Effects of roughage source and level on intake by feedlot cattle[1]

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ABSTRACT: Intake by beef cattle fed high-concentrate, grain-based diets is likely controlled primarily by metabolic factors and not limited by bulk fill. Nonetheless, small increases (e.g., 5% of dry matter or less) in the concentration of bulky roughage and changing from less fibrous to more fibrous sources of roughage typically increase dry matter intake (DMI) by feedlot cattle. Reasons for increased DMI with changes in roughage level and source are not understood fully. Energy dilution effects caused by added dietary fiber might be responsible for altered DMI, but the quantity of dietary net energy for gain provided by roughage shows little relationship to changes in DMI with roughage source and level. Altered rate of ruminal acid production as a result of roughage source and level might affect DMI through various mechanisms, including increased chewing and/or rumination with increased saliva flow; altered ruminal and/or intestinal digesta kinetics; and altered site and extent of digestion. We hypothesized that much of the effect of roughage source and level on DMI by feedlot cattle could be accounted for by changes in dietary neutral detergent fiber (NDF). Data from 11 published trials involving roughage source and level effects on intake by feedlot cattle were compiled. The dataset included 48 treatment means, with roughage sources such as hays, straws, byproducts, and silages, and with roughage levels ranging from 0 to 30% of dry matter. Effects of dietary roughage level (percentage of dry matter), NDF (percentage of dietary NDF from roughage), or effective NDF (eNDF, percentage of dietary eNDF from roughage) and the random effects of trial on DMI (percentage of body weight) were evaluated using mixed-model regression procedures. Tabular values were used to obtain estimates of NDF and eNDF. Using trial-adjusted means, dietary roughage level accounted for 69.9% of the variation in DMI, whereas the percentage of dietary NDF and eNDF supplied by roughage accounted for 92.0 and 93.1%, respectively, of the variation in DMI. The relationship between dietary NDF (percentage supplied by roughage) and DMI (percentage of body weight) for trial-adjusted data was given by: DMI = 1.8562 − (0.02751 × NDF) ($P < 0.01$; root mean square error = 0.0447); intercepts differed ($P < 0.02$) among trials, but slopes did not ($P > 0.18$). Based on these results, the percentage of NDF supplied by roughage in diets can be used to predict effects of roughage source and level on DMI by feedlot cattle, and NDF supplied by roughage might be a useful method for exchanging roughage sources in finishing diets.

Key Words: Beef Cattle, Fiber, Intake, Roughage

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Introduction

Adding a low percentage of roughage to high-concentrate diets helps prevent digestive upsets and maximizes energy (NEg) intake by feedlot cattle. In a recent survey of 19 consulting nutritionists in the major cattle feeding states, Galyean and Gleghorn (2001) reported that finishing diets contained from 4.5 to 13.5% (DM basis) roughage (mean = 8.89%, mode = 9%), with alfalfa hay and corn silage being the most common sources. Both roughage level and source influence DMI, and thereby NEg intake (Defoor et al., 2002), which ultimately affects feedlot performance and carcass characteristics; however, reasons for the effects of roughage on feed intake are not fully understood. Physical and chemical characteristics of roughages, such as bulk density and concentrations of fiber (e.g., NDF) and other nutrients are likely involved (Defoor et al., 2002), and effects of roughage on DMI also seem to be associated with differences in ruminal fermentation and digesta kinetics. Nonetheless, the specific ways by which these roughage characteristics affect DMI have not been suf-

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ficiently quantified to allow for prediction of differences in DMI among roughage sources and levels that occur in practice. This review will summarize the results of research in which different roughage sources and levels have been fed in high-concentrate diets for feedlot cattle. In addition, we will examine the role that the NDF supplied by roughage plays in contributing to differences in DMI among roughage sources and levels and the biological basis for the effects of roughage in feedlot diets.

Effects of Roughage Source and Level on Dry Matter Intake by Feedlot Cattle

Several studies have investigated the effects of roughage source and/or level on DMI and performance by feedlot cattle fed high-concentrate diets. Gill et al. (1981) used 240 steers in a 121-d feeding trial to evaluate five roughage levels (8, 12, 16, 20, and 24% of DM) in diets based on high-moisture corn, steam-flaked corn, or a 50:50 mixture (DM basis) of high-moisture and steam-flaked corn. Roughage was a mixture of alfalfa (⅓ on a DM basis) and corn silage (⅔ on a DM basis). Across grain type, increasing roughage level increased DMI, but effects on ADG and feed:gain (**F:G**) depended on grain type, with 8, 12, and 16% roughage being optimal for steam-flaked corn, the 50:50 mixture, and high-moisture corn grain types, respectively. Kreikemeier et al. (1990) fed steam-rolled wheat diets with 0, 5, 10, or 15% roughage (DM basis; 50:50 mixture of alfalfa hay and corn silage) to finishing beef steers. Daily DMI increased linearly ($P = 0.08$) with increasing roughage level. Similar to the results of Gill et al. (1981) with steam-flaked corn, ADG and gain:feed ratio were optimized with the 5 and 10% roughage levels.

