IMPROVING INTAKE AND PERFORMANCE OF FORAGE-BASED RATIONS

D. R. Mertens
USDA-Agricultural Research Service
US Dairy Forage Research Center
Madison, WI

INTRODUCTION

Animal performance is the product of the supply, nutrient and energy concentration, intake, digestibility, and metabolism of a ration. Assuming that the ration is freely available, intake is the most important factor that affects animal performance. Of the variation in digestible dry matter (DDM) or digestible energy (DE) intake among animals and feeds, 60 to 90% is related to differences in intake, whereas only 10 to 40% is related to differences in digestibility (Crampton et al., 1960; Reid, 1961).

The relationship between intake and animal performance is complex. Does intake determine animal performance (intake as an input) or does animal performance determine intake (intake as a response)? This dichotomy reflects the difficulty in measuring the intake potentials of feeds and using them to formulate rations. It also indicates the very real difference in predicting intake as a response to a diet of known ingredient and chemical composition, compared to estimating intake to formulate a ration to meet a target level of animal performance. In the first instance, the diet composition is the known input, and animal performance and intake are unknown responses. In the second instance, animal performance and intake are the known (assumed) inputs and diet composition is the unknown variable to be solved. When mixed diets are fed, animal nutritionists can, and probably should, formulate diets to optimize performance or profit using intake as a known input. Thus, predicting intake becomes a crucial step in formulating rations for improved animal performance.

It is clear that a range of dry matter intakes (DMI) can be used to formulate optimal rations; however, two levels of intake are of special interest. The first is the highest intake possible that will allow the animal to perform optimally which corresponds to rations with the lowest energy density and highest proportion of forage. The second is the lowest possible intake that will meet the animals needs which represents the diet with the highest energy density and greatest proportion of concentrates. After these extremes are determined, any intake within this range that maximizes profit, productivity, or efficiency can be selected using a variety of computer programs. This discussion will describe the mechanisms of intake regulation and relate them to a practical system for formulating rations that is based on neutral detergent fiber (NDF) and net energy of lactation (NE_L). Much of this material has been excerpted from two book chapters (Mertens, 1992; 1994) and you are encouraged to read them for additional information.

THEORIES OF INTAKE REGULATION

Factors affecting intake, and the stimuli and mechanisms that regulate it, are incompletely known as indicated by the diversity of information in the reviews of Conrad (1966), Balch and Campling (1969), Campling (1970), Baumgardt (1970), Baile and Meyer (1970), Jones (1972), Baile and Forbes (1974), Journet and Remond (1976), Bines (1979), Waldo (1986), Grovum (1987), NRC (1987), and Owens et al. (1991). Although debate about intake regulation continues, apparently three mechanisms control long term intake in animals. On one extreme, energy intake is regulated to maintain body weight, whereas at the opposite extreme intake is limited by the capacity of the gastrointestinal tract to process feed residues. At all levels of intake potential the animal's behavioral adaptation to the ration, feeding environment, and management modifies intake.

Physiological Regulation. When animals are fed high energy rations that are palatable, low in fill, and readily digested, intake is regulated to meet the energy demands of the animal, unless the diet is fermented too rapidly and digestive disorders occur. The central role of energy is consistent with the observation that excess energy cannot be easily dissipated; therefore, its intake must be regulated to balance requirements and obey the First Law of Thermodynamics (conservation of energy). The energy demand and intake potential of an animal depends on its species, sex, physiological state (maintenance, growth, pregnancy, and lactation), size, body shape, and health. In addition, certain environmental factors such as ambient temperature and photoperiod, as well as management treatments such as exogenous hormones or growth promoters, can directly influence an animal's energy demand and intake potential.

Physiological regulation of intake can be interpreted to mean that the DMI of the animal times the energy concentration in diet DM will equal the animal's energy demand. This mechanism of intake regulation can be described easily by a simple algebraic equation that can be rearranged to solve for the energy concentration or

