Application of Physically Effective Fiber in Diets for Feedlot Cattle

D. G. Fox and L. O. Tedeschi
Animal Science Department
Cornell University
Ithaca, NY

Introduction

Feeds high in fiber are included in backgrounding diets to prevent excessive fat deposition during early post weaning growth, to market forage and to change marketing date, and in high energy finishing diets to control acidosis. In backgrounding diets, the fiber inclusion level depends on maximum acceptable ADG to control fat deposition and cost of gain. In some finishing diets, it is desirable to find the combination of forage and concentrate feeds that will maximize ADG without reducing cell wall digestion. In most finishing diets, however the fiber inclusion level is that needed to control acidosis and keep the cattle on feed. Historically, the inclusion level for forage to achieve the above objectives has been set based on experience and some experimental evidence. The effect of fiber level on animal performance is highly related to its effect on rumen health and its functionality, and animal requirements relative to the end products of rumen fermentation. To predict dietary fiber level required to achieve the desired animal performance, the variables that must be accounted for are level of intake of fermentable cell wall and non cell wall carbohydrates and their rates of digestion and passage, the effect of fiber intake and particle size on rumination and rumen pH, microbial nitrogen requirements and yield, intestinal digestion, and animal tissue requirements. Given the complexity of the interactions among these variables, it is apparent that fiber requirement is not a constant, and must be determined in each unique production situation. Therefore, a ruminal model is needed to account for the effects of these variables and their interactions.

The 7th Revised Edition of the National Research Council Nutrient Requirements of Beef Cattle (NRC, 2000) included the rumen model of the Cornell Net Carbohydrate and Protein System (CNCPS) as described by Russell et al. (1992), Sniffen et al. (1992), and Fox et al. (1992, 1995) in its' model level 2 solution to account for these effects. The most recent update of this model is in CNCPS version 5.0, which also contains the NRC (2000) requirements. The purpose of this paper is to explain how the CNCPS rumen model works and can be applied for evaluating fiber level in feedlot diets, and how the new CNCPS rumen model under development will evaluate diet fiber levels in a more dynamic way.

Prediction of Ruminal Degradation of Fiber and Non-fiber Carbohydrates

Ruminal fermentation and nutrient escape in the CNCPS model is predicted from intake of feed carbohydrate and protein fractions, their unique rates of digestion and passage, and microbial growth on the fiber carbohydrates (FC) and non-fiber carbohydrates (NFC) consumed at a particular rumen pH.

The importance of stimulating salivary flow in buffering the rumen is well documented (Beauchemin, 1991). The data of Welch (1986) indicate particle size and density, and hydration rate, affect chewing and rumination time. In the CNCPS, the growth rate of bacteria that digest available FC and NFC depends on rumen pH, which is predicted from percentage of NDF in the diet and effectiveness of the NDF in stimulating chewing and rumination (eNDF). The percentages of FC and NFC that are fermented in the rumen vary, depending on digestion and passage rates. 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 post-ruminally, the proportion depending on rates of digestion and passage of the protein fractions in the feeds. There are four N fraction requirements that must be met in evaluating a ration with the CNCPS; for two microbial categories (ammonia for the FC and peptides and ammonia for the NFC fermenting bacteria), and for two animal requirement categories (MP and essential amino acids). In evaluating a diet, one must be able to determine how well all four requirements are being met.

In the CNCPS, rumen microorganisms are categorized into those that ferment FC and NFC, as described by Russell et al. (1992). The FC microorganisms ferment cellulose and hemicellulose and grow more slowly, and utilize ammonia as their primary N source for microbial protein synthesis. The NFC microorganisms ferment starch, pectin and sugars, grow more rapidly and can utilize ammonia and amino acids as N sources. The FC and NFC microorganisms have different maintenance requirements (the CNCPS assumes 0.05 and 0.15 g of carbohydrate per g of microorganism per hour, respectively), and efficiency of growth of NFC digesting bacteria is optimized at 14% peptides as a percentage of NFC. These values are conservative and are based on the observations 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 NFC and FC to meet respective microbial growth requirements. The rate of microbial growth of each category is directly proportional to the rate of carbohydrate digestion, as long as a suitable N source is available. When ruminal N is deficient, ruminal degradation of CHO fractions and microbial protein produced are reduced to the level allowed by the N available in the rumen (Tedeschi et al., 2000). The extent of digestion in the rumen depends on digestion rates of FC and NFC feed fractions and how rapidly these fractions pass out of the rumen. Therefore, the extent of digestion depends on factors such as level of intake, particle size, rate of hydration, lignification, and inherent characteristics of each carbohydrate and protein fraction.

Accounting for the Effects of Diet eNDF Content on Ruminal pH and Fermentation

Experimental data (Swingle et al., 1990; Zinn et al., 1990; Poore et al., 1993; Knowlton et al., 1998) and evaluations with the CNCPS (Fox et al., 1995) have indicated a high extent of rumen fermentation is desirable to maximize total tract starch and fiber digestion and microbial amino acid production. However, a high rate and amount of ruminal starch digestion leads to a decline in rumen pH, causing a reduction in microbial protein synthesis (Russell et al., 1992), cell wall digestion (Pitt et al., 1996) and acidosis (Owens et al., 1996). Owens et al. (1996) indicated the level of and type of

concentrates in the diet and degree of processing were all strongly related to the rate of starch fermentation and level of sub-clinical acidosis. They indicated the most common management practices that help prevent acidosis are diluting the diet with roughage and regulating starch intake. Beauchemin (1991) and Mertens (1997) indicated characteristics of the feed that stimulate chewing and rumination are highly important in maintaining a desirable rumen pH.

