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Intake and milk production of cows fed diets that differed in dietary neutral detergent fiber and neutral detergent fiber digestibility[1]

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ABSTRACT

The objectives of this study were to determine how feeding diets that differed in dietary neutral detergent fiber (NDF) concentration and in vitro NDF digestibility affects dry matter (DM) intake, ruminal fermentation, and milk production in early lactation dairy cows. Twelve rumen-cannulated, multiparous Holstein cows averaging 38 ± 15 d (±standard deviation) in milk, and producing 40 ± 9 kg of milk daily, were used in a replicated 4 × 4 Latin square design with 28-d periods. Treatment diets were arranged in a 2 × 2 factorial with 28 or 32% dietary NDF (DM basis) and 2 levels of straw NDF digestibility: 1) LD, untreated wheat straw (77% NDF, 41% NDF digestibility) or 2) HD, anhydrous NH_3-treated wheat straw (76% NDF, 62% NDF digestibility). All 4 diets consisted of wheat straw, alfalfa silage, corn silage, and a concentrate mix of cracked corn grain, corn gluten meal, 48% soybean meal, and vitamins and minerals. Wheat straw comprised 8.5% DM of the 28% NDF diets and 16% DM of the 32% NDF diets. Cows fed 28% NDF and HD diets produced more milk, fat, and protein than those consuming 32% NDF or LD diets. Dry matter intake was greater for cows consuming 28% NDF diets, but intakes of DM and total NDF were not affected by in vitro NDF digestibility. Intake of digestible NDF was greater for cows consuming HD diets. Ruminal fermentation was not affected by feeding diets that differed in NDF digestibility. Ruminal NDF passage rate was slower for cows fed HD than LD. No interactions of dietary NDF concentration and in vitro NDF digestibility were observed for any parameter measured. Regardless of dietary NDF concentration, increased in vitro NDF digestibility improved intake and production in early lactation dairy cows.

Key words: neutral detergent fiber digestibility, neutral detergent fiber, intake, milk production

INTRODUCTION

Forages typically make up half or more of the diet of lactating cattle and profoundly affect energy and carbohydrate intake. Maximizing digestible carbohydrate intake from forage is an important management goal, because energy needed for maintenance and milk production often exceeds the amount of energy high-producing cows can consume.

Forage NDF is a major factor affecting feed intake and rumen fill in high-producing cows. Waldo (1986) suggested that diet NDF content is the best single chemical predictor of DMI in dairy cows. Mertens (1987) proposed that voluntary feed intake of dairy cattle is limited by digestive tract fill when high-NDF diets are fed. Forage NDF, however, is not a homogeneous dietary component. Ruminal digestibility of forage NDF can range from less than 25% to over 75% for different forage types (NRC, 2001). Several studies with brown midrib mutant (***bm3***) corn silage demonstrated that lactating dairy cows will consume more DM and produce more milk when fed corn silages that have greater NDF digestibility (**NDFD**; Dado and Allen, 1996; Oba and Allen, 1999a, 2000a; Tine et al., 2001; Qiu et al., 2003). Oba and Allen (1999b) evaluated the relationship of NDFD and animal performance in published research and estimated that a 1-unit increase in forage NDFD in vitro or in situ was associated with increases of 0.17 kg/d of DMI, 0.23 kg/d of milk yield, and 0.25 kg/d of 4.0% fat-corrected milk.

Direct evaluation of the effect of forage NDFD on animal performance is complex, because it is difficult to obtain forages that differ only in NDF digestibility. Previous experiments that suggested that higher NDFD improved intake and animal performance have had the effect of NDFD confounded by differences in forage NDF concentration or differences in the types and quantities of dietary NDF used to formulate test diets, or both (Grant et al., 1995; Dado and Allen, 1996; Oba and Allen, 1999a, 2000a; Weiss and Wyatt, 2002; Qiu et al., 2003). Treating wheat straw with anhydrous NH_3 has been shown to consistently increase NDFD with little change in the chemical composition of the straw (Sundstøl et al., 1978). Use of untreated

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and ammoniated straw could serve as a good model for altering dietary NDFD with minimal experimental confounding.

This study was conducted to investigate the effect of feeding diets that differed in dietary NDF concentration and in vitro NDFD on DMI, ruminal fermentation, and milk production in early lactation dairy cows. Wheat straw was incorporated into test diets to provide a concentrated source of NDF. Untreated and ammoniated wheat straw were used to vary the concentration of digestible fiber with minimal effects on the concentrations of other dietary ingredients or dietary nutrients. We hypothesized that feeding early lactation cows diets with higher NDFD would increase energy intake and productivity.

MATERIALS AND METHODS

Preparation of Wheat Straw

Wheat straw (**WS**) ammoniation was accomplished by a stack method similar to that described by Sundstøl et al. (1978). Small square bales of WS that weighed approximately 20 kg each were stacked in a 2.7-m-diameter plastic silage bag (Ag Bag International, Warrenton, OR). A 15 m × 7.5 cm diameter pipe with evenly spaced openings was positioned through the center of the bales within the bag. The pipe protruded from one end of the bag, and the plastic was wrapped around the pipe to seal off the interior of the bag from the outside. The other end of the bag was tightly sealed. Anhydrous NH_3 was then applied at 0.048 g of NH_3/kg of WS DM. The WS remained in the sealed bags for 53 d, with an average recorded daily outside temperature of 13°C. Bales of anhydrous ammoniated WS were then removed from the bag and chopped with a stationary tub grinder (Gehl Implement, West Bend, WI) to a geometric mean particle length of 8.35 mm.

