4 Carbohydrates

Carbohydrates are the major source of energy in diets fed to dairy cattle and usually comprise 60 to 70 percent of the total diet. The main function of carbohydrates is to provide energy for rumen microbes and the host animal. A secondary, but essential, function of certain types of carbohydrates is to maintain the health of the gastrointestinal tract. The carbohydrate fraction of feeds is a complex mixture of numerous monomers and polymers that are usually defined according to analytic procedures and availability to the animal. Carbohydrates are broadly classified as either nonstructural or structural. Nonstructural carbohydrates (NSC) are found inside the cells of plants and are usually more digestible than structural carbohydrates that are found in plant cell walls.

NONSTRUCTURAL CARBOHYDRATES

Sugars, starches, organic acids, and other reserve carbohydrates such as fructans make up the NSC fraction and are major sources of energy for high producing dairy cattle. Nonstructural carbohydrates and pectin are highly digestible and are generally increased in the diet at the expense of neutral detergent fiber (NDF) to meet the energy demands of lactating dairy cows. Ruminal fermentation of NSC varies greatly with type of feed and conservation and processing methods.

Nonfibrous carbohydrate (NFC) as calculated by difference: NFC = 100 − (%NDF + %CP + %Fat + %Ash) and NSC (also referred to as total nonstructural carbohydrates), as measured by enzymatic methods (Smith, 1981) are distinct fractions. Mertens (1988) reported that the concentrations of NFC and NSC are not equal for many feeds and the terms should not be used interchangeably. The difference between NFC and NSC concentrations varies considerably (Table 4-1). Much of the difference is caused by the contribution of pectin and organic acids. Pectin is included in NFC but not in NSC. When using the modified (ferricyanide as the colorimetric indicator) enzymatic method of Smith (1981), starch, sucrose, and fructans are measured as NSC. For forages, particularly grasses, fructans and sucrose are major components of NSC. Sucrose is found in beet and citrus pulp and other byproduct feeds. For many of these feeds, the NSC is likely all sugars. For corn silage, grains, and most byproducts, the NSC is nearly all starch (Miller and Hoover, 1998). Table 4-2 illustrates the differences in the components that make up NFC for selected feedstuffs. Depending on preservation method and grain type the composition of NSC can vary greatly, which can affect the rate and extent of digestion and the overall energy value of the feed for the animal.

TABLE 4-1 Nonstructural (NSC) and Nonfiber (NFC) Analyses of Selected Feedstuffs (adapted from Miller and Hoover, 1998)

Feedstuff	NDF	NFC[a]	NSC[b]
	% of DM		
Alfalfa silage	51.4	18.4	7.5
Alfalfa hay	43.1	22.0	12.5
Mixed mainly grass hay	60.9	16.6	13.6
Corn silage	44.2	41.0	34.7
Ground corn	13.1	67.5	68.7
Beet pulp	47.3	36.2	19.5
Whole cottonseed	48.3	10.0	6.4
High moisture shelled corn	13.5	71.8	70.6
Barley	23.2	60.7	62.0
Corn gluten meal	7.0	17.3	12.0
Soyhulls	66.6	14.1	5.3
Soybean meal, 48 % CP	9.6	34.4	17.2

[a]NFC, % = 100 − (NDF, % + CP, % + fat, % + ash, %).
[b]NSC = nonstructural carbohydrates determined using an enzymatic method (Smith, 1981).

