Forage Fragility, Fiber Digestibility, and Chewing Response in Dairy Cattle

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Abstract

The physically effective neutral detergent fiber **(peND-F)** system is based on measurement of forage or feed particle size and NDF content with the objective of accurately predicting chewing response. However, we know that different NDF sources of similar particle size may elicit variable chewing responses. Fragility, defined as the rate of particle size reduction of a feed when ball milled, may improve prediction of chewing response when combined with measures of particle size. We have found a positive relationship between NDF digestibility and fragility. In some cases, it appears that NDF digestibility may be more useful in adjusting peNDF values than a direct measure of fragility. Assessment of forage physical properties shouldn't stop with a simple particle size measurement to optimize chewing and productive responses of dairy cattle.

Introduction

Mertens (1997) defined peNDF as the fraction of NDF that stimulated chewing and contributed to a ruminal digesta mat. He also proposed a standard laboratory method for measuring peNDF that involved dry sieving and measuring the fraction of particles retained on the 1.18-mm sieve multiplied by the sample NDF content. This large particle pool requires rumination and has a high resistance to escape from the rumen of sheep (Poppi et al., 1985). Mertens (1997) summarized a large data set that showed a positive correlation between peNDF measured by dry sieving, ruminal pH, and milk fat percentage in dairy cattle. Based on the Mertens (1997) data set, the minimal requirement for peNDF in lactating dairy cows has been defined as approximately 21 to 23% of ration dry matter **(DM)** to maintain ruminal pH above 6.0 and milk fat above 3.4% for Holstein cattle. Recently, we summarized data from 12 studies that measured peNDF using only the standard dry sieving method to evaluate the relationship between dietary peNDF and efficiency of 4% fat-corrected milk production (FCM/DM intake) to remove confounding effects of variation in peNDF methodology (Grant, 2008, unpublished). The relationship is shown in Figure 1, and the highest efficiencies have been measured for diets containing peNDF concentrations between approximately 21 and 24% of ration DM.

Since 1997, the peNDF system has become widely used within the CPM-Dairy and Cornell Net Carbohydrate Protein System **(CNCPS)** ration formulation models to predict the effect of forage particle size on cow chewing response and ruminal pH. A practical problem had been lack of an on-farm tool that accurately measured peNDF and resulted in physical effectiveness factors **(pef)** similar to those obtained by the standard dry sieving method. To address this problem, we developed the Z-Box to effectively measure peNDF for common forages and total mixed rations **(TMR)** in on-farm situations (Cotanch

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and Grant, 2006). Currently, our Forage Lab at Miner Institute is refining the Z-Box method for dry forages and TMR based primarily on dry forages. Additionally, we have been modifying the Z-Box sieves to provide measurement of forage and TMR particle distributions similar to the Penn State Particle Separator **(PSPS)** (Lammers et al., 1997; Kononoff et al., 2003). Finally, preliminary research (Cotanch et al., 2010, unpublished) indicates that insertion of a larger screen in place of the 1.18-mm screen of the Penn State system results in better measurement of pef.

Particle Size Versus Fragility

A major assumption of the peNDF system is that forage particle size explains all of the variation in chewing response. This assumption is not always true because we know that forages of similar particle length may elicit substantially different chewing times per kilogram of NDF. For example, oat straw may elicit nearly twice as much chewing as alfalfa hay at a similar particle size (data summarized in Mertens, 1997). Grass and alfalfa hays resulted in a range of 111 to 152 minutes of chewing/kg (50.5 to 69.1 min/lb) NDF compared to nearly 200 minutes of chewing/kg (90.9 min/lb) NDF from oat straw. This difference in chewing response has been a recognized limitation within the peNDF system and currently nutritionists use their best judgment to adjust rations based on herd response to compensate for differences among forage sources in their ability to stimulate chewing.

Several methods have been reported for measuring relative differences in forage particle fragility. Years ago, Troelson and Bigsby (1964) devised a mechanism to specifically examine forage particle size distribution after artificial mastication. More recently, two commonly used methods include: 1) comminution energy which is the energy required to grind a sample through a mill, and 2) shear force which measures the force needed for a blade to pass through the forage stem using a Warner-Bratzler or similar machine common in meat science laboratories. Casler et al. (1996) developed a particle size reduction index using a ball mill to grind forage particles. The percentage of particles passing through a 1-mm screen upon milling was considered to be an index of forage fragility.

Although it has not been investigated, Mertens (1997) and others have suggested that differences in forage fragility, or related characteristics such as stem brittleness, may explain the variation in chewing response not explained by particle size. Fragility is defined as the relative rate at which forage is reduced in particle size during chewing or some laboratory simulation of chewing action. Fragility may be related to lignin content and digestibility, as well as to anatomical differences among plant species such as cell wall thickness (Van Soest, 1994). Consequently, digestibility of the forage cell wall may be predictive of forage fragility. As an example, Minson (1990) summarized data for grasses that related composition with resistance to comminution and voluntary intake in sheep. The grasses were categorized as high (81%), medium (72%), and low (56%) DM digestibility. As digestibility of the grass increased, NDF content decreased, grinding energy decreased, eating and ruminating times decreased, and voluntary intake increased.