Animals

The Animal Care and Use Committee of the College of Agriculture and Life Sciences of the University of Wisconsin-Madison approved all procedures involving animals. Twelve multiparous lactating Holstein cows from the University of Wisconsin-Madison Dairy Cattle Research Center were used. All cows were fitted with rumen cannulas 3 wk before the experiment. At the beginning of the experiment, cows averaged 38 ± 15 DIM (±SD) and produced 40 ± 9 kg of milk daily. Body weights of the cows averaged 638 ± 54 kg and 658 ± 52 kg at the beginning and end of the study, respectively.

Cows were housed in a stanchion barn and fed individually. Wood shavings were used as bedding. Cows were milked twice daily at 0400 and 1600 h in a milking parlor and were allowed access to an outside concrete area daily for 2 h after each morning milking, except on days when rumen pH, NH_3-N, and VFA were collected. All cows had free access to water.

Experimental Design and Diets

The trial was designed as a replicated 4 × 4 Latin square. Experimental periods were 28 d (21 d of treatment adaptation and 7 d of data collection). Treatments were arranged as a 2 × 2 factorial with 2 levels of dietary NDF concentration: 28 vs. 32% (DM basis) and 2 levels of in vitro NDF digestibility: lower in vitro NDF digestibility, obtained with untreated WS (LD), and higher in vitro NDF digestibility, obtained by treating WS with anhydrous NH_3 (HD). Ingredient compositions of the experimental diets are shown in Table 1. Dietary NDF concentration was adjusted by replacing alfalfa silage and corn silage with wheat straw. Wheat straw comprised 8.5% of the DM for the 28% NDF diets and 16% of the DM for the 32% diets. Alfalfa silage and corn silage NDF content averaged 37 and 35% (DM basis), respectively (Table 2). Urea was added to diets containing untreated WS to assure that all diets contained similar levels of ruminally available CP. All diets were formulated to be isonitrogenous and to meet or exceed the National Research Council (2001) recommendations for CP, Ca, P, NaCl, and vitamins A, D, and E of a 600-kg multiparous cow producing 40 kg of milk/d.

Diets were fed as a TMR, with ratios of forage to concentrate of 58:42 and 62:38 in 28% NDF and 32% NDF diets, respectively. Cows were fed for ad libitum intake twice daily at 1000 and 1500 h in equal portions. The amount of feed offered was adjusted daily to obtain approximately 10% orts (as-fed basis).

Sample Collection and Analysis

Milk production was recorded at each milking during the final 7 d of each period. Milk samples from the a.m. and p.m. milking collected on 4 consecutive days (d 24 to 27 of each period) were analyzed for protein, fat, lactose, and MUN by infrared analysis (Agsource Milk Analysis Laboratory, Menomonie, WI) with a Fossmatic-605 (Foss Electric, Hillerød, Denmark). Body weight was measured at 0900 h, 2 d before the start of the first period and on the last 2 d of each period.

Dry matter contents of the feed components were determined weekly using a 60°C forced-air oven for 48 h; results were used to make weekly adjustments to

Table 1. Ingredient composition (g/100 g of DM) of experimental diets

	28% NDF		32% NDF	
Ingredient	LD[1]	HD[1]	LD	HD
Untreated wheat straw	8.5	—	16.2	—
Ammoniated wheat straw	—	8.5	—	16.2
Alfalfa silage	21.7	21.7	23.4	23.4
Corn silage	27.7	27.7	22.5	22.5
Corn grain, cracked, dry	29.7	29.7	25.3	25.3
Soybean meal, 48%	6.6	6.6	6.6	6.6
Corn gluten meal	4.1	4.1	4.3	4.3
Calcium phosphate (di-)	0.5	0.5	0.5	0.5
Magnesium oxide	0.1	0.1	0.1	0.1
Limestone	0.2	0.2	0.2	0.2
Salt	0.5	0.5	0.5	0.5
Urea	0.1	—	0.1	—
Vitamin and mineral mix[2]	0.3	0.3	0.3	0.3

[1]LD = lower in vitro NDF digestibility obtained by untreated wheat straw; HD = higher in vitro NDF digestibility obtained by anhydrous NH_3-treated wheat straw.

[2]Contained 0.55% Mn, 0.55% Zn, 0.35% Fe, 0.14% Cu, 0.008% I, 0.006% Se, 0.002% Co, 3,304 IU/g of vitamin A, 1,101 IU/g of vitamin D, and 11 IU/g of vitamin E.

as-fed ratios of forages and concentrate in the TMR. The amounts of TMR offered and refused were measured daily, and DMI was recorded during the final 7 d of each period. Feed samples were collected weekly during each experimental period, dried at 60°C for 48 h, ground to pass through a 1-mm screen (Wiley mill, Arthur H. Thomas, Philadelphia, PA), and analyzed for DM, OM, CP, NDF, ADF, and starch. Orts were collected during the last 4 d of each period and were composited by animal proportional to the wet weight of feed refused each day. The composite ort samples were dried, processed, and analyzed by the same methods as the feed samples.