Recently, Hall et al. (1999) developed a method to fractionate the neutral detergent soluble carbohydrates (NDSC) in feedstuffs. Differential solubilities of carbohydrates were used to partition NDSC into organic acids and oligosaccharides soluble in ethanol/water from starch and neutral detergent soluble fiber (NDSF) that are insoluble. The method allows the partitioning of the NDSC on a nutritionally relevant basis into 1) organic acids, 2) total

TABLE 4-2 Composition of the NFC[a] Fraction of Selected Feedstuffs (adapted from Miller and Hoover, 1998)

Feedstuff	Sugar	Starch	Pectin	Volatile Fatty Acids
	% of NFC			
Alfalfa silage	0	24.5	33.0	42.5
Grass hay	35.4	15.2	49.4	0
Corn silage	0	71.3	0	28.7
Barley	9.1	81.7	9.2	0
Corn grain	20.9	80.0	0	0
Beet pulp	33.7	1.8	64.5	0
Soyhulls	18.8	18.8	62.4	0
Soybean meal 48% CP	28.2	28.2	43.6	0

[a]NFC calculated by difference as shown in footnote 2, Table 4-1.

ethanol/water-soluble carbohydrate, 3) starch, and 4) neutral detergent soluble fiber.

The optimal concentration of NSC or NFC in diets for lactating cows is not well defined. To avoid acidosis and other metabolic problems, the maximum concentration of NSC should be approximately 30 to 40 percent of the ration dry matter (DM) (Nocek, 1997). The acceptable concentrations for NFC are probably 2 to 3 percentage units higher than for NSC. The optimal concentration of NSC or NFC in diets of high producing cows are related to: 1) the effects of rapidly degradable starch on ruminal digestion of fiber, which can decrease the differences between diets relative to total carbohydrate digestion; 2) the amount of NSC or NFC that replaces NDF in the diet, as this can affect volatile fatty acid production, rumination, and saliva production; 3) site of starch digestion; 4) dry matter intake (DMI) and physiologic state of the animal; and 5) conservation and processing methods used to alter rate and extent of NSC or NFC digestion.

Alteration of dietary NFC influences ruminal fermentation patterns, total tract digestion of fiber and milk fat percentage (Sievert and Shaver, 1993; Sutton and Bines, 1987). Batajoo and Shaver (1994) concluded that for cows producing over 40 kg of milk, the diet should contain more than 30 percent NFC, but found little benefit of 42 percent over 36 percent NFC. Nocek and Russell (1988) suggested that 40 percent NFC was optimal in diets for lactating cows from an evaluation of diets based on alfalfa silage, corn silage, and 50:50 alfalfa:corn silage; dietary NFC ranged from 30 to 46 percent. Hoover and Stokes (1991) regressed data from Nocek and Russell (1988) and found that when dietary NFC was greater than 45 to 50 percent or less than 25 to 30 percent, milk production was decreased. In another study, the percentage and yield of milk protein increased when NFC in the dietary DM was increased from 41.7 to 46.5 percent (Minor et al., 1998).

Starch comprises 50 to 100 percent of the NSC in most feedstuffs. In addition to total starch level, the rate and extent of ruminal starch digestion also may affect the amount of a particular starch source that can safely be added to a diet. Rate of fermentation of starch varies extensively by type of grain and grain processing. Herrera-Saldana et al. (1990) ranked the degradability of starch from various sources as follows: oats > wheat > barley > corn > sorghum. Processing methods, such as fine grinding and steam flaking also may alter ruminal availability of starch. Lykos and Varga (1995) demonstrated that effective degradability of starch in situ for cracked corn, fine ground corn, and steam flaked corn was 44.4, 64.5 and 75.4 percent, respectively. In addition, the effective degradability of starch was increased for ground versus cracked soybeans whether raw or roasted. Most grain processing methods increase both rate of starch fermentation and ruminal starch digestibility. Reducing particle size by cracking and grinding significantly increases rate of starch digestion (Galyean et al., 1981; McAllister et al., 1993) and effects are greater with unprocessed than heat processed grains. Grinding increases both rate of digestion and rate of passage, which have counteractive effects on ruminal digestibility (Galyean et al., 1979). Animal characteristics and DMI affect rate of passage. Therefore, fine grinding may have less effect on ruminal starch digestibility at higher DMI, due to faster rate of passage, such as for high producing dairy cows.