Preliminary Research: NDF Digestibility and Forage Fragility

Miner Institute recently developed a ball milling method to assess the fragility of a wide range of forages (Cotanch et al., 2007). Briefly, forage samples are dried and placed in a ball mill loaded with ceramic balls because unpublished observations by Dr. Jim Welch at the University of Vermont had indicated that this process mimicked the grinding action of molar teeth. The forage samples are sieved using the standard method for measurement of pef prior to ball milling **(pef_i)** and again following ball milling **(pef_{BM})**. Fragility is determined as the change in pef value (proportion of particles ≥1.18-mm sieve as determined by dry vertical sieving) of the ball-milled forage from the original sample:

$$(pef_i - pef_{BM})/pef_i \times 100\%$$

A fragility value of 100%, highly fragile forage, would equate to complete reduction of particle size to less than 1.18 mm. A fragility value of 0, very tough forage, would reflect no reduction in particle size upon ball milling, $pef_i = pef_{BM}$. The change in pef, or fragility, versus 24-h in vitro NDF digestibility **(NDFD)** for a range of forages is shown in Figure 2. The R^2 indicates that the 24-h NDFD explains about 60% of the variation in forage fragility. Generally, brown midrib **(bmr)** corn silage is typical of forages at the upper range whereas straws would be typical of forages at the lower range of NDFD and fragility. The potential exists to combine a "fragility factor," related to NDFD, with the pef derived by sieving to arrive at a superior value to predict cow chewing response.

Rationale for Chewing Response Study with Cattle

We measured the chewing response to forages of similar particle size that represented the extremes shown in the data set of Figure 2. Four forages were evaluated:

1. Low NDF digestibility grass hay with a low fragility value, and
2. High NDF digestibility grass hay with a high fragility value.

These forages fit the expected positive relationship between NDF digestibility and forage fragility shown in Figure 2. The final two grass hays contained similar NDF digestibility, in the middle of the digestibility range (~40% NDFD), with

3. High fragility value, and
4. Low fragility value. These forages did not fit the general relationship since they had similar NDFD yet substantially different fragility as measured by ball milling.

We chose to use grass hays in this study because we did not want to confound our chewing results by:

1. Different plant species (grass, legume, corn silage, and cereal grains),
2. Moisture content (dry hay, and silages), or
3. Genetics such as bmr.

Using test forages, such as poor quality straw and bmr corn silage, would have expanded the range in NDF digestibility and fragility, but we would have been far less able to control particle size, and we would not have been able to assess the separate and potentially important effects of factors such as moisture. We chose to feed the hays to 18.5-month old heifers rather than adult dairy cows primarily because of the limited supply of these grass hays. Fortunately, at least one reference indicates that the relative rumination response for larger heifers, such as we used, is similar to adult cows (Welch and Hooper, 1988).

The overall purpose of the study was to determine if the fragility factor assessed by ball milling would be of any practical use in adjusting pef values to better predict the cow's chewing response – the ultimate bioassay for the peNDF system. In addition, we learned more about the interactions among forage NDFD, forage fragility, and cow chewing response.

The four test hays were chosen after preliminary analysis for 24-h in vitro NDFD and ball-mill fragility to establish a matrix of treatments encompassing both high and low 24-h NDFD and fragility for evaluation of chewing response when fed as the primary dietary ingredient (Figure 3). All grass hays were chopped using a Haybuster, Model

H-1100 (DuraTech Industries International, Inc., Jamestown, ND) with a 2-inch screen to help ensure similar initial particle length and to avoid sorting when fed. Hay A (low NDFD, low fragility) and Hay B (medium NDFD, low fragility) were first cuttings from crop year 2007. Hay C (high NDFD, high fragility) and Hay D (medium NDFD, high fragility) were second cuttings from crop year 2007.

Chewing Responses to Forage Fragility and Digestibility

Comparison of grass hays

Table 1 summarizes some of the basic nutrient composition of the four grass hays that we evaluated plus the supplemental grain mix. To answer the questions posed in the objectives, the appropriate grass hay comparisons are:

- Hay A versus Hay C. This compares the low NDFD, low fragility hay (A) versus the high NDFD, high fragility hay (C).

- Hay B versus Hay D. This compares the two medium NDFD hays that differed markedly in their fragility; high fragility (Hay D) and low fragility (Hay B).

Comparison of these hays allowed us to determine if heifer chewing response follows the relationship shown in Figure 2 between 24-h NDFD and fragility. Our expectation was that the low fragility, low digestibility hay would stimulate more chewing response than the high fragility and digestibility forage at a similar particle size. In addition, the chewing response to the two grasses that had similar NDFD, but different fragilities, allowed us to assess how significant a role fragility plays in stimulating chewing response.

Fiber digestibility, particle size, and fragility

In vitro NDFD at 24 h was higher for Hay C than for Hay A (Table 2). The in vitro 24-h NDFD for Hay A was 31.4% compared with 54.8% of NDF for Hay C. The in vitro 24-h NDFD for Hay B and Hay D were more similar and averaged 45.5% of NDF. The indigestible NDF was much lower for Hay C (25.9%) versus Hay A (50.7%), and similar for Hay B versus Hay D (average of 37.2%).