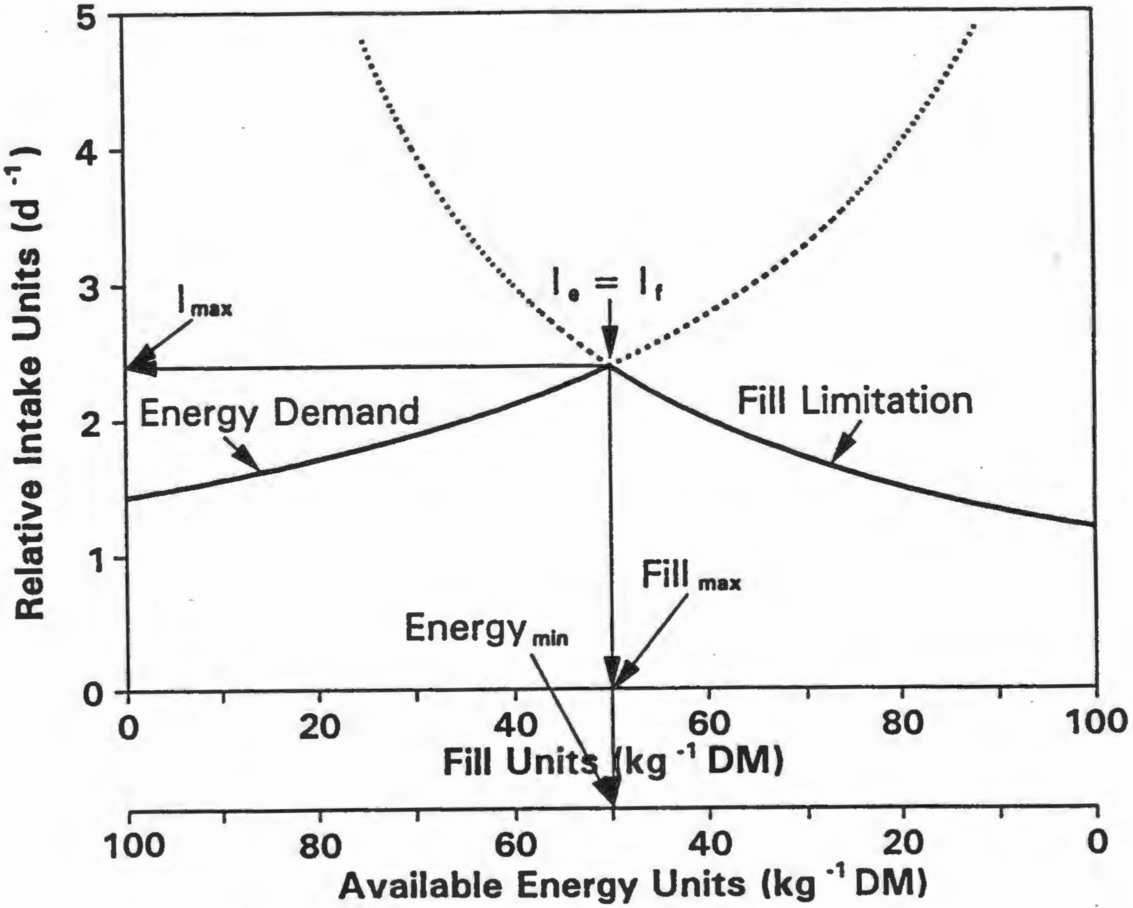

Figure 1. Illustration of the bi-phasic, discontinuous nature of intake regulation based on simple algebraic equations describing expected intakes when limited by physiological energy demand (I_e) or physical fill (I_f). Maximum intake (I_{max}) occurs at the intersection of the two theories of intake regulation and defines the diet having maximum fill ($Fill_{max}$) and minimum energy concentration ($Energy_{min}$) which meets the animal's energy requirement and maximizes ruminal fill.

intake needed to meet a specific animal requirement or potential:

$I_e \times E = R$ Equation 1

$E = R/I_e$ Equation 2

$I_e = R/E$ Equation 3

where I_e is intake (kg/d) expected when energy demand is regulating intake, E is the energy concentration of the diet (Mcal/kg), and R is the animal's energy requirement or output (Mcal/d).

Equation 3 indicates that intake is a positive, linear function of the animal's energy requirement; therefore, intake will increase with increasing energy demand by the animal. Equation 3 also indicates that intake is a reciprocal function of the feed characteristic (available energy concentration). As energy concentration in the diet increases, intake will decline in a curvilinear manner (Figure 1). Conversely, if energy concentration of the diet decreases, intake must increase to meet energy demand. Although animals will attempt to regulate intake to meet energy demand, intake must be limited by factors other than energy concentration of the diet when the animal cannot consume enough feed to meet its energy demand. The role of physical limitation will be discussed in the next section.

It is important to recognize that intake is not the only response in equation 1 that can be varied by the animal. If energy concentration is too low and intake cannot be adjusted to accommodate a target level of production potential, the animal has the ability to reduce energy output by reducing productivity or increasing the use of body reserves. Thus, the animal effectively changes its output (R) to match allowable energy input. This dichotomy, that the animal can vary either energy intake or energy output to achieve equilibrium, indicates the problem in using this theory of intake regulation alone to predict intake or formulate rations.

When formulating rations, intake is assumed to be a known input and equation 2 is used to define the energy concentration needed in the ration. If intake is assumed to be lower than maximal, the energy concentration needed in the diet will be calculated to be greater than the minimum necessary to meet energy requirements. To no one's surprise, ration formulation systems that underestimate intake apparently work because they are self-fulfilling prophesies. Low estimates of intake result in high estimates of energy concentration needed in the diet which result in low intakes that match those used to formulate the ration. If the database used to generate intake prediction equations contains diets with higher concentrations of energy than necessary to meet the animal's requirements, intakes predicted by these equations will be lower than the maximum that can be achieved by animals. These low estimates of intake can be used to formulate rations, but the rations may not be optimal.

Physical Limitation. When animals are fed diets that are palatable, yet high in bulk (fill) and low in available energy concentration, intake is limited by some restriction of capacity in the digestive tract (Balch and Campling, 1962; Campling, 1970; Bines, 1971; Baile and Forbes, 1974). These diets result in intakes of energy that cannot meet the animal's potential demand and the animal reduces performance or loses weight to accommodate the limits of the diet. Physical distension of the reticulorumen generally has been accepted as the major factor limiting intake of many forages and high fiber diets. The term "fill" is useful in discussions of intake regulation only when it is used to indicate the maximum occupied volume of the rumen when intake is limited by distension. Too often, fill is used to describe any or all measurements of the weight of ruminal contents. Fill can only be measured when the rumen is full, immediately after the end of a meal in which intake is limited by bulk. If stretch receptors are involved, perhaps volume rather than weight of ruminal contents should be used to measure "fill".

The fill limitation concept of intake regulation indicates that when animals are fed palatable rations in adequate supply that are high in fill, intake is limited by the intake capacity or constraint of the animal. Physical limitations to intake can be interpreted to mean that the intake of the animal times the diet's filling effect equals the animal's intake constraint. This mechanism of intake limitation can be easily described by a simple algebraic equation that can be rearranged to solve for the filling effect or intake allowed by a specific animal intake constraint:

$I_f \times F = C$ Equation 4

$F = C/I_f$ Equation 5

$I_f = C/F$ Equation 6

where I_f is intake (kg/d) expected when fill is limiting intake, F is the volume (in liters) of the filling effect (L/kg) of the diet, and C is the animal's intake capacity or constraint (L/d).