Results of lactation studies that compared starch sources with differing digestibilities have been variable and may be related to the carbohydrate source and how it is processed, level of intake, the basal forage in the ration, and the degradability of the protein source. Herrera-Saldana and Huber (1989) reported higher milk production with a barley-cottonseed meal diet than with a sorghum grain-cottonseed meal diet, while McCarthy et al. (1989) and Casper et al. (1990) reported higher milk production by cows fed diets with corn grain compared with barley. Milk yield was increased for cows in early lactation by increasing ruminally available starch fed as steam flaked sorghum instead of dry rolled corn (Moore et al., 1992; Poore et al., 1993) or fed as ground instead of cracked corn (Knowlton et al., 1996). Wilkerson and Glenn (1997) demonstrated an increase in yield of milk for cows fed high moisture corn versus dry corn (41.7 vs. 39.7 kg/d) and ground corn versus rolled corn (41.8 vs. 39.6 kg/d). Ruminal digestibility of starch was greater for high moisture corn than dry corn whether corn was rolled or ground. Lykos et al. (1997) demonstrated that increasing the rate of NSC digestion from 6 to 7.9 percent/h significantly increased milk yield 2.5 kg/d and protein yield 130 g/d. Aldrich et al. (1993) observed 4 percent lower FCM yields when diets high in rapidly fermentable nonstructural carbohydrates (81 percent ruminal degradable NSC) were fed to lactating cows during early lactation. Diets with increased ruminally degraded starch did not affect milk yield or FCM in other studies (Clark and Harshbarger, 1972; Oliveira et al., 1993, 1995). Varga and Kononoff (1999) evaluated the relationship between dietary concentration or intake of NSC or NFC and milk yield in 16 studies published in the *Journal of Dairy Science* from 1992 through 1998. The relationships between concentration of NSC or NFC and milk yield were poor ($r^2 = 0.04$). The relationship between NFC intake and milk yield was good ($r^2 = 0.40$); a 1 kg increase in NFC intake resulted in a 2.4 kg increase in milk yield. See a more detailed discussion related to starch processing in Chapter 13.

STRUCTURAL CARBOHYDRATES

Crude fiber, acid detergent fiber, and neutral detergent fiber are the most common measures of fiber used for routine feed analysis, but none of these fractions are chemically uniform. Neutral detergent fiber measures most of the structural components in plant cells (i.e., cellulose, hemicellulose, and lignin). Acid detergent fiber does not include hemicellulose, and crude fiber does not quantitatively recover hemicellulose and lignin. Neutral detergent fiber is the method that best separates structural from nonstructural carbohydrates in plants, and NDF measures most of the chemical compounds generally considered to comprise fiber. Within a specific feedstuff, concentrations of NDF, ADF, and crude fiber are highly correlated, but for mixed diets that contain different fiber sources, the correlations among the different measures of fiber are lower. Neutral detergent fiber is the best expression of fiber available currently, but recommendations are also given for ADF because of its widespread use. Crude fiber will not be discussed because it is considered obsolete.

On average NDF is less digestible than nonfiber carbohydrates; therefore, the concentration of NDF in feeds or diets is negatively correlated with energy concentration. The chemical composition of the NDF (proportions of cellulose, hemicellulose, and lignin) affects the digestibility of the NDF fraction. Therefore, feeds or diets with similar NDF concentrations will not necessarily have similar NE_L concentrations, and certain feeds or diets with high NDF may have more NE_L than another feed or diet with lower concentrations of NDF.

The maximum amount of NDF that should be included in diets is a function of the NE_L requirement of the cow, the minimum amount of NFC needed for good ruminal fermentation, and the potential negative effects of high NDF on feed intake. In most cases, the maximum NDF concentration will be determined by the NE_L requirement of the cow. In a summary of published studies, NDF concentration usually did not constrain DMI when diets were formulated to provide adequate NE_L (Mertens, 1994). Based on Mertens (1994), DMI may have been limited when cows producing approximately 40 kg of milk/d were fed diets with more than about 32 percent NDF. For cows producing 20 kg/d of milk, DMI was not restricted until the diet contained about 44 percent NDF. Source of NDF, especially with respect to rate and extent of NDF digestion, will influence those values (Oba and Allen, 1999).

