Maximizing Forage Use by Dairy Cows

David R. Mertens

USDA-Agricultural Research Service, US Dairy Forage Research Center, Madison WI 53706
Email: David.Mertens@ars.usda.gov

■ Take Home Messages:

- The NDF (neutral detergent fiber) intake system takes into account both forage quality and cow production and uses simple equations to determine the maximum proportion of forage in dairy rations
  - Ingredient NDF concentration can be used to formulate diets because it is negatively related to energy density, fiber is related to fill effect and minimal effective fiber is needed to maintain cow health and ruminal function
  - The difference in NDF among ingredient is much less than the difference between fiber and non-fiber among feeds
  - The system maximizes forage in the diet at the point that also meets the energy demand for target or potential milk production
  - For high producing cows, the maximum forage ration is limited by the minimum requirement for effective fiber
- Maximum forage use by dairy cows also requires that:
  - Negative impacts of starch and low ruminal pH on forage digestion be minimized
  - Forage nutritional value be maximized (lower NDF and higher NDFD)
  - Adequate forage production/procurement is available because rations formulated by the NDF intake system are typically higher in forage content than what is currently fed

■ Introduction

Maximizing forage use in dairy rations involves two factors: (1) maximizing the proportion of forage that can be in the ration and still allow the cow to optimize production and (2) maximizing the digestion and utilization of forage when it is included in a mixed ration of forage and concentrates. Because forages have lower intake potential and digestibility than concentrates there is an inherent conflict between adding forage and meeting the ration energy density required by high producing cows. Likewise there is an inherent conflict between fiber digestion and concentrate feeding because rapidly fermenting feeds tend to depress the digestion of fiber. These conflicting conditions indicate that indeed there is an optimum proportion of forage in the diet that maximizes its utilization. The objectives of this paper are to describe a quantitative system for calculating the maximal proportion of forage in a dairy ration and to discuss those characteristics of the forage and concentrate in the ration that can be used to fine-tune rations to maximize forage use by dairy cows.

▪ Maximizing the Proportion of Forage in Dairy Rations

Without consideration of the performance level of the cow, we could easily conclude that the maximum forage in a dairy ration would be 100%. However, practical experience suggests that 100% forage rations do not maximize productivity nor do they often maximize profitability or efficiency. Milk production results in a high energy demand, but ruminal fill of high fiber rations often limits the ability of cows to meet their genetic disposition to produce milk. In my previous paper (Mertens, 2009) I described a simple concept of intake regulation for dairy cows that uses two competing mechanisms to determine their daily intake. For high-energy, low-fiber rations, cows regulate intake to match the energy demand of their genetically programmed (target) milk production. For low-energy, high-fiber rations, cows consume the ration to meet their fill limitation and reduce milk production until energy output equals energy input. This latter mechanism explains why 100% forage diets do not allow cows to achieve maximum production.

The “art” of dairy ration formulation typically followed the guidelines that the forage:concentrate (**F:C**) ratio should be between 40:60 and 60:40. Within these boundaries higher producing cows need rations with ratios closer to 40:60 and higher quality forages allow ratios to be closer to 60:40. With these thumb-rules there is always debate about the description of corn and cereal grain silages (are they forages or concentratrates?). When I taught Feeds and Feeding, I recommended that corn silage should be considered 50% forage and cereal grain silages should be considered 70% forage to use these guidelines successfully. The “art of feeding” involved the fine-tuning of the F:C ratio based on experience and formulating a concentrate mixture that provided adequate protein, minerals and vitamins. However, much less fine-tuning would be required and the objective of maximizing forage in rations could be achieved more quickly if a quantitative system could be developed to predict the F:C ratio for any combination of cow requirements and forage quality.

Characteristics of the NDF Intake System

The simple mathematical descriptions of the two mechanisms of intake regulation have interesting properties that can be used to formulate rations for specific objectives. First, they include characteristics of both the animal and the ration. Thus, they should effectively formulate rations for a broad range of cow requirements and forage qualities. Second, the ration characteristics (fill and energy density) are inversely related to one another and both can be related to the NDF concentration, which can be routinely determined by laboratory analysis. Third, when expressed on the common scale of NDF, the two mechanisms result in oppositely curving lines that intersect. High-school algebra (which you thought you might never use) indicates that the intersection of two lines defines a unique solution for both equations. Because the lines curve upward in opposite directions at the point of intersection, we can also conclude that the unique solution will be a maximum (Figure 1).

Before we develop a quantitative system for predicting the maximum amount of forage to feed, it is pertinent to determine if the simple mechanisms of intake regulation qualitatively match expectations (Figure 1). If a low-fiber (30% NDF), high-energy ration is fed to higher and lower producing dairy cows, we should expect that the higher producing cow would have higher intake, which is what the simple intake system predicts. If a high-fiber (60% NDF), low-energy ration was fed, we would expect both cows to have lower dry matter intake (**DMI**) and not be able to meet their milk production potential, which the simple intake system also predicts. Realistically, we would expect the cow with the greater production potential to “stuff” herself and eat more of the high fiber ration than a lower producing cow in an attempt to compromise between fill discomfort and production potential. The simple model would have to be modified to describe this expectation, but because we do not typically want to limit production by feeding rations that are too high in fiber we can ignore this limitation of the simple NDF intake system.