Equation 6 indicates that intake is a linear function of the intake constraint of the animal and will increase as the animal's intake constraint increases. Equation 6 also indicates the potential difficulty facing an animal that has access to a diet that is high in fill. Because intake is a reciprocal function of the feed's filling effect, it will decrease in a curvilinear manner as the fill of the forage or diet increases (Figure 1). However, intake can only go so low and allow the animal to obtain enough energy to survive or attain its performance potential. Equation 4 indicates that if appetite is large due to a high energy demand, the animal can accommodate a diet high in fill by increasing its intake constraint (C).

The possibility that the animal can vary either intake or capacity in response to a diet of a given filling effect illustrates the confusion associated with defining C. Although the animal can increase its constraint, it is obvious there is a maximum beyond which the gut cannot stretch and a passage rate it cannot exceed. This maximum intake capacity when animals are fed forages or diets that are so high in fill that performance or even maintenance of life cannot be sustained is of little importance in the practical formulation of rations. It seems more logical to define C in relation to the intake that is needed to meet a target requirement. This capacity is more appropriately termed an intake constraint because the upper limit of intake capacity that is acceptable is constrained by energy requirements needed to meet the animal's performance potential.

In ration formulation, intake is assumed to be known and equation 5 can be used to calculate the filling effect of the ration that is allowed under the constraint of a given production target. If intake is estimated to be too low, the acceptable filling effect of the diet will be estimated to be too high. This will result in a low intake that does not meet the animal's energy needs. The safest strategy when formulating rations is to use equation 2 with a slightly low estimate of intake because it will at least guarantee that the energy concentration in the diet will be adequate to meet animal requirements. Conversely, using only equation 5 to formulate rations will not guarantee that the animal's energy needs are met, but only indicates that its rumen will be full.

Psychogenic Modulation. In humans and other animal species, taste, smell, texture, and visual appeal can affect both short and long term intake. In addition, emotional states, social interactions, and learning can modify the intake of foods. Mertens (1985) postulated that similar factors affect the feed intake of animals and suggested that they be aggregated into a class of psychogenic modifiers or modulators of intake. The psychogenic regulation of food intake involves the animal's behavioral response to inhibitory or stimulatory factors in the feed or feeding environment that are not related to the feed's energy value or filling effect.

The psychogenic modulation of intake can be interpreted to mean that the expected or predicted intake potential, based on the physiological or physical mechanisms, is modified by some proportional factor. This mechanism of intake modulation can be described by a simple algebraic equation that can be rearranged to measure the psychogenic effect:

$I_a = I_p \times M$ Equation 7

$M = I_a/I_p$ Equation 8

where I_a is the actual or observed intake (kg/d) of the animal, I_p is the predicted intake potential (kg/d) of the animal and diet based on physiological or physical control mechanisms, and M is the proportional psychogenic modulation factor (dimensionless ratio).

It is proposed that psychogenic modulation is multiplicative rather than additive based on the logic that animals with greater intake potential will have a larger absolute change in intake. Equation 8 offers the potential for quantifying the modulating effects of management, disease, social interactions, and palatability on long term intake regulation. It is speculated that M will be less than 1.0 in most circumstances because most psychogenic effects inhibit intake. The concept of a psychogenic modulator can be criticized as a "fudge factor" that adjusts predicted intake to match that actually observed. Although this contention is plausible, it fails to recognize the real differences in intake that occur on neighboring farms when animals of similar production potential are fed similar rations. The psychogenic modifier can be used to account for these differences after the effects of variations in NDF and NE_L are removed. This concept allows the quantification of this effect so it can be investigated and related to the animal, dietary, and management factors that affect M.

The most commonly recognized feed characteristic that impacts psychogenic modulation of feed intake is palatability. Palatability is defined as any feed characteristic that stimulates or inhibits the intake of a feed whether it is fed alone or is a choice among alternative feeds. Mertens (1994) provides a method for quantifying the palatability of forages that is based on their relative intake when their NDF content are similar. Although this system is simple and may include several confounding effects, it can serve as a practical method of modifying the NDF-Energy Intake System (Mertens, 1987; 1992) to accommodate differences in intake among NDF sources.

INTEGRATION OF INTAKE MECHANISMS

The physiological, physical, and psychogenic mechanisms of intake regulation each establish independent controls on intake which need to be integrated into a common equation. The physical and physiological mechanisms of intake control provide limits at the opposite extremes of forage quality. In any situation, the lesser of the two intake limits will predict the intake potential of a specified animal-feed combination. This system of controls can be described by an equation that can be combined with equation 7 to predict actual intake under conditions when feed availability is not limiting:

$I_p = \min (I_e, I_f)$ Equation 9
$I_a = \min (I_e, I_f) \text{ X } M$ Equation 10
where all terms are as previously defined.

Equation 9 implies that intake regulation is a discontinuous function of diet or forage characteristics because in any specific situation, either energy demand or fill limits intake. In general, the energy value and filling effect of diets or forages are inversely related. This allows equations 3, 6, and 9 to be described by a graph with inversely related X-axes (Figure 1). The psychogenic modifier (M) in equation 10 would modify Figure 1 by a simple scalar adjustment to the Y-axis.

One of the characteristics of this simple model of intake regulation based on dual control mechanisms is the occurrence of a unique solution (Figure 1). Because fill and energy concentrations in feeds are inversely and curvilinearly related to intake potential, the intersection of equations 3 and 6, when $I_e = I_f$, is the maximum intake that can both meet the animal's energy demand and fill the rumen. Solving for the maximum constrained intake yields the following equations:

$I_{max} = I_p$, when $I_e = I_f$ Equation 11
$R/E = C/F_{max}$ Equation 12
$F_{max}/E = C/R$ Equation 13
$F_{max} = (E \text{ X } C)/R$ Equation 14
where I_{max} is the maximum intake (kg/d) that will still provide the energy needed to meet the animal's requirements, F_{max} is the maximum filling effect (L/d) of a diet that can meet the animal's needs, and all other variables are as previously defined.