Bartle et al. (1994) fed alfalfa and cottonseed hulls at 10, 20, or 30% of the dietary DM to finishing beef cattle. Within each roughage level, DMI was less and efficiency of gain was greater for cattle fed the alfalfa than for cattle fed the cottonseed hull diets. Across roughage level, DMI increased at a faster rate for cottonseed hull diets than for alfalfa diets (approximately 0.10 vs. 0.05 kg of DMI for each 1% increase in roughage level). Assuming that cattle fed high-concentrate diets attempted to eat to a constant energy level, the greater rate of change with cottonseed hulls might have reflected a greater rate of dietary energy dilution as the level of cottonseed hulls increased compared with alfalfa. The energy dilution with cottonseed hulls should be accounted for, in part, by its higher NDF concentration compared with alfalfa, such that a smaller percentage of cottonseed hulls would be needed to provide the same intake of NDF as a larger percentage of alfalfa. Bartle et al. (1994) reported that ADG was similar for cattle fed 10 and 20% alfalfa; however, cattle fed the 30% alfalfa diets gained less than those fed the 10 and 20% alfalfa diets, evidently because they could not consume enough DM to compensate for the energy dilution. Cattle consuming the 10% cottonseed hull diets gained at a rate similar to cattle consuming the 10 and 20% alfalfa diets. Because of the greater rate of energy dilution per unit of cottonseed hulls, however, the cattle consuming the 20 and 30% cottonseed hull diets could not consume enough DM to express their potential for ADG. We interpret these data to indicate that one step toward describing effects of roughage source and level on DMI might be to equalize the dietary percentage of NDF supplied by roughage.

Guthrie et al. (1996) fed heifers diets with alfalfa, cottonseed hulls, and sorghum sudangrass hay at either 7.5 or 15% of DM in whole shelled corn-based diets. The DMI and ADG were greater by heifers fed the cottonseed hull and sorghum sudangrass hay diets than by those fed alfalfa. Results of this experiment indicated the possibility that cattle might sometimes overcompensate for energy dilution associated with different roughage sources. Guthrie et al. (1996) compared DMI, ADG, and F:G by cattle consuming alfalfa at 10% and sorghum sudangrass hay at 5, 7.5, and 10% of dietary DM. Dry matter intake and ADG by cattle fed the three levels of sorghum sudangrass hay were greater than by those fed the alfalfa diet, but F:G did not differ among diets. Calculated dietary NDF concentration (NRC, 1996) was slightly less for the 5% sorghum sudangrass hay diet than for the 10% alfalfa diet; however, DMI per unit of BW was similar for these two treatments (1.89 and 1.87% of BW for 5% sorghum sudangrass hay and 10% alfalfa, respectively).

Theurer et al. (1999) fed alfalfa, cottonseed hulls, and wheat straw to steers as the roughage source in three finishing diets. All three diets contained a base concentration of 6% alfalfa and were formulated to supply an equal percentage of NDF from roughage by adding an additional 6% alfalfa, 2.8% cottonseed hulls, or 3.7% wheat straw. Adding 2.8% cottonseed hulls or 3.7% wheat straw was as effective for maintaining DMI and ADG as adding an additional 6% alfalfa, indicating that low-quality roughage sources generally have a higher roughage value than higher quality forages and that much of this effect can be attributed to differences in concentrations of NDF.

Shain et al. (1999) fed 224 yearling steers either dry-rolled corn-based diets with no roughage or diets balanced to provide equal percentages of NDF from alfalfa and wheat straw. Roughage sources were ground to pass through 0.95-, 7.62-, or 12.7-cm screens. The alfalfa and wheat straw contained 42.8 and 82.0% NDF and were included at 10 and 5.2% of dietary DM, respectively, to provide equal levels of NDF from roughage. Dry matter intake was least for cattle fed the all-concentrate diet, but did not differ between alfalfa and wheat straw across chop lengths. Cattle fed the alfalfa diets gained faster and were more efficient than those fed the wheat straw diets, regardless of chop length. No differences in ADG or F:G were detected between steers fed wheat straw and the all-concentrate diet, and altering roughage particle size (chop length) had no effect on ADG or F:G. Reasons for the differences noted by

Shain et al. (1999) in ADG and gain efficiency between the wheat straw and alfalfa diets are not clear; however, because the CP concentration, energy density, and DMI were similar between the diets, it is possible that differences were attributable to the effects of the roughage sources on digesta kinetics, as will be discussed in a subsequent section.