The following procedures were used on feed and ort samples. Analytical DM was determined by oven-drying at 100°C for 24 h. Organic matter was determined by ashing at 550°C for 720 min. Neutral detergent fiber fraction was determined using α-amylase and sodium sulfite (Sigma no A3306, Sigma Chemical Co., St Louis, MO) and was corrected for ash content according to Van Soest et al. (1991) adapted for Ankom[200] Fiber Analyzer (Ankom Technology, Fairport, NY). Acid detergent fiber was determined using the procedure described by Goering and Van Soest (1970) adapted for Ankom[200] Fiber Analyzer. Crude protein was determined by micro-Kjeldahl analysis (AOAC, 1990). Starch was determined using a colorimetric assay including a refined cornstarch sample as described by Bal et al. (2000). Particle size distribution of forages and TMR was determined by using the Wisconsin particle size separator, according to the ASAE S424.1 protocol (ANSI, 1998).

In Vitro NDFD Procedure

The in vitro NDFD procedure was modified from that described by Goering and Van Soest (1970). Composition of the in vitro media (buffer, macro- and micromineral solutions) and reducing solution used are detailed in Goering and Van Soest (1970). Forages were dried for 48 h in a forced-air oven and ground to pass a 1-mm screen in a Wiley mill (Arthur H. Thomas).

Table 2. Chemical composition (g/100 g of DM) of experimental wheat straws and silages

	Wheat straws[1]		Silages	
Item	Untreated	Ammoniated	Alfalfa	Corn
DM, %	85.9	85.0	37.5	33.6
OM	92.1	92.5	93.0	92.4
CP	5.7	6.4	22.7	8.7
NDF	77.2	76.4	36.9	35.0
ADF	53.2	54.7	33.2	20.8
Starch	1.6	2.1	3.2	25.4
NDF digestibility (48 h), % of NDF[2]	41.2	62.1	47.0	50.1

[1]Untreated = untreated wheat straw; ammoniated = anhydrous NH_3-treated wheat straw.

[2]University of Wisconsin Soil and Forage Analysis Laboratory, wet chemistry report, Marshfield.

Samples (0.5 g) were weighed into 125-mL Erlenmeyer flasks in quadruplicates. Forty milliliters of in vitro media was added to the sample in each flask and allowed to stand overnight. The next morning, 2 mL of reducing solution was injected into each flask and sealed with rubber policeman stoppers. The mixture of medium and reducing solution was equilibrated for 40 min in a 39°C circulating water bath under CO_2. During this period, the color of the medium changed from pink to colorless, which indicated that reduction of medium was achieved. Rumen fluid was collected from a fistulated nonlactating Holstein cow. The donor cow was fed once daily a TMR that contained 45% oat silage, 45% corn silage, and 10% concentrate mix. Approximately 4,000 mL of whole rumen contents was collected into a prewarmed thermos and immediately transported to the laboratory. Rumen contents were immediately flushed with CO_2 then blended and squeezed through 2 layers of cheesecloth. Ten milliliters of filtered rumen fluid was added to each flask containing the feed, medium, and reducing solution so that the final volume:volume ratio of rumen fluid to medium was 1:4. The flasks were connected to a CO_2 manifold and continuously swirled in a 39°C water bath for 48 h. Flasks were then removed and immediately frozen to stop fermentation. The contents of each flask were then transferred into a 60-mL beaker that contained approximately 50 to 75 mL of neutral detergent solution, sodium sulfite, and heat-stable α-amylase (A-5426, Sigma Chemical Co.) and were refluxed for 1 h. The contents of the beaker were then transferred to a Gooch crucible and filtered under vacuum to isolate the fiber residue. The residual fiber was rinsed with hot water and acetone, dried at 105°C for 24 h, and weighed.

Ruminal Parameters

Rumen fluid was sampled via rumen cannula from each cow before feeding (0 h) and at 1.5-h intervals for 24 h on d 23 of each period. A composite of 60 mL of rumen fluid was collected from 5 different locations in the rumen with a metal filter probe. Rumen pH was determined immediately after the samples were collected (Twin pH-Meter Model B-123, Spectrum Technologies Inc., Plainfield, IL). One milliliter of rumen fluid was acidified with 20 μL of 50% H_2SO_4 and frozen until analysis for VFA (Supelco Inc., Bellefonte, PA) as described by Bal et al. (2000). One milliliter of rumen fluid was mixed with 20 μL of 50% TCA and frozen until analysis for NH_3-N (Chaney and Marbach, 1962).

On the last day of each period, the rumen contents of each cow were evacuated 3 h postfeeding to determine rumen digesta mass and volume. The rumen contents were mixed, and a subsample was taken for DM determination.

Digestibility

Lanthanum in solution (0.2 g/mL) was used as an external marker to measure total tract DM, OM, ADF, and NDFD (Hartnell and Satter, 1979). Lanthanum was ruminally dosed in capsules at 12-h intervals for the last 14 d of each period to provide 0.88 g of La/cow per day. Fecal samples were collected every 8 h during a 4-d interval, and the sampling times were staggered such that the entire 24-h day was represented to account for possible diurnal variation in fecal flow. Fecal samples were dried at 60°C for 48 h, pooled within period for each cow, and ground to pass through a 1-mm screen (Wiley mill, Arthur H. Thomas). One gram of fecal samples was dry-ashed at 500°C for 960 min. The ash was dissolved by adding 15 mL of hydrochloric acid and diluted to 50 g with lithium hydroxide solution. Concentrations of La were then determined by direct current plasma emission spectroscopy (Spectra Metrics Inc., subsidiary of Beckman Instruments Inc., Andover, MA) as described by Combs and Satter (1992). Total tract DM, OM, NDF, and ADF digestibility were calculated from fecal La concentration and nutrient concentrations in diets fed, orts and feces.