NDF-Energy Intake System. The conceptual framework of intake regulation has practical utility in ration formulation only when it can be related to specific feed and animal characteristics that are routinely measured. In addition, the theory can be tested only when the vague concepts of the feed's filling effect and available energy, and the animal's intake constraint and energy requirements are quantitatively defined. Mertens (1985, 1987, 1992) developed and refined the concept that NDF and NE_L can serve as proxies for the filling effect and available energy in the accepted theories of intake regulation. They can be used as starting points for relating mechanisms of intake regulation to feed and animal (dairy cow) characteristics simultaneously and can serve as reference points for relating intake mechanisms to a routinely measured characteristic of feeds (NDF).

Neutral detergent fiber can be used to formulate dairy rations effectively because it accounts for the major differences in feeds, i.e., the difference between NDF and neutral detergent solubles (NDS). If rations are balanced for NDF, we can achieve about 70 to 80% of the potential effectiveness in formulating optimal dairy rations with respect to intake and energy density. The NDF-Energy Intake System is not intended to replace practical feeding wisdom about feeds, rather it is proposed as a first step in developing a quantitative method for insuring that differences in the fiber concentration of feeds are considered when formulating rations. As more information is gained and digestion kinetics, specific gravity, feed volume, and rate of particle size reduction and passage can be routinely measured or estimated, NDF concentration can be refined to more accurately estimate the true filling effect of the forage or diet.

The objective of the NDF-Energy Intake System is to identify the optimal NDF content in the ration that maximizes forage and fiber intake, while meeting the energy requirements for a target level of milk production. This occurs at the point where the curves representing the two intake regulation mechanisms cross (Figure 2). The optimal NDF concentration in the ration serves as an upper limit for intake or percentage of forage in the diet which meets the energy needs for a specified production target. This point may not represent the absolute maximum intake of dry matter or NDF because cows given diets higher in NDF than the optimum will attempt to consume more of these diets to meet the energy required by their production potential. However, they will not be able to meet their potential requirements when the NDF concentration in the ration is too high, and will invariably reduce milk production and lose body weight in an attempt to accommodate a suboptimal diet.

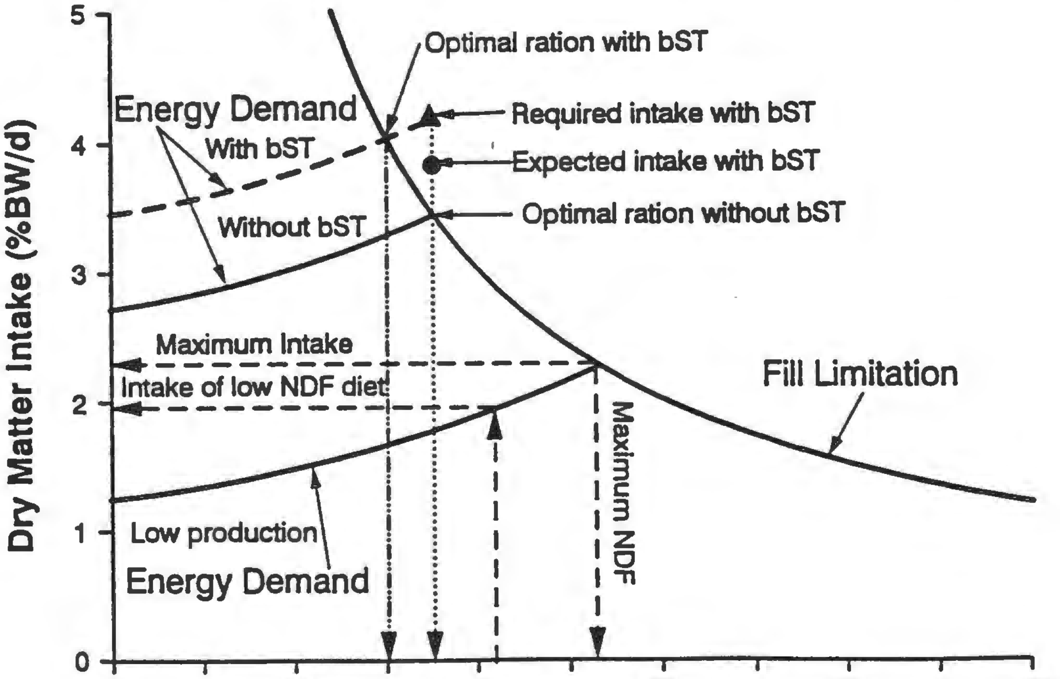

Figure 2. Prediction of intake using the NDF-Energy Intake System when feeding rations with optimal and suboptimal concentrations of NDF. Feeding a low NDF diet to a low producing cow results in reduced intake. Injecting cows with bovine somatotropin (bST) increases energy demand and requires lower NDF concentration to obtain optimal rations. Feeding rations suitable for animals without bST will result in suboptimal intakes and less than optimal production response to bST.

Table 1. Carbohydrate composition of selected feeds and roughage value fractions useful in formulating dairy rations.