The as-is particle distributions measured using the PSPS indicate that all forages had relatively similar percentages of particles on the top screen except for Hay B (Table 3). Consequently, Hay B had slightly greater particles retained in the second screen than the other grasses, and particles retained on the pan were relatively similar across all forages. Given the physical nature of these grasses, obtaining an accurate measure of particle size was difficult because some particles were extremely fine and others were easily entangled on the sieves and so they did not pass through the openings easily. Consequently, there is variability among the measured pef obtained using several methods. Basic particle distributions obtained with the PSPS indicate that the large particle pool (i.e. top two screens) were similar among the four chopped hays.

The fragility was much less for Hay A versus Hay C and was lower for Hay B than for Hay D. The greater susceptibility of Hay C to particle size reduction versus Hay A was related to higher NDFD, whereas the greater rate of particle breakdown for Hay D versus Hay B appeared to be unrelated to NDFD digestibility.

The pef was relatively similar across the four grasses when measured using the standard dry sieving method (Mertens, 1997), although Hay C did have a $pef_{1.18}$ that was ~20% lower than the other grasses. When pef was assessed using the 3.35-mm screen and the standard dry sieving method, all four forages had very similar particle sizes. The $pef_{3.35}$ has been proposed to be a more valid measure of pef in cattle than the 1.18-mm screen, which was originally based on sheep data (Grant and Cotanch, 2005).

Consequently, the peNDF content of the four grass hays (pef x NDF%) varied among the forages as a function of the NDF content of the grass plus the pef. In general, Hay C was slightly lower than the other grass hays due to its lower content of NDF.

Feed consumption of heifers

Table 4 summarizes the feed intake and body weight data for the heifers fed these four grass hays plus the concentrate mix. Dry matter and NDF intakes were greater for heifers fed Hay C than Hay A. This presumably reflects the lower percentages of NDF and acid detergent lignin, and greater 24-h NDFD and fragility for Hay C versus Hay A. Intake of NDF was similar for Hay B and Hay D, which presumably reflected the much greater fragility for Hay D compared with Hay B at similar NDFD. The average heifer body weight and body condition score (data not shown) were similar across all four treatments.

Chewing response by heifers

Table 5 summarizes the chewing responses by the heifers to the four grasses differing in fragility and 24-h NDFD. Total chewing activity (min/kg NDF intake) was greater for Hay A compared with Hay C. This increase in chewing agrees well with the lower fragility and NDFD of the Hay A versus Hay C. In particular, rumination activity (min/kg NDF intake) was 16% greater for Hay A versus Hay C and resulted in ~1/2 hour more rumination time daily. The chewing activity for heifers fed Hay B versus Hay D was similar. Eating activity trends were similar to those observed for total chewing and ruminating.

General discussion of fragility and digestibility data

The lower fragility, lower NDFD hay compared with the high fragility, high NDFD hay resulted in:

- Greater NDF, indigestible NDF, and lignin,
- Lower 24-h NDFD,
- Lower fragility,
- Similar pef, perhaps lower for Hay C depending on measurement technique, and
- Greater ruminating response.

If we assume similar particle size, then the greater chewing response to Hay A was due largely to the lower NDFD and fragility. We also know that 24-h NDFD explains about 60% of the variation in fragility measured using the ball milling technique. Even though the difference in rumination time is small, there may be benefit in adjusting a pef value based on a measure of fragility or indirectly via a measure of NDFD.

If we compare the two hays with similar NDFD, the hay with the lower fragility resulted in:

- Greater NDF and lignin,
- Similar 24-h NDFD,
- Lower fragility,
- Similar pef, and
- Similar ruminating response.

Hay B and Hay D had similar NDFD, but different fragility at similar particle size. Both hays stimulated similar rumination responses. Chewing response appeared to be less related to fragility when NDFD was similar. In all forages, it is interesting that those with the least indigestible NDF stimulated a larger than expected amount of chewing per unit of indigestible NDF.

Importance of Fragility Versus NDFD

With these four grass hays, we were able to assess the relative importance of NDFD versus fragility (rate of particle break-down while ball milling) as factors that influence chewing response in dairy cattle. For grass hays that fit the general relationship between NDFD and fragility the differences in NDFD and fragility were related to differences in chewing for grasses of similar particle size. Specifically, the more digestible and more fragile grass elicited ~30 min/day less chewing than the less digestible, less fragile grass hay. The peNDF system currently would have predicted similar chewing between the forages per kilogram of NDF based on their similar pef. An important question is: does the ~30 min/day of chewing not predicted by particle size make a biologically meaningful difference to the cow? We can answer this question based on reported values for saliva production during chewing and associated buffer delivery to the rumen (Grant et al., 1990):

- 28 min/day difference in rumination time between Hays A and C,
- Assume chewing response between large, mature heifers and mature cows is similar (Welch and Hooper, 1988),
- 8.03 L/day more saliva produced (rumination salivation rate = 274 ml/min), and
- 48 g/day more bicarbonate available to the animal (6000 mg/L of bicarbonate in saliva).

