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Article

Michael Thonney
Cornell University

FORMULATION OF RUMINANT DIETS USING BY-PRODUCT INGREDIENTS ON THE BASIS OF FERMENTABLE NDF AND NONSTRUCTURAL CARBOHYDRATES

Michael L. Thonney and Douglas E. Hogue
Cornell University
Ithaca, NY
mlt2@cornell.edu

ABSTRACT

The carbohydrate portion of ruminant diets formulated with by-product ingredients should contain a minimum level of fermentable NDF (FNDF) and a maximum level of nonstructural carbohydrates (NSCHO). This concept is supported by data from six feeding trials designed to quantify the optimum levels of these fiber fractions for growing lambs. The pooled data from these trials show that the effect of NDF on feed intake depended upon the fermentability of the NDF. While NDF, alone, could explain only 30% of the variation in feed intake, a regression equation with NDF divided into two component parts: 1) FNDF; and 2) indigestible NDF (INDF), could account for 85% of the variation of the 31 diet means in the pooled data from the six experiments. Increasing dietary FNDF dramatically increased intake and prevented metabolic disturbances, likely because FNDF provided substrates for rumen microorganisms to produce fermentation products desirable to maintain health and absorptive function of the rumen papillae that, in turn, absorbed substrates useful for metabolism by animal tissues. Based upon these results, a plan and a computer tool to formulate diets based on FNDF and NSCHO was developed. Example formulations containing by-product ingredients using this plan are provided for self-feeding diets for lactating ewes, growing lambs, lactating dairy cows, and feedlot cattle.

INTRODUCTION

Diets for ruminants traditionally have been balanced for energy, protein, vitamins, and minerals. Because rumen function must be maintained for optimum animal production, minimum fiber levels also often are specified as a given percentage of forage or NDF, but digestibility of the fiber is seldom considered in diet formulation. Although Krehbiel et al. (2006) recently proposed that an upper limit on the ME concentration existed in diets for feedlot cattle to optimize growth and efficiency, this approach does not account for the different ruminal effects of the various carbohydrates that provide dietary energy. During the past 20 years at the Cornell sheep farm, experiments were conducted to define the minimum fiber requirements of growing lambs. Results from those experiments led to the conclusion that the fermentable portion of the NDF (FNDF) should be balanced against nonstructural carbohydrates (NSCHO).

Development and maintenance of the ruminal absorptive surface requires products of microbial digestion, the volatile fatty acids (VFA; Flatt et al., 1958; Warner et al., 1956) and it seems logical that the best balance of VFAs to maintain rumen function comes from fermentation of NDF. Alternatively, fermentation of diets high in NSCHO increases ruminal lactic acid, which is about 10 times stronger than acetic, propionic, and butyric acids. This can lead to rumen parakeratosis and displaced abomasa (Van Soest, 1994). Metabolic acidosis can result, especially when fermentation of diets high in NSCHO results in high levels of the D-isomer of lactic acid because this isomer is metabolized very slowly by mammalian tissues (Krehbiel et al., 1995). Thus, a minimum level of FNDF and a maximum level of non-structural carbohydrates (NSCHO) should be specified for ruminant diets. In this review, we provide evidence that ruminant diets should be formulated for these carbohydrate components.

MATERIALS AND METHODS

Calculation of Carbohydrate Fractions

The indigestible NDF (INDF) was calculated based upon the amount of DM that was not digested from each feed ingredient. Metabolic fecal losses, assumed to be 10 to 15% of the dry matter (Van Soest, 1994), were subtracted from DM indigestibility (100 – digestibility) to determine the amount of DM, and thereby NDF, that was not digested (INDF). Fermentable NDF (FNDF) was NDF of the feed ingredient minus INDF. NSCHO was calculated as the difference between 100 and the total of NDF, CP, EE and Ash.