Feedstuff	Calc NE_L[a] (Mcal/kg)	NRC NE_L (Mcal/kg)	CP	EE	Ash	CF	ADF	NDF	ANDF[b]	NDF_f[c]	RVAdj[d] (% NDF)	RV[e]	NFC[f]	TNC[g]	Starch
Alfalfa pellets, 3/8"	1.18	1.33	17.2	2.4	10.6	29.8	36.0	47.5	14.3	0.0	60.0	28.5	22.3	20.1	4.5
Alfalfa hay, early veg.	1.46	1.50	22.9	3.1	10.2	21.9	28.0	38.4	38.4	38.4	95.0	36.5	25.4	22.9	4.0
Alfalfa hay, mid bloom	1.28	1.30	17.2	2.1	9.1	29.8	36.0	47.5	47.5	47.5	95.0	45.1	24.1	21.7	2.6
Alfalfa sil., early veg.	1.53	1.50	23.9	4.2	10.7	20.5	26.5	36.3	36.3	36.3	90.0	32.7	24.9	21.2	2.0
Bahiagrass, early veg.	1.05	1.20	13.8	2.5	8.8	26.9	32.6	66.6	66.6	66.6	100.0	66.6	8.3	6.0	2.0
Bermudagrass hay (Coastal), late veg.	1.07	1.23	13.6	2.4	5.9	29.0	33.0	70.0	70.0	70.0	100.0	70.0	8.1	6.1	2.4
Bermudagrass (Coastal), pellets	0.96	1.23	13.6	2.4	5.9	29.0	33.0	70.0	70.0	0.0	45.0	31.5	8.1	6.1	2.4
Brewers grains, dried	1.66	1.50	28.0	7.0	4.8	14.9	23.0	47.0	14.1	0.0	35.0	16.5	13.2	12.0	3.8
Corn distillers grains with solubles	1.94	2.04	29.0	10.3	5.0	9.9	19.0	38.0	11.4	0.0	30.0	11.4	17.7	14.1	2.4
Corn gluten feed	1.69	1.91	23.0	4.0	7.5	8.0	10.0	35.0	10.5	0.0	50.0	17.5	30.5	26.0	23.3
Corn dry grain,medium grind	1.98	1.96	10.0	4.3	1.6	2.6	3.0	10.0	10.0	0.0	20.0	2.0	74.1	73.4	71.9
Corn, steam flaked	2.09	2.04	10.0	4.3	1.6	2.6	3.0	10.0	10.0	0.0	20.0	2.0	74.1	73.4	71.9
Corn hominy feed	2.02	2.01	11.2	6.5	2.6	5.2	6.0	23.0	12.0	0.0	30.0	6.9	56.7	52.0	31.0
Corn silage, well-eared	1.60	1.60	8.0	3.1	3.8	20.0	24.0	43.0	43.0	43.0	95.0	40.9	42.1	39.5	35.6
Corn silage, average	1.51	1.50	8.4	3.0	4.2	23.0	28.0	48.0	48.0	48.0	95.0	45.6	36.4	30.7	27.7
Cottonseed, whole with lint	2.11	2.23	23.0	20.0	4.8	26.0	34.0	49.0	41.7	49.0	85.0	41.7	3.2	1.6	0.3
Cottonseed hulls	0.46	0.98	4.4	1.7	2.8	48.0	70.0	89.0	71.2	89.0	80.0	71.2	2.1	1.9	1.0
Cottonseed meal, solv. extr.	1.53	1.72	46.5	1.5	7.0	14.1	20.0	30.0	12.0	0.0	30.0	9.0	15.0	7.5	1.5
Pangolagrass hay	0.93	1.03	9.3	2.1	8.2	35.0	42.0	72.0	72.0	72.0	100.0	72.0	8.4	6.0	4.0
Peanut meal, mech. extr.	1.96	1.91	51.0	5.6	5.2	9.0	13.0	17.0	12.0	0.0	30.0	5.1	21.2	14.8	4.8
Sorghum grain (milo), medium grind	1.94	1.82	11.5	3.2	2.0	3.0	6.0	14.0	12.0	0.0	20.0	2.8	69.3	68.6	67.2
Sorghum sil., forage var., soft dough	1.13	1.30	7.2	2.2	5.1	26.3	34.4	65.2	65.2	65.2	95.0	61.9	20.3	15.4	4.6
Sorghum sudangrass sil., early veg.	1.27	1.51	15.0	3.9	10.5	28.0	34.0	59.0	59.0	59.0	95.0	56.1	11.6	8.8	2.6
Soybean hulls, fine grind	1.28	1.77	15.0	2.4	5.0	36.0	46.0	64.0	19.2	0.0	20.0	12.8	13.6	13.2	5.3
Soybean meal 44% CP	1.80	1.94	49.9	1.5	7.3	7.0	10.0	14.0	12.0	0.0	20.0	2.8	27.3	13.7	2.7
Wheat bran	1.58	1.60	17.1	4.4	6.9	9.0	12.0	42.0	12.6	0.0	45.0	18.9	29.6	27.0	21.0
Wheat silage	1.23	1.28	12.3	4.2	7.5	29.0	41.0	60.5	60.5	60.5	100.0	60.5	15.5	15.2	13.4

[a] Calc. $NE_L = 2.28*[.93*CP+2*EE+.92*(1 - CP - Ash - NDF) + (.80 - .5*NDF)*(NDF - LIG)*(1 - LIG^{2/3}/NDF^{2/3})] - .10$

[b] ANDF = Adjusted NDF for concentrates to reflect the reduced filling effect of ground fiber sources.

[c] NDF_f = NDF from forages.

[d] RV Adj = Roughage value adjustment factor for converting NDF to roughage value units.

[e] RV = Roughage value based on a standard of 100 for a hypothetical long, grass hay containing 100% NDF.

[f] NFC = Nonfibrous carbohydrates = 100 - CP - EE - Ash - NDF.

[g] TNC = Total nonstructural carbohydrate by the method of Smith.