The minimum amount of dietary NDF needed is based largely on ruminal and cow health. The concentration of NDF is inversely related to ruminal pH because NDF generally ferments slower and is less digestible than NFC (i.e., less acid production in the rumen), and because the majority of dietary NDF in typical diets is from forage with a physical structure that promotes chewing and saliva production (i.e., buffering capacity). Various indices have been used to monitor ruminal conditions including milk fat percentage, ruminal pH, rumen VFA concentrations, and time spent chewing. Those measures respond quickly to dietary changes and can be monitored in short-term studies. Long-term effects of poor ruminal health may include increased prevalence of laminitis (Nocek, 1997) and displaced abomasum (Shaver, 1997), but the literature is extremely limited on long-term health responses to dietary NDF concentration.

Based on several studies with cows fed alfalfa-based diets and corn grain as the primary starch source (Colenbrander et al., 1991; Hansen et al., 1991; Weiss and Shockey, 1991; Clark and Armentano, 1993; Depies and Armentano, 1995), diets with 25 percent total NDF resulted in similar milk production with a similar composition as did diets with higher NDF concentrations. In these studies, dietary DM contained 16 to 20 percent NDF from forage. Forage is defined as feedstuffs that are composed of stems, leaves, and possibly grain and is fed as fresh material, hay, or silage (e.g., corn silage is considered a forage even though it contains corn grain). Diets with less than 25 percent total NDF and less than about 16 percent NDF from forage depressed milk fat percentage (Clark and Armentano, 1993; Depies and Armentano, 1995). Few studies designed to determine the minimum amount of NDF needed with corn silage diets have been conducted. Milk fat percentage for cows fed corn silage-based diets with 24 percent NDF was less than that for cows fed 29 or 35 percent NDF (Cummins, 1992), but in another study (Bal et al., 1997) production of milk fat and milk was not different among cows fed corn silage-based diets with 25 or 29 percent NDF. Corn silage elicits similar or greater chewing activity by cows than does alfalfa silage (Mertens, 1997), and mean NDF digestibility is similar for corn and alfalfa silages (Kung et al., 1992); therefore, the minimum amount of NDF needed to maintain ruminal function when diets are based on corn silage is probably similar to that for diets based on alfalfa silage assuming particle size is adequate. The NDF content of corn silage must be measured using amylase, or NDF values will be inflated and the risk of supplying insufficient dietary NDF is increased (See Chapter 13).

NDF Recommendations

Based on the above cited studies, the recommended concentration of total dietary NDF for cows fed diets with alfalfa or corn silage as the predominate forage and dry ground corn grain as the predominant starch source was set at 25 percent of dietary DM with the condition that 19 percent of dietary DM must be NDF from forage (Table 4-3). The minimum recommended NDF concentration is increased as the amount of forage NDF in the diet decreases (discussed below). The NDF concentration in the diet must be higher when the forage is finely chopped, but because of the limited amount of data available we did not quantify this relationship. Diets that are formulated at the minimum concentration of NDF should be based on the actual composition of the feedstuffs, not table values. The potential for errors in mixing and feed delivery should be considered, and when the probability for errors is high, diets should be formulated to be above the minimum NDF concentration.

Although cows appear to be able to tolerate diets with 25 percent NDF and 19 percent NDF from forage, those recommendations are for very specific situations (i.e, the diet contains forage with adequate particle size, dry corn grain is the predominant starch source, and diets are fed as total mixed rations). Diets with small particle forage, diets with starch sources that have higher ruminal availability than corn, diets that have less than about 19 percent NDF from forage, and diets not fed as total mixed rations will require higher minimum concentrations of NDF. Inclusion of supplemental buffers may decrease the amount of NDF required in the diet (Allen, 1991). Furthermore, the minimum recommended concentration of NDF should not be considered the optimal concentration. Lower producing cows require less energy, and diets should contain NDF concentrations greater than the minimum.