For a mature, lactating Holstein dairy cow, the total daily production of salivary bicarbonate is ~700 to 800 g/day. So, the greater response in chewing for Hay A that was not predicted by particle size is ~5 to 10% of the total daily buffer production. It appears that the peNDF system, based solely on particle size, does an adequate job of predicting chewing and associated saliva and buffer flow to the rumen for cows fed these grass hay diets, but even with these tightly matched grasses, there is potential for improvement in prediction of chewing and associated productive responses. The potential certainly exists for forages that differ more in NDF digestibility and fragility (such as straws or stovers versus bmr forages or very high quality grasses and legumes), measurement of NDF digestibility or fragility could improve the ability of pef to predict chewing response.

The comparison of chewing response for cattle fed Hays D and B helps us to determine whether NDF digestibility or fragility is more important in explaining the chewing response observed when hays of similar particle size are fed. These two grass hays had similar NDFD (44 to 47%) but quite different fragility (30 to 64%), and still they both elicited equivalent chewing response. This result implies that NDFD is more important in explaining chewing response than is fragility for grass forage particles of similar particle size. Otherwise, the fact that Hay D had 2x greater fragility than Hay B would have resulted in less chewing response. Also, Hay A had the lowest NDFD of all the hays, and it was the only hay that elicited increased rumination time, despite the fact that Hays B, C, and D ranged from 30 to 80% in fragility. This data set indicates that NDFD may be more important than fragility *per se* for predicting chewing response of similarly sized forage particles, at least for grass hay.

Implications for Ration Formulation

1. For the range of grass hays evaluated in this study (31 to 55% NDFD; 30 to 80% fragility) that reflects what would commonly be fed, measuring NDFD may be more important than fragility *per se*.

2. For forages of other types, and for grasses outside this range that we evaluated, fragility may be more important. But, cow response trials would be needed to confirm this idea.

3. Currently, use of pef without adjusting for fragility is satisfactory in many cases although there is potential to improve prediction of cow responses.

4. Routine measurement of NDF digestibility is recommended because of:

   a. The known relationship between NDFD and energy content of the forage, and

   b. The apparently stronger relationship between NDFD and chewing time compared with fragility and chewing time in this data set. As forage NDFD increases, we would expect less chewing to be elicited per kilogram of NDF.

5. High NDFD, high fragility sources stimulate less chewing per unit of NDF at similar particle size, thus one needs to feed more forage, formulate for higher peNDF, or supplement with lower NDF digestibility (and likely lower fragility) forage.

It is possible to draw a relationship for grasses between NDFD and chewing that could be used to adjust pef as shown below:

Grass A:	Grass C:
31% NDFD	55% NDFD
46% Fragility	81% Fragility
149 min TCT/kg NDF	130 min TCT/kg NDF

Mertens (1997) reported that the mean total chewing time **(TCT)** for long grass hay = 150 min/kg (68.2 min/lb) NDF. Therefore, pef of 1.0 (100%) = 150 min TCT/kg NDF. Each unit of pef then is equal to 1.5 min TCT/kg NDF (150/100). Based on our data (shown above), for every 5-unit increase in NDFD, at equal pef, there is a 0.79 unit decrease in TCT per kg NDF (assumes linear relationship):

$\Delta TCT/\Delta NDFD = (49-130)/(55-31) =$
$19/24 = 0.79$

If pef of a test grass is 0.80 based on dry sieving and with NDFD of 45%, then we can calculate the adjusted pef based on our data set:

45-31 = 14%-units difference in NDFD between test hay and base hay (Grass A)

14 x 0.79 = 11 min TCT; 11 min TCT/1.5 = 7.3 pef units or 0.073 proportion of pef

So, adjusted pef = 0.80 – 0.073 = 0.72

Preliminary Lactation Study Comparing Dry Grass Hay versus Wheat Straw

A preliminary study was recently completed at Miner Institute (2009, unpublished) that evaluated the effect of adding either 3.6 lb of grass hay or 3 lb of wheat straw to diets fed to lactating dairy cows in order to supply similar amounts of NDF from each forage source. Table 6 summarizes some of the key information from the study. The purpose of the study was to evaluate the short-term response of the cows to dietary supplementation with forages commonly used to boost peNDF under conditions where forage particle size was controlled. The practical on-farm question was whether moderate quality grass hay (commonly called "heifer hay") would elicit a chewing response similar to more expensive wheat straw.

The grass hay had greater NDFD and fragility, but the pef and particle size was similar for both hay and straw. In fact, the two TMR were similar in particle size. The primary behavioral response was a reduction in rumination time of ~30 min/day. We are currently summarizing the effect of diet on productive responses. But, we would anticipate some effect on milk fat output given the reduction in chewing. The important point to note is that the difference in chewing observed was unrelated to particle size since pef did not differ between the two diets.

We are currently planning a follow-up study to be conducted in 2010 that will compare diets containing straw, bmr corn silage, and an intermediate forage base, at similar particle size, for the impact on chewing and productive responses in lactating cows.