Smith and Waldo (1969) and Mertens (1985, 1986) found that this feed characteristic (effective NDF) (eNDF) could be quantified by determining the feed NDF content, then measuring the percent of the NDF remaining on a 1.18 mm screen after vertical shaking of the dry feed. Mertens (1997) indicated particles smaller than this readily pass out of the rumen and provide little stimulus for chewing. Values reported by Mertens (1986) were used to develop the eNDF values in the CNCPS (Sniffen et al., 1992), which were used in the NRC (2000) and CNCPS feed composition tables. Some feed eNDF values reported by Sniffen et al. (1992) were adjusted for density, hydration and degree of lignification of the NDF, based on practical judgment of the authors. Using data in the literature, Pitt et al. (1996) evaluated several approaches to predicting rumen pH; diet content of forage, NDF, a mechanistic model of ruminal fermentation, or the eNDF values published by Sniffen et al. (1992). Pitt et al. (1996) developed an equation (figure 1A) that gave predictions of ruminal pH similar to the mechanistic model for diet eNDF values lower than 35%, with the advantage of simplicity and flexibility in application. This equation is used in the CNCPS to predict pH. When diet eNDF is greater than 24.5, computed ruminal pH is held constant at 6.46 (Figure 1A). Figure 1A indicates the points from the steer diet eNDF data used in the development of the equation had a better fit than the sheep and dairy cow data. These data points gave an equation in which pH = 0.0392×eNDF + 5.4929, with an r^2 of 75.4%. This equation gives nearly the same pH at a diet peNDF of 8% (typical of high energy feedlot diets) as the Pitt et al. equation (figure 1) used in the model (5.80 vs 5.76, respectively). *Thus the CNCPS pH equation is applicable to feedlot cattle.*

Mertens (1997) differentiated between eNDF and physically effective NDF (peNDF), which he described as the physical characteristics of fiber (primarily particle size) that influence chewing and rumination activity; *thus the percentage of the NDF retained on a screen with 1.18 mm openings after dry sieving is the procedure for measuring peNDF*. Mertens (1997) found that 71% of the variation in rumen pH was accounted for by peNDF. Thus the CNCPS eNDF values are more correctly defined as peNDF, since most are based on the % of NDF retained on a 1.18 mm screen as described by Mertens (1997). The CNCPS version 5.0 includes the CPM Dairy feed library, in which the eNDF values have been revised to correspond to the peNDF values of Mertens (1997).

The data of Russell et al. (1992) and Pitt et al. (1996) showed that rumen pH below 6.2 results in linear reductions in microbial protein production and FC digestion rate. In the CNCPS, microbial yield is reduced 2.5% for each percentage unit reduction in eNDF below 20 percent, and the equations of Pitt et al. (1996) are used to adjust FC digestion rate. Figure 1B shows the decline in digestion rate for four forages with different digestion rates (4, 6, 8 and 10%/hour when rumen pH is above 6.2). This figure shows that forages with high digestion rates under optimum rumen pH conditions (typically those low in lignin) are the most affected by this adjustment since this adjustment sets the NDF digestion rate to 2.2 to 2.4%/h at pH 5.7 independently of the optimum NDF digestion rate.

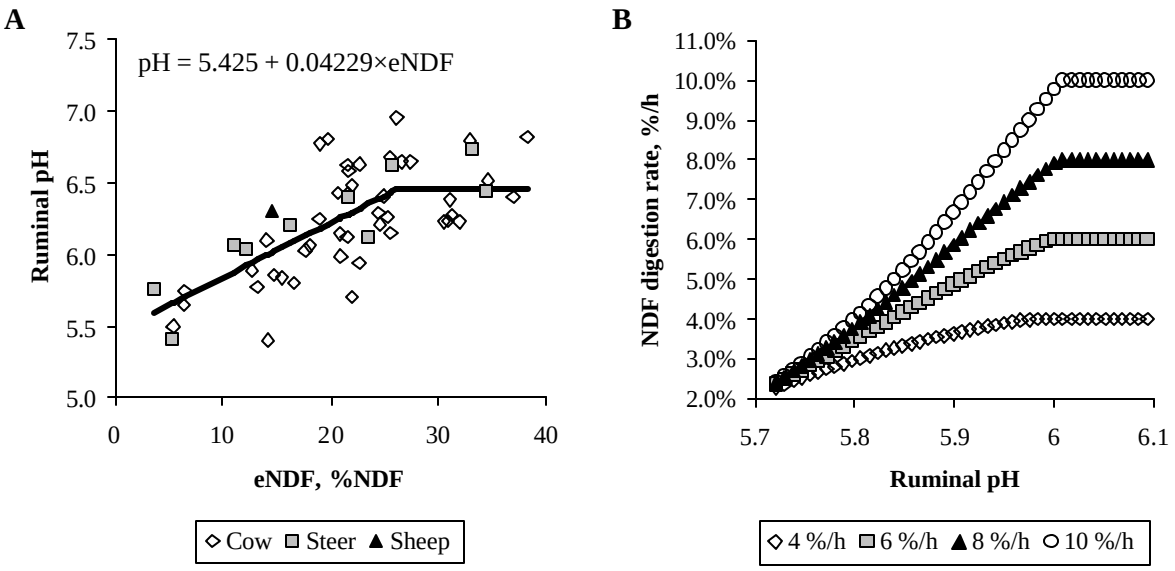

Figure 1. (A) Relationship of eNDF and ruminal pH. (B) effect of ruminal pH on NDF digestion rate for four forages with different FC degradation rates at optimal rumen pH (4, 6, 8 and 10%/h).