TABLE 4-3 Recommended Minimum Concentrations (% of DM) of Total and Forage NDF and Recommended Maximum Concentrations (% of DM) of NFC for Diets of Lactating Cows When the Diet is Fed as a Total Mixed Ration, the Forage has Adequate Particle Size, and Ground Corn is the Predominant Starch Source[a]

Minimum forage NDF[b]	Minimum dietary NDF	Maximum dietary NFC[c]	Minimum dietary ADF[d]
19[e]	25[e]	44[e]	17[e]
18	27	42	18
17	29	40	19
16	31	38	20
15[e]	33	36	21

[a]Values in this table are based on the assumption that actual feed composition has been measured; values may not be appropriate when values from feed tables are used.

[b]All feeds that contain substantial amounts of vegetative matter are considered forage. For example, corn silage is considered a forage, although it contains significant amounts of grain.

[c]Nonfiber carbohydrate is calculated by difference 100 - (%NDF + %CP + %Fat + %Ash).

[d]Minimum dietary ADF recommendations were calculated from NDF concentrations (See text).

[e]Diets that contain less fiber (forage NDF, total NDF or total ADF) than these minimum values and more NFC than 44 percent should not be fed.

The committee decided to adjust NDF recommendations based on the concentration of NDF from forage in the diet. The primary reason was that source of NDF has a major impact on cow response to NDF concentrations, and concentration of forage NDF is easily obtainable under field conditions. Forages that are long or coarsely chopped provide NDF in a form that is distinctly different from NDF in nonforage sources such as soyhulls, wheat midds, beet pulp, and corn gluten feed. The NDF from grain sources are also considered nonforage fiber sources. Many nonforage fiber sources have a relatively large pool of potentially degradable NDF, small particle size, and relatively high specific gravity (Batajoo and Shaver, 1994). Nonforage fiber sources have similar or faster passage rates than many forages (Bhatti and Firkins, 1995), and many have rates of NDF digestion that are similar to or slower than those of forages. A large proportion of the potentially available NDF from nonforages may escape ruminal fermentation resulting in less acid production in the rumen (Firkins, 1997).

Most sources of nonforage NDF are significantly less effective at maintaining milk fat percentage than are forages (Swain and Armentano, 1994; Vaughan et al., 1991; Clark and Armentano, 1993, 1997). Based on an empirical relationship developed by Allen (1997), NDF from nonforage was only 0.35 times as effective at maintaining rumen pH as was NDF from forage. Firkins (1997) concluded that NDF from nonforage was about 0.6 times as effective at maintaining NDF digestibility in the gastrointestional tract as was NDF from forage. Based on chewing activity, Mertens (1997) concluded that NDF from high NDF nonforage sources (i.e., byproducts) was about 0.4 and for other concentrates between 0.3 and 0.8 times as effective as NDF from forage. Based on these three studies, the average effective value of NDF from nonforage was set to 50 percent of that for NDF from forage. For every 1 percentage unit decrease in NDF from forage (as a percentage of dietary DM) below 19 percent, the recommended concentration of total dietary NDF was increased 2 percentage units, and maximum NFC concentration was reduced 2 percentage units (Table 4-3). A possible exception to this relationship is whole linted cottonseed. Whole cottonseeds appear to have significantly more value at maintaining milk fat percentage than do other sources of NDF from nonforage fiber sources (Clark and Armentano, 1993).