Current Status: Relationship Between NDFD and Forage Fragility

Figure 4 shows the relationship we have obtained when we combine selected data from a field study conducted with a regional feed company, along with some of our own samples collected at Miner Institute. This relationship may evolve as we add more data to our fragility/NDFD data base. Visual assessment of this figure suggests that there is a relationship between NDFD and fragility up to a certain point, perhaps ~40% NDFD. But, beyond this point, there is no relationship between NDFD and fragility. It does make sense that above a certain NDFD, greater NDFD results in no further enhancement in fragility. We intend to follow-up on defining this relationship by adding more forages to the sample data base in 2010.

Development of pef Adjustment Factors

For users of CPM-Dairy or models based on CNCPS, adjustment factors for pef values would be useful to better predict chewing response among various forages. Based on the small data set we have created to date, we have suggested fragility adjustment factors for grass forages and corn silage (Table 7). These factors should be viewed as preliminary only and open to future refinement. But, they do represent a first step that may prove useful to nutritionists who desire a method for adjusting pef while formulating rations.

Other Potential Applications of Fiber Digestibility and Fragility Measurements

A rate of particle size reduction may also be calculated from these data. Models that predict particle flow from the rumen are sensitive to rate of large particle breakdown. The original procedure was ball milling for 6 hours and measuring change in pef of the sample. Using this technique, rates of particle size reduction ranged between 5.0 and 13.4%/hour. The method was adjusted by changing the ratio of balls to sample to reduce time needed for grinding down to 15 minutes. With the new technique, rates of particle reduction ranged between 2.00 and 4.26% per 15 min. Interestingly, these rates of particle reduction are similar to reported rates of large particle reduction in lactating dairy cows fed corn silage and alfalfa hay-based diets of 7.1%/hour (Woodford and Murphy, 1988) and 3.38%/hour for sheep (Ulyatt, 1983). If verified, the ball milling technique may be a useful laboratory method for estimating in vivo rates of particle breakdown. Another potential application of the relationship between NDFD and fragility would be to consider the inverse: Is there any benefit of measuring fragility to predict NDFD? Because measurement of NDFD can be highly variable, it is possible that a ball milling method would have much less variation associated with it. In order for this idea to work, the relationship between NDFD and fragility would need to be tight. More samples need to be analyzed to know the true relationship between NDFD and fragility, although at this point we are assuming that the general relationship shown in Figure 2 is true.

Conclusions

The NDFD and fragility are related. We can use this relationship to improve prediction of chewing response to peNDF when forage NDF sources differ in chewing response. Assessment of forage physical properties really shouldn't stop with a simple particle size measurement to optimize chewing and productive responses of dairy cattle.

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Table 1. Composition of grass hay and grain mix used in a chewing study.

Item, % of DM	Hay A	Hay B	Hay C	Hay D	Grain
Crude protein	8.1	7.8	12.1	10.4	27.2
NDF[1]	66.1	70.7	58.6	59.2	26.5
ADL[2]	6.5	5.6	4.1	4.5	3.1
Starch	1.8	1.9	1.9	1.7	29.9
Sugars	8.0	8.3	9.5	15.6	6.0

[1]Neutral detergent fiber.
[2]Acid detergent lignin.

Table 2. Digestibility and fragility of grass hays used in a chewing study.

Item	Hay A	Hay B	Hay C	Hay D
24-h IVNDFD[1], % of NDF	31.4	43.7	54.8	47.3
120-h IVNDFD, % of NDF	49.3	60.2	74.1	65.4
Indigestible NDF, %	50.7	39.8	25.9	34.6
Fragility, %	46.2	30.0	80.7	63.9

[1]In vitro neutral detergent fiber digestibility.

Table 3. Particle distributions of chopped grass hays fed in a chewing study.

Item	Hay A	Hay B	Hay C	Hay D
Penn State Particle Separator, % as-fed				
>19.0 mm	28.0	19.9	27.2	31.3
8.0 to 19.0 mm	27.5	31.0	21.9	22.9
<8.0 mm	44.6	49.1	50.9	45.8
$pef_{3.35mm}$[1]	0.13	0.12	0.11	0.15
$peNDF_{1.18mm}$[2]	33.5	32.2	21.4	28.9
$peNDF_{3.35mm}$[3]	9.0	9.2	6.6	9.3

[1]Physical effectiveness factor measure using 3.35-mm screen.
[2]Physically effective neutral detergent fiber measured using 1.18-mm screen.
[3]Physically effective neutral detergent fiber measured using 3.35-mm screen.

Table 4. Intake and body weight of Holstein heifers fed forages with varying NDF digestibility and fragility in a chewing study.

Item	Hay A	Hay B	Hay C	Hay D	SEM	*P*
Dry matter intake (DMI), kg/day[1]	9.56^{d}	9.95^{c}	11.32^{a}	10.87^{b}	0.18	<0.001
DMI, % of BW/day	1.73^{d}	1.81^{c}	2.04^{a}	1.96^{b}	0.04	<0.001
NDF[2] intake, kg/day	5.40^{b}	5.96^{a}	5.84^{a}	5.82^{a}	0.12	<0.001
NDF intake, % of BW/day[3]	0.98^{b}	1.08^{a}	1.05^{a}	1.05^{a}	0.03	<0.001
BW, kg	572	570	573	570	11	0.340

^{abcd} Least squares means within a row without a common superscript differ ($P < 0.05$).