Defoor et al. (2002) used 12 medium-framed beef heifers in three simultaneous, 4 × 4 Latin square intake trials to evaluate the effects of dietary NDF supply from alfalfa, sorghum sudangrass hay, wheat straw, or cottonseed hulls fed in each Latin square at 5, 10, or 15% of the dietary DM. Within each roughage level, NDF supplied by roughage accounted for the majority of variation in NEg intake/kg of $BW^{0.75}$ among the sources. The NEg intake/kg of $BW^{0.75}$ tended ($P < 0.10$) to be greater when heifers were fed cottonseed hulls, sorghum sudangrass hay, or wheat straw than when fed alfalfa. In a second experiment, 105 heifers were used in a 140-d finishing trial to evaluate methods of dietary roughage exchange. Alfalfa at 12.5% of the dietary DM was used as a standard, and cottonseed hulls and sorghum silage were each fed at three different levels compared with alfalfa: 1) an equal percentage of DM basis; 2) an equal NDF from roughage basis; and 3) an equal NDF from roughage basis, where only NDF from particles larger than 2.36 mm (**ReNDF**) were considered to contribute to the NDF. No differences ($P > 0.10$) in DMI, ADG, gain:feed, or NEg intake/kg of $BW^{0.75}$ were detected between alfalfa and cottonseed hulls exchanged on an equal NDF basis. With sorghum silage, exchanging with alfalfa on an equal ReNDF basis resulted in no differences ($P > 0.10$) in DMI, NEg intake/kg of $BW^{0.75}$, or ADG. Defoor et al. (2002) suggested that their data provided a preliminary indication that NDF supplied by roughage and/or roughage NDF from particles larger than 2.36 mm might provide a useful index of roughage value in high-concentrate finishing diets.

Literature data make it clear that roughage source and level can have substantial effects on DMI by cattle fed high-concentrate diets. Effects of larger changes in roughage level (e.g., greater than 5% of DM) on DMI might simply reflect energy dilution, such that cattle increase DMI presumably in an attempt to maintain energy intake. It is doubtful; however, that small changes in roughage level or changes in roughage source could affect energy density enough to account for the relatively large increases or decreases often observed in DMI as a result of these changes. Occasionally, overcompensation in DMI occurs, with associated improvements in performance. Changes in the fraction of dietary NDF supplied by roughage as levels and sources change seem to be associated with effects of roughage level and source on DMI. In the next section, data from the studies reviewed above are used to evaluate the role of NDF supplied by roughage in accounting for differences in DMI by feedlot cattle.

Literature Data Analysis

To evaluate the role of NDF supplied by roughage in accounting for changes in DMI by feedlot cattle, we compiled data from the seven studies reviewed in the previous section involving 11 trials (48 treatment means) in which effects of roughage source and level on DMI by feedlot cattle were evaluated. Most data from these studies were means for pens of cattle fed for extended periods (e.g., mean values for a typical finishing period); however, data from Defoor et al. (2002) included short-term intake data from individually fed (21 d) and penned (35 d) cattle. For each data point, the average BW of cattle during the trial period was used to express DMI as a percentage of BW. Because several of the studies did not include an estimate of the NDF content of the roughage sources, tabular values from NRC (1996) were used to determine the percentage of dietary NDF supplied by roughage. Similarly, tabular effective NDF (**eNDF**) and NEg values of NRC (1996) were used to determine the percentage of dietary eNDF and megacal of NEg supplied by roughage. A summary of the data obtained from these experiments is presented in Table 1.

The dependent variable DMI (percentage of BW) was regressed on the independent variables of dietary roughage level (percentage of DM), NDF, eNDF, or NEg from roughage using the MIXED procedure of SAS (SAS Inst., Inc., Cary, NC). The basic procedures for pooling data from multiple studies described by St-Pierre (2001) were used. The dependent variable was fit to a model that included a fixed slope and intercept in addition to a random slope and intercept clustered by trial (St-Pierre, 2001). An unstructured variance–covariance matrix was assumed for the intercepts and slopes; however, the slope–intercept covariance was not significant ($P > 0.20$) for any of the dependent variables, and this term was subsequently deleted from the models. Trial-adjusted DMI data were calculated as described by St-Pierre (2001) and regressed on the independent variables using simple linear regression.

To illustrate the process and goal of the mixed-model analysis we conducted, data for DMI vs. NDF supplied by roughage for the 11 trials that comprised the data set are presented in Figure 1. Visual appraisal of the trend lines for the various trials suggests that DMI responded similarly to changes in NDF supplied by roughage across trials, but that baseline DMI values varied considerably among trials. Indeed, the change in DMI among trials (vertical differences among trend lines) is far greater than the effect of changes in NDF supplied by roughage on DMI within a given trial (vertical differences within a trial). Trial or study effects are typically important in pooled data analyses (St-Pierre, 2001), with such effects in the present analysis likely reflecting differences in cattle factors (age, type, and management), seasonal differences, differences attributable to dietary factors other than roughage, and a myriad of other unknown, random factors. The mixed-

