Chewing, rumen pool characteristics, and lactation performance of dairy cows fed 2 concentrations of a corn wet-milling coproduct with different forage sources¹

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ABSTRACT

We used a novel corn wet-milling coproduct [CMP; approximately 70% dry matter, 28% crude protein, 36% neutral detergent fiber (NDF), and 18% nonstructural carbohydrates] in diets formulated to contain 18.4% forage NDF, 17.4% crude protein, 20.2% starch, and 3.7% sugar. Six primiparous, rumen-cannulated Jersey cows were assigned to a 6 × 6 Latin square design with a 2 × 3 factorial arrangement of treatments. Diets were formulated to contain 20 and 30% CMP with 3 forage sources [corn silage (CS) and 40.5% NDF, CS replaced with 10% alfalfa hay (AH) and 45.0% NDF, or CS replaced with 7% grass hay (GH) and 67.4% NDF], with each providing 18.4% forage NDF in the diet. Total-tract digestibilities of NDF, N, and organic matter were not affected by treatment. Similarly, no treatment effects were detected for kinetics of NDF disappearance in situ from CMP or respective forage source or for N disappearance in situ from CMP. Grass hay increased total and liquid pool size of rumen contents compared with AH (by 3.2 and 3.0 kg, respectively). Total time spent chewing increased in cows fed GH by over 35 min compared with those fed AH, partially due to a trend for increased minutes spent ruminating. Mean particle size of rumen contents also tended to be higher in the GH (0.55 mm) than AH (0.69 mm) diets. No effects on production of milk or milk components were detected, but dry matter intake (DMI) tended to decrease when CMP increased from 20 to 30%. Gross feed efficiency (fat-corrected milk/DMI) tended to be greater when cows were fed AH and GH compared with CS and was greater for AH than GH diets. In diets containing low starch, increasing CMP from 20 to 30% potentially

maintained similar fat-corrected milk production with lower DMI. However, more consideration also should be given to interactions among forages with respect to fill, digestion, and passage of fiber with increased inclusion rates of CMP.

Key words: corn-milling coproduct, forage source, rumination

INTRODUCTION

Our aims were to better characterize a novel corn-milling product (**CMP**) that is higher in CP and lower in NDF than the traditional corn-milling products, yet has relatively low starch concentration. This unground product has a physical form that is long enough to potentially provide effective fiber. Weiss (2012) concluded that CMP was best used to replace concentrate because milk fat production was decreased when the CMP replaced forage plus grain; the starch:forage NDF (**fNDF**) ratio was predictive for milk fat concentration. We reasoned that potential interactions of CMP inclusion rate with forage source can be postulated from studies with soybean hulls, which have similar degradation kinetics to corn gluten feed (Firkins, 1997). Grant (1997) summarized responses from several studies evaluating potential interactions of forage particle size and usage of soybean hull fiber. Because of the high concentration and potential digestibility of NDF from soybean hulls, retention time of the soybean hulls in the rumen is a critical factor influencing ruminal digestibility of total dietary NDF. Substitution of 25% of a silage mixture with coarsely chopped hay increased the percentage of long particles in the ventral rumen and helped retain soyhulls for more extensive ruminal NDF digestibility (Weidner and Grant, 1994). As with soybean hulls, we hypothesized that CMP would have a similar potential for ruminal NDF digestibility to increase if a portion of the corn silage (**CS**) was replaced by chopped hay to increase ruminal mat consistency and slow the passage rate of the highly degradable CMP particles.