Combined Lamb Feeding Experiments

Six experiments, each lasting about 42 d with about 72 lambs of similar numbers of ewes and rams, were conducted to determine the minimum fiber requirements for optimum feed intake of growing lambs shortly after weaning (40 to 73 days of age) using the STAR management system (Lewis et al., 1996). Lambs had Dorset or Finnsheep or cross dams and were sired within each experiment either by Dorset or Finn x Dorset rams or by Suffolk rams. Diets were formulated based upon analysis of feed ingredients and calculated INDF values based upon the intake discount factors of Van Soest (1992) for digestibility. Various amounts of oat hulls, soy hulls, or other by-product ingredients that contained relatively high concentrations of NDF but differed in fermentability were included (Figure 1). In addition to fiber sources, soybean meal for protein, and appropriate mineral and vitamin supplements; corn or barley comprised the remainder of each diet with vegetable oil added to control dust.

Results were averaged over five to six pens of two lambs per diet; diet means were adjusted for the effect of experiment based upon the results of a statistical analysis that included the fixed effect of experiment and the continuous effects (covariates) of INDF and FNDF. After adjusting for experiment, the diet means were analyzed to determine the effect of INDF and FNDF on feed intake based upon two- and three-dimensional plots of the data and upon regression analysis. The complete regression model predicted dry matter intake from INDF, FNDF, INDFxFNDF, $INDF^2$, $FNDF^2$, and $INDF^2$x $FNDF^2$. A step-down procedure removed nonsignificant effects until only effects with P-values < 0.05 remained.

Other trials

Results from feeding trials with diets balanced for FNDF and NSCHO also are described for lactating ewes, lactating dairy cows, lambs fed high-fiber diets, and feedlot cattle.

Implementation

The Dugway Nutritional Plan (DNP) conceptualizes this approach to balance diets for FNDF and NSCHO. The plan will be presented in the results and discussion section. To implement diet formulation based upon the DNP, a Microsoft Access-based feed formulation tool was developed. The architecture and availability of the software are presented in the results and discussion section.

RESULTS AND DISCUSSION

Combined Lamb Feeding Experiments

High feed intake is a reliable indicator of excellent rumen function and of overall animal health. Several models predict that feed intake will first increase and then decline as the concentration of dietary NDF increases from zero to a high concentration (Fisher, 1996; Mertens, 1987). As shown in Figure 1, intake declined as expected when poorly fermentable NDF from oat hulls was added to the diet. In contrast, intake increased as highly fermentable NDF from soy hulls or other ingredients was added to the diet. In fact, the NDF concentration of the diet for the lambs that had the highest intake was 54%, while the NDF concentration of the diet for the lambs that had the lowest intake was 36%. Thus, the relationship of feed intake to dietary fiber differed depending upon the fermentability of the fiber.

To account for the fermentability of the NDF, the effect of both FNDF and INDF on feed intake for the lambs in these experiments was examined (Figure 2). The data points on the left side of the figure where INDF increases at low FNDF confirm the traditional concept that feed intake first increases and then declines as INDF increases (Fisher, 1996; Mertens, 1987). The data points on the right side of the figure show that this reduction in feed intake that occurs with high INDF can be mitigated if the diet has a high FNDF.

The relationship between feed intake and the fermentable and indigestible components of NDF was quantified by regression (Figure 3). This equation contains cross product terms and quadratic terms for INDF and FNDF producing the curved surface shown in Figure 3. Thus, feed intake generally curves up and then down as INDF increases. But feed intake generally curves up as FNDF increases, particularly at high INDF levels. Note that only two factors (INDF and FNDF) can explain 85% of the variation in diet mean feed intakes over a wide range of experimental diets for lambs. From these results, we conclude that diets should contain minimum levels of FNDF for rumen microorganisms to produce fermentation products desirable to maintain health and absorptive function of the rumen papillae (Flatt et al., 1958; Warner et al., 1956) that, in turn, absorb substrates useful for metabolism by animal tissues.