Rate of Passage

Lithium Co-EDTA (**Co**) and chromium-mordanted WS NDF (**Cr**) were prepared as described by Udén et al. (1980) and used as markers for liquid and solid passage rates, respectively. The Co was ground using a mortar and pestle. Chromium-mordanted fiber was prepared from WS NDF ground through a 6-mm screen using a Wiley mill. Twenty grams of Co and Cr were placed in the rumen on d 23 at the time of the morning feeding. Fecal grab samples were taken at 0, 4, 8, 12, 16, 20, 25, 33, 41, 45, 51, 58, 70, 83, 95, 108, and 120 h after dosing to determine the rate of passage. Fecal samples were dry-ashed at 500°C for 960 min and prepared as described in the digestibility section. Fecal marker concentrations of Co and Cr were determined by direct current plasma emission spectroscopy (Spectra Metrics Inc., subsidiary of Beckman Instruments Inc.) as described by Combs and Satter (1992).

Fecal Co and Cr excretion curves were fitted to the double-compartment model represented by 2 exponential constants and a time delay (Grovum and Williams, 1973):

$$Y = Ae^{-k_1(t - TT)} - Ae^{-k_2(t - TT)}$$

where $k_1 < k_2$ for $t \geq TT$ and $Y = 0$ for $t < TT$, where Y = marker concentration (mg/kg); A = scale parameter; k_1 = ruminal rate of passage (%/h); k_2 = lower digestive tract rate of passage (%/h); t = sampling time postdosing (h); and TT = transit time. Total mean retention time in the digestive tract was calculated as the sum of retention in the rumen ($1/k_1$) and in the lower digestive tract ($1/k_2$) plus the transit time (TT). Data were analyzed by nonlinear regression using the NLIN (iterative Marquardt method) procedure of SAS (SAS Institute, 1999). Liquid outflow rate from the rumen was determined by regression of the natural log of Co concentration from the declining portion of the fecal excretion curve versus time.

Statistical Analyses

All data were analyzed as a 4 × 4 replicated Latin square with a factorial arrangement of treatments using the MIXED model procedure in SAS (SAS Institute, 1999). The model for DMI, milk production, and milk composition was: $Y_{ijklm} = \mu + S_i + C_{j(i)} + P_k + F_l + D_m + (F \times D)_{lm} + e_{ijklm}$, where μ = overall mean; S_i = random effect of square (i = 1 to 3); $C_{j(i)}$ = random effect of cow within square (j = 1 to 4); P_k = fixed effect of period (k = 1 to 4); F_l = fixed effect of dietary NDF level (l = 1 to 2); D_m = fixed effect of dietary in vitro NDFD level (m = 1 to 2); $(F \times D)_{lm}$ = fixed effect of interaction of F_l and D_m; and e_{ijklm} = random residual error, assumed to be normally distributed.

Ruminal pH, NH_3-N, and VFA concentrations were analyzed by time as repeated measurements, using the first-order autoregressive covariance structure, which provided the model with the best fit according to the Schwarz Bayesian criterion. Terms specified for random statement were square, cow within square, and period × NDF × NDFD × cow. The final model included: $Y_{ijklmn} = \mu + S_i + C_{j(i)} + P_k + F_l + D_m + (F \times D)_{lm} + R_n + e_{ijklmn}$, where μ = overall mean; S_i = random effect of square (i = 1 to 3); $C_{j(i)}$ = random effect of cow within square (j = 1 to 4); P_k = fixed effect of period (k = 1 to 4); F_l = fixed effect of dietary NDF level (l = 1 to 2); D_m = fixed effect of dietary in vitro NDFD level (m = 1 to 2); $(F \times D)_{lm}$ = fixed effect of interaction of F_l and D_m; R_n = fixed effect of time of sampling analyzed as repeated measurements (n = 1 to 16); and e_{ijklmn} = random residual error, assumed to be normally distributed.

Square × NDF, square × NDF digestibility, square × NDF × NDF digestibility, period × NDF, period × NDF digestibility, and period × NDF × NDFD interactions were originally included in the models but were removed because the interactions were not significant ($P > 0.25$). Significance was declared at $P \leq 0.05$. A trend was considered to exist if $0.05 < P \leq 0.10$. All reported values are least squares means unless otherwise stated.

RESULTS AND DISCUSSION

Forages and Dietary Composition

Chemical composition of the wheat straws and silages used are presented in Table 2. The ammonization procedure has little effect on DM, OM, NDF, ADF, and starch concentrations between the wheat straws. Crude protein content of the ammoniated WS increased slightly from 5.7 to 6.4% of DM. Treatment of WS with anhydrous NH_3 increased in vitro NDFD by 20.9 units. The change in in vitro NDFD is consistent with previously published data (Sundstøl et al., 1978).

Nutrient compositions of the 4 experimental diets are shown in Table 3. Nutrient concentrations were similar within level of dietary NDF concentration. All 4 diets had similar dietary CP concentration. Wheat straw NDF contributed 27% of forage NDF in 28% NDF diets

Table 3. Nutrient and fiber composition (g/100 g of DM) of experimental diets

	28% NDF		32% NDF	
Item	LD[1]	HD[1]	LD	HD
DM, %	50.6	50.6	52.4	52.4
OM	92.5	92.4	92.5	92.5
CP	17.6	17.5	17.4	17.4
Starch	29.9	30.1	25.9	26.5
NDF	28.3	28.2	32.5	32.4
FNDF[2]	24.2	24.1	28.9	28.8
ADF	19.7	19.6	22.6	22.9
NDF digestibility (48 h),[3] % of NDF	47.1	52.6	45.8	53.8

[1]LD = lower in vitro NDF digestibility obtained by untreated wheat straw; HD = higher in vitro NDF digestibility obtained by anhydrous NH_3-treated wheat straw.