[1]1 kg = 2.205 lb

[2]Neutral detergent fiber.

[3]Body weight.

Table 5. Chewing activity of Holstein heifers fed forages with varying NDF digestibility and fragility.

Item	Hay A	Hay B	Hay C	Hay D	SEM	*P*
Intake						
Dry matter intake, kg/day[1]	9.49^{c}	9.94^{c}	11.41^{a}	10.91^{b}	0.18	<0.001
NDF[2] intake, kg/day	5.34^{b}	5.94^{a}	5.88^{a}	5.84^{a}	0.12	<0.001
Total chewing						
min/day	790	765	756	772	15	0.095
min/kg NDF intake	149^{a}	130^{b}	130^{b}	132^{b}	3	<0.001
min/kg iNDF intake[3]	294^{d}	327^{c}	501^{a}	383^{b}	9	<0.001
Eating						
min/day	267	278	261	275	10	0.244
min/kg NDF intake	50^{a}	48^{a}	45^{b}	47^{a}	2	0.018
min/kg iNDF intake	99^{d}	119^{c}	173^{a}	136^{b}	5	<0.001
Ruminating						
min/day	523^{a}	487^{b}	495^{ab}	497^{ab}	10	0.011
min/kg NDF intake	99^{a}	83^{b}	85^{b}	85^{b}	2	<0.001
min/kg iNDF intake	195^{c}	208^{c}	329^{a}	246^{b}	6	<0.001

^{abcd} Least squares means within a row without a common superscript differ ($P < 0.05$).

[1]kg = 2.205 lb.

[2]Neutral detergent fiber.

[3]Indigestible neutral detergent fiber intake.

Table 6. Effect of grass hay versus wheat straw supplementation of lactation diet.

Item	Diet	
	Hay (3.6 lb)	Straw (3.0 lb)
Chemical composition of forages		
24-h NDFD, %[1]	33	22
Fragility, %	83	34
pef[2]	0.52	0.53
Behavior response		
Eating, min/day	250	249
Ruminating, min/day	479	505

[1]Neutral detergent fiber digestibility.
[2]Physical effectiveness factor.

Table 7. Suggested pef[1] adjustment factors for grass forage and corn silage.

	24-h NDF digestibility[2]	Fragility (%)	Adjustment factor
Grass forages			
	30	50	0
	40	60	0.06
	50	70	0.10
	60	80	0.19
Corn silage			
	30	65	0
	40	75	0.07
	50	85	0.13
	60	95	0.20

[1]Physical effectiveness factor.
[2]Neutral detergent fiber.