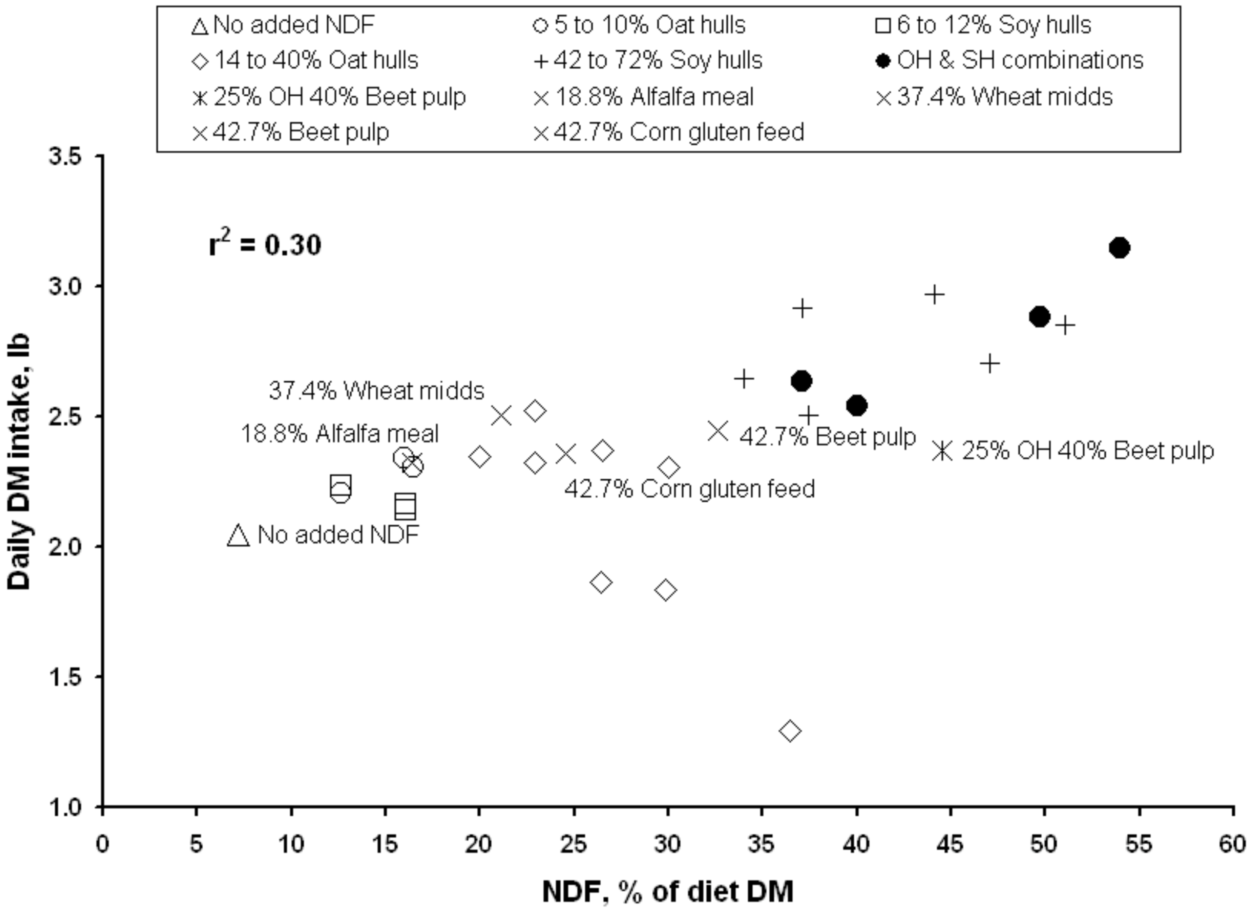

Figure 1. Relationship of feed intake to the concentration of neutral detergent fiber (NDF) in the diet of growing lambs.