Many nonforage fiber sources such as CMP are provided in a ration at about 20% (Stern and Ziemer,

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1995); increasing the inclusion rate would require considerations related to energy density and DMI. Firkins et al. (2002) increased wet brewers grains up to about 26% of the diet through partial substitution for both grain and forage to decrease bulk fill limitation of DMI and potentially minimize negative associative effects (i.e., prevent a decrease in NDF digestibility) of wet brewers grains fiber. In that study, NE_L concentration decreased with increasing dietary concentration of brewers grains, but cows compensated by increasing DMI to maintain the same NE_L intakes and, therefore, lactation performance. A relatively narrow window of inclusion of physically effective NDF exists to maximize ruminal NDF digestibility while minimizing the risk for depressed DMI (Zebeli et al., 2012), and the ability to maximize NDF digestibility in diets formulated in these inclusion windows depends on limiting starch appropriately (Zebeli et al., 2010). We noted that decreasing DMI tended to occur between 20 and 30% inclusion rates (Boddugari et al., 2001; Mullins et al., 2010; Weiss, 2012). Thus, we reasoned that increasing from 20 to 30% inclusion of CMP prioritized the need to characterize potential interactions with the physical effectiveness of fNDF in moderately low-starch diets. Moreover, diluting corn starch and CS percentages of the total forage in diets should decrease risk for depressed milk fat when feeding CMP (Weiss et al., 2009). In CS-based diets, we assumed that we could increase the density of the rumen mat by feeding a highly physically effective fiber source, such as grass hay (GH). Compared with alfalfa hay (AH), GH should be less fragile and might stimulate chewing to a greater extent (Kammes and Allen, 2012a), but GH also could be more filling than AH.

We hypothesized that forage source would have minimal effect on production or the rumen environment, including volume of rumen contents when CMP was included at 20% of dietary DM; however, when CMP was increased to 30%, we expected that CS + AH would increase diet physical effectiveness and ruminal fluid weight more than would CS alone, but potentially less than CS + GH. We expected corresponding responses in rumination activity and for ruminal and total-tract NDF digestibilities. Our objectives were to assess the potential for interactions among CMP concentration and forage source for measures of rumination, rumen pool characteristics, and site of NDF digestibility (based on Dacron bag insertion and fecal spot sampling) and resultant influence on lactation performance by Jersey cows.

MATERIALS AND METHODS

Six ruminally cannulated primiparous Jersey cows were assigned to 1 of 6 diets in a 6×6 Latin square de-

sign with a 2×3 factorial arrangement of treatments. All procedures were approved by The Ohio State University Institutional Animal Care and Use Committee (Columbus). Cows were housed in a tie-stall barn and averaged 108 ± 20 DIM when the experiment began in March 2011. The trial ended in July 2011.

Diets contained either 20 or 30% CMP on a DM basis and 3 different forage combinations (Table 1). Forage was provided as corn silage only (CS), corn silage + 10% alfalfa hay (AH), or corn silage + 7% grass hay (GH). Grass hay was added to the GH rations to provide the same amount of fNDF as the AH rations. All rations were balanced for 18.4% fNDF and NSC (chemical analysis of starch plus sugars) at about 24% to maximize usability of the energy in CMP and prevent fill from limiting intake due to high levels of NDF. All diets were balanced to contain 16.4% CP and approximately 10.3% RDP using the Dairy NRC (2001) feed library, and slightly exceeded its prediction of RDP requirements (assumed to be a Jersey cow producing 24.2 kg of milk with 4.20% fat and 3.60% protein; DMI of 15.9 kg/d). The CMP was delivered about every 3 wk (coinciding with each experimental period and assessed by the statistical block for period for nutrient digestibilities) and stored on concrete in a hoop barn with an open side (facing east) for access by skid loader. We noted highly consistent nutrient composition between each CMP batch because the vendor (Cargill, Dayton, OH) blended the product and provided quality control to minimize differences among batches. A composite of each period's samples of CMP, CS, AH, and GH were submitted to Dairy One (Ithaca, NY) for analyses of NDF, ADF, CP, NFC (by difference calculation), starch, and 80% ethanol-soluble carbohydrates (Table 2).

Experimental periods were 21 d, except for the first period, which was 28 d to allow for adjustment to the new diets; the last 10 d were used for sampling and data collection. Diets were mixed once daily and fed twice daily to allow for 5% orts, except during sampling weeks, when orts were cut to 3% to reduce sorting against long particles. Cows had continuous access to water except in the holding pen or milking parlor. They were fed after returning to stalls to decrease cross-contamination of diets. Body weights were measured weekly after the a.m. milking and before feeding.