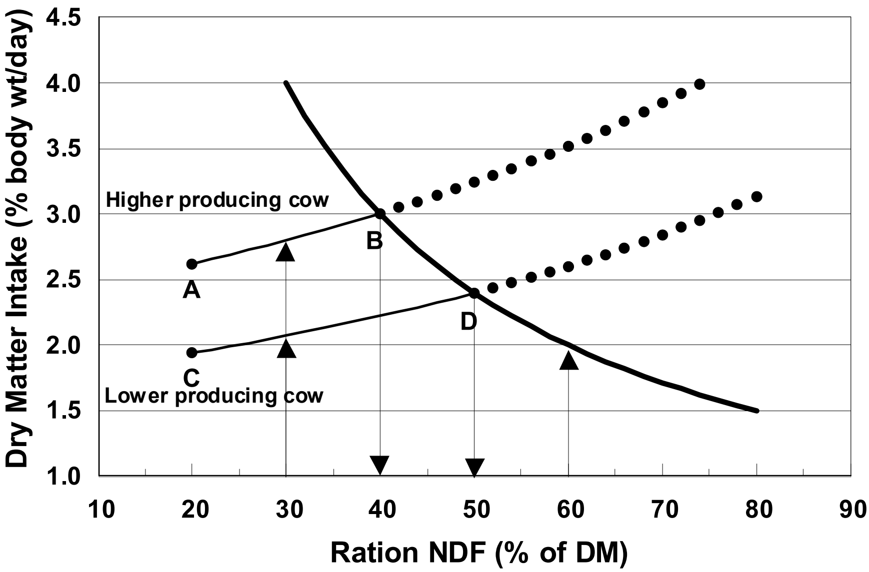

Figure 1. Illustration of intakes predicted using simple mechanisms of regulation based on energy demand or fill processing limitation. Dark curved line represents fill limitation. Line A-B and dotted extension represents energy demand regulation by a higher producing cow and line C-D and dotted extension presents energy demand regulation for a lower producing cow.

In most circumstances, we are interested in formulating the most profitable ration that allows cows to meet their maximum potential to produce milk. These rations would be located in the range of ration NDF indicated by line A-B for higher producing cows and line C-D for low producing cows. Note that the simple intake system predicts that the range of feasible diets narrows as the production level of the cow increases, which also agrees with our expectations. The NDF intake system also indicates that as we increase the fiber and reduce the energy density of feasible rations the intake of the cows should increase (going from A to B or C to D). We would expect that as the energy density of the ration decreases, cows will have to eat more of it to meet their energy requirements.

The most interesting and useful points in Figure 1 are B and D for higher and lower producing cows, respectively. These are the points at which the energy demand and fill limitation curves intersect. At these points, cows can meet their energy demand for maximum milk potential AND maximize the amount of fill they can comfortably process each day. It defines the ration with maximum DMI for the cow, which is also the ration with the maximum NDF that is feasible to feed. Because forages are the feed ingredient with highest fiber and lowest energy density, points B and D also define the ration with maximum forage proportion. The concept of maximizing DMI for a given level of milk production is disturbing to some because it automatically results in the lowest feed efficiency (kg of milk / kg of ration). For a given milk production and energy density in a ration, we would not want to maximize DMI because it lowers feed efficiency. However the NDF intake system is maximizing intake by minimizing energy density and maximizing forage proportion. If nutrients in forage cost less, then point B or D are the most profitable rations for the specific set of milk production potential and forage quality. If this is not the case, then some rations on the A-B or C-D lines are most profitable.

Using the NDF intake system to formulate dairy rations has been criticized (often by someone who has never tried to use it) because “the NDF intake model is too simple” or because “everyone knows that all NDF is not alike and is difficult to measure.” In response to the first criticism, a simple model that is useful is better than a complicated model that cannot be used. Granted, a model that is intended to predict intake in all situations needs to be complex, but this is not the case when the model is used to formulate a ration to achieve a target intake under defined circumstances (Mertens, 1994). In response to the second criticism, there is an official method for measuring amylase-treated NDF (**aNDF**) that has been demonstrated to be repeatable among laboratories (Mertens 2002). Although NDF is not the same chemical constituent among sources, the differences in the NUTRITIONAL properties among NDF sources is minor compared to the difference between NDF and non-NDF in those sources. Regardless of the source, all NDF occupies space in the digestive tract, requires/stimulates chewing activity, and digests slowly and incompletely. When compared directly, most methods of formulating maximum forage dairy rations will obtain results similar to the NDF intake system, but will require more fine-tuning to maximize forage use.