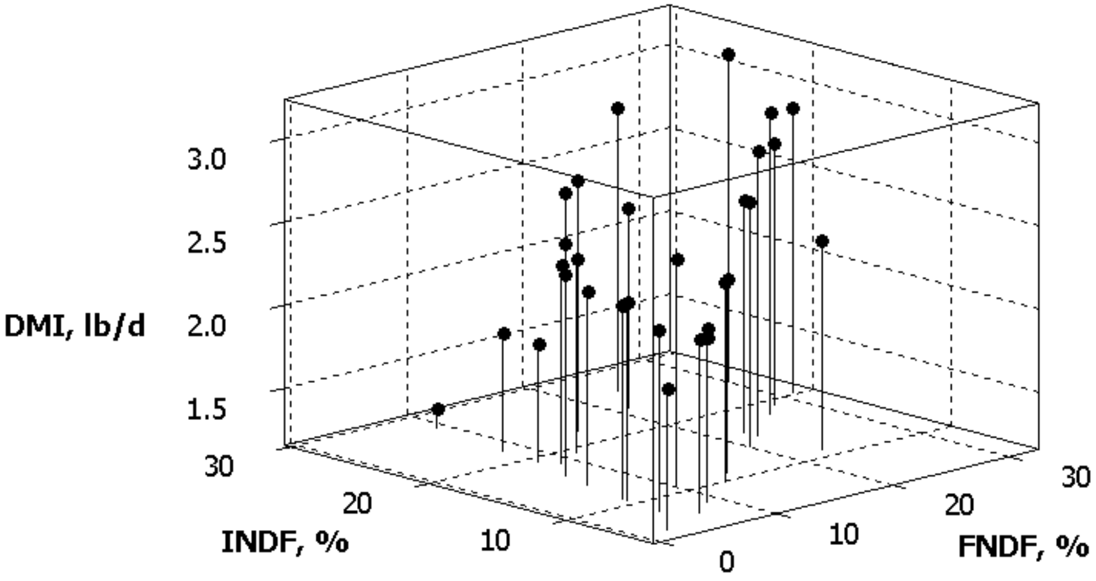

Figure 2. Relationship of feed intake to the dietary concentrations of indigestible neutral detergent fiber (INDF) and fermentable NDF (FNDF).

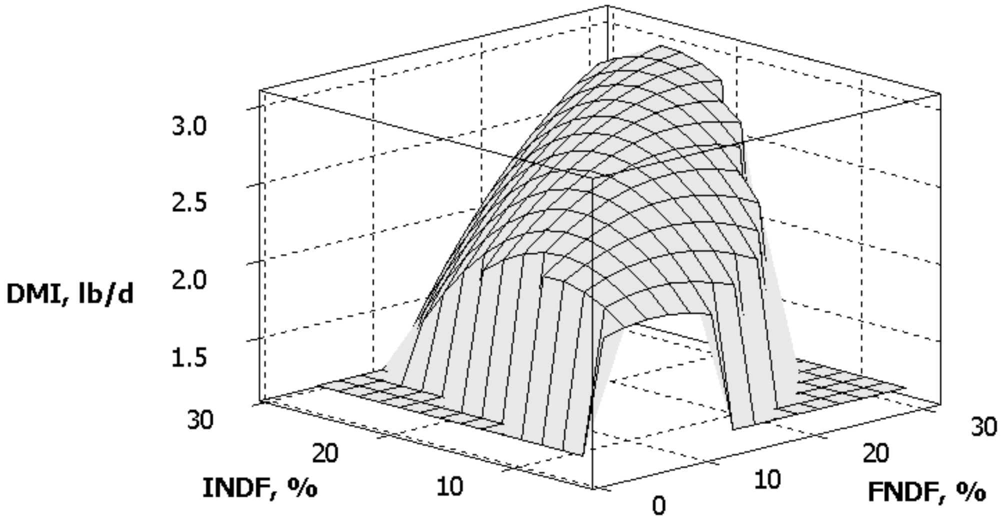

Figure 3. Surface plot showing the equation that describes the relationship of dry matter intake (DMI) to dietary indigestible neutral detergent fiber (INDF) and fermentable NDF (FNDF) concentrations. The equation was $DMI = 1.59 + 0.1014*INDF + 0.00610*INDF*FNDF - 0.00228*FNDF^2 - 0.00584*INDF^2$ with $SE = 0.14$ and $r^2 = 0.85$.

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Feeding Ewes with Triplet Lambs

These feeding trials (Hogue, 1994) were conducted to determine if a diet with sufficient FNDF would allow ewes nursing twins or triplets to consume enough feed to prevent weight loss in early lactation. Hay consumption was restricted to the amounts shown in Table 1.

Total feed intake was much higher than the NRC (1985) expected dry matter intake of 6 lb for ewes of this weight rearing twins during early lactation. In fact, total DMI of ewes in trial 2 was almost 7% of body weight. Furthermore, although digestibility data were not available, the available energy fed in this trial most probably exceeded that anticipated by the NRC (1985). Instead of losing weight, these ewes all gained weight while their triplet lambs gained rapidly and at an outstanding rate in trial 2. These results indicate that, if the diet is formulated properly so that intake is not limited, a negative energy balance for ewes with twins or triplets during early lactation is not obligatory.