Video recording was conducted to assess chewing behavior. To minimize errors resulting from time spent outside of the stall and away from the camera, cows were monitored for 48 h during each period on d 11 through 15, with the exclusion of an hour spent outside of the stall twice per day for milking (0430 and 1600 h), during which time we assumed that cows were not ruminating. By forwarding the video in 5-min intervals,

Table 1. Ingredient composition of diets with 2 concentrations of corn-milling product and 3 forage sources

Item	Diet ¹					
	20% CMP			30% CMP		
	CS	AH	GH	CS	AH	GH
Corn silage, kernel processed	45.0	33.1	33.1	45.0	33.1	33.1
Chopped alfalfa hay	0	10.0	0	0	10.0	0
Chopped grass hay	0	0	7.0	0	0	7.0
CMP ²	20.0	20.0	20.0	30.0	30.0	30.0
Soybean hull pellets ³	1.0	1.0	1.0	1.0	1.0	1.0
Concentrate						
Shelled corn, ground	7.64	13.44	13.94	4.00	9.91	10.12
Soybean hulls	11.15	10.75	10.75	8.37	7.44	8.28
Soybean meal, 48% CP	11.91	1.44	10.98	6.17	0.00	7.25
Amino Plus ⁴	0.00	7.80	0.00	2.14	5.54	0.00
Fancy bleachable tallow	0.91	0.91	0.91	0.92	0.91	0.91
Limestone	1.30	1.03	1.29	1.31	1.04	1.30
Trace-mineralized salt ⁵	0.50	0.50	0.50	0.51	0.50	0.50
Selenium, 90 mg/454 g	0.14	0.14	0.14	0.14	0.14	0.14
Zinc sulfate	0.001	0.001	0.001	0.001	0.001	0.001
Copper sulfate	0.001	0.001	0.001	0.001	0.001	0.001
Vitamin A, 30,000 IU/g	0.011	0.010	0.010	0.010	0.010	0.010
Vitamin D, 3,000 IU/g	0.036	0.036	0.036	0.037	0.036	0.036
Vitamin E, 20,000 IU/454 g	0.047	0.047	0.046	0.047	0.047	0.047
Biotin 100 ⁶	0.34	0.34	0.34	0.34	0.34	0.34
Rumensin, ⁷ 90 g/454 g	0.006	0.006	0.006	0.006	0.006	0.006

¹Corn-milling product (CMP) with corn silage (CS) only or with CS partially substituted with alfalfa hay (AH) or grass hay (GH).

²Corn-milling product from Cargill Corn Milling (Dayton, OH).

³Soybean hulls were used as a carrier for chromic oxide for digestibility measurements.

⁴Ag Processing Inc. (Hiawatha, KS).

⁵Guaranteed analysis: 36.6% Na, 56.4% Cl, 3,500 mg of Zn/kg, 2,800 mg of Mn/kg, 1,750 mg of Fe/kg, 350 mg of Cu/kg, 70 mg of I/kg, and 70 mg of Co/kg.

⁶DSM Nutritional Products (Parsippany, NJ).

⁷Elanco Animal Health (Greenfield, IN). Formulated to provide 11 g/908 kg on a DM basis.

rumination, eating, and standing or lying activities were recorded and summarized as in Harvatine et al. (2002b).

Feed offered andorts were mixed and sampled for 4 consecutive days (d 16 to 20) just before feeding. The samples of TMR were composited per animal per period, and refusals were similarly composited as a percentage of total refusals. Samples were dried at 55°C in a forced-air oven for 48 h to determine DM. Adjustments were made before each collection period for DM (on a 55°C basis) of forages and CMP. Samples were

ground through a 2-mm screen in a Wiley mill (Arthur H. Thomas Co., Philadelphia, PA) before laboratory analysis of subsamples for DM at 105°C. Subsamples were analyzed in duplicate for CP by Kjeldahl determination (Bremner and Keeney, 1965), using a Foss Tecator digestion system (Foss Tecator AB, Höganäs, Sweden); NDF with sodium sulfite and heat-stable α-amylase (Van Soest et al., 1991), using an automated apparatus (Ankom Technology Corp., Fairport, NY); and ash in a muffle oven at 450°C overnight. Composites of TMR were analyzed for ADF, ADL, neutral deter-