Table 1. Summary of the literature data used for mixed model regression analyses

					Roughage		
Reference	Trial	Roughage source[a]	DMI, % of BW	Roughage, % of DM	NDF, % of DM	NEg, Mcal/kg	eNDF, g/g of NDF
Bartle et al. (1994)	1	CSH	1.89	10	88.3	0.15	0.980
	1	CSH	2.12	20	88.3	0.15	0.980
	1	CSH	2.37	30	88.3	0.15	0.980
	2	CSH	1.92	10	88.3	0.15	0.980
	2	CSH	2.16	20	88.3	0.15	0.980
	2	CSH	2.45	30	88.3	0.15	0.980
Defoor et al. (2002)	3	ALF	1.27	4.86	47.1	0.68	0.920
	3	ALF	1.29	10.01	47.1	0.68	0.920
	3	ALF	1.33	15.16	47.1	0.68	0.920
	3	SS	1.30	5.01	66	0.62	0.980
	3	SS	1.33	10.03	66	0.62	0.980
	3	SS	1.55	15.03	66	0.62	0.980
	3	CSH	1.36	5.11	88.3	0.15	0.980
	3	CSH	1.49	10.22	88.3	0.15	0.980
	3	CSH	1.69	15.31	88.3	0.15	0.980
	3	WS	1.39	5.03	78.9	0.11	0.980
	3	WS	1.42	10.1	78.9	0.11	0.980
	3	WS	1.67	15.19	78.9	0.11	0.980
	4	ALF	1.72	12.8	47.1	0.68	0.920
	4	CSH	1.58	2.61	88.3	0.15	0.980
	4	CSH	1.70	6.12	88.3	0.15	0.980
	4	CSH	1.78	12.93	88.3	0.15	0.980
	4	SSIL	1.68	3.65	60.8	0.74	0.810
	4	SSIL	1.83	8.06	60.8	0.74	0.810
	4	SSIL	1.69	14.07	60.8	0.74	0.810
Gill et al. (1981)	5	⅓ ALF:⅔ CS	2.03	8	46.37	0.89	0.847
	5	⅓ ALF:⅔ CS	2.08	12	46.37	0.89	0.847
	5	⅓ ALF:⅔ CS	2.11	16	46.37	0.89	0.847
	5	⅓ ALF:⅔ CS	2.16	20	46.37	0.89	0.847
	5	⅓ ALF:⅔ CS	2.19	24	46.37	0.89	0.847
Gutherie et al. (1996)	6	SS	1.89	4.86	66	0.62	0.980
	6	SS	2.01	7.27	66	0.62	0.980
	6	SS	1.97	9.7	66	0.62	0.980
	6	ALF	1.87	10.08	47.1	0.68	0.920
	7	ALF	2.04	10.15	47.1	0.68	0.920
	7	SS	2.18	10.16	66	0.62	0.980
Kreikemeier et al. (1990)	8	½ ALF:½ CS	2.10	0	46.55	0.84	0.865
	8	½ ALF:½ CS	2.14	5	46.55	0.84	0.865
	8	½ ALF:½ CS	2.16	10	46.55	0.84	0.865
	8	½ ALF:½ CS	2.20	15	46.55	0.84	0.865
Shain et al. (1999)	9	ALL CONC	2.49	0	0	0	0.000
	9	ALF	2.70	10	47.1	0.68	0.920
	9	WS	2.75	5.2	78.9	0.11	0.980
	10	ALF—FINE	2.52	10	47.1	0.68	0.920
	10	ALF—COARSE	2.56	10	47.1	0.68	0.920
Theurer et al. (1999)	11	ALF	1.74	12	47.1	0.68	0.920
	11	CSH–ALF mix	1.79	8.8	60.2	0.51	0.939
	11	WS–ALF mix	1.81	9.7	59.2	0.47	0.943

[a]CSH = cottonseed hulls; ALF = alfalfa hay; SS = sorghum sudangrass hay; WS = wheat straw; SSIL = sorghum silage; CS = corn silage; ALL CONC = all concentrate; ALF—FINE = alfalfa hay ground to pass a 0.95-cm screen; ALF—COARSE = alfalfa hay ground to pass a 7.6-cm screen.

model analysis allows these random effects of trial and interactions of trial with independent variables to be modeled, so that the strength of the relationship between the dependent and independent variables can be determined. Trial-adjusted data for the relationship between DMI and NDF supplied by roughage are shown

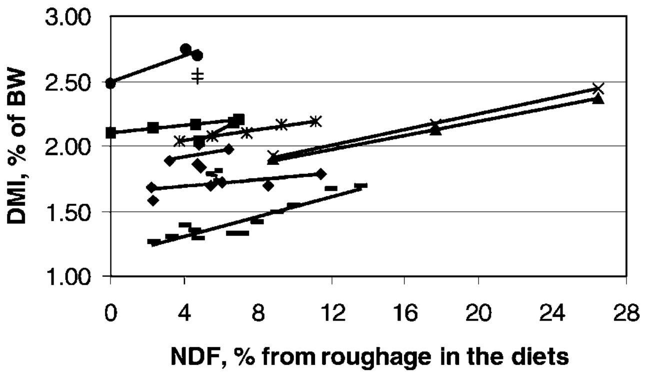

Figure 1. Plot of DMI (percentage of BW) vs. percentage of dietary NDF supplied by roughage for the 11 trials used in the data set. Individual data points are treatment means. References for the trials are shown in Table 1.