Lactating Dairy Cows

After demonstrating in sheep that, by including sufficient FNDF in the diet, feed intake of animals in early lactation could be increased sufficiently to prevent body weight loss, this theory was tested with high producing dairy cows in the Cornell herd. A supplement of 70% soy hulls, 20% corn, and 10% Ren-plus was added to the feed already being consumed by high-producing lactating dairy cows. These cows consumed all of their original feed in addition to the 6 to 8 pounds of this supplement daily. This increased milk production in the Cornell herd by about 20% or 16 pounds per day. These findings further confirm that ruminant diets need to include a minimum concentration of FNDF in order to optimize feed intake.

Effect of High-Fiber Diets on Lamb Growth

Based upon the experiments outlined above from Hogue (1987; 1991) we formulated a diet with corn, corn gluten feed, and soy hulls that could be self-fed

Table 1. Observed feed intake and body weight gains of triplet-rearing ewes and their lambs

Item	Trial 1 (30 days)	Trial 2 (41 days)
Ewe feed intake	lb/d	lb/d
Hay	2.0	3.3
Pellets[1]	6.9	7.6
Total	8.9	10.9
Daily gain	lb/day (n)	lb/day (n)
Ewes	0.29 (8)	0.55 (14)
Lambs	0.49 (23)	0.71 (42)
3 lambs	1.47	2.13

[1] High Energy Lamb Pellets, Agway Inc., Syracuse, NY. A key ingredient to improve intake was 20% soy hulls.

to lambing and lactating ewes to substitute for the more expensive hay. Because the lambs also had access to the high-fiber ewe feed, the effect of that diet on efficiency and growth of lambs also was quantified in a feeding experiment comparing 1) a soy hull diet (64% corn, 20% soy hulls, 10% soybean meal); 2) a high fiber diet (35% corn, 34% corn gluten feed, 23% soy hulls); and 3) a corn gluten feed diet (54% corn, 37% corn gluten feed) with the remainder of the diets being 2.2% vegetable oil, 2.2% vitamin-mineral premix, and 2 to 4.1% limestone (to maintain Ca:P at 2:1); all on a DM basis.

No metabolic disturbances among lambs fed any of the diets were detected, indicating that proper rumen function. Growth and feed intake results sufficient FNDF was provided by each diet for are shown in Table 2. As expected by the random assignment of lambs to diets, initial weights were similar across diets. Although lambs fed the soy hull diet gained faster and had heavier weights, the effect of diet on growth rate was not significant. Lambs fed the high fiber diet consumed more dry matter either per day ($P = 0.01$) or as a proportion of body weight ($P < 0.001$) but grew less efficiently ($P < 0.001$) than lambs fed the other diets. There was no significant difference in growth, feed intake or feed efficiency between lambs fed the soy hull diet and those fed the corn gluten feed diet.

Our results do not fit models that have used NDF (Mertens, 1987) and DDM or functions of DDM such as NE_m (Fox et al., 1992) to predict feed intake. The dry matter intake of the high fiber diet in our experiment was much higher than that of the soy hull or corn gluten feed diets even though the three diets had similar predicted DDM. Furthermore, traditional models of feed intake would have predicted lower – not higher – dry matter intake for the higher fiber diet. In contrast and in support of the necessity to balance for FNDF, increased NDF fermentability resulted in higher feed intakes in dairy cows consuming diets with the same level of NDF (Oba and Allen, 1999). The dramatic intake-enhancing effect of diets high in FNDF also indicates that ruminant diets cannot be balanced properly by assuming a given intake level independent of the feed ingredients included in the diet.

Table 2. Effect of fiber level and protein source on growing lambs

	Diet				*P*-value for orthogonal contrast	
Item	Soy hull	High fiber	Corn gluten feed	SEM*	High fiber vs others	Soy hull vs corn gluten feed
Initial weight, lb	45.4	45.9	45.4	1.1	ns	ns
Final weight, lb	73.6	71.6	72.1	1.5	ns	ns
Gain, lb/day	0.67	0.62	0.64	0.02	ns	ns
DMI**, lb/day	2.19	2.36	2.10	0.06	0.010	ns
Gain/DMI	0.307	0.263	0.303	0.007	<0.001	ns
DMI, % BW	3.69	4.09	3.63	0.08	<0.001	ns

*Standard error of the mean.
**Dry matter intake.