The NDF-Energy Intake System assumes that all NDF acts alike in dairy rations. Obviously this is not true because the particle sizes, density, chewing requirement, passage rate, digestion rate and extent of digestion of NDF varies among sources. One of the first differences in NDF that must be considered when using the NDF-Energy Intake System to formulate rations using high-fiber, by-product feeds is particle size. It is intuitive that finely ground NDF does not have the same filling effect as long forage fiber because it has less volume per kg of dry matter and passage through the digestive tract will be more rapid than that of larger particle sizes. Therefore, the NDF of ground, high-fiber by-product feeds should be adjusted to reflect this difference. A useful crude adjustment based on practical experience is to assign any ground, high-fiber feed with NDF less than 40% the value of 12% adjusted NDF (ANDF) or its measured NDF if it is less than 12%. This approximation assumes that ground feeds with less than 40% NDF will have the same filling effect as the corn-soybean meal concentrates used in the experiments that determined the optimal NDF intake constraint. The ANDF of any ground, high-fiber feed with more than 40% NDF is calculated as 0.3*(NDF), which assumes that these feeds have only 30% of the filling effect of long forages. The NDF, ANDF, and roughage values (Mertens, 1992) for selected feed ingredients are given in Table 1. Note the correction to the equation for calculating NE_L given in the footnote of Table 1.

Calculating Maximum Forage Contents in Dairy Rations. Our research suggests that the maximum NDF intake (NDFI) that cows in mid to late lactation will consume comfortably, without reducing milk production below their potential, is 1.2% of body weight per day (%BW/d) with a standard deviation of approximately 0.1%BW/d. By decreasing the average value by one standard deviation we can insure that 85% of the cows in a group will be able to consume NDFI of 1.1%BW/d. This conservative estimate of maximum NDFI is recommended to insure that adequate concentrates are included in rations. Preliminary evaluation suggests that the NDF intake constraint of mature beef cattle (Mertens, unpublished) and sheep (Mertens, 1973) is also approximately 1.2% BW/d. Animals have some ability, within limits, to adjust gut capacity to meet the short term demands imposed by a bulky diet that does not meet their energy needs (Figure 2). However, it seems inappropriate to base a conceptual model of intake regulation for use in formulating rations on this exception because it will often result in reduced performance or losses in body weight.

Although the average NDFI obtained from optimal NDF experiments is satisfactory in most situations, the fiber intake capacity of cows may vary with age and stage of lactation. Based on body shape it seems reasonable that a first-lactation cow of the same weight as an older cow will not have as much body capacity. Similarly, cows in early lactation may not have as large a capacity as later in lactation because the rumen and intestines have been constrained by internal fat deposits and the reproductive tract during pregnancy. Several experiments were combined to develop equations describing the change in NDFI during lactation. It appeared from this summary that first lactation cows have less capacity than older cows of the same weight, and cows in early lactation have lower NDFIC than in mid and late lactation (See Table 25.4 in Mertens, 1992). It is uncertain whether cows in early lactation eat less because they are programmed by lactational hormones to utilize body reserves or because they have limited gut capacity.

The recommended maximum proportion of forage in the ration that will allow an average cow to maintain a specified level of milk production can be calculated using the formula:

$$F_{max}=[NDFIC*(CNE)-ANER*(CNDF)]/[NDFIC*(CNE-FNE)+ANER*(FNDF-CNDF)]$$

where:

F_{max}= maximum fraction of forage in the total ration,

CNE = NE_L of the concentrate (Mcal/kg DM), for a corn-soybean meal mixture this is approximately 1.90,

FNE = NE_L of the forage (Mcal/kg DM)

for corn silage: FNE = 2.394 -.0193*(%NDF)
for legumes: FNE = 2.323-.0216*(%NDF)
for grasses: FNE = 2.863 - .0262*(%NDF)

where: %NDF is forage NDF expressed as % on a dry matter (DM) basis, CNDF = adjusted NDF (ANDF) content of the concentrate (fraction of DM), for a corn-soybean meal mixture this is approximately 0.12,

FNDF = NDF content of the forage (fraction of DM)

ANER = net energy requirement adjusted for intake (Mcal/day)
= NER*.92/[1-.04*(MMNT-1)]

NER = net energy requirement of the cow
= .08* ($BW^{.75}$) + .74*(FCM) -4.92*(LOSS) + 5.12*(GAIN)

where: BW = body weight in kg = .454*BW in lbs.

FCM = .40*(MILK) + .15*(%FAT)*(MILK)

MILK = milk yield (kg) = .454*milk yield (lbs)

% FAT = milk fat content (percent)

LOSS = body weight loss (kg) = .454*BW loss (lbs)

GAIN = body weight gain (kg) = .454*BW gain (lbs)

MMNT = multiples of maintenance intake
= NER/.08*($BW^{.75}$)

NDFIC = NDFI*BW/100 = NDF intake constraint in kg per day,

where: BW = body weight in kg = .454*BW in lbs and NDFI is 1.1%BW/d or from Table 25.4 in Mertens (1992). It is suggested NDFI values from Table 25.4 be decreased by one standard deviation (0.10) to insure that rations will meet the needs of 85% of the cows in a group.

RNDF= F_{max}*FNDF + (1-F_{max})*CNDF,
where: RNDF is ration NDF as a fraction of DM.

DMI = NDFIC/RNDF,
where DMI is dry matter intake in kg/d. To convert DMI to lbs/d multiply by 2.2.

An example calculation using this formula is provided by Mertens (1992). There is an error in the original printing that may cause confusion (the daily gain of the cow in the example is 1.1 lbs/d, not 0.5 lbs/d). The formula for F_{max} gives the maximum fiber in the ration that is recommended to meet the animal's energy requirements and provide an estimate of the maximum DMI to use in formulating rations. This equation provides the critical DMI needed to formulate rations. In some situations of high milk production targets, it may be desirable to feed fat as oil seeds, animal fat, or commercial fat products. This modification of the ration can easily be incorporated into the NDF-Energy Intake System by increasing the CNE value to reflect the energy density of the concentrate portion of the ration that contains the added fat. The result of feeding fat when using the NDF-Energy Intake System, is that more forage can be included in the ration, or forages with lower quality can be used and still maintain optimal performance.