Mertens (1997) developed the following table to use as a guide in determining peNDF from his experimental data base. For example, a coarsely chopped grass hay with an NDF of 65% has a peNDF of 62% eNDF (65×0.95).

Table 1. Physical effectiveness factors (PEF) for feeds with different physical forms[1]

Physical form class	TLC[2] cm	PEF factor[3]	Grass hay	Grass silage	Corn silage	Alfalfa hay	Alfalfa silage	Conc.
Forage								
Long		1.00	Long					
Coarse chopped	4.8 to 8	0.95	Coarse	Coarse		Long		
Med. to coarse chopped	2.4 to 4	0.90	Med.	Med.	Coarse	Coarse		
Med chopped	1.2 to 2.0	0.85	Fine	Fine	Med.	Med.	Coarse	
Med. to fine chopped	0.6 to 1.0	0.80			Fine	Fine	Med.	
Fine chopped	0.3 to 0.5	0.70					Fine	
Ground	0.15 to 0.25	0.40						
Concentrates								
Rolled		0.80						HM corn
Rolled		0.70						Barley
Coarse		0.60						Cracked corn
Medium		0.40						Medium corn
Fine		0.30						Fine/Pellet

[1] Mertens (1997).

[2] Theoretical length of cut.
[3] Proportion of NDF effective in stimulating chewing and rumination.

These tabular values for eNDF can be used as a guide in estimating peNDF of a feed. Additional factors not accounted for in the peNDF system that can influence rumen pH are total grain intake and its digestion rate, and form of grain (whole, rolled, and flaked corn will stimulate rumination but corn meal may not; a higher proportion of the starch in whole corn will escape ruminal fermentation compared to processed corn and other grains). Also forages that are highly hydrated (fresh forage or low DM silage) may not stimulate chewing as much as the same forage in a dry form. Therefore adjustments to peNDF must be made in these cases to make the system reflect these conditions. The effect of Ionophores on acidosis needs to be modeled; they inhibit the growth of *Streptococcus bovis*, which produces lactic acid, which is 10 times stronger than the normal volatile fatty acids produced in the rumen. Fermentation of highly digestible feeds that are high in pectin (soybean hulls, beet pulp, etc.) will not produce the drop in pH as grains do.

Setting peNDF Requirements for Beef Cattle Feedlot Diets

We recommend peNDF requirements of 7 to 10% in the ration DM for high energy rations. This recommendation is based on the eNDF predicted by the equation of Pitt et al. (1996) required to keep rumen pH above 5.7, the threshold below which cattle typically reduce intake (Britton and Stock, 1989). Strasia and Gill (1990) concluded that finishing rations for cattle should contain at least 7% "high roughage" factor; the feedlot case study evaluation presented later in this paper supports this recommendation. If the goal is to maximize cell wall digestibility to optimize forage utilization, the requirement is a minimum of 20% peNDF in the diet DM.

Accounting for peNDF Effects on Rate of Passage

The primary factors affecting passage rate of feeds through the digestive tract are intake and the competition between intake, degradation, and passage rates (Van Soest, 1994). The studies of Welch (1986) indicated particle size, density, and hydration rate also affect the passage rate of feeds. Calculation of ruminal degradation and escape of carbohydrate and protein fractions assume steady state conditions and are determined in the CNCPS by the following formulas, using digestion rates for each carbohydrate and protein fraction, and the passage rate equation which uses percentage of forage and percentage of eNDF (NRC 2000; Fox et al., 2000):

$$\text{Ruminally degraded} = \text{Amount} \times (Kd_{ij} / (Kd_{ij} + Kp_j))$$
$$\text{Ruminally escaped} = \text{Amount} \times (Kp_j / (Kd_{ij} + Kp_{ij}))$$

Where Kd_{ij} is degradation rate of the i^{th} fraction of the j^{th} feed and Kp_j is passage rate of the j^{th} feed.

Digestion rates are feed specific, and depend primarily on type of starch and protein, degree of lignification, and degree of processing (Sniffen et al., 1992; Fox et al., 2000). Ruminal passage rates are a function of level of intake, feed type (forage vs. grain) and particle size, which is represented by the feed peNDF value. Passage rates are computed as shown below.

$$kp_f = (0.38 + (22 \times DMI / SBW^{0.75}) + 2 \times FORAGE^2) / 100$$
$$kp_c = (-0.424 + (1.45 \times Kp_f)) / 100$$

Where DMI is dry matter intake, g/day, FORAGE is forage concentration in the diet, g/g, kp_f is forage passage rate, kp_c is concentrate passage rate, and SBW is shrunk body weight, kg.

The passage rates are adjusted for individual feed NDF and peNDF, using a multiplicative adjustment factor (Af) computed for the j^{th} feed by the equations below.

For forages:

$$Af_j = 100 / (NDF_j \times peNDF_j + 70)$$
$$Kp_j = kp_f \times Af_j$$

For concentrates:

$$Af_j = 100 / (NDF_j \times peNDF_j + 90)$$
$$kp_j = kp_c \times Af_j$$

Where $peNDF_j$ is physically effective NDF concentration of of the j^{th} feed, g/g.