Feedlot Cattle

The principle of balancing for minimum FNDF and maximum NSCHO has been applied at a custom feedlot in the Finger Lakes Region of New York since 2001. This paved, covered lot has a one-time capacity of 1,000 in pens of 75 to 250 head. Initial success with a diet based upon whole shelled corn, corn gluten feed, and a premix was followed by adding soy hulls to the mix.

Currently, the diet contains 70% corn and 30% custom pellet. This pellet contains 65% wheat midds, 30% soy hulls, 4% mineral-vitamin package (including Rumensin), and 1% urea. A pen of cattle starts with two big round hay bales and is fed 50% corn and 50% pellets for a few days before switching to the 70% corn and 30% pellet diet.

No cases of metabolic upsets, acidosis, or cattle going off feed have been detected since the diets first included sufficient FNDF. Excellent rates of gain, feed efficiency, and carcass grades have resulted from these diets. An example of performance based on a pen of heifers marketed in November 2006 is given in Table 3.

Table 3. Performance indicators of 70 heifers

Item	Value
Initial weight, lb	707
Final weight, lb	1192
Days fed	158
Average daily gain, lb/d	3.07
Feed/lb gain	8.54
Dry matter intake/lb gain	7.64
Feed cost/lb gain	$0.45
Yardage/lb gain	$0.11
Total cost/lb gain	$0.57
Death loss	1.4%
Net sale value per animal	$1,047.00
Net return	$30.60

The Dugway Nutritional Plan

The Dugway Nutritional Plan (DNP) was developed to provide an effective method of feeding ruminants and to overcome some limitations of traditional systems. Specifically, the DNP recognizes that diet formulation can have a significant effect on feed intake and also that the proper balance of dietary components can effectively prevent most metabolic disturbances such as acidosis and animals going off-feed.

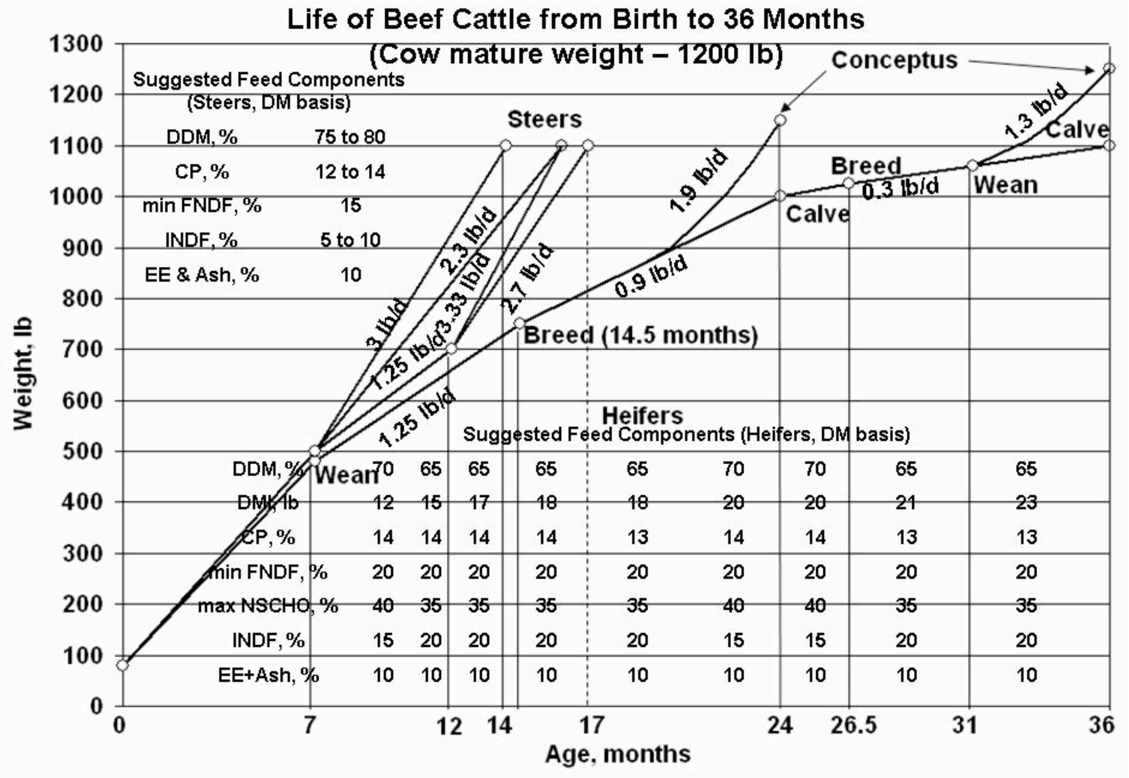
Pooled energy values such as TDN, DE, ME, NE, NE_m, NE_g, NE_l, and NEL are ignored in the DNP. Instead, diets are balanced on the carbohydrate components that generally make up these pooled values. The other dietary components are Ash, EE and Protein fractions (that is, CP or soluble, degradable, escape, and indigestible N), which are comparable to generally accepted systems. Because both EE and ash in ruminant diets are generally about 5%, it is suggested both are to be included at about this level and not discussed further. For simplicity, the protein fraction(s) are only considered as the total or crude protein. The carbohydrates are divided into INDF, FNDF, and NSCHO and are the variable fractions that receive the most emphasis in the DNP. Decreasing the INDF in the diet and/or increasing the feed intake are the most effective ways of increasing the supply of nutrients available for animal production. However, at high feed intakes, the proper balance between FNDF and NSCHO becomes important, especially for preventing metabolic disturbances.