Table 2. Chemical composition (% of DM, unless otherwise noted) of corn-milling product (CMP) and forages

Item	CMP	Corn silage	Alfalfa hay	Grass hay
DM ¹ (%)	65.7	34.1	81.2	82.5
NDF	35.6	40.5	45.0	67.4
ADF	11.4	29.9	35.4	50.5
CP	27.5	8.2	19.9	11.1
NFC	29.3	40.6	27.4	15.6
Starch	10.7	27.9	0.6	2.2
ESC, ² simple sugars	7.3	0.8	4.4	4.4

¹Laboratory DM at 105°C. The CMP averaged 71.8% DM when dried at 55°C.

²80% ethanol-soluble carbohydrates.

gent-insoluble CP (without sulfite correction but with amylase), and acid detergent-insoluble CP (without sulfite), assuming $N \times 6.25$ (Van Soest et al., 1991). All fiber values except for ADL were reported without ash correction. Ether extract was analyzed according to the method of the Association of Official Analytical Chemists (AOAC, 1990). Starch and sugars were determined by Dairy One. Briefly, samples were pre-extracted in 80% ethanol and then analyzed for sugar (Hall et al., 1999). Residues were solubilized using an autoclave and incubated with glucoamylase, and glucose was analyzed using glucose oxidase with a YSI Analyzer (YSI Inc., Yellow Springs, OH). Minerals were determined by the Service Testing and Research (STAR) Lab (Wooster, OH) using wet ashing in perchloric and nitric acids followed by analysis of the extracts using inductively coupled plasma emission spectrometry. Daily milk production was recorded electronically for all cows using a DeLaval milking system (DeLaval International AB, Tumba, Sweden) equipped with AfiFarm records (Afi-milk Ltd., Kibbutz Afikim, Israel). Milk samples were collected from 4 consecutive milkings on d 16 to 19 and composited by cow. An aliquot of each milk sample was analyzed for fat and true protein using infrared procedures and for MUN using a Skalar SAN Plus segmented flow analyzer (Skalar Analytical BV, Breda, the Netherlands) by DHI Cooperative Inc. (Columbus, OH).

Total-tract digestibilities of NDF, N, and OM were determined using chromic oxide (Cr_2O_3) as a marker. Pellets (95% soyhulls and 5% Cr_2O_3) were dosed twice daily through the rumen cannula at the morning and evening feedings in amounts equaling 1% of the average DMI for each cow during the period. Rectal grab samples were collected twice per day on d 17 to 20 to represent every 1.5 h of a 12-h period between feedings. Fecal samples were dried at 55°C and composited by weight each period and then ground through a 2-mm screen with a Wiley mill. Fecal samples (0.5 g) were ashed in duplicate overnight at 600°C. Chromium was extracted from the residue using manganese sulfate in phosphoric acid and potassium bromate solution (Williams et al., 1962), except that the calcium chloride was omitted because samples were analyzed for Cr using inductively coupled plasma spectrometry (STAR Lab) rather than atomic absorption spectroscopy. Samples of the Cr_2O_3 pellets were also analyzed for Cr concentration to quantify dosages. The NDF, OM, and N concentrations of TMR, Orts, and fecal samples were determined as described above. Flows and resulting digestibilities were calculated using standard techniques as described by Merchen (1988). The NE_L concentration was estimated by inputting treatment averages for

cow production and for TMR analyses into the Dairy NRC (2001) software.