Evaluating peNDF Levels in Feedlot Diets with the CNCPS: A Feedlot Case Study

Data from closeouts over a 12 month period of 8,624 steers fed corn based rations in a Kansas feedlot (Guiroy et al., 2001) were used to evaluate the effect of diet peNDF on predicted rumen pH, rumen NDF and starch digestion, and feed energy values, using CNCPS version 5.0. The steers had an average initial weight of 684 lb and an average final weight of 1,173 lb, DMI was 21.9 lb and ADG was 3.93 lb/day. The ration contained 7% chopped mature alfalfa hay and 83.5% corn (50% cracked and 50% flaked).

Feed composition. The first step is to characterize the chemical and peNDF composition of the feeds fed. Table 2 shows the feed composition values used for this case study. Feed composition for use in the CNCPS rumen model is described by carbohydrate and protein fractions and is used to compute the amount of FC and NFC available for each of the two microbial pools. Digestion rates have been developed for common feeds, based on data in the literature (Sniffen et al. 1992, NRC, 2000, Fox et al., 2000). Nearly all of the critical carbohydrate and protein fractions can be routinely determined by feed testing laboratories, using the methods described by Van Soest et al. (1991), such as NDF, lignin, CP, soluble protein, neutral and acid detergent insoluble protein (NDFIP and ADFIP, respectively). The first section of Table 2 shows the chemically determined fractions, the second section

shows the peNDF values, and the third section shows the digestion rates (kd) for carbohydrates (CHO) A (sugars and short oligosaccharides), B1 (starch and pectin) and B2 (ruminally available NDF) and for protein (PROT) fractions with fast (B1), intermediate (B2) and slow (B3) digestion rates. Based on discussions with the feedlot's consulting nutritionist, the feeds and their chemical composition and digestion rate information were chosen from the CNCPS version 5.0 feed library and the peNDF values were chosen from Table 1. Total carbohydrates are computed from these chemical composition values as 100 - (Crude Protein + Fat + Ash). Then carbohydrates are partitioned into fiber and and nonfiber by subtracting NDF from total carbohydrates, with the available fiber being NDF – NDFIP - (Lignin × 2.4). Then the amounts of starch and sugars are computed from their percentages in the nonfiber fraction.

Table 2. Composition of feeds in the feedlot case study

	Units	Alfalfa hay	Cracked corn	Flaked corn
Chemical composition				
NDF	% of DM	51.0	9.0	9.0
Lignin	% of NDF	20.4	2.22	2.22
Crude Protein (CP)	% of DM	13.0	9.80	9.80
Soluble CP	% of CP	27.0	11.00	8.0
NPN	% of Sol. CP	70.0	73.0	73.0
NDF Insoluble Protein	% of CP	29.0	15.0	15.0
ADF Insoluble Protein	% of CP	16.0	5.0	5.0
Starch	% of NFC	64.0	98.5	98.5
Fat	% of NFC	1.80	4.06	4.03
Ash	% of DM	9.00	1.46	1.46
Physical composition				
peNDF	% of NDF	90	60	70
Carbohydrate (CHO) and Protein (PROT) digestion rates (kd)				
CHO B1 kd (starch rate)	%/h	30	15.0	30.0
CHO B2 kd (NDF rate)	%/h	5.5	6.0	6.0
PROT. B2 kd	%/h	9.0	6.0	4.0
PROT. B3 kd	%/h	1.25	0.09	0.08
Starch intestinal dig.	%	75.0	75.0	95.0

Ruminal fiber and non fiber carbohydrate degradation and microbial protein production is predicted from the amounts of feed FC and NFC as described previously, and the integration of their rates of digestion and passage, which in turn determines the N requirements of each pool, microbial protein produced and MP available from this source, carbohydrates escaping digestion and digested postruminally and ME derived from the diet. Simultaneously, the degraded and undegraded protein pools are predicted, which are used to determine N 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 soluble protein is nearly all degraded in the rumen, and contains PROT A, which is the NPN, and PROT B1,which is true protein. The PROT B1 is computed as the difference between soluble protein and NPN. The acid detergent insoluble protein (ADFIP) is assumed to be unavailable, and is called the PROT C fraction. Nearly all of the PROT B3 fraction or slowly degraded protein fraction escapes ruminal degradation, and is computed by subtracting the value determined for ADIP from the value determined for NDFIP. The PROT B2 fraction, which is partly degraded in the rumen, depending on digestion and passage rates, is estimated as CP - (PROT B1 + PROT B3 + PROT C). Intestinal digestibility of the amino acids is assumed to be 100% for those in the PROT B1 and PROT B2, and 80% for those in the PROT B3 protein escaping ruminal degradation.

Predicted passage rate. Figure 2 shows the effect of eNDF on passage rate of the alfalfa with the NDF at 40, 60, 80, or 100 % eNDF. Passage rate increases as eNDF decreases because the smaller feed particle size does not have to be ruminated to pass out of the rumen. Note the slight increase in passage rate with increased diet forage % due to its' the "push" effect.