The Ash, EE, Protein fractions, INDF, FNDF and NSCHO components can be summed together or properly pooled and adjusted to estimate a pooled energy value such as TDN or DE or ME or NE, but that pooling is unnecessary and redundant. Furthermore, the effects of the individual components are lost when pooled.

Minimum levels of FNDF and maximum NSCHO are suggested. Animals fed diets high in good quality forage such as the beef cow herd and sheep either at maintenance or pregnant or suckling a single lamb usually will have diets that exceed the minimum FNDF in the diet and not approach the maximum suggested level of NSCHO. Higher producing lactating dairy cows, ewes suckling 2, 3, or 4 lambs, feedlot lambs, and feedlot cattle fed high grain diets often will not meet the suggested minimum FNDF and maximum NSCHO levels unless the diets are balanced carefully.

The growth and production of beef cattle up to 3 years of age and the suggested dietary components for them are depicted in Figure 4. These are presented for the growth and production of heifers up to 36 months and for steers up to harvest at about 1100 pounds. A mature cow weight of 1200 lb was assumed.

The suggested feed components for the steers are not as detailed as that given for the heifers. Primarily the suggestion is that the DDM of the diet is as high as appropriate (and the INDF as low) but that sufficient FNDF is included to balance the high levels of NSCHO. The FNDF level is suggested to be at least 15%. The CP level is reduced from 14 to 12% from early to later growth periods and the DMI depends upon the stage of growth and weight of the steers. This level of 15% FNDF will allow the animals to maintain adequate rumen function and prevent metabolic disturbances.



Suggested Feed Components
(Steers, DM basis)

DDM, %	75 to 80
CP, %	12 to 14
min FNDF, %	15
INDF, %	5 to 10
EE & Ash, %	10

Suggested Feed Components (Heifers, DM basis)

DDM, %	70	65	65	65	65	70	70	65	65
DMI, lb	12	15	17	18	18	20	20	21	23
CP, %	14	14	14	14	13	14	14	13	13
min FNDF, %	20	20	20	20	20	20	20	20	20
max NSCHO, %	40	35	35	35	35	40	40	35	35
INDF, %	15	20	20	20	20	15	15	20	20
EE+Ash, %	10	10	10	10	10	10	10	10	10

Figure 5. Life of beef cattle and suggested feed component levels from birth to 36 months. Suggested component levels are based upon feed composition tables that include fermentable neutral detergent fiber (FNDF) levels computed assuming intakes at one times maintenance.

Feed Component Values

Some approximate feed component values are given in Table 4. Included are several forages at different maturity levels, the major grains and a variety of by-products that now are widely available for feeding. Values are listed for nonstructural carbohydrates (sugars and starches), neutral detergent fiber (NDF) divided into fermentable (FNDF) and indigestible (INDF), crude protein (CP), ether extract (EE), and ash. These components sum to 100% of the dry matter.