[2]FNDF = forage NDF.

[3]Calculated based on 48-h in vitro NDF digestibility of individual feeds.

Table 4. Mean geometric particle size of forages and experimental diets

Item	Mean[1] (mm)
Alfalfa silage	6.05
Corn silage	5.53
Untreated wheat straw	7.61
Ammoniated wheat straw	8.35
28% NDF, LD[2]	3.21
28% NDF, HD[2]	3.37
32% NDF, LD	3.75
32% NDF, HD	3.84

[1]Mean geometric particle size of forages and TMR were determined by dry-sieving using the University of Wisconsin forage particle size separator in accordance with ASAE standard S424 (ASAE, 1998). Diagonal diameters of openings in screens were 26.90, 18.00, 8.98, 5.61, and 1.65 mm.

[2]LD = lower in vitro NDF digestibility obtained by untreated wheat straw; HD = higher in vitro NDF digestibility obtained by anhydrous NH_3-treated wheat straw.

and 43% of forage NDF in 32% NDF diets. Replacing untreated WS with anhydrous treated WS in the diets increased dietary in vitro NDFD by 5.5 and 8.0 percentage units for the 28% NDF and 32% NDF diets, respectively.

Distribution of geometric mean particle sizes of the untreated and treated wheat straws was similar (Table 4). Within level of dietary NDF concentration, geometric mean particle size was similar across experimental diets.

Feed Intake

There were no significant interactions between dietary NDF concentration and in vitro NDFD on DM, OM, or NDF intake. Therefore, only the main effects will be discussed.

Voluntary DM and OM intakes were greater when cows consumed diets containing 28% NDF as compared with 32% NDF (Table 5). The decrease in intake with increasing dietary NDF is consistent with the hypothesis that rumen fill limited DM and OM intake on the 32.0% NDF diets (Mertens, 1987; Allen, 1996). Dry matter intake did not differ due to in vitro NDF digestibility. Previous studies with early lactating dairy cows have shown an increase in DMI when dietary NDFD was increased by feeding *bm3* corn silage compared with isogenic normal corn silage (Dado and Allen, 1996; Oba and Allen, 1999a, 2000a; Tine et al., 2001) or high-digestible fiber alfalfa compared with low-digestible fiber alfalfa (Dado and Allen, 1996). Oba and Allen (1999b) reported that a 1-unit increase in forage in vitro NDFD was associated with a 0.17 kg/d increase in DMI from 13 sets of forage comparisons. In the present study, cows fed HD diets consumed 0.6 kg/d more DM than cows fed LD diets. Although the numerical increase was not statistically significant, a 1-unit increase in forage in vitro NDFD was associated with 0.17 kg/d increases in DMI.

Cows fed the 28% NDF diet consumed less NDF than cows fed 32% NDF diets, which suggests that intake of cows fed the lower-fiber diets was not limited by gut fill (Mertens, 1987). In vitro fiber digestibility did not affect NDF intake when expressed in kilograms or as a percentage of body weight. Cows fed the 32% NDF diets consumed more digestible fiber than cows fed diets containing 28% NDF. Intake of digestible NDF was also greater for cows fed HD diets compared with LD diets. Cows fed 32% NDF diets consumed an additional 0.54 kg/d of NDF and 0.27 kg/d of digestible NDF compared with 28% NDF diets. Total fiber intake did not differ when the untreated or ammoniated WS was incorporated into the diets, but digestible NDF intake increased by 0.37 and 0.69 kg/d when untreated straw was replaced with ammoniated straw. Oba and Allen (1999a) proposed that cows fed more degradable NDF consume additional digestible NDF, because the NDF fraction is more readily degraded, thus leaving the ru-

Table 5. Effect of dietary NDF concentration and in vitro NDF digestibility on intake of DM, NDF, digestible NDF, and OM

	28% NDF		32% NDF			Significance[1] (*P*-value)		
Item	LD[2]	HD[2]	LD	HD	SEM	F	D	F × D
DMI								
kg/d	22.8	23.4	21.7	22.3	0.8	0.03	0.24	0.96
% of BW	3.56	3.63	3.36	3.49	0.2	0.04	0.23	0.67
NDF intake								
kg/d	6.28	6.39	6.84	6.92	0.2	0.002	0.54	0.94
% of BW	0.98	0.99	1.06	1.09	0.1	0.002	0.46	0.77
Digestible NDF intake								
kg/d	2.95	3.32	3.13	3.72	0.1	0.001	0.001	0.17
OM intake, kg/d	21.0	21.5	20.0	20.5	0.7	0.03	0.26	0.95

[1]F = main effect of dietary NDF; D = main effect of in vitro NDF digestibility; F × D = interactions.

[2]LD = lower in vitro NDF digestibility obtained by untreated wheat straw; HD = higher in vitro NDF digestibility obtained by anhydrous NH_3-treated wheat straw.