Determining whether changes in milk fat percentage, ruminal pH, or chewing activity are caused by altering dietary NDF or NFC is difficult because their concentrations are correlated. On average, dietary concentrations of NDF and NFC have a high negative correlation (Armentano and Pereira, 1997). If all nutrients are held constant except for NDF and NFC, a change in NDF concentration from 33 to 28 percent of dietary DM (a 15 percent decrease) means that NFC must increase from 40 to 45 percent of dietary DM (an 11 percent increase) (Armentano and Pereira, 1997). However, because of variations in dietary concentrations of CP and supplemental fat, the correlation is not perfect. The concentrations of NFC in a diet with 25 percent NDF could vary by 2 to 9 percentage units. Diets with excess NFC can cause ruminal upsets and health problems (Nocek, 1997). Therefore, the minimum NDF required must be considered in conjunction with NFC concentrations. Diets that contain lower concentrations of CP and ether extract should have higher NDF concentrations. Recommended maximum NFC concentrations are presented in Table 4-3. The minimum concentration of NDF should be increased so that the maximum recommended concentrations of NFC are not exceeded.

QUALITATIVE ADJUSTMENTS TO NDF RECOMMENDATIONS

Source of Starch Milk fat percentage, ruminal pH, and ruminal VFA profile are often altered when starch availability in the rumen is increased (e.g., steam-flaked vs. dry processed grains, high moisture vs. dry grains, or corn vs. barley) even when the concentration of dietary NDF is not altered. These alterations in ruminal fermentation and milk fat percentage suggest that the NDF requirement increases when sources of readily available starch replace dry ground corn in the diet. Ruminal fermentation profiles and milk fat data from Knowlton et al. (1998) suggest that diets that contain high moisture corn should contain at least 27 percent NDF. Cows fed diets based on barley should contain about 34 percent NDF (Beauchemin, 1991). Insufficient information is available to give specific recommendations for diets that contain other starch sources. However, diets with steam-flaked corn, steam-flaked sorghum, or other sources of starch that have a high ruminal availability should contain more than 25 percent NDF and less than 44 percent NFC.

Particle Size of Forage Particle size of forage as well as concentration of NDF in the diet has an impact on ruminal pH. Allen (1997) reported that when finely chopped forage was substituted for coarsely chopped forage, salivary buffer flow decreased by nearly 5 percent, but an increase in forage NDF in the diet from 20 to 24 percent increased salivary buffer flow less than 1 percent. The mean particle size of alfalfa hay necessary to maintain rumen pH, chewing activity, and milk fat percentage appears to be about 3 mm (Grant et al., 1990a; Woodford et al., 1986; Shaver et al., 1986). Diets with alfalfa silage that had a mean particle length less than about 3 mm resulted in depressed milk fat, decreased rumen pH, and reduced time spent chewing (Grant et al., 1990b; Beauchemin et al., 1994). Allen (1997) evaluated the relationship between particle length of forage and total time spent chewing using data from 10 dairy cattle experiments and found a clear breakpoint at approximately 3 mm at which point no further increase in particle length affected total chewing time. The concentration of NDF in the diet should be increased by several percentage units when the mean particle size of the forage is less than about 3 mm. Diets that contain finely ground forages and sources of rapidly fermentable starch (e.g., barley or high moisture corn) may require even more dietary NDF to maintain milk fat percentage. Quantitative measures of particle size (i.e., mean particle size, mean standard deviation and/or distribution) rather than qualitative descriptions (e.g., coarsely chopped) are needed to improve the accuracy of assessing fiber requirements of dairy cows.

Effective Fiber The effective fiber concept is an attempt to formulate diets not only for NDF but also for the ability of a diet to stimulate chewing (Sudweeks et al., 1981; Mertens, 1992, 1997). The origin of the effective fiber concept was to meet the minimum fiber requirement that would maintain milk fat percentages (Mertens, 1997). Effective fiber values were assigned to feeds based on changes in milk fat. When only milk fat is used as the response variable, the physical effects of NDF on chewing, salivation, and ruminal buffering are confounded with metabolic effects caused by different chemical composition of the feeds (Allen, 1997). For example, the effect of feeding whole cottonseed on milk fat percentage may be a result of both its fiber and fat contribution to the diet. Milk composition of cows during mid to late lactation is more sensitive to changes in ration composition than is milk composition of cows during early lactation. For animals in early lactation, ruminal pH is a more meaningful response variable for determining fiber requirements than are other factors (Allen, 1997). Most of the trials evaluating the effectiveness of NDF lasted only a few weeks. Long-term effects on ruminal health, laminitis, and production are not known.