in Figure 2b. Although large random trial differences in intercepts were noted, the slope was not affected by trial. Thus, the slope of the overall line might be useful to describe the expected change in DMI per unit of BW with changes in NDF supplied by roughage. At the very least, these trial-adjusted data illustrate that there is a close relationship between DMI and dietary NDF supplied by roughage, thereby allowing us to more clearly elucidate the specific reasons (e.g., differences in NDF content) for effects of roughage source and level on DMI in these 11 trials.

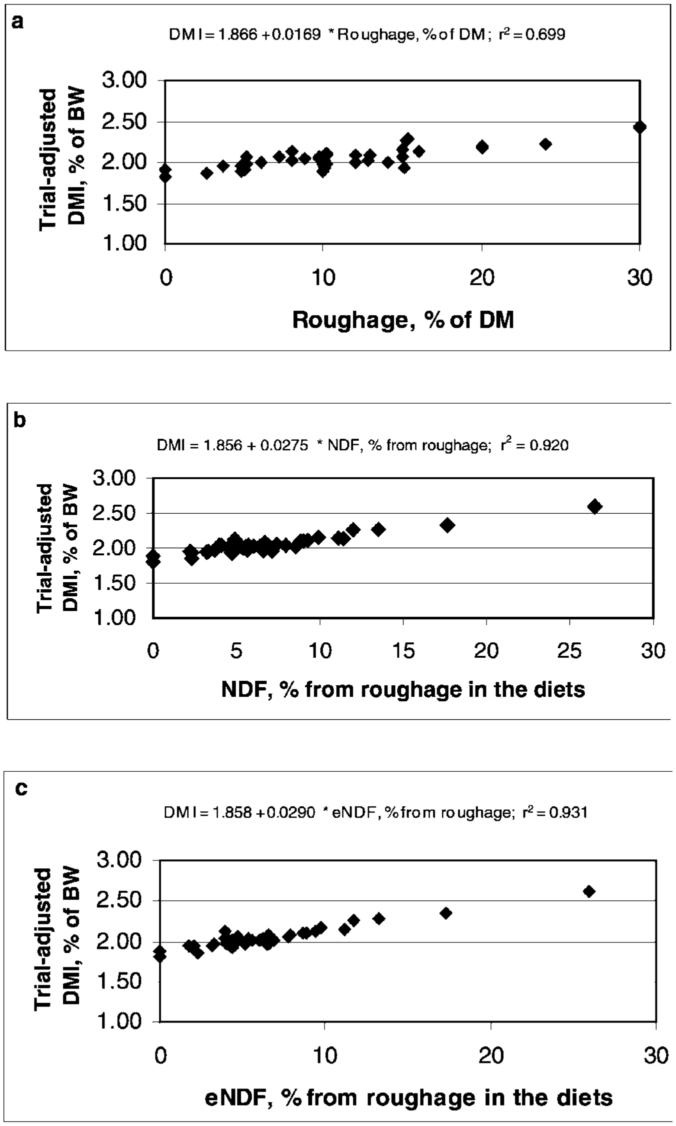

Figure 2. Plots of trial-adjusted DMI (percentage of BW) vs. a) roughage level (percentage of DM); b) NDF (percentage of dietary NDF supplied by roughage); and c) effective NDF (eNDF; percentage of dietary eNDF supplied by roughage).

Results for the regression of trial-adjusted data for DMI vs. roughage level, NDF supplied by roughage, and eNDF supplied by roughage are shown in Figures 2a, 2b, and 2c, respectively. Overall intercept and slope estimates for these three variables were highly significant ($P < 0.001$). Intercepts differed ($P < 0.02$) among trials for all three variables, but slopes did not ($P >$ 0.18 for NDF and eNDF; $P > 0.27$ for roughage level). As noted previously, dietary NEg supplied by roughage also was evaluated as an independent variable, but the slope for NEg was not significant ($P > 0.28$; data not shown). This finding suggests that the relatively small differences among the data points in dietary NEg supplied by roughage were not useful for describing changes in DMI and that simply accounting for these small changes in energy dilution does not fully describe the effects of roughage source and level on DMI by feedlot cattle. Roughage level (Figure 2a) was clearly associated with changes in DMI, but the r^2 (0.699) was considerably less than for NDF supplied by roughage (0.920) and eNDF supplied by roughage (0.931). We interpret these results to suggest that most of the effect of changes in roughage level and source on DMI by feedlot cattle can be ascribed to changes in dietary NDF supplied by roughage. In these data, eNDF accounted for such a slight improvement beyond NDF that its use would not seem worthwhile in practice. Nonetheless, eNDF might be more descriptive than NDF for certain roughage sources, as evidenced by the superior results in exchanging sorghum silage for alfalfa on the basis of NDF retained on a 2.36-mm screen compared with NDF alone in the study of Defoor et al. (2002).