Table 6. Effect of dietary NDF concentration and in vitro NDF digestibility on milk production and milk composition

	28% NDF		32% NDF			Significance[1] (*P*-value)		
Item	LD[2]	HD[2]	LD	HD	SEM	F	D	F × D
Milk production, kg/d	39.3	40.8	36.5	38.6	2.3	0.001	0.004	0.60
4% FCM, kg/d	35.9	37.4	33.0	34.6	2.7	0.001	0.01	0.88
Milk composition, %								
True protein	2.76	3.03	2.67	2.71	0.1	0.14	0.24	0.38
Fat	3.41	3.42	3.31	3.29	0.1	0.02	0.91	0.77
Lactose	4.76	4.79	4.71	4.76	0.1	0.01	0.008	0.58
Milk component yield, kg/d								
True protein	1.08	1.25	0.98	1.04	0.1	0.02	0.07	0.40
Fat	1.34	1.40	1.22	1.28	0.1	0.001	0.04	0.88
Lactose	1.88	1.97	1.74	1.84	0.1	0.001	0.001	0.82
MUN, mg/dL	14.2	13.7	15.8	14.7	0.4	0.001	0.001	0.12

[1]F = main effect of dietary NDF; D = main effect of in vitro NDF digestibility; F × D = interactions.

[2]LD = lower in vitro NDF digestibility obtained by untreated wheat straw; HD = higher in vitro NDF digestibility obtained by anhydrous NH_3-treated wheat straw.

men at a greater rate and facilitating greater DM and NDF intake.

Milk Production and Composition

Increasing the concentration of dietary NDF significantly decreased yields of milk, fat, true protein, and 4.0% FCM (Table 6). The decreases in milk production were consistent with the observed decreases in DMI (Table 5). At both dietary NDF concentrations, feeding HD diets increased yields of milk and 4.0% FCM. Feeding HD diets contributed to an additional 1.5 and 1.6 kg/d of FCM for 28% NDF and 32% NDF diets, respectively. Though not statistically significant, the increase in DMI for the low-fiber and high-fiber diets increased by 0.6 kg/d, which suggests that the increase in milk yield due to improved NDFD was due to increased intake of digestible DM. Previous studies observed an average 2.4 kg/d increase in milk production when feeding diets in which NDFD was increased by feeding *bm3* corn silage compared with isogenic normal corn silage (Dado and Allen, 1996; Oba and Allen, 1999a, 2000a; Tine et al., 2001). In these studies, the increase in milk production was primarily attributed to increased DMI. Our data suggest that milk yield was increased primarily by increased intake of digestible NDF. A 1-unit increase in forage in vitro NDFD increased 4% FCM by 0.18 and 0.11 kg/d in 28% NDF and 32% NDF diets, respectively.

Percentage of milk true protein was not affected by dietary NDF concentration or in vitro NDF digestibility. However, yield of milk true protein was significantly lower when cows were fed the 32% NDF diets as compared with the diets with 28% NDF. Cows fed HD diets tended to produce more milk protein than cows fed LD diets. Greater milk protein yield may be attributed to an increase in microbial protein production caused by increased energy intake from lower dietary NDF concentration and higher degradable NDF (DePeters and Cant, 1992).

Milk fat percentage was approximately 0.1% units lower for cows consuming the 32% NDF diets than the 28% NDF diets. This is inconsistent with previous literature (Beauchemin, 1991). A possible explanation for a decrease in fat test when cows were fed the greater-fiber diets could be that the cows sorted the straw from the diets. We measured the amount of orts and analyzed their fiber content, however, and found no indication that cows sorted the high-fiber diets differently than the low-fiber diets. Milk fat percentage was not affected by in vitro NDF digestibility. Yield of milk fat was greater for cows fed the lower NDF diets, and cows fed HD diets produced more milk fat compared with cows fed LD. The greater yields of milk fat associated with HD and 28% NDF diets were a result of greater milk production. This finding is different than results reported by others (Dado and Allen, 1996; Oba and Allen, 1999a, 2000a), who observed an average 0.15% decrease in milk fat percentage when early lactating cows were fed higher NDFD diets. Results of this study indicate that increased yield of milk components is directly related to the increased supply of digestible carbohydrates provided by either lower-fiber diets or diets with more highly digestible fiber.

Milk lactose concentrations differed by level of fiber and fiber digestibility, but the differences were numerically small and likely not physiologically meaningful. Yield of milk lactose differed by level of fiber and fiber digestibility and was directly related to milk production. Milk urea N content was significantly lower when cows consumed the 28% NDF diets as compared with the 32% NDF diets, and MUN significantly decreased

Table 7. Effect of dietary NDF concentration and in vitro NDF digestibility on ruminal pH, NH_3-N, and VFA

	28% NDF		32% NDF			Significance[1] (*P*-value)		
Item	LD[2]	HD[2]	LD	HD	SEM	F	D	F × D
pH	6.50	6.46	6.54	6.52	0.04	0.01	0.14	0.54
NH_3-N, mg/dL	12.9	11.2	14.9	13.0	0.6	0.002	0.003	0.83
VFA, m*M*	90.4	91.0	90.4	89.1	1.8	0.38	0.74	0.38
Acetate, mol/100 mol	56.6	56.7	57.4	56.8	1.0	0.49	0.73	0.65
Propionate, mol/100 mol	18.8	19.4	18.4	18.2	0.8	0.02	0.64	0.24
Butyrate, mol/100 mol	10.3	10.5	9.77	9.68	0.3	0.001	0.91	0.52
A:P[3]	3.08	3.03	3.19	3.20	0.1	0.006	0.67	0.46

[1]F = main effect of dietary NDF; D = main effect of in vitro NDF digestibility; F × D = interactions.