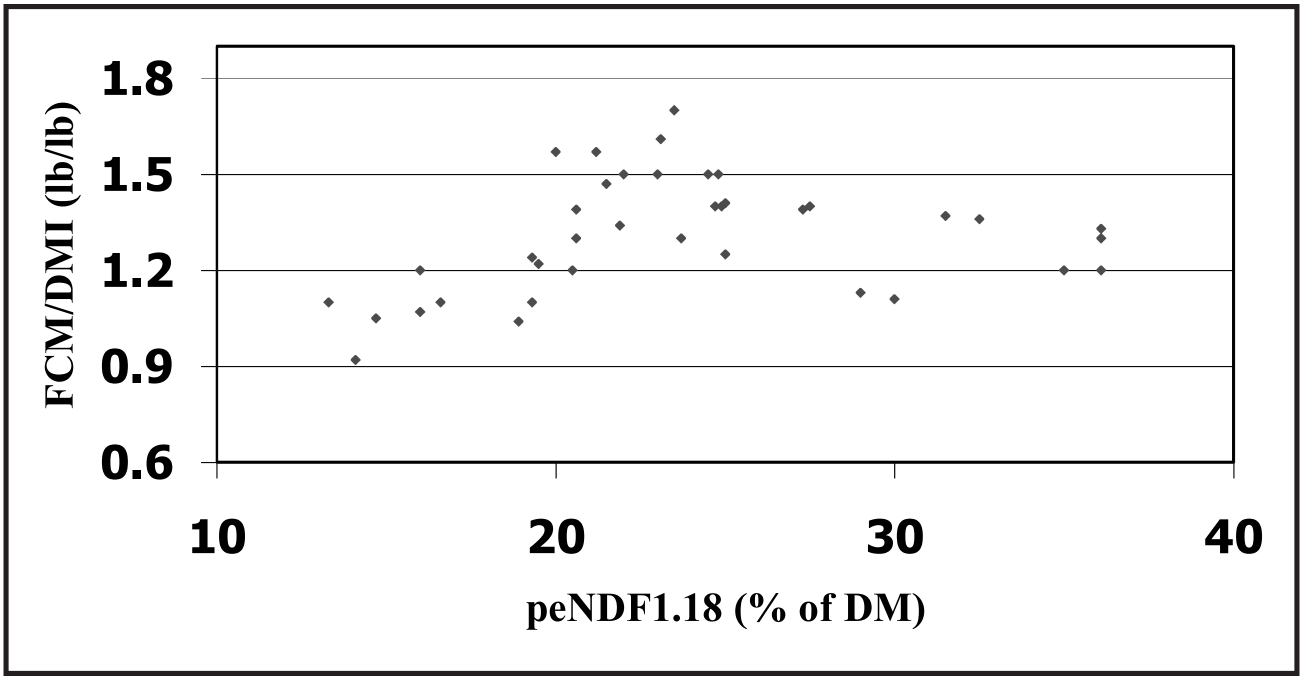

Figure 1. Relationship between physically effective NDF (peNDF) measured using standard method ($peNDF_{1.18}$) versus efficiency of 4% fat-corrected milk production (FCM/DMI) (Grant, 2008, unpublished).

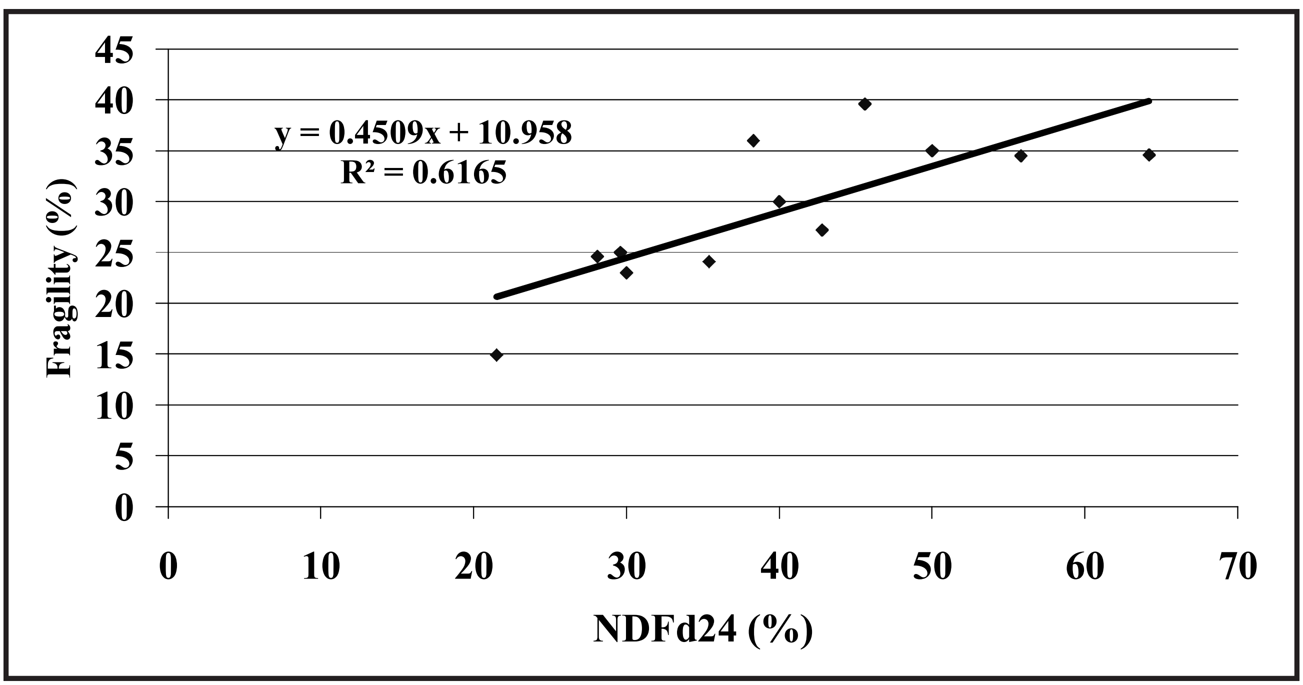

Figure 2. Relationship of the 24-h in vitro NDF digestibility (NDFd24) of various forages with the fragility of the forages as measured by change in physical effectiveness factor following ball milling.