Several researchers have suggested that chewing response is an important characteristic of feeds (Balch, 1971), and that dairy cows have a minimum requirement for chewing activity (Sudweeks et al., 1981; Norgaard, 1986). Mertens (1997) proposed that two terms should be used to distinguish between the effectiveness of fiber in maintaining milk fat percentage or in stimulating chewing activity. Effective NDF (eNDF) was defined as the sum total ability of the NDF in a feed to replace the NDF in forage or roughage in a ration so that the percentage of milk fat is maintained. Physically effective NDF (peNDF) is related to the physical characteristics of NDF (primarily particle size) that affect chewing activity and the biphasic nature of ruminal contents.

Different systems have been proposed to measure effective NDF. Mertens (1997) developed the peNDF system using regression analysis to assign physical effective factors (PEF) to classes of NDF based on the chewing activity they stimulated. The PEF of feeds is expressed relative to the chewing activity of cows when they are fed long grass hay. The PEF of long grass hay was set to 1; coarsely chopped grass silage, corn silage, and alfalfa silage had PEF values of 0.9 to 0.95; and finely chopped forage had values of 0.7 to 0.85. Diets with 22 percent of the DM as physically effective NDF maintained average rumen pH at 6, and diets with 20 percent physically effective NDF maintained milk fat percentage at 3.4 percent for Holstein cows during early to mid lactation. The proportion of DM (or NDF) retained on a sieve with an aperture of 1.18 mm was proposed by Mertens (1997) as a simple laboratory method that might be applicable to the routine analysis of physically effective NDF in feeds. The *Nutrient Requirements of Beef Cattle* (National Research Council, 1996) defined effective NDF as the percentage of total NDF that is retained on a screen with 1.18 mm or greater openings after dry sieving. Buckmaster et al. (1997) developed an effective fiber intake based on particle size distributions from a three screen (>19 mm, 8 to 19 mm, and <8 mm) sieve (Lammers et al., 1996) and the NDF concentration of each fraction. In that system, average legume and corn silages had similar effectiveness values, and both were about 10 percent less than the average value for grass silage (Kononoff et al., 1999). More information is needed to determine the accuracy of all these systems to measure the effectiveness of forage sources for altering milk fat and chewing time.

At the present time, the lack of standard, validated methods to measure effective fiber of feeds or to establish requirements for effective fiber limits the application of this concept. Mertens (1997) peNDF concept is a step towards the quantification of the chemical and physical attributes of fiber into a single measurement. However, this concept is currently not validated; not enough feeds have values, and requirements have not been determined. Effective NDF should be a measure of the sum total ability of a feed to replace forage or roughage in a ration so that the percentage of fat in milk and rumen pH are maintained (Mertens, 1997). Differences in the rate and extent of digestion of NDF and the difference between ruminal digestibility of NDF and NFC are related to acid production and ultimately the ability of a feed to maintain ruminal pH. These factors can differ among different sources of NDF especially when forage and nonforage sources of NDF are compared. More research is needed to identify other chemical and physical characteristics of feeds that influence their ability to maintain optimal ruminal function and animal health before specific values for effectiveness of various forage and nonforage fiber sources can be determined. Because of these problems, a requirement for effective NDF is not given. Dietary NDF concentrations, however, may have to be altered based on differences in particle size of the forage and source of NDF.

Supplemental dietary buffers Supplemental dietary buffers increase buffering capacity in the rumen (Erdman, 1988) and should reduce the NDF requirement. Detailed information on the effects of buffers and recommendations regarding their use are in Chapter 9.