Samples of forage and CMP were taken each period, dried at 55°C, equilibrated with the atmosphere, and ground using the Wiley mill (2-mm screen). Three grams of CMP was weighed into Dacron bags and heat-sealed. Forages were composited to represent their respective proportion of dietary forage in amounts that totaled 3 g of sample. Bags were heat-sealed and incubated in the rumen for 0, 2, 4, 8, 12, 24, 48, 72, and 96 h. After removal, bags were rinsed in cold tap water until the water ran clear (about 3 to 5 min) and then dried at 55°C in a forced-air oven for at least 48 h and allowed to equilibrate with the atmosphere. Analysis for NDF (using sulfite) was conducted on the forage and CMP residues, and N disappearance was determined on the CMP residue using Kjeldahl analysis, as described above.

Standard rumen measurements of pH, ammonia, and VFA were taken on d 20 at 0, 3, 6, and 9 h after the a.m. feeding. Rumen samples were taken from 4 different locations (1 each from the central dorsal, ventral dorsal, middle cranial, and middle caudal regions), combined, and squeezed through 4 layers of cheesecloth. The pH was measured immediately using an Accumet portable pH meter (Fisher Scientific, Waltham, MA) before acidification of 50 mL with 3 mL of 6 N HCl and was frozen until further analysis. Samples were later thawed to room temperature and centrifuged at $15,000 \times g$ for 20 min. The supernatant was filtered through Whatman no. 1 filter paper (Whatman International Ltd., Maidstone, UK). An aliquot of supernatant was analyzed for NH_3 -N (Chaney and Marbach, 1962), and the remaining supernatant was analyzed for VFA according to Harvatine et al. (2002a).

Rumen evacuations were conducted 2 h before feeding and 2 h postfeeding on d 20 and 21, respectively, for measurement of the rumen pool size (Dado and Allen, 1995). Total contents were removed by hand or via a large cup for liquid. Rumen contents were then separated into liquid and solid using a wine press. Each component was weighed, and subsamples were reconstituted to equal the proportion of liquid to solid in the rumen. Subsamples were then frozen until further analysis. The rest of the rumen contents were returned to the cow within 30 min of evacuation initiation. After freezing ($-20^\circ C$) for storage and thawing, rumen samples were subsampled again, dried at 55°C, and ground using a Wiley mill (2-mm screen). Samples from each of the 2 evacuations were composited into 1 sample per period per cow and analyzed for NDF, DM, and N. Triplicate samples (5 g each) of TMR, Orts, and samples from rumen evacuations were incubated in situ

for 10 d in the rumen of a mid-lactation Jersey cow fed a lactation diet similar to our diets. Residue was analyzed for NDF using the same procedure described above and was assumed to be completely indigestible NDF (**iNDF**). The iNDF in orts was subtracted from iNDF in the TMR to calculate iNDF intake.

Ruminal NDF degradation was determined using the pool and flux method (Harvatine et al., 2002b). Passage rate (k_p) of iNDF was calculated as the intake of iNDF/ruminal pool size of iNDF. The k_p of the potentially digestible NDF (**pdNDF**; i.e., NDF – iNDF) was assumed to be equivalent to the k_p of iNDF. To predict ruminal NDF digestibility and degradation rate (k_d) of the potentially digestible NDF fraction, the following equations were used:

$$k_d \text{ (h}^{-1}\text{)} = [(pdNDF \text{ intake}/24)/\text{ruminal pdNDF pool size}] - k_p \text{ of iNDF}; \quad [1]$$

$$\text{Apparent ruminal digestibility (\%)} = (pdNDF \text{ intake}/NDF \text{ intake}) \times [k_d/(k_d + k_p)] \times 100. \quad [2]$$

Samples of TMR and orts composites for each period were analyzed using the Penn State Particle Separator (The Pennsylvania State University, University Park) according to manufacturer's instructions, with 2 screens (19 and 8 mm) and a pan (Lammers et al., 1996). The particle size of rumen contents was measured using 4 screens (screen sizes 4.75, 2.36, 1.18, and 0.30 mm) in a procedure modified from Shaver et al. (1988). Briefly, ruminal contents were subsampled, and 100 to 150 g of as-is sample was wet-sieved through the 4 screens. Residue on each screen was rinsed, filtered, and dried at 55°C. Samples of TMR also were wet-sieved similarly except for using screens with pore sizes of 9.5, 4.75, 2.36, and 0.425 mm. A log-normal distribution was assumed (Murphy and Zhu, 1997). Cumulative proportions of 55°C DM mass retained on each screen or larger were plotted against the logarithms (base 10) of screen size. From the linear regression, solving for $y = 0$ provided the logarithm of the mean particle size; the logarithm of the standard deviation was calculated as the inverse of the slope.