Useful Quantitative Equations Derived from the NDF Intake System

As shown in the previous paper (Mertens, 2009) the simple NDF intake system can be derived from several basic equations. When high-energy, low fiber rations are fed, intake is regulated by energy demand (I_e);

$I_e = R/E$; where R = animal’s energy requirement and E = ration’s energy density, which can be calculated from NDF. When low-energy, high fiber rations are fed, intake is limited by fill processing capacity (I_f):

$I_f = C/F$; where C = animal’s fill processing capacity and F = ration’s filling effect, which is related to NDF.

Do not be concerned about the algebra need to solve the simple NDF intake system. Derivations are provided to show that the final equation describing maximum forage ration is the result of simple mathematical logic. To formulate rations that meet both the animal's demand for energy and also its capacity for fill, we solve for the intersection of the lines when:

$I_e = I_f$, which can be expanded to:

R/E = C/F.

Each of these terms can be defined.

R = cow's daily NEL requirement (NRC, 1989) for a target level of milk production and composition and body weight gain or loss (**NER**) that is adjusted for intake depression to a 3X maintenance equivalent (**ANER**),

R = ANER = NER*.92 / [1-.04*(MMNT-1)], where **MMNT** = multiples of maintenance = NER / (NEL for maintenance).

E = f*FNEL + (1 – f)*CNEL; where E is the net energy of lactation (**NEL**) concentration of the ration, **f** = fraction of the ration that is forage, **FNE** = forage NEL concentration and **CNE** = concentrate NEL concentration.

C = cow's daily NDF processing intake capacity

C = NDFIC = optNDFI*BW; where **NDFIC** = NDF intake constraint and **optNDFI** is the optimum NDF intake (% body weight/day) that cows can comfortably consume and meet target milk production, and

F = $RNDF_{fill}$ = f*$FNDF_{fill}$ + (1 – f)*$CNDF_{fill}$; where $RNDF_{fill}$ = filling effect of the ration, f = fraction of the ration that is forage, $\mathbf{FNDF_{fill}}$ = forage NDF contributing to fill (fraction of DM) and $\mathbf{CNDF_{fill}}$ = concentrate NDF contributing to fill (fraction of DM).

This results in the following equation:

ANER / [f*FNE + (1 – f)*CNE] = NDFIC / [f*$FNDF_{fill}$ + (1 – f)*$CNDF_{fill}$], which can be solved for "f" to determine the maximum forage fraction in the ration ($\mathbf{f_{max}}$).

Remember we are solving for the intercept B or D in Figure1:

f_{max} = [NDFIC*(CNE) - ANER*($CNDF_{fill}$)] / [NDFIC*(CNE - FNE) + ANER*($FNDF_{fill}$ – $CNDF_{fill}$)].

To determine maximum DMI ($\mathbf{DMI_{max}}$) for the target production and maximum comfortable NDF processing capacity;

$I_e = I_f$ = C/F, which solves to:

DMI_{max} = NDFIC / [f*$FNDF_{fill}$ + (1 – f)*$CNDF_{fill}$].

Although these equations seem complex, they can easily be programmed into a spreadsheet or done on a calculator. Perhaps an example can demonstrate the utility of the NDF intake system. What is the maximum proportion of a ration that can be fed using a grass forage containing 50% NDF that is fed to a 650 kg cow producing 40 kg of 4%fat-corrected milk **(FCM)** and gaining 0.2 kg/d, assuming a optimum NDF intake of 1.2% body weight/d?

NER = (.08*$BW^{.75}$) + (.74*4%FCM) - (4.92*BW_Loss) + (5.12*BW_Gain)

NER = .08*128.7 + .74*40 – 4.92*0 + 5.12*.2

$NER = 10.30 + 29.6 - 0 + 1.02$
$NER = 40.92$
$MMNT = NER / (.08*BW^{.75})$
$MMNT = 40.92 / (.08*128.7)$
$MMNT = 3.97$
$ANER = NER*.92 / [1 - .04*(MMNT - 1)]$
$ANER = 40.92*.92/ [1 - .04*(3.97 - 1)]$
ANER = 42.73 Mcal/d

$NDFIC = optNDFI*BW/100$
$NDFIC = 1.2*650/100$
NDFIC = 7.8 kg/d

$FNDF_{fill} = .50$
$FNE = 2.86-0.0262*FNDF*100$ (equation for grass forages)
$FNE = 2.86-0.0262*.50*100$
FNE = 1.550 Mcal/kg
$CNDF_{fill} = .12$ (typical for simple mixtures of grain and protein supplements)
CNE = 1.90 Mcal/kg

$f_{max} = [NDFIC*(CNE) - ANER*(CNDF_{fill})] / [NDFIC*(CNE - FNE) + ANER*(FNDF_{fill} - CNDF_{fill})]$
$f_{max} = [7.8*1.9 - 42.73*.12] / [7.8*(1.90 - 1.55) + 42.73*(.50 - .12)]$
$f_{max} = [14.82 - 5.13] / [2.73 + 16.24]$
$f_{max} = 9.69 / 18.97$
$f_{max} = .511$