[2]LD = lower in vitro NDF digestibility obtained by untreated wheat straw; HD = higher in vitro NDF digestibility obtained by anhydrous NH_3-treated wheat straw.

[3]A:P = acetate:propionate ratio.

when cows consumed HD compared with LD diets. This difference may be explained by the increased energy intake from the higher NDFD WS and lower dietary NDF concentration. Additional energy enhances rumen microbial protein production and NH_3 utilization, which decreases rumen NH_3, blood, and MUN (Roseler et al., 1993). These findings also suggest that the effects of fiber digestibility are mediated primarily through rumen digestion and metabolism.

Rumen Fermentation

Ruminal pH was not influenced by in vitro NDFD (Table 7). Although not significant ($P = 0.14$), ruminal pH was numerically lower in HD diets compared with LD diets. Previous studies involving early lactating dairy cows observed an average 0.15-unit decrease in ruminal pH when feeding diets with higher NDFD (Grant et al., 1995; Dado and Allen, 1996; Oba and Allen, 2000a). Allen (2000) suggested that forages with high-fiber digestibility would ferment more quickly in the rumen, leading to greater production of fermentation acids, resulting in lower ruminal pH. In this study, ruminal pH was greater when cows consumed the 32% NDF diets compared with the 28% NDF diets. In the present study, average ruminal pH was relatively high across diets (>6.45). The incorporation of WS into the diets provided additional physically effective NDF that stabilized the rumen environment; in addition, the diets contained urea, NH_3, and alfalfa silage, which also may have helped to neutralize VFA as they were produced in the rumen. Oba and Allen (2000a) observed that alfalfa silage and corn silage with greater in vitro NDFD did not decrease the physical effectiveness of forage NDF.

Ruminal NH_3 concentrations were lower with 28% NDF diets compared with 32% NDF diets. Ruminal NH_3 levels were also lower on HD diets compared with LD diets. Additional energy provided by the HD and 28% NDF diets allowed greater utilization of rumen NH_3 for microbial protein synthesis (Nocek and Russell, 1988). In the present study, the concentrations of ruminal NH_3 and MUN followed a similar pattern (Table 6).

Concentrations of ruminal propionate and butyrate were greater for the 28% NDF diets than the 32% NDF diets. The ratio of acetate to propionate was greater than 3:1 for all diets but was greater for cows fed 32% NDF compared with cows fed the 28% NDF diets. Milk fat percentage did not differ due to dietary NDF concentration, and fat test was not correlated with ratio of acetate to propionate (Table 7). Ruminal VFA concentration and molar proportions of acetate, propionate, and butyrate were not affected by in vitro NDF digestibility. Our results are consistent with previous studies; Oba and Allen, 2000a), but other studies have observed slight increases in molar proportions of propionate with higher in vitro NDFD (Dado and Allen, 1996; Weiss and Wyatt, 2002; Qiu et al., 2003).

Ruminal Rate of Passage

The passage rate of Co-EDTA marker was faster when cows consumed the 28% NDF diets than the 32% NDF diets. These results are consistent with the greater DMI observed when cows consumed the 28% NDF diets. Mertens (1987) reported that liquid passage rates are positively correlated with feed intake. Rumen retention times were greater when cows consumed the HD diets and also when they were fed the 32% NDF diets. Furthermore, 32% NDF and HD diets increased mean retention time through the gastrointestinal tract. Feeding cows diets with higher in vitro NDFD increased solid rate of passage from the lower digestive tract but tended to decrease solid rate of passage from the rumen (Table 8). Previous data regarding the effects of feeding cows diets higher in NDFD have been incon-

Table 8. Effect of dietary NDF concentration and in vitro NDF digestibility on passage rate of liquids and mordanted wheat straw NDF

	28% NDF		32% NDF			Significance[1] (*P*-value)		
Item	LD[2]	HD[2]	LD	HD	SEM	F	D	F × D
Liquid outflow rate, h^{-1}	0.096	0.090	0.079	0.086	0.01	0.007	0.85	0.10
Fractional outflow of solids								
k_1,[3] h^{-1}	0.034	0.027	0.029	0.026	0.01	0.17	0.07	0.43
k_2,[4] h^{-1}	0.20	0.28	0.23	0.28	0.03	0.66	0.01	0.60
Transit time, h	11.7	11.9	13.1	12.5	0.7	0.10	0.76	0.52
Rumen retention time, h	30.6	41.7	45.7	51.5	7.3	0.005	0.05	0.53
Mean retention time, h	47.5	57.8	63.7	68.2	7.4	0.001	0.06	0.45

[1]F = main effect of dietary NDF; D = main effect of in vitro NDF digestibility; F × D = interactions.

[2]LD = lower in vitro NDF digestibility obtained by untreated wheat straw; HD = higher in vitro NDF digestibility obtained by anhydrous NH_3-treated wheat straw.

[3]k_1 = ruminal rate of passage.

[4]k_2 = lower digestive tract rate of passage.

sistent. Dado and Allen (1996) observed no differences in rumen solids passage attributable to in vitro NDF digestibility. Allen (1996) suggested that forages higher in NDFD may be more buoyant and ruminal rate of passage might be slower for particles with greater buoyancy. Transit time tended to be greater when cows consumed the 32% NDF diets as compared with the 28% NDF diets, but transit time was not affected by in vitro NDF digestibility.