If changes in DMI (and thereby intake of net energy) accurately reflect differences among roughage levels and sources, the strong relationship we observed between NDF supplied by roughage and DMI in these literature data supports the concept that NDF supplied by roughage could be used practically as a means of exchanging roughage sources in feedlot diets. As noted previously, we used NRC (1996) tabular values for NDF and eNDF in our analysis. Use of directly measured values, or at least values selected from a local or regional historical database, should provide even greater precision in defining effects of roughage on DMI. Further research is needed to test the value of NDF supplied by roughage as a means of exchanging roughages in feedlot diets. Similarly, because our data for eNDF were derived from tabular estimates, the role of eNDF or some type of index related to the physical effectiveness of NDF in describing the effects of roughage in feedlot diets needs further study. Finally, our data included only a few commonly used roughage sources (alfalfa hay, corn silage, cottonseed hulls, sorghum sudangrass hay, sorghum silage, and wheat straw), so extension of these findings to other sources of NDF (e.g., high-fiber byproduct feeds) would require further research.

Biology of Roughage Level and Source Effects

Energy Dilution. Physical fill would rarely limit intake of high-concentrate diets, so when a high-concentrate diet is diluted by roughage, the animal typically eats more feed to maintain energy intake. Compensation via increased DMI is possible until the point that roughage (fiber) level is sufficiently high to impose restrictions on fill or perhaps eating rate. This concept is illustrated in the data of Bartle et al. (1994), in which cattle fed 10 and 20% alfalfa diets had equal ADG, but increasing the level of alfalfa to 30% of the diet decreased ADG. Similarly, cattle fed 20 and 30% cottonseed hulls, although consuming more DM, gained less than those fed 10% cottonseed hulls. Below the point of restriction, relatively small changes in fiber level in the diet resulting from either increased roughage level or a switch to a higher-fiber roughage source can stimulate DMI to the point that the total energy intake is increased (e.g., a quadratic effect of roughage level on energy intake). This concept is illustrated by the results of Guthrie et al. (1996), in which ADG was greater in cattle fed 7.5 and 10% sorghum sudangrass hay diets than in those fed a 10% alfalfa diet. As noted previously, NEg supplied by roughage was not a significant factor related to DMI in the literature data that we analyzed. This result presumably reflects the fact that for many of the data points in the literature database, the change in NEg supplied by roughage with changes in roughage source and level was relatively small. It seems likely that energy dilution per se would affect DMI of high-concentrate diets only when differences in fiber level are large (e.g., Bartle et al., 1994), whereas differences in DMI resulting from smaller, more subtle changes in fiber level (e.g., Guthrie et al., 1996) might result from factors other than energy dilution, such as changes in ruminal and/or metabolic acidity or digesta kinetics as will be discussed in subsequent sections.

Ruminal, Intestinal, and Metabolic Acidity. Alterations in the quantity of and/or temporal pattern of acid production within the gut and the subsequent metabolic acid load via absorption could account for many of the effects of NDF from roughage on DMI by feedlot cattle. Acidosis negatively affects intake by feedlot cattle (Fulton et al., 1979a,b); thus, the quadratic response in DMI often noted with small increases in NDF supplied by roughage might reflect effects on acid load. For example, if bite size were relatively constant with high-concentrate diets, the ratio of grain to NDF in each bite would decrease for a diet with a greater NDF supply from roughage compared with a lower-fiber diet. Allen (1997) noted that the balance between production of fermentation acids and secretion of salivary buffers was the primary determinant of ruminal pH. Hence, with a higher NDF intake per unit of grain, one might expect a higher, or at least more stable, ruminal pH. The resulting lower metabolic acid load also could be lower simply because the proportion of fermentable substrate per bite would be less, and the greater proportion of NDF in each bite might stimulate more chewing and saliva secretion. If the total number of bites increases until acid load becomes limiting, total energy intake might exceed what would be expected from compensation for energy dilution alone. The level of NDF from roughage required to elicit overcompensation in DMI likely differs among roughage sources and within a roughage source as NDF concentration of the source changes with maturity.