$RNDF = [f_{max}*FNDF_{fill} + (1 - f_{max})*CNDF_{fill}]$
$RNDF = [.511*50 + (1-.511)*.12]$
RNDF = .314 or 31.4%

$DMI_{max} = NDFIC / RNDF$
$DMI_{max} = 7.8 / .314$
DMI_{max} = 24.8 kg/d

After the concentrate mixture is formulated based on the initial estimate of F:C ratio, the value for $CNDF_{fill}$ and CNE can be adjusted and another iteration of the above calculations can be used to determine the F:C of the final ration.

The NDF intake system accounts for both forage and cow differences as demonstrated by using it to generate maximum-forage rations for forages of different fiber concentrations and for cows with different target milk production. The NDF intake system estimates that the maximum proportion of forage in the ration will decrease as the NDF concentration of the forage increases (Table 1). For cows with high milk production (45 kg/d 4% FCM) and grass forages with less than 50% NDF, it is possible to maximize forage within the 40:60 to 60:40 F:C window. However, for grass forages greater than 55% it is difficult to create rations that do not contain too much forage. This illustrates the need to have forages with high nutritive value when milk production is high. One unusual aspect of the NDF intake system is that predicted intake of maximum forage rations is higher for those containing forages with higher NDF. This increased intake is related to the increased concentrate in rations containing high-fiber forages.

Table 1. Effect of changing grass forage NDF concentration on rations that maximize forage proportion for a 650 kg cow, gaining 0.3 kg/d and producing 45 kg/d of 4% fat-corrected milk using a barley-based concentrate containing 4% supplemental fat, 11% NDF_{fill} and 1.87 Mcal/kg.

Characteristic	Grass NDF, % of DM			
	45	50	55	60
optNDFI, % BW/d	1.20	1.20	1.20	1.20
Forage, % of ration DM	52.6	44.1	38.0	33.4
peNDF, % of ration DM	25.0	24.2	23.6	23.2
NDF_{fill}, % of ration DM	28.9	28.2	27.7	27.4
NDF, % of ration DM	32.9	33.0	33.0	33.0
DM Intake, %BW/d	4.15	4.25	4.33	4.39

For a given forage quality, the NDF intake system correctly indicates that dairy rations must contain less forage as the target milk production increases. Thus, it provides a ration formulation system that can account for differences in both forage quality and cow performance. The system predicts the maximum proportion of a given forage that can be fed and still meet milk production demands. It also estimates the maximum DMI that will be needed. However, rations with less forage will also allow cows to meet their production potential as long as they provide adequate fiber for ruminal health and function.

Table 2. Effect of changing milk production on rations that maximize forage proportion for a 650 kg cow gaining 0.3 kg/d using a barley-based concentrate containing 4% supplemental fat, 11% NDF_{fill} and 1.87 Mcal/kg and grass forage containing 55% NDF.

Characteristic	4% Fat-corrected Milk Yield (kg/d)			
	35.0	40.0	45.0	50.0
optNDFI, % BW/d	1.20	1.20	1.20	1.20
Forage, % of ration DM	50.3	43.7	38.0	33.0
peNDF, % of ration DM	28.8	26.0	23.6	21.6
NDF_{fill}, % of ration DM	33.1	30.2	27.7	25.5
NDF, % of ration DM	37.4	35.0	33.0	31.2
DM Intake, %BW/d	3.62	3.97	4.33	4.70

Refinements of the Simple NDF Intake System for Practical Use

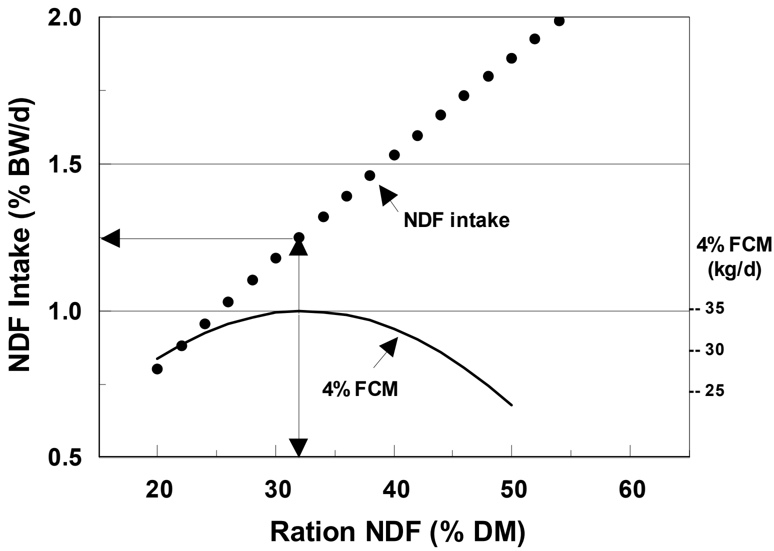

Figure 2. Typical 4% fat-corrected milk and NDF intake responses for a range of ration NDF concentrations. The optimum NDF intake occurs at the point of maximum milk yield and is usually near 1.25% of body weight per day for cows in mid to late lactation.