Calculating Minimum Forage Contents in Dairy Rations. As milk production rises, the amount of forage that can be fed decreases and approaches the minimum forage that maintains ruminal function. When nutrients purchased in grains are more economical than those in forages, it is most profitable to feed minimal forage or fiber source. In addition, rations highest in fiber may not be optimal in hot environments. In these cases it may be desirable to feed minimum fiber rations (or decrease the estimate of NDFI used to formulate acceptable diets). The minimum forage content of dairy rations is less easily established than the maximum because individual cows vary in chewing activity and sensitivity to milk fat depression or acidosis. The structural carbohydrates measured by NDF are the components of feed that require chewing activity for particle size reduction and passage and can serve as the basis for formulating rations to insure that rumen function and health is maintained. Not only is the level of NDF in the diet important, but also the size of the fiber particles is critical for stimulating chewing activity when minimal forage is fed.

Roughage value (RV), which represents the chewing requirement of a feed, can be defined in terms of fiber content and particle size (Sudweeks, et al., 1981). More chewing is required by feeds that are higher in NDF. Conversely, reducing the particle size of fiber decreases the chewing that will be required. A Standard Roughage Value Unit has been proposed that is based on NDF content and particle size (Mertens, 1986). A hypothetical, standard feed containing 100% NDF in long form would be assigned a RV of 100. All other feeds could be ranked relative to the RV Standard of 100 based on their NDF content and particle size.

More research is needed to perfect laboratory techniques for measuring RV and to determine dairy cow requirements for it. Nonetheless, the concept is valuable in discussing ration formulation. Substituting the term "roughage value" for "effective fiber" or "minimum fiber" helps clarify that we are attempting to account for physical, as well as chemical, characteristics of carbohydrates that affect ruminal function in dairy cows. The RV given in Table 1 can be used as an initial attempt to incorporate both fiber content and particle size in a practical, quantitative system for formulating dairy rations when non-forage fiber sources are used. To insure that adequate RV is present in dairy rations, it is recommended that the ration contain at least 21% RV. The minimum fraction of fiber source in a dairy ration can be determined by the following equation:

F'_{min}= (RVMIN - CRV)/(FRV - CRV)
where:
F'_{min} = minimum fraction of fiber source in the ration,
RVMIN= .21 = recommended minimum fraction of RV in the ration,
CRV= concentrate RV = .02 for a corn + soybean meal mixture,
FRV= fiber source RV, and other variables as previously defined.

When formulating rations for minimum forage, NDF can be used as a substitute for RV by making some assumptions. The critical requirement in minimum forage rations for dairy cows is to provide a minimum amount of fiber, in the physical size necessary, to maintain a functioning ruminal environment. To insure that adequate long fiber is present in dairy rations, it is recommended that at least 75% of the NDF in the ration come from long or coarsely chopped forage. The minimum forage content of dairy rations can be determined by the following equation:

F_{min}= CNDF*.01*MIN/[FNDF*(1-.01*MIN) + CNDF*.01*MIN]
where F_{min} = minimum fraction of forage in the ration,
MIN = 75 = minimum percentage of total NDF from forages,
CNDF= ANDF of concentrates, and other variables as previously defined.

If forages are extremely expensive, it may be possible to lower the minimum NDF from forages to 70%. However, some cows will not maintain fat test when fed these rations. Thus, when feeding dairy rations containing minimum forage it may be advisable to include supplemental buffers or high-fiber concentrate feedstuffs in the ration. In addition to requiring that 70 to 75% of the NDF in the ration comes from forage, it is also recommended that the total NDF in the ration exceed 25%. When cows were fed diets containing less than 25% NDF in the total ration dry matter we observed that they selected the coarse stems and cobs and left grain in the mangers. In addition, cows fed rations containing less than 25% NDF often went off-feed and exhibited significant milk fat depression.

Both minimum RV and minimum NDF should insure that adequate fiber is available in the ration to stimulate rumination activity. However, starch concentrations of the rations may be too high when they contain minimum NDF or RV. Adding an additional constraint to the formulation system may be necessary to balance the nonstructural carbohydrates in minimum fiber rations. Because nonfibrous carbohydrates (NFC) is calculated from NDF, and total nonstructural carbohydrate (TNC) is highly correlated to NFC, balancing rations for NFC and TNC will not accomplish anything that is not accomplished by formulating rations for NDF. However, starch is not perfectly correlated to NDF and it represents the major source of lactic acid production in the rumen. Lactic acid produced during starch fermentation is usually responsible for ruminal acidosis and off-feed disorders. Thus, it is recommended that starch not exceed more that 30% of the ration dry matter. Including this constraint when formulating rations containing minimum NDF or RV often results in adding 10 to 20% soybean hulls or other digestible, nonstarch-containing feeds to rations.

CONCLUSION

The prediction of intake and its use in formulating rations to improve animal performance is complicated by the fact that characteristics of the animal, diet, and feeding situation influence intake. Equations that attempt to predict intake solely as a function of animal characteristics (BW, production level, BW change, physiological state, etc.) or diet properties (fiber, bulk, energy density, chewing requirement, nutrient balance, etc.) will not have universal applicability and are doomed to failure. These equations fail because they implicitly assume that only one component of the intake regulation system (i.e., animal, diet, or feeding situation) limits intake in all instances. These limitations can be overcome by describing accepted theories of intake regulation in simple mathematical equations and integrating the three mechanisms so the concepts of intake constraint and energy demand of the animal, filling effects and energy availability of the diet, and palatability and feeding management are considered simultaneously in a single system of equations.