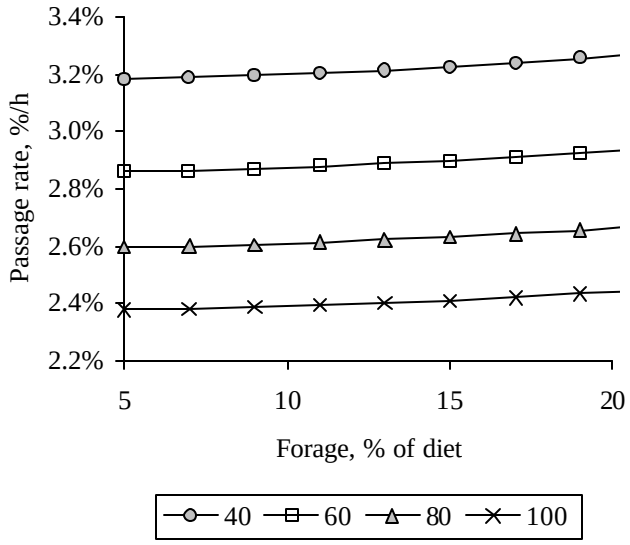

Figure 2. The effect of changing the peNDF% on passage rate (%/h) of alfalfa from 40 to 60, 80, or 100% with different levels of forage in the diet for the case study steer (avg. SBW of 920 lb with a DMI of 22 lb/d).

Model predictions for the case study. Table 3 shows predicted NDF and starch degraded in the rumen, microbial protein produced, and diet NE_m and NE_g values for four situations:

1. For the actual ration fed (base ration),

2. The base ration fed at a maintenance level of intake,
3. The base ration with peNDF factor reduced to 0.80 and 0.30 in the alfalfa hay and corn respectively, based on the values in Table 1, and
4. The proportions of alfalfa hay and corn changed to provide 20% diet peNDF.

The evaluation of the actual ration fed indicated it contained 8% peNDF, which results in a predicted rumen pH of 5.8. In agreement with the actual ADG of 3.93 lb/d, the predicted ADG was 3.92 lb/d. The ruminal degradability of the flaked corn is 11% higher than the cracked corn, mainly because of a higher starch digestion rate (Table 2). As a result, a greater amount of starch is digested, more MP from microbial protein is produced, and the NE_m and NE_g are 4 and 6% higher, respectively. The second evaluation shows these same values when this ration was fed at maintenance level (no ADG). Ruminal digestibilities for NDF and starch increase because of a slower rate of passage; as a result, NE_m and NE_g values increased. The third evaluation shows what happens if the peNDF factor is decreased to 0.80 for the alfalfa and 0.30 for the corn. The ration peNDF decreases to 5%, reducing the rumen pH to 5.6. As a result, percentage of the NDF that is digested in the rumen declines to zero, due to a very slow digestion rate. As a result, the alfalfa NE_m is reduced from 0.41 to 0.24 and the NE_g is reduced from 0.17 to 0.01, and MP from microbial protein for all three feeds is reduced. The last comparison shows the effect of increasing peNDF in the ration to 20%, the point above which NDF digestion rate is maximized. Compared to the actual ration fed, a higher percentage of the NDF is digested in the rumen compared to the actual feed fed, because of the higher rumen pH.

Table 3. Effect of level of intake and ration eNDF level on rumen degradability and NE values for a Kansas feedlot case study

	Mature alfalfa hay	Cracked corn	Flaked corn
Actual ration fed (base): peNDF = 8%, pH = 5.8 and predicted ADG = 3.92 lb/d[a]			
NDF, % rumen degraded	24.3	35.1	35.3
Starch, % rumen degraded	92.7	80.0	89.0
Starch rumen degraded, g/d	120	2535	2806
MP from microbial protein, g	28	256	315
NE_m, Mcal/lb	0.41	0.99	1.03
NE_g, Mcal/lb	0.17	0.68	0.71
Base ration at maintenance intake			
NDF, % rumen degraded	31.6	51.9	52.1
Starch, % rumen degraded	96.4	90.7	95.1
Starch rumen degraded, g/d	48	1115	1165
MP from microbial protein, g	12	115	133
NE_m, Mcal/lb	0.47	1.03	1.05
NE_g, Mcal/lb	0.22	0.71	0.73
Base ration at peNDF of 5%: pH = 5.6 and predicted ADG = 3.68 lb/d			
NDF, % rumen degraded	0	0	0
Starch, % rumen degraded	92.0	79.6	88.6
Starch rumen degraded, g/d	119	2521	2794

MP from microbial protein, g	19	222	272
NE_m, Mcal/lb	0.24	0.96	1.00
NE_g, Mcal/lb	0.01	0.65	0.69
Forage increased to 20% peNDF: pH = 6.3 and predicted ADG = 2.69 lb/d			
NDF, % rumen degraded	29.6	46.3	46.5
Starch, % rumen degraded	92.0	78.3	87.9
Starch rumen degraded, g/d	624	1598	1786
MP from microbial protein, g	217	218	279
NE_m, Mcal/lb	0.44	0.98	1.02
NE_g, Mcal/lb	0.19	0.67	0.71

[a] Actual ADG was 3.92 lb/day.

Prediction of feed net energy and metabolizable protein values. The CNCPS uses the feed carbohydrate and protein fractions digested ruminally and post ruminally to predict TDN. This TDN value is sensitive to carbohydrate and protein fraction pool sizes and their digestion rates, and passage depends on level of intake and particle size as indicated by feed eNDF value. Then DE is computed from TDN, ME is computed from DE, and NE_m and NE_g are computed from ME, using the NRC (2000) equations.

The coefficients used to predict intestinal digestibilities and fecal losses are 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, since high energy feedlot diets are high in NFC and over 75% of most ruminally available NFC are ruminally digested (table 3). Until carbohydrate digestion rates can be accurately and routinely measured, the use of a more complex intestinal submodel could result in a multiplication of errors.