A key factor in the NDF intake system is the optimum NDF intake (**optNDFI)**. As shown in Figure 2, this is not the maximum NDF intake of dairy cows rather it is the intake of NDF that maximizes production. When fed rations very high in fiber (>40%) dairy cows can eat greater amounts of NDF, but they cannot meet their energy demand and therefore reduce production and body weight. Although the average optNDFI for dairy cows in mid to late lactation is 1.25% body weight/day (% BW/d), with a standard deviation of 0.1% BW/d, it varies with lactation number and stage of lactation. It appears that first lactation cows have a lower daily NDF processing ability than older cows, which may be related to the lower body capacity per kilogram of weight. A side profile shows that younger animals have less body depth and capacity than older cattle. Similarly, the deposition of internal fat and volume of the fetus compress digestive capacity in late lactation that apparently requires time for expansion during early lactation (Table 3).

Table 3. Change in optimal NDF intake with lactation number and week of lactation.

Week of lactation	First Lactation	Second + Lactation
	- % of BW/day -	
2	0.78	0.87
4	0.91	1.00
8	1.05	1.17
12	1.12	1.26
16	1.14	1.29
20	1.14	1.30
24	1.13	1.27
28	1.11	1.24
32	1.08	1.19
36	1.04	1.13
40	1.01	1.08
44	0.97	1.01
Dry cows	0.92	0.95

To function correctly for cows in the first 60 days of lactation, it is necessary to take into account the tissue loss that is an integral part of early lactation. The hormones that initiate and stimulate milk production are lipolytic and cause females of all species to mobilize the fat accumulated during pregnancy for milk production during early lactation. This is the reason why attempts to prevent body weight loss during early lactation fail and why adding fat or high levels of starch to early-lactation rations can actually reduce intake and negatively affect lactation performance. In early lactation, it may be more desirable to have fill limiting intake instead of energy demand because it will help to expand fill processing capacity more rapidly and prevent dietary fats and glucogenic (glucose generators such as propionate from ruminal fermentation) precursors from limiting intake. Most body weight loss occurs in the first 30 days of lactation and typically averages -1.1, -1.4 and -1.6 kg/d for lactations 1, 2, and 3, respectively. Allen (personal communication) recommends that starch concentration and fermentability be reduced in early lactation to prevent intake suppression and in late lactation to minimize fattening. However, at the time of peak lactation to mid lactation it is often best to feed rations with less than maximal forage content to insure that intake is not inhibited by fill (I usually reduce optNDFI by 0.1 to accomplish this). If the correct body weight loss and optimum NDF intake are used, the NDF intake system predicts higher fiber and lower concentrate contents in rations for early lactating cows and more accurately predicts intake of early lactation cows (Table 4).

Table 4. Effect of changing body weight loss and optimum NDF intake on rations that maximize forage proportion for a 650 kg cow during the first 30 days of lactation and producing 40 kg/d of 4% fat-corrected milk using a barley-based concentrate containing 4% supplemental fat, 11% NDF_{fill} and 1.87 Mcal/kg and grass forage containing 55% NDF.

Characteristic	Average body weight loss (kg/d)			
	-1.60	0.00	-1.60	0.00
optNDFI, % BW/d	0.90	0.90	1.20	1.20
Forage, % of ration DM	44.4	30.8	62.9	46.3
peNDF, % of ration DM	26.3	20.6	34.0	27.1
NDF_{fill}, % of ration DM	30.5	24.5	38.7	31.4
NDF, % of ration DM	35.3	30.4	41.8	35.9
DM Intake, %BW/d	2.95	3.67	3.10	3.82

In addition to the cow's impact on optNDFI, characteristics of the forage also affect optNDFI. Meta-analysis (Mertens, 2006) of a compilation of experiments in which forages with different NDF digestibilities (NDFD) were compared,indicates that cows eat and produce more when fed forages with higher NDFD. Higher NDFD should increase the breakdown of fiber resulting in greater fiber intake and within experiment NDFI (kg/d) was increased 0.00485 for each percentage of in vitro NDF digestibility at 48 hr of fermentation (IVNDFD48h) of the forage in the ration. This factor can be added to the calculation of NDFIC in the NDF intake system to include the effects of increased fiber digestibility of the forage on the maximum proportion of forage that can be fed and still meet the target production of the cow.