The extent to which the NDF content of the diet or NDF supplied by roughage is related to chewing time, saliva flow, and ultimately to ruminal pH, however, is open to question. In ruminally cannulated steers given ad libitum access to 90% concentrate (steam-flaked sorghum) diets (Moore et al., 1987), rumination time was greater with 10% wheat straw than with 10% of either cottonseed hulls or alfalfa (308 vs. 180 and 210 min/d, respectively). Ruminal pH was numerically greater for the diet containing wheat straw than for those containing alfalfa or cottonseed hulls (6.2 vs. 5.9 and 5.8, respectively), but did not differ among the three roughage sources. Thus, wheat straw, but not cottonseed hulls, seemed to alter chewing time and ruminal pH, even though both of these high-NDF roughages tended to increase DMI relative to alfalfa (Moore et al., 1987). Similarly, Shain et al. (1999) reported that steers fed a dry-rolled corn-based diet containing wheat straw spent more total time ruminating than steers fed a dry-rolled corn-based diet containing alfalfa; however, ruminal pH did not differ between cattle fed diets containing alfalfa or wheat straw ground to pass through a 2.54-cm screen. Pitt et al. (1996) reported a fairly strong relationship ($r^2 = 0.521$) between ruminal pH and the eNDF concentration of dairy, beef, and sheep diets. In contrast, Nocek (1997) reported that eNDF accounted for approximately 5% of the variation in ruminal pH in a dataset of mean ruminal pH values with lactating dairy cows. Allen (1997), also using a literature database, found that NDF content of the dietary DM was not related to ruminal pH in dairy cows. Nonetheless, Allen (1997) noted that forage NDF as a percentage of the DM was significantly related to ruminal pH, which supports the concept that NDF from roughage might be related to ruminal pH, thereby accounting, at least in part, for the relationship that we observed between NDF from roughage and DMI by beef cattle fed high-concentrate diets. The statistical analyses conducted by Pitt et al. (1996), Allen (1997), and Nocek (1997) did not seem to use mixed-model methodology that would have allowed random study effects to be accounted for, which might explain some of the variation in results among these studies. In addition, animal-to-animal variation in ruminal pH and the ability to handle an acid load seems fairly substantial, even in model systems where a relatively constant acid load is applied (Brown et al., 2000). Such variation, as well as potentially large diurnal fluctuations in ruminal pH, would decrease the ability of dietary NDF or eNDF to account for a substantial proportion of the variation in mean ruminal pH.

Inherent buffering capacity has been suggested as an aspect of roughages that might account for differences in ruminal and metabolic acid loads and ultimate effects on DMI. However, Allen (1997) noted that buffering by feeds would be more likely to occur at a pH less than 5. Moreover, Allen (1997) calculated that the potential direct buffering by the diet was a small fraction of buffering by saliva. Thus, given that the maximal roughage level in feedlot diets is approximately 15%, with lower levels typically used in practice, inherent buffering capacity of roughages is probably not very important in accounting for effects of roughage source and level on DMI of high-concentrate diets by finishing beef cattle.

It is unknown whether roughage source and level affects absorption of acids from the rumen or acidity in the small and large intestines. It seems unlikely that increasing NDF supplied by roughage in a high-concentrate diet would directly affect absorption of VFA from the rumen. Similarly, direct effects of roughage on absorption of acids from the intestines seem unlikely. Allen (1997) suggested that changes in ruminal papillae surface area among diets might affect the susceptibility of cattle to acidosis, which could be related to differences resulting from dietary NDF supplied by roughage. Whether roughage source or level in feedlot finishing diets affects ruminal surface area for absorption is unknown. The NDF supplied by roughage might exert effects on digesta kinetics and associated water flux that affect digesta flow through the intestines and absorption of acid postruminally. Because DMI and water intake are positively associated (NRC, 1996), the increased DMI noted with higher dietary concentrations of NDF from roughage could be linked to a positive effect on acid load simply by an associated increase in water intake and dilution of acid. Incomplete mixing of water with ruminal contents (Allen, 1997) would tend to lessen the effects of greater water intake. In addition, increased water intake might merely shift site of acid absorption (i.e., rumen vs intestines) and thereby not greatly alter total metabolic acid load; however, the temporal pattern of acid absorption would perhaps be altered so as to spread the metabolic acid load more evenly over time. To our knowledge, effects of roughage source and level in beef cattle finishing diets on water intake have not been investigated.

