV. Predicting amino acid adequacy. J. Anim. Sci. (71:1298).

Pitt, R.E., Van Kessel, J.S., Fox, D.G., Barry, M.C. and Van Soest, P.J. 1993. A model of ruminal volatile fatty acids produced from carbohydrate fermentation based on the Cornell net carbohydrate and protein system. Agric. and Biol. Eng. Staff Rep. No. 93-2, Anim. Sci. Mimeo No. 167.

Roseler, D.K. 1991. The use of nutrition models in the commercial feed industry. Proc. Cornell Nutr. Conf.:66.

Roseler, D.K. 1994. Development and evaluation of feed intake and energy balance prediction models for lactating dairy cattle. PhD Thesis, Cornell University, Ithaca, NY.

Russell, J.B., O'Connor, J.D., Fox, D.G., Van Soest, P.J. and Sniffen, C.J. 1992. A net carbohydrate and protein system for evaluating cattle diets. I. Ruminal fermentation. J. Anim. Sci. 70:3551.

Sniffen, C.J., O'Connor, J.D., Van Soest, P.J., Fox, D.G. and Russell, J.B. 1992. A net carbohydrate and protein system for evaluating cattle diets. II. Carbohydrate and protein availability. J. Anim. Sci. 70:3562.

Stone, W.C., Chase, L.E. and Fox, D.G. 1992. Field Application of the Cornell Net Carbohydrate and Protein System in a progressive dairy herd. Proc. Cornell Nutr. Conf.

Theurer, C.B. 1991. Update of ruminal by-pass story with emphasis on energy sources. In: Proc. Southwest Nutr. and Management Conf. p 107. Tempe, AZ.

Tylutki, T.P., Fox, D.G. and Anrique, R.G. 1994. Predicting net energy and protein requirements for growth of implanted and nonimplanted heifers and steers and nonimplanted bulls varying in body size. J. Anim. Sci. 72:1806.

Van Soest, P.J., Robertson, J.B. and Lewis, B.A. 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. J. Dairy Sci. 74:3583.