A second refinement for the NDF intake system is the adjustment of NDF values for the filling effect of non-forage fiber sources such as beet pulp and distillers grains. To keep the system simple, fill was directly related to NDF and this approach seems to work when mixed rations contain only forage, grain, and protein supplement. Some have suggested that perhaps only the NDF in forage should be used for ration formulation by simply assuming that

0.75 of the optNDFI should come from forage. However, this approach assumes that non-forage NDF has no effect on ration characteristics like energy density, chewing activity or fill processing capacity. The recommended approach is to adjust the NDF values of non-forage fiber sources to more closely predict their impact on intake. When fed in small proportions (total of < 0.20 of ration DM), non-forage fiber sources containing < 40% NDF typically obtain intakes similar to that of simple concentrate mixtures containing 12% NDF. Thus, a simple approach can be used to adjust the NDF of a ground non-forage fiber source to reflect its NDF_{fill} (Table 5):

For concentrates < 12 % NDF:	NDF_{fill} = NDF.
For concentrates between 12 and 40% NDF:	NDF_{fill} = 12%.
For concentrates > 40% NDF:	NDF_{fill} = 0.3 X NDF.
For long or chopped forages :	NDF_{fill} = NDF.
For ground or pelleted forages:	NDF_{fill} = 0.3 X NDF.

This empirical system is effective for meeting the needs of ration formulation. However, given that conceptually the filling effect of a feed was related to its volume (Mertens, 2009), it might be more rigorous to adjust NDF for the proportional decrease in feed volume per unit of NDF compared to chopped forage.

The final refinement of the NDF intake system is the addition of a minimum fiber requirement. Although the system indicates that any ration along the energy demand lines (A-B) or (C-D) in Figure 1 is acceptable, there is a point at which the ration becomes too low in fiber to meet the minimum fiber requirements of dairy cows. As milk production increases, the range in diets that meet the cow' energy demand decreases to the point that the maximum forage ration is defined by the minimum fiber requirement. Dairy cows have a minimum fiber requirement that is needed to maintain ruminal health and function and to prevent milk fat depression. Mertens (1997) related this requirement to chewing activity and devised a system based on physically effective NDF (**peNDF**), which is the fiber that stimulates/requires chewing activity. He used a compilation of data from research on chewing activity of cows to develop physical effectiveness factors (**pef**) that can be used to adjust NDF to reflect its impact on chewing (Table 5). Mertens (1997) suggested that the minimum requirement of peNDF is about 21% of ration DM.

The minimum peNDF requirement adds the third and final equation to the NDF Intake system:

RpeNDF = [f_{max}*FpeNDF + (1 – f_{max})*CpeNDF]; where **RpeNDF** = ration physically effective NDF (% of DM), f_{max} = maximum forage content in the ration; **FpeNDF** = forage physically effective NDF, and **CpeNDF** = concentrate physically effective NDF.

If RpeNDF is less than 21%, there is no feasible ration and either the milk production of the cow must be reduced or the quality of the forage or concentrate must be increased.

Table 5. Crude protein and NDF composition (% of DM) of selected feeds with adjustments using fill factor (ff) to calculate NDF_{fill} and physical effectiveness factor (pef) to calculate physically effective fiber.

Feedstuff	CP	NDF	ff	NDFfill	pef	peNDF
Alfalfa hay, 1/10th bloom	20.8	42.9	1.0	42.9	0.95	40.8
Alfalfa hay, mid bloom	17.8	50.9	1.0	50.9	0.95	48.4
Alfalfa hay, pre-bud	22.8	36.3	1.0	36.3	0.95	34.5
Alfalfa pellets, 3/8"	19.2	41.6	0.3	12.5	0.40	16.6
Barley grain	12.5	20.8	=	12.0	0.40	8.3
Barley silage, headed	12.0	56.3	1.0	56.3	0.90	50.7
Barley straw	4.4	72.5	1.0	72.5	1.00	72.5
Beet pulp	10.0	45.8	0.3	13.7	0.40	18.3
Brewers grains, dried	29.2	47.4	0.3	14.2	0.40	19.0
Canola meal	37.8	29.8	=	12.0	0.40	11.9
Canola seed	20.5	17.8	=	12.0	0.40	7.1
Corn distillers grains w/ solubles	29.7	38.8	=	12.0	0.40	15.5
Corn distillers grains w/o solubles	25.0	44.0	0.3	13.2	0.40	17.6
Corn grain, dry	9.4	9.5	1.0	9.5	0.40	3.8
Corn grain, high moisture	9.2	10.3	1.0	10.3	0.40	4.1
Corn gluten feed	23.8	35.5	=	12.0	0.40	14.2
Corn silage, few ears	9.7	54.1	1.0	54.1	0.90	48.7
Corn silage, average	8.8	45.0	1.0	45.0	0.90	40.5
Corn silage, well-eared	8.5	40.0	1.0	40.0	0.90	36.0
Cottonseed hulls	6.2	85.0	0.9	76.5	0.40	34.0
Cottonseed meal, solv. extr.	44.9	30.8	=	12.0	0.40	12.3
Cottonseed, whole, w/ lint	23.5	50.3	0.9	45.3	0.40	20.1
Grass silage, immature	16.2	51.0	1.0	51.0	0.90	45.9
Grass silage, mid-maturity	14.8	58.2	1.0	58.2	0.90	52.4
Grass silage, mature	12.7	66.6	1.0	66.6	0.90	59.9
Linseed meal, solv. extr.	32.6	36.1	=	12.0	0.40	14.4
Oat silage, headed	12.9	60.6	1.0	60.6	0.90	54.5
Oats grain	13.2	30.0	=	12.0	0.40	12.0
Soybean hulls, fine grind	13.9	60.3	0.3	18.1	0.40	24.1
Soybean meal 44%CP	49.9	14.9	=	12.0	0.40	6.0
Soybean meal 48%CP	53.8	11.0	1.0	11.0	0.40	4.4
Soybean seeds, roasted	39.2	19.5	=	12.0	0.40	7.8
Sunflower meal with hulls	28.4	40.3	0.3	12.1	0.40	16.1
Triticale silage	13.8	59.7	1.0	59.7	0.90	53.7
Wheat bran	17.3	42.5	0.3	12.8	0.40	17.0
Wheat grain, hard red	14.2	13.4	=	12.0	0.40	5.4
Wheat middlings	18.5	36.7	=	12.0	0.40	14.7
Wheat silage	12.0	59.9	1.0	59.9	0.90	53.9
Wheat straw	4.8	73.0	1.0	73.0	1.00	73.0