The equations used to predict ME from DE reflect the variation in methane produced across a wide range in diets. The equations used to predict NE_m and NE_g reflect the wide variation in metabolites produced from the range in diets fed to growing cattle, accounted for 89 and 58% of the diet NEm and NEg, respectively with little bias (NRC, 2000). A metabolic submodel has to be able to predict heat increment and efficiency of use of absorbed carbohydrate, VFA, 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 vast metabolic routes connecting the numerous tissue and metabolic compartments, the multiple nutrient interactions, and the sophisticated metabolic regulations which drive the partitioning of absorbed nutrients in various productive states. Pitt et al. (1996) has described the prediction of ruminal VFA produced within the CNCPS structure as a first step.

Developing a Sub-Model to Estimate Ruminal pH from VFA Production

As discussed previously, factors other than peNDF may have a more systematic and predictive role in determining the ruminal pH. For example, Yang et al. (2001) reported that starch processing had a large effect on ruminal pH. Water intake and saliva flow dictate the amount of ruminal VFA that is washed out of the rumen. This wash out process has a large impact on the amount of VFA that has to be absorbed via the rumen wall (Allen, 1997). Therefore, the VFA content in the rumen and fluid dilution rate control the ruminal pH. Meng et al. (1999) demonstrated that increasing the dilution rate from 2.5 to 20% per h resulted in an increase on ruminal pH from 5.78 to 6.91. Russell (1999) suggested that when cattle are fed a large amount of grain, ruminal carbohydrate digestion, VFA production, and consequently ruminal VFA concentrations are much higher, but the fluid dilution rate is relatively slower than animals fed primarily hay. Under these conditions, a high proportion of the VFA produced in the rumen has to be absorbed there.

A dynamic ruminal sub-model based on the structure of the CNCPS model is being developed to account for the effects of ruminal VFA production, absorption, and fluid dilution rate on ruminal pH. There are several variables that must be accounted for in developing this dynamic model. The feeding behavior (feeding frequency, i.e. 1x, 2x, 3x per d; time spent chewing and ruminating, oscillation of eating pattern), has a large impact on the amount, type, and the time that carbohydrate is available for the ruminal bacteria (Dado and Allen, 1994). Accurate and consistent measurements of degradation rates have an effect on amount of carbohydrate degraded in the rumen; there are differences between degradation rates derived using different nonlinear functions (Fitzhugh, 1976). The fluid dilution rate (or liquid passage rate) has to be as accurate as possible in order to estimate the amount of VFA washed out of the rumen. Dynamics of VFA absorption in the rumen must be accounted for to ensure that models can predict the amount of available VFA for animal production of meat or milk (Dijkstra et al., 1993). The water intake (influx in the rumen) is also a part of the VFA absorption dynamics since it affects the rumen viscosity and therefore the free movement of VFA within the rumen (Russell, 1999).

In this dynamic ruminal sub-model, the rates of degradation of carbohydrates are used in an exponential function to estimate the amount of carbohydrates degraded and escaped during the simulation interval. Then, the amount of carbohydrate degraded is converted to acetate, propionate, butyrate, and lactate as described by Pitt et al. (1996) and Pitt and Pell (1997). A sub-model of ruminal lactate dynamics is also incorporated to estimate the amount of lactate converted to VFA. The model described by Dijkstra et al. (1993) is used to compute the amount of VFA absorbed and the liquid passage rate is used to compute the amount of VFA escaping the rumen. Several equations for computing pH from ruminal VFA concentration (mM) have been reported (Argyle and Baldwin, 1988; Tamminga and Van Vuuren, 1988). We developed an exponential equation (as shown below) to compute pH from VFA (mM) from published experiments. A sub-model for intake oscillation is currently being developed using System Dynamics (Sterman, 2000) based on feeding behavior studies of heifers and dairy cows (Dado and Allen, 1994; Deswysen et al., 1987; Harb and Campling, 1985; Vasilatos and Wangsness, 1980).

$$\text{Ruminal pH} = 7.2809 \times \text{Exp}(-0.0013 \times (\text{VFA}))$$

Where VFA is volatile fatty acids, mM.

The ration fed in the feedlot case study was evaluated with this model (Figure 3), using the feed composition values shown in Table 2. Scenario 1 assumed three feeding times (8am, 1pm, and 6pm) with 30, 30, and 40% of the total daily ration intake fed at each respective time. Scenario 2 assumed two feeding times (8am and 4pm) with 40 and 60% of the total daily ration intake fed at each respective time. The simulations in figure 3 were for a 24 hr period after the cattle were adapted to the ration and the rumen had reached steady state conditions. The high pH before the first feeding of the day is due to reduced intake and rumination during the night. Then rumen pH drops as intake and accumulated rumen VFA increase during the day. Although the average pH did not vary between simulations (6.20 and 6.22 for scenarios 1 and 2, respectively), the pH range was shorter in the first scenario (5.8 to 6.76) than the second scenario (5.74 to 6.82) simulations. This is due to the greater amount that is fed at each time in scenario 2 compared to scenario 1.