The DDM, CP, EE and Ash values were taken from existing tables, primarily those of Van Soest (1992). Digestible dry matter (DDM) generally was considered to be equivalent to TDN except for feeds rich in EE or Ash. Furthermore, INDF is highly negatively correlated with DDM so that one or the other could be omitted. However, digestible dry matter at one times maintenance was included so that INDF could be calculated as the difference between indigestibility and endogenous fecal losses. Highly digestible feeds like corn yield about 10% endogenous losses while forages yield about 15% (Van Soest, 1994). Intake levels higher than maintenance result in a depression in digestibility (Van Soest et al., 1992; Wagner and Loosli, 1967). Because it is primarily fiber digestibility that is depressed as intake increases, the ingredient FNDF levels would be lower for producing animals with consumptions above maintenance. To compensate for this digestibility depression, correspondingly higher FNDF levels were suggested in Figure 4 for growing, pregnant, and lactating cattle. Most feed components will have considerable variation and therefore the numbers in Table 4 should be considered as being approximate.

Feedform Diet Formulation Software

A simple Microsoft Access-based program was developed to balance diets based upon the Dugway Nutrient Plan. Included are modifiable tables of feed components and suggested levels of components for sheep and cattle. Formulation is based upon the substitution method. Premixes can be formulated and added directly to the table of feed components. After balancing a complete diet, the ingredients that are not the substitution ingredient can be specified as a supplement. Details are available at [http://www.sheep.cornell.edu/sheep/management/economics/cspsoftware/feedform/], from where the program can be downloaded.

IMPLICATIONS

Grain by-products that contain high concentrations of FNDF are available to balance diets of high-producing ruminants. Providing adequate FNDF prevents rumen metabolic disturbances that limit feed intake and production. FNDF, INDF, and NSCHO values have been estimated for common feed ingredients, suggested dietary levels for these carbohydrate fractions have been estimated and a formulation tool has been developed and is available to use these estimates to balance diets for cattle and sheep.

Table 4. Some approximate feed component values for intake at maintenance*

Ingredient	NSCHO	FNDF	INDF	CP	EE	Ash	DDM
Forages	- - - - - - - - - - - -	-	- - % of dry matter	- -	- - - -	- - - - - -	- - - - -
Alfalfa							
Early bloom	27	19	23	19	3	9	62
Mid bloom	25	21	25	17	3	9	60
Late bloom	23	23	32	12	2	8	53
Orchard grass							
Early bloom	20	37	20	10	3	10	65
Late bloom	13	36	31	8	3	9	54
Timothy							
Late veg.	20	40	15	14	3	8	70
Early bloom	18	40	21	11	3	7	64
Late bloom	14	39	29	8	3	7	56
Seed stage	14	34	38	6	2	6	47
Corn silage, 45% grain	42	28	13	9	3	5	72
Wheat straw	2	40	45	3	2	8	40
Grains							
Barley							
Heavy	63	14	5	13	2	3	84
Light	52	17	11	14	2	4	77
Corn	75	6	3	10	4	2	87
Oats, 32 lb/bushel	37	27	15	13	3	5	73
Wheat	69	10	6	11	2	2	84
By-products							
Beet pulp	32	40	14	8	1	5	74
Citrus pulp (15 pls[a] in FNDF)	44	32	6	7	4	7	82
Corn germ meal	6	50	12	26	3	3	76
Corn gluten feed	18	40	5	25	7	5	83
Cottonseed hulls	0	50	40	4	2	4	45
Dried brewers grains	17	28	18	26	7	4	67
Dried distillers grains	10	42	8	26	10	4	80
Hominy	25	50	5	12	7	1	85
Oat hulls	9	28	50	4	2	7	35
Soy hulls	11	62	8	12	2	5	80
Wheat midds	40	32	5	18	3	2	83
Protein supplement							
Soybean meal, 44% CP	28	9	5	49	2	7	80

*NSCHO, nonstructural carbohydrate; FNDF, fermentable neutral detergent fiber; INDF, indigestible NDF; CP, crude protein; DDM, digestible dry matter.

[a] Pectin-like-substances.

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