Although the manual calculation of the equations of the NDF intake system best illustrates how it works to formulate rations that maximize forage use, least-cost (linear programming) solutions are best at determining which feasible solution is most profitable for a given target milk production. The NDF intake system can be easily implemented in linear programming by three constraints:

$ANER \leq \sum (Amt_i{*}NE_i)$,

$NDFIC \geq \sum (Amt_i{*}NDFfill_i)$, and

$peNDFR \leq \sum (Amt_i / \sum(Amt_i){*}peNDF_i)$; where ANER = net energy of lactation adjusted to a 3X maintenance equivalent (Mcal/d), NDFIC = cow's daily NDF processing intake capacity (kg/d), **peNDFR** = minimum requirement for physically effective NDF (% of ration DM), and **Amt_i**, **NE_i**, **$NDFfill_i$**, and **$peNDF_i$** = the amount, net energy, fill adjusted NDF, and physically effective NDF of the i^{th} feed, respectively. The area of feasible rations is in shown in Figure 2.

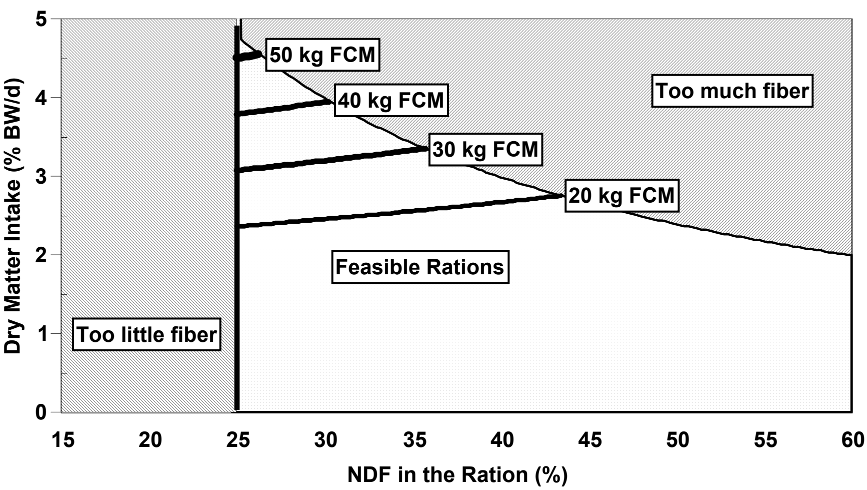

Figure 2. Area of feasible rations based on the NDF intake system.

▪ Maximizing the Digestion of Forage in Mixed Rations

It is well known that mixing concentrates with forage reduces the digestion of fiber in the forage. However, the mechanism for this negative effect is unknown making it difficult to overcome. There is some indication that fiber-digesting bacteria are sensitive to lower ruminal pH. Thus, any dietary modification that helps to maintain pH such as providing adequate fiber for chewing activity, adding supplemental buffers, or reducing the fermentability of starch sources may minimize the negative impact of concentrates on fiber digestion.

Starch in the diet may directly inhibit fiber digestion because bacteria have a high affinity for starch, and after they come in contact, bacteria easily ferment it and grow rapidly. This rapid fermentation and growth of starch-digesting bacteria can shift the microbial population very quickly away from fiber utilizing microbes. If dry corn or milo (slowly-fermenting starches) is used in the ration, starch can be limited to less than 30% of ration dry matter. But if more rapidly fermenting starches (high-moisture or thin flaked corn, barley, oats or wheat) the starch content of the ration should not exceed 26% of ration DM.