Characteristics of Ruminal Digesta, Digesta Flow, and Site and Extent of Digestion. Fairly wide ranges in NDF supplied by roughage seem to affect the physical nature of ruminal contents. Moore et al. (1987) reported a tendency for cattle fed a high-concentrate diet with 10% cottonseed hulls to have a higher ruminal fill than those fed alfalfa and wheat straw diets, and a tendency for the cottonseed hull diet to have a higher percentage of ruminal DM in the fiber mat than alfalfa (2.4 vs. 0%). The lower percentage of fiber in the mat with alfalfa was probably a result of greater rate of passage of alfalfa than of cottonseed hulls and wheat straw from the rumen (Moore et al., 1990; Poore et al., 1990). The cottonseed hull diet had a lower percentage of ruminal DM in the fiber mat than wheat straw (2.4 vs. 19.9%), which was consistent with the greater time spent ruminating when animals were fed the wheat straw diet. Stratification or layering of ruminal contents has been implicated as a factor related to rumination in cattle (Van Soest, 1982; Welch, 1982; Moore et al., 1990; Poore et al., 1990). As noted previously, greater chewing during eating and rumination might result in greater saliva production, which could buffer the rumen of cattle fed high-concentrate diets (Owens et al., 1998). Conversely, greater rumination might increase mastication of grain in some diets, thereby increasing rate and extent of fermentation in the rumen (Owens et al., 1998). For example, Owens and Ferrell (1983) measured rumination time by steers fed a whole shelled corn-based diet with 5% roughage and noted a tendency for greater ADG by steers that ruminated up to 150 min/d than by those that ruminated approximately 65 min/d. This difference was most likely related to improved utilization of the whole corn as a result of greater mastication rather than increased saliva production and ruminal buffering. In contrast, Gill et al. (1981) indicated that non-ruminating steers gained faster than ruminating steers when fed diets based on steam-flaked corn, high-moisture corn, or a mixture of the two.

Changes in passage of dietary components from the rumen could be related to changes in DMI resulting from differences in roughage source and level. If NDF from roughage increases passage of the grain portion of the diet, less fermentation would occur in the rumen, resulting in a decreased acid load and potentially greater DMI. Nonetheless, grain starch seems to be used most efficiently when fermented in the rumen, and intestinal starch digestion capacity might be limited (Huntington, 1997), so passage of unfermented starch might be counterproductive to optimizing efficiency. Moore et al. (1990) fed ruminally cannulated steers 65% concentrate steam-flaked grain sorghum-based diets that contained either 35% alfalfa or 50:50 mixtures of alfalfa with cottonseed hulls or wheat straw. Replacing half of the alfalfa with cottonseed hulls increased DMI and tended to increase the passage rate of the grain. Poore et al. (1990) measured passage rates of grain and roughage in 30, 60, and 90% concentrate diets containing 50:50 mixtures of wheat straw and alfalfa. Within each concentrate level, ruminal passage rate was greater for alfalfa than for wheat straw, decreasing by 13 and 28%, respectively, in the 90 vs. 60% concentrate diet. Passage of steam-flaked grain sorghum, however, was not influenced by diet, which does not support the hypothesis that higher roughage levels might increase passage of unfermented starch from the rumen. Similarly, Eng et al. (1964) reported that mean retention time of hay, but not of corn, was increased as concentration of corn increased from 25 to 75% in the diets of sheep. In contrast, Owens and Goetsch (1986) and Wylie et al. (1990) reported that increasing dietary roughage decreased residence time of grain in the rumen. Cole et al. (1976) reported a trend for decreased ruminal and total tract starch digestibility for diets containing 7, 14, and 21% cottonseed hulls compared with 0% cottonseed hulls in whole shelled corn-based diets, which the authors attributed to an increase in the rate of passage of grain with increasing cottonseed hulls. Other reports, however, have indicated positive effects of cottonseed hulls relative to alfalfa on total tract digestibility of starch in whole shelled corn-based diets (Teeter et al., 1981; Rust and Owens, 1982; Goetsch et al., 1986). Results of the feeding trial reported by Shain et al. (1999) suggested that compared with alfalfa, wheat straw might adversely affect the passage and utilization of dry-rolled corn, even when fed to provide the same level of NDF in the diet; however, no differences were noted in rate of ruminal starch disappearance or passage of Yb-labeled corn between the two roughage sources. Overall, currently available data suggest that effects of NDF supplied by roughage on passage of grain from the rumen, and thereby on site and extent of grain (starch) digestion, are probably not large within the normal range of roughage levels used in feedlot diets.

Summary and Conclusions

Our literature review and data analyses suggest that exchanging dietary roughage on the basis of NDF concentration instead of an equal percentage of DM basis might eliminate much of the variation in DMI and performance that often occurs when roughage sources are changed in practice. However, balancing for NDF alone might not be an entirely satisfactory means of exchange because other characteristics related to physical effectiveness of NDF sometimes affect roughage value. Formulating to a specific NDF concentration with different roughage sources probably accounts for most of the effect of roughage source and level on DMI, but it does not fully account for the aggregate of small differences in fiber sources that might affect chewing time and kinetics of digestion and passage of roughage and grain. Whether these differences in physical effectiveness of NDF are sufficiently large to warrant their consideration in formulation practices is unknown, and further research, coupled with practical evaluation of the use of NDF supplied by roughage as a means of roughage exchange, is needed.

Implications

Changes in roughage source and level affect dry matter intake by feedlot cattle. Based on analysis of published data, the percentage of neutral detergent fiber supplied by roughage in high-concentrate, feedlot diets accounts for most of the variation in dry matter intake caused by roughage source and level. Although neutral detergent fiber supplied by roughage might provide a useful basis for exchanging roughages in feedlot diets, the biological reasons for changes in dry matter intake associated with changes in roughage source and level need further study.

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