Intake prediction also is affected by the information that is known and the purpose for estimating intake. When a ration is formulated, an intake prediction is needed under the assumption that the animal's requirements are known and will be met. Diet properties are unknown, but it is implicitly assumed that they will be optimized for some function (profit, cost, production, etc.) under some set of known constraints. The NDF-Energy Intake System was designed to predict intake under these circumstances. The system should predict intake most accurately when animals are near their maximal production. The NDF intake constraint is useful because it provides an upper limit to DMI and maximum forage in the ration that will allow the animal to maximize performance. Any intake less than this prediction is acceptable as long as the ration is formulated to have the increased energy density needed to meet the energy demands of the animal and contains the minimum fiber needed to maintain proper ruminal function.

The concepts used to formulate rations containing maximum or minimum forage, as well as rations containing minimum RV and maximum starch, can be easily incorporated into a linear programming, least-cost ration, or profit-maximizing balancing system. The equations presented in this paper are provided to demonstrate these concepts. The NDF-Energy Intake System offers a quantitative approach to the formulation of dairy rations that is an improvement over most systems currently in use for balancing carbohydrates and energy in rations. As with any system of formulating rations, the practical experience of the nutritionist should always be used to make adjustments when encountering atypical situations.

REFERENCES

Baile, C.A., and J.M. Forbes. 1974. Control of feed intake and regulation of energy balance in ruminants. Physiol. Rev. 54:160-214.

Baile, C.A., and J. Mayer. 1970. Hypothalamic centres: Feedbacks and receptor sites in the short-term control of feed intake. p. 254-263. In A.T. Philipson (ed.) Physiology of digestion and metabolism in the ruminant. Oriel Press Ltd. Newcastle upon Tyne, England.

Balch, C.C., and R.C. Campling. 1962. Regulation of voluntary intake in ruminants. Nutr. Abstr. Rev. 32:669-686.

Balch, C.C., and R. C. Campling. 1969. Voluntary intake of food. p. 554-579. In W. Lenkeit, K. Breirem, and E. Crasemann (ed.) Hanbuch der Tierernahrung Vol.1. Paul Parey, Hamburg.

Baumgardt, B.R. 1970. Control of feed intake in the regulation of energy balance. p. 235-253. In A.T. Philipson (ed.) Physiology of digestion and metabolism in the ruminant. Oriel Press Ltd. Newcastle upon Tyne, England.

Bines, J.A. 1971. Metabolic and physical control of food intake in ruminants. Proc. Nutr. Soc. 30:116-122.

Campling, R.C. 1970. Physical regulation of voluntary intake. p. 226-234. In A.T. Philipson (ed.) Physiology of digestion and metabolism in the ruminant. Oriel Press Ltd., Newcastle upon Tyne, England.

Conrad, H.R. 1966. Symposium on factors influencing the voluntary intake of herbage by ruminants: Physiological and physical factors limiting intake. J. Anim. Sci. 25:227-235.

Crampton, E.W., E. Donefer, and L.E. Lloyd. 1960. A nutritive value index for forages. J. Anim. Sci. 19:538-544.

Grovum, W.L. 1987. A new look at what is controlling food intake. p. 1-39. In F.N. Owens (ed.) Proc. Symp.: Feed intake by beef cattle. Oklahoma State Univ. Agric. Expt. Sta., Stillwater.

Mertens, D.R. 1973. Application of theoretical mathematical models to cell wall digestion and forage intake in ruminants. Ph.D. dissertation. Cornell Univ., Ithaca, NY. Diss. Abstr. 74-10.

Mertens, D.R. 1985. Factors influencing feed intake in lactating cows: From theory to application using neutral detergent fiber. p. 1-18. In Proc. Georgia Nutr. Conf., Univ. of Georgia, Athens.

Mertens, D.R. 1986. Effect of physical characteristics, forage particle size and density on forage utilization. Proc. Am. Feed Ind. Assoc. Nutrition Symposium-1986, Arlington, VA, pp.91.

Mertens, D.R. 1987. Predicting intake and digestibility using mathematical models of ruminal function. J. Anim. Sci. 64:1548-1558.

Mertens, D.R. 1992. Nonstructural and structural carbohydrates. p. 219-235. In H.H. Van Horn and C.J. Wilcox (ed.) Large dairy herd management. Am. Dairy Sci. Assoc., Champaign, IL.

Mertens, D.R. 1994. Regulation of forage intake. p. 450-493. In G.C. Fahey, Jr. and M Collins (eds.) Forage Quality, Evaluation and Utilization. Am. Soc. Agron., Madison, WI.

NRC (National Research Council). 1987. Predicting feed intake of food-producing animals. National Academy Press, Washington, DC. 85 pp.

Owens, F.N., J Garza, and P. Dubeski. 1991. Advances in amino acid and N nutrition in grazing ruminants. In Proc. 2nd Grazing Livestock Nutr. Conf., Aug. 2-3, 1991, Steamboat Springs, CO. Oklahoma State Univ. Agr. Exp. Sta. Misc. Pub. MP-133. p. 109-137.

Reid, J.T. 1961. Problems of feed evaluation related to feeding dairy cows. J. Dairy Sci. 11:2122-2133.

Sudweeks, E.M., L.O. Ely, D.R. Mertens and L.R. Sisk. 1981. Assessing minimum amounts and form of roughages in ruminant diets: Roughage value index system. J. Animal Sci. 53:1406.

Waldo, D.R. 1986. Effect of forage quality on intake and forage-concentrate interactions. J. Dairy Sci. 69:617-631.