One side-effect of this rapid growth of starch-digesting bacteria is that they can use all of the soluble protein for their growth and metabolism, leaving a deficiency of nitrogen for fiber utilizing bacteria. It is recommended that about 1/3 of the nitrogen in the ration be soluble and rumen degradable.

In addition to its impact on chewing activity and salivary buffering, adequate long or chopped fiber also affects the dynamics of fiber entrapment and retention in the rumen. Although fiber concentration in the ration may be adequate, if it is all finely chopped, the ruminal contents become less biphasic (mat of long fiber particles floating on a liquid layer of small escapable particles). This changes the dynamics of fiber passage and allows a more rapid escape of fiber particles, which results in depression of fiber digestion. Fiber digests slowly compared to all other ration components and it can only be digested efficiently if it is retained in the rumen for an adequate time.

To truly maximize forage in the ration, the nutritional quality of the forage must also be maximized. Based on the discussion in my previous paper (Mertens, 2009), nutritional quality of forages is maximized by reducing NDF and increasing NDF digestibility (**NDFD**). It is often observed that alfalfa increases intake and cow performance. Much of this response is due to the lower NDF of alfalfa, but alfalfa may also increase rate of passage because it degrades into particles that are more cuboidal compared to grass particles that are long and slender and tend to be entrapped in the mat and pass more slowly. Although high forage nutritional quality should be a goal, it is possible to go overboard.

At some point (<35% NDF for alfalfa and <45% for grasses), it is possible to produce forages that cannot be used as the sole forage in rations because of difficulties in formulating rations with balanced protein and soluble carbohydrate composition. These high quality forages may have a place in rations (in small proportions) as supplements and appetite stimulants. However the costs of producing or purchasing them may not justify their production and use.

Those using the NDF intake system are often surprised by the amount of forage that can be used and find that too little forage was harvested. Just because rations can contain more forage does not mean that this is the only ration that can be fed. The system's advantage is that it can define the upper limit for both forage proportion in the ration and DMI. The ration that is finally formulated and fine-tuned should be the one that is most profitable.

■ Conclusions

The neutral detergent fiber (NDF) intake system uses equations that describe simple mechanisms of intake regulation to determine the maximum proportion of forage in dairy rations. Because these equations describe both the regulation of intake to meet the energy demands of milk production by the cow and also the intake limited by the digestive tract filling effect of the diet it takes into account both forage quality and cow production when estimating the maximum proportion of forage that can be in a ration and still meet the production potential of the cow. Ingredient NDF concentration can be used to formulate diets using the system because it is negatively related to energy density, fiber is related to the filling effect of a feed, and minimal effective fiber is needed to maintain cow health and ruminal function. Although the system is simple and NDF differs among sources, it is useful because the difference in NDF among ingredients is much less than the difference between fiber and non-fiber components in feeds. The NDF intake system maximizes forage in the diet at the point that also meets the energy demand for target or potential milk production. The range in feasible rations narrows as the production of cows increases. Thus, for high producing cows, the maximum forage ration is limited by the minimum requirement for effective fiber. After the ration with maximum forage content is formulated, additional factors need to be optimized to insure that maximum forage is used efficiently. The negative impacts of starch and low ruminal pH on forage digestion needs to be minimized by altering concentrate ingredients. Forage nutritional value also needs to be maximized by selecting forages with lower NDF and higher NDF digestibility. Finally, adequate forage production/procurement must be available because rations formulated by the NDF intake system are typically higher in forage than what is currently fed.

■ References

Mertens, D.R. 1992. Nonstructural and structural carbohydrates. In: Van Horn, H.H., and Wilcox, C.J. (eds.) Large Dairy Herd Management. Am. Dairy Sci. Assn., Champaign, IL. p. 219-235.

Mertens, D.R. 1994. Regulation of forage intake. In: Fahey Jr., G.C., (ed.) Forage Quality, Evaluation, and Utilization. Am. Soc. Agron., Madison, WI. p. 450-493.
Mertens, D.R. 1997. Creating a system of meeting the fiber requirements of dairy cows. J. Dairy Sci. 80:1463-1481.
Mertens, D. R. 2002. Gravimetric determination of amylase-treated neutral detergent fiber in feeds using refluxing in beakers or crucibles: Collaborative study. J. AOAC 85:1217-1240.
Mertens, D.R. 2006. Do We Need to Consider NDF Digestibility in the Formulation of Ruminant Diets? 27th Western Nutrition Conf., Sept. 19-20, Winnipeg, Manitoba p. 75-98.
Mertens, D.R. 2009. Impact of NDF Content and Digestibility on Dairy Cow Performance. Proc. 27^{th} Annual Western Canadian Dairy Seminar. Red Deer, Alberta. (this publication)
NRC (National Research Council). 1989. Nutrient Requirements of Dairy Cattle 6^{th} Revised edition). National Academy Press. Washington D.D. 157 pp.