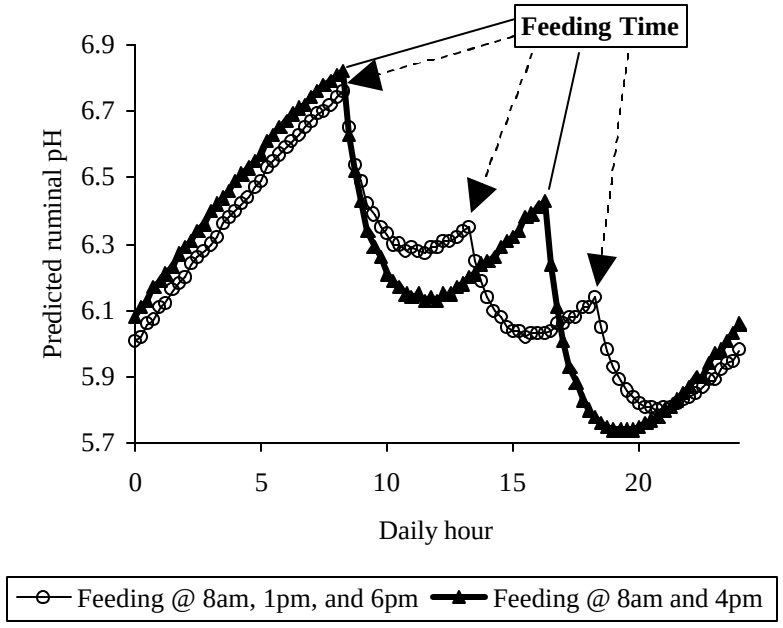

Figure 3. The effect of two feeding schedules (30%, 30%, and 40% of the total daily ration intake fed at 8am, 1pm, and 6pm, respectively vs 40% and 60% of the total ration fed at 8am and 4 pm, respectively) using the CNCPS dynamic ruminal sub-model to predict VFA and pH.

Table 4 compares the number of hours the rumen was at different ruminal pH levels. Scenario 1, which had three feeding times, had longer periods of high ruminal pH (above 6) and shorter periods of low ruminal pH (below 6) compared to scenario 2, which had only two feeding times.

Table 4. Hours at various pH levels

Ruminal pH Range	Scenarios	
	1	2
Above 6.4	5	6
6.4 to 6.3	3	3
6.3 to 6.2	3	3
6.2 to 6.1	3	5
6.1 to 6.0	5	1
6.0 to 5.9	1	1
5.9 to 5.8	4	2
Below 5.8	0	3

The fluctuation pattern of ruminal pH shown in Figure 3 and Table 4 will likely change after the intake oscillation is modeled. It is expected that scenario 1 (3 feeding times) would have a smaller impact on ruminal digestibility than scenario 2 given the shorter fluctuations in ruminal pH. Calsamiglia et al. (2002) found that ruminal pH kept constant at 5.7 had a negative impact on digestibility of apparent DM, NDF and ADF, lower total and branch-chained VFA acids concentrations, and lower acetate and higher propionate proportions than high ruminal pH kept constant at 6.4. They also reported that varying ruminal pH between 5.7 and 6.4 for 4h each, did not affect these parameters compared to ruminal pH kept constant at 6.4. Based on this information, the amount of time the rumen pH stays below a certain pH value likely has an effect on ruminal functions that affect microbial growth and consequently feed degradation. Future versions of the CNCPS model will include a dynamic model to predict the best combination of feeds, feed processing, feeding strategy and frequency to minimize the negative effects of low ruminal pH on feed digestion and biological values.

Conclusions

The rumen sub-model in the CNCPS version 5.0 can be used to evaluate the adequacy of diet peNDF content. However, it does not account for key variables affecting rumen pH, including the interactions of starch intake, feeding frequency, and fluid dilution rate on ruminal VFA level. Future versions of the CNCPS model will include a more dynamic ruminal sub-model to provide the capability to evaluate the effects of diet fiber level, feed processing, and feeding strategy on ruminal pH to maximize feed utilization by the ruminal bacteria and energy available for animal production.

References

Allen, M. S. 1997. Relationship between fermentation ancid production in the rumen and the requirement for physical effective fiber. J. Dairy Sci. 80:1447-1462.

Argyle, J. L. and R. L. Baldwin. 1988. Modeling of rumen water kinetics and effects of rumen pH changes. J. Dairy Sci. 71:1178-1188.

Beauchemin, K. A. 1991. Ingestion and mastication of feed by dairy cattle. Veterinary Clinics of North America: Food Animal Practice. 7:439-463.

Britton, R. and R. Stock. 1989. Acidosis: A continual problem in cattle fed high grain diets. Pages 8-15 in the Proc. Cornell Nutr. Conf. Feed Manuf., Syracuse, NY

Calsamiglia, S., A. Ferret, and M. Devant. 2002. Effects of pH and pH fluctuations on microbial fermentation and nutrient flow from a dual-flow continuous culture system. J. Dairy Sci. 85:574-479.

Dado, R. G. and M. S. Allen. 1994. Variation in and relationships among feeding, chewing, and drinking variables for lactating dairy cows. J. Dairy Sci. 77:132-144.

Deswysen, A. G., W. C. Ellis, and K. R. Pond. 1987. Interrelationships among voluntary intake, eating and ruminating behavior and ruminal motility of heifers fed corn silage. J. Anim. Sci. 64:835.

Dijkstra, J., H. Boer, J. Van Bruchem, M. Bruining, and S. Tamminga. 1993. Absorption of volatile fatty acids from the rumen of lactating dairy cows as influenced by volatile fatty acid concentration, pH and rumen liquid volume. Br. J. Nutr. 69:385-396.

Fitzhugh, H. A., Jr. 1976. Analysis of growth curves and strategies for altering their shape. J. Anim. Sci. 42:1036-1051.