Nutrient Digestibility and Rumen Digesta Pools

Total tract digestibility of DM, OM, and ADF was not affected by in vitro NDFD or dietary NDF concentration (Table 9). Total tract digestibility of NDF was not affected by in vitro NDFD ($P = 0.22$), but cows fed HD diets had numerically greater estimates of NDFD compared with LD diets. The slower ruminal rate of passage and longer rumen and mean retention times associated with HD (Table 8) may have slightly increased digestion of NDF. Tine et al. (2001) observed that when DMI was kept similar, total tract digestibility of NDF was greater when cows consumed *bm3* corn silage compared with isogenic normal corn silage. Oba and Allen (2000b) observed no significant changes in total tract digestibility of NDF when cattle were fed ad libitum *bm3* corn silage compared with isogenic normal corn silage and reported that total tract digestibility of NDF was negatively correlated with increased DMI and rate of passage.

Total tract digestibility of NDF was greater for cows consuming 32% NDF compared with 28% NDF diets. The lower DMI and higher rumen retention time associated with 32% NDF diets increased total tract digestibility of NDF.

There are still some questions about the accuracy of in vitro NDFD in estimating in vivo NDFD (Weiss and Wyatt, 2002). In the current study, a 5.5 and 8.5% unit difference in 48-h in vitro NDFD resulted in no difference in in vivo digestibility for the 28 and 32% NDF diets, respectively. Numerically, the in vivo NDFD values were lower than the in vitro NDFD values. Similarly, Oba and Allen (2000b) reported a 9.4 percentage unit difference in 30-h in vitro NDFD between *bm3* corn silage and control silage, but no difference in in vivo NDF digestibility.

Characterization of rumen digesta from cows indicated few differences between in vitro NDFD and

Table 9. Effect of dietary NDF concentration and in vitro NDF digestibility on DM, OM, NDF, and ADF digestibility (% digestibility)

	28% NDF		32% NDF			Significance[1] (*P*-value)		
Item	LD[2]	HD[2]	LD	HD	SEM	F	D	F × D
DM	66.1	67.5	66.5	66.0	1.4	0.38	0.51	0.14
OM	63.2	64.6	63.6	63.0	1.5	0.39	0.52	0.15
NDF	40.5	43.3	44.8	45.4	2.1	0.03	0.22	0.40
ADF	42.6	44.4	44.9	44.0	2.0	0.51	0.76	0.32

[1]F = main effect of dietary NDF; D = main effect of in vitro NDF digestibility; F × D = interactions.

[2]LD = lower in vitro NDF digestibility obtained by untreated wheat straw; HD = higher in vitro NDF digestibility obtained by anhydrous NH_3-treated wheat straw.

Table 10. Effect of dietary NDF concentration and in vitro NDF digestibility on body weight, rumen digesta mass, and volume

	28% NDF		32% NDF			Significance[1] (*P*-value)		
Item	LD[2]	HD[2]	LD	HD	SEM	F	D	F × D
BW, kg	651.4	653.0	648.4	646.4	15.9	0.16	0.94	0.61
BW change, kg/28 d	10.4	1.7	8.0	0.3	5.7	0.70	0.15	0.97
Rumen digesta								
Mass, kg	82.0	82.9	86.5	86.9	3.8	0.11	0.86	0.53
DM, %	11.7	12.3	12.1	12.8	0.6	0.38	0.14	0.88
Volume, L	93.5	96.3	96.9	98.3	5.0	0.55	0.29	0.55

[1]F = main effect of dietary NDF; D = main effect of in vitro NDF digestibility; F × D = interactions.

[2]LD = lower in vitro NDF digestibility obtained by untreated wheat straw; HD = higher in vitro NDF digestibility obtained by anhydrous NH_3-treated wheat straw.

dietary NDF concentrations (Table 10). Rumen mass numerically was greater with 32% NDF diets but was not affected by in vitro NDF digestibility. The volume of rumen digesta was similar across treatments. Oba and Allen (2000b) reported that cows fed higher dietary NDF concentration had significantly greater rumen digesta volume and mass. In contrast, a previous study by Dado and Allen (1996) showed rumen digesta volume and mass to be equivalent between diets and concluded that cows fed higher NDFD diets can process additional DM under the same rumen volume.

CONCLUSIONS

Regardless of dietary NDF concentrations, improved in vitro NDFD increased productivity in early lactation dairy cows. Yield of milk, fat, and protein were greater for cows fed HD and 28% NDF diets. Percentages of milk fat and true protein were not affected by in vitro NDF digestibility. Intake of digestible NDF was higher for cows fed HD diets, although intake of DM and total NDF was not affected by in vitro NDF digestibility. Given that DM and NDF intake were not affected by in vitro NDF digestibility, the positive milk production responses observed with HD diets are likely due to the increased digestible NDF intake.

Results from this study and from Oba and Allen (2000b) and Tine et al. (2001) show that diets that differ in in vitro NDFD are utilized differently by dairy cattle and that apparent total tract NDFD coefficients may not necessarily be similar to in vitro NDFD values. Apparent total tract NDFD is not only influenced by ruminal degradability of fiber but also by changes in ruminal metabolism and solids passage.

Feeding diets that are balanced to provide higher levels of in vitro NDFD could increase energy intake in early lactating dairy cows. Analyzing forages for in vitro NDFD is an additional tool to better predict forage quality and forage utilization by dairy cattle.

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