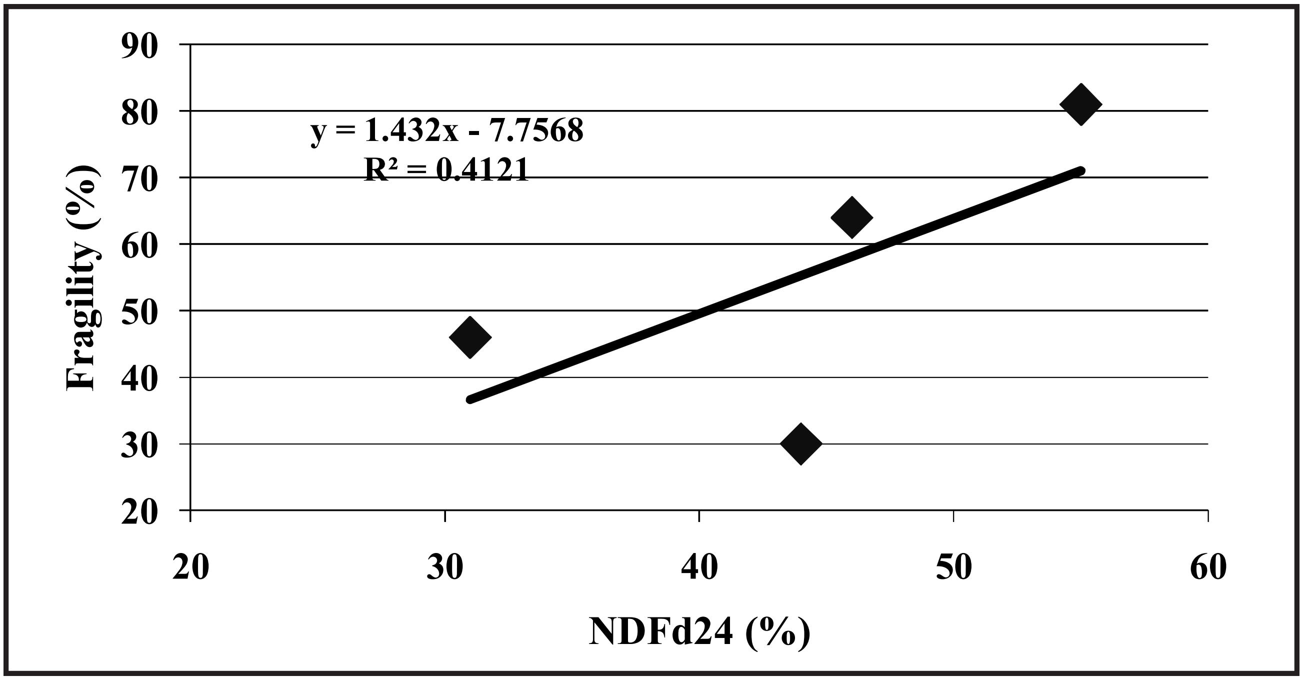

Figure 3. Fiber digestibility at 24 h (NDFd24) and fragility of four grass hays fed during a heifer chewing study.

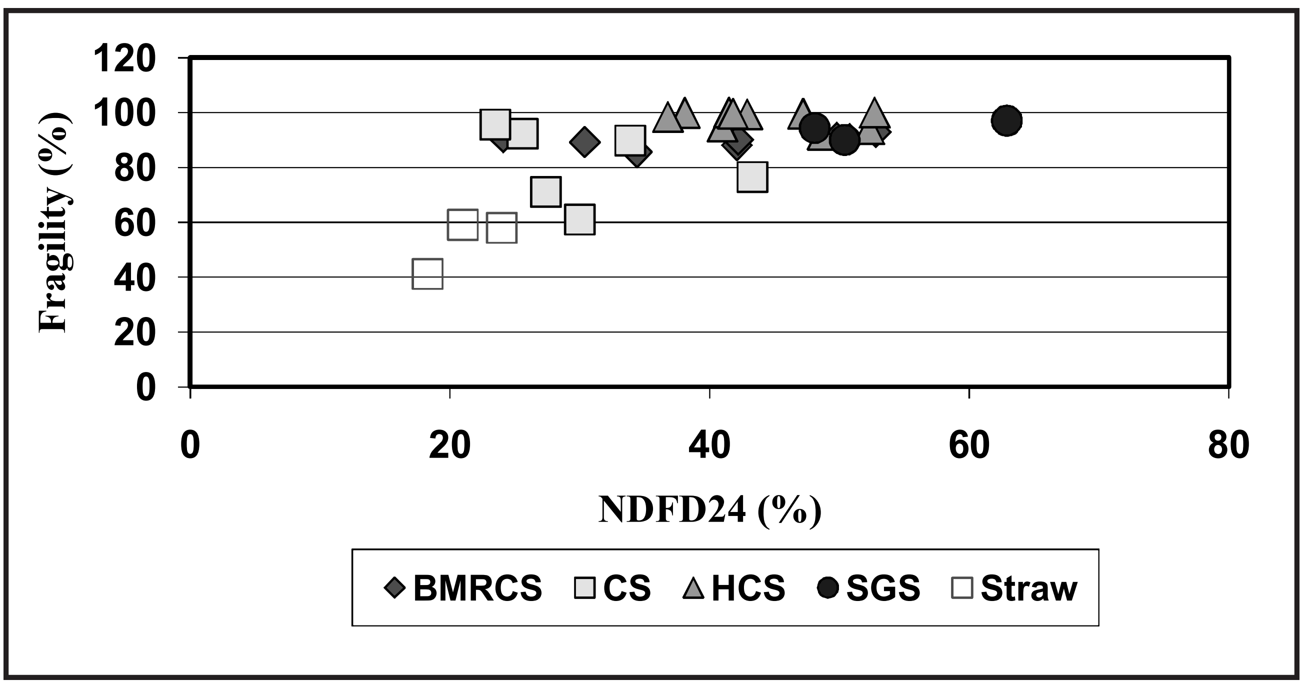

Figure 4. Relationship between NDF digestibility at 24 h (NDFD 24) and forage fragility. Sample set combined from field study and Miner Institute samples collected in 2007 to 2009 (BMRCS = brown midrib corn silage, CS = corn silage, HCS = haycrop silage, and SGS = small grain silage).