Fox, D.G., C.J. Sniffen, J.D. O'Connor, J.B. Russell, and P.J. Van Soest. 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., M. C. Barry, R. E. Pitt, D. K. Roseler, and W. C. Stone. 1995. Application of the Cornell net carbohydrate and protein model for cattle consuming forage. J. Anim. Sci. 73:267-277.

Fox, D. G., T. P. Tylutki, M. E. Van Amburgh, L. E. Chase, A. N. Pell, T. R. Overton, L. O. Tedeschi, C. N. Rasmussen, and V. M. Durbal. 2000. The Net Carbohydrate and Protein System for evaluating herd nutrition and nutrient excretion: Model documentation. Mimeo No. 213. Animal Science Dept., Cornell University, Ithaca, NY.

Guiroy, P. J., D. G. Fox, L. O. Tedeschi, M. J. Baker, and M. D. Cravey. 2001. Predicting individual feed requirements of cattle fed in groups. J. Anim. Sci. 79:1983-1995.

Harb, M. Y. and R. C. Campling. 1985. Variation among pregnant, non-lactating dairy cows in eating and ruminating behavior, digestibility and voluntary intake of hay. Grass Forage Sci. 40:109.

Knowlton, K. F., B. P. Glenn, and R. A. Erdman. 1998. Performance, ruminal fermentation, and site of starch digestion in early lactation cows fed corn grain harvested and processed differently. J. Dairy Sci. 81:1972-1984.

Meng, Q., M. S. Kerley, P. A. Ludden, and R. L. Belyea. 1999. Fermentation substrate and dilution rate interact to affect microbial growth and efficiency. J. Anim. Sci. 77:206-214.

Mertens, D.R. 1985. Effect of fiber on feed quality of dairy cows. Page 209 in 46th Minnesota Nutr. Conf., Univ. Minnesota, St. Paul.

Mertens, D.R. 1986. Effect of physical characteristics, forage particle size and density on forage utilization. Page 91 in Proc. Nutr. Symposium, St. Luis, MO. Am. Feed INd. Assoc., Arlington, VA.

Mertens, D.R. 1997. Creating a system for meeting the fiber requirements of dairy cows. J. Dairy Sci. 80:1463.

National Research Council. 2000. Nutrient Requirements of Beef Cattle. National Academy Press, Washington, DC.

Owens, F.N., D. Secrist, J. Hill, and D. Gill. 1996. A new look at Acidosis. Page 1 in the Proc. Southwest Nutrition Conference, Phoenix, AZ.

Pitt, R. E. and A. N. Pell. 1997. Modeling ruminal pH fluctuations: interactions between meal frequency and digestion rate. J. Dairy Sci. 80:2429-2441.

Pitt, R. E., J. S. Van Kessel, D. G. Fox, A. N. Pell, M. C. Barry, and P. J. Van Soest. 1996. Prediction of ruminal volatile fatty acids and pH within the net carbohydrate and protein system. J. Anim. Sci. 74:226-244.

Pitt, R. E., J. S. Van Kessel, D. G. Fox, M. C. Barry, and P. J. Van Soest. 1996. Prediction of ruminal volatile fatty acids and pH within the net carbohydrate and protein system. J. Animal Sci. 74:226.

Poore, M.H., J.A. Moore, R.S. Swingle, T.P. Eck, and W.H. Brown. 1993. Response of lactating Holstein cows to diets varying in fiber source and ruminal starch digestibility. J. Dairy Sci. 76:2235.

Russell, J. B. 1999. Excessive grain feeding; acid-resistent bacteria and their impact on cattle. Pages 73-79 in Recent Advances in Animal Nutrition in Australia.ed.

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

Smith, L.W. and D. R. Waldo. 1969. Method for sizing forage cell particles. J. Dairy Sci. 52:2051.

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

Sterman, J. D. 2000. Business Dynamics: Systems thinking and modeling for a complex world. Irwin McGraw-Hill, New York.

Strasia, C.A. and D.R. Gill. 1990. Formulating feedlot diets. Great Plains Beef Cattle Handbook. Fact sheet 1800.

Swingle, R.S., J. Moore, M. Moore, and T. Eck. 1990. Utilization of starch from processed sorghum grain. In: Proc. Southwest Nutr. And Management Conf. P. 52. Tempe, AZ.

Tamminga, S. and A. M. Van Vuuren. 1988. Formation and utilisation of end products of lignocellulose degradation in ruminants. Anim. Feed Sci. Technol. 21:141-159.

Tedeschi, L.O., D.G. Fox and J.B. Russell. 2000. Accounting for the effects of a ruminal nitrogen deficiency within the structure of the Cornell Net Carbohydrate and Protein System. J. Anim. Sci. 78:1648.

Van Soest, P. J. 1994. Nutritional Ecology of the Ruminant (2nd ed.). Comstock Publishing Associates, Ithaca, NY.

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

Vasilatos, R. and P. J. Wangsness. 1980. Feeding behavior of lactating dairy cows as measured by time-lapse photography. J. Dairy Sci. 63:412.

Welch, J.G. 1986. Physical parameters of fiber affecting passage from the rumen. J. Dairy Sci. 69:2750.

Yang, W. Z., K. A. Beauchemin, and L. M. Rode. 2001. Effects of grain processing, forage to concentrate ratio, and forage particle size on rumen pH and digestion by dairy cows. J. Dairy Sci. 84:2203-2216.

Zinn, R.A. 1990. Optimizing the value of steam-flaked corn in diets for feedlot cattle. In: Proc. Southwest Nutr. and Management Conf. Page 36. Tempe, AZ.