Feeding method Essentially all recent experiments on fiber requirements have used total mixed rations (TMR). When cows consume a TMR, rate of NSC consumption is moderated due to simultaneous consumption of fiber. Because forage is consumed at the same time as concentrate, increased chewing and salivation occurs, and rumen buffering capacity is high when the NSC is being fermented. Experiments specifically designed to determine whether NDF requirements are increased when cows are fed concentrate separately from forages have not been conducted.

Feeding forage separately from concentrate alters diurnal patterns for pH and fermentation acids in the rumen. The degree of change depends on feeding frequency of the concentrate and the fermentability of the concentrate. Diurnal changes in ruminal pH and fermentation acids are very pronounced when concentrates that are predominantly NFC are consumed twice daily compared with TMR feeding (Robinson, 1989). These severe changes in ruminal pH may be associated with reduced milk fat percentage and yield. When concentrate is offered more than twice daily (e.g., using a computer-controlled concentrate feeder), fewer effects on production, milk composition, and ruminal conditions have been reported (Cassel et al., 1984; Robinson, 1989; Maltz et al., 1992).

The NDF requirement when concentrates are fed twice daily and separately from forages is unknown but is probably higher, and maximum NFC concentrations are lower than the values in Table 4-3. Increased dietary NDF concentrations may not completely overcome the problem associated with the rapid consumption of large amounts of grain. In such cases, the NDF concentration of the concentrate mixture may have to be increased.

Cows grazing high quality pasture and fed concentrate twice daily, often (Polan et al., 1986; Berzaghi et al., 1996), but not always (Holden et al., 1995), produce milk with reduced fat even when they are fed diets that appear adequate in NDF. Lowered milk fat percentage may be caused by reduced salivation when cows are grazing, the highly digestible nature of the fiber in high quality pasture, and the rapid consumption of grain caused by feeding concentrate only twice daily and separately from forage. When high fiber concentrates (e.g., beet pulp or corn gluten feed) replaced starchy feeds (corn or barley) in diets of grazing cows milk fat percentage was increased (Meijs, 1986; Garnsworthy, 1990). However, when a concentrate based on corn was fed alone, or mixed with corn silage twice daily, to grazing cows no difference was observed in milk fat percentage (Holden et al., 1995). The corn silage did not reduce the intake of corn grain but should have increased the time needed to consume the corn. Because data are not available, specific recommendations for NDF concentrations of diets for grazing cattle are not known; therefore, the guidelines in Table 4-3 may not be adequate for grazing cattle. Limited data (Holden et al., 1995) suggest that cows grazing high quality pasture and fed concentrate twice daily should be fed a ruminal buffer (mixed with the concentrate), or the concentrate should not be comprised solely of starchy feedstuffs.

ADF Requirement

Expressing the fiber requirement as NDF is superior to ADF for many reasons; however, ADF requirements are given because of the widespread use of ADF. The ADF requirements shown in Table 4-3 were derived from the recommended NDF concentrations. Concentrations of NDF and ADF are highly correlated within forage classifications. Regression equations were developed to estimate ADF concentrations from NDF concentrations for corn silage, grass forage, and legume forage:

$$\text{Corn silage ADF, \%} = -1.15 + 0.62\ \text{NDF, \%}\ (r^2 = 0.89,\ syx = 1.4,\ N = 2425)$$

$$\text{Grass forage ADF, \%} = 6.89 + 0.50\ \text{NDF, \%}\ (r^2 = 0.62,\ syx = 3.1,\ N = 722)$$

$$\text{Legume forage ADF, \%} = -0.73 + 0.82\ \text{NDF, \%}\ (r^2 = 0.84,\ syx = 2.0,\ N = 2899)$$

The ADF requirements shown in Table 4-3 were derived by formulating numerous test diets that included a wide variety of feedstuffs. The composition values used for all feeds were from Table 15-1 except the ADF concentration of forages were estimated using the above regression equations. The dietary concentration of ADF that resulted when most diets met NDF requirements was set as the ADF requirement. Factors described previously that increase the NDF requirement will also increase the ADF requirement.

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