Disappearance kinetics from Dacron bags were analyzed with PROC NLIN of SAS (version 9.4; SAS Institute Inc., Cary, NC). Resulting parameter estimates were analyzed using PROC MIXED of SAS using ANOVA. Cow was a random effect, and period and treatment were fixed effects. Ruminal characteristics (pH and concentrations of $\text{NH}_3\text{-N}$ and VFA) were evaluated over time using repeated measures in which the covariance structure used was autoregressive order 1.

Because no interactions with time were detected, main-effect means were compared among treatments. Means were partitioned into the following preplanned orthogonal contrasts: (1) main effect of CMP: 30% CMP with CS, AH, and GH versus 20% CMP with CS, AH, and GH diets; (2) main effect of CS versus hays: 20% CMP-CS and 30% CMP-CS diets versus 20% CMP-AH, 20% CMP-GH, 30% CMP-AH, and 30% CMP-GH diets; (3) main effect of hay source excluding the CS diets: 20 and 30% CMP diets with AH versus 20 and 30% CMP diets with GH; (4) interaction of CMP and forage: 30% CMP-CS, 20% CMP-AH, and 20% CMP-GH diets versus 20% CMP-CS, 30% CMP-AH, and 30% CMP-AH diets; and (5) interaction of CMP and hay excluding the CS diets: 20% CMP-AH and 30% CMP-GH versus 30% CMP-AH and 20% CMP-GH diets. Significance was declared at $P \leq 0.05$ for main effects and at $P \leq 0.10$ for trends.

RESULTS AND DISCUSSION

Diet Composition

No visible molding or detectable heating (based on daily observations by feeders) of CMP was observed during the course of this experiment. Chemical composition of the forages and CMP are shown in Table 2. When the CMP was dried at 105°C in a forced-air oven, volatiles would have been lost. Our 55°C DM (mean = 71.8% with a SD = 2.5%, as delivered to the barn for the 6 periods; data not shown) more closely approximated the manufacturer's expectations of 70% based on drying at 60°C under vacuum to retain volatiles.

All diets (Table 3) were about 1% lower in CP than balanced values and slightly higher in ADF and NDF, except for the 20% CMP diet with CS only, which was about 1% lower in NDF. Because separate analyses of grain mixes, forages, and CMP resulted in target (or slightly higher) CP percentages based on weighted means of their dietary contributions, these analyzed values in Table 3 probably reflect the challenge of collecting representative samples from TMR. Because the forage sources were weighed daily and NDF was measured from only those components, fNDF among diets (18.1 to 18.5%) was similar to what we balanced (18.4%). The diets were formulated to be low in both NFC and fNDF to make room for greater inclusion of the CMP in the diets. Analyzed NSC (starch plus sugars) ranged between 20 and 22% on a DM basis, which was similar to expectations.

The 2 diets with CS had numerically greater percentages of particles in the 8-mm screen for both TMR and orts, which explains the numerically lower percentage of particles in the pan (Table 3). The corn was chopped

Table 3. Nutrient composition (% of DM, unless otherwise noted) and particle sizes for TMR for cows fed diets with 2 concentrations of corn-milling product and 3 forage sources

Item	Diet ¹					
	20% CMP			30% CMP		
	CS	AH	GH	CS	AH	GH
DM (%)	47.3	52.9	51.3	46.7	51.2	53.4
NDF	33.0	35.9	38.8	36.0	37.1	36.9
Forage NDF	18.2	18.5	18.1	18.2	18.5	18.1
ADF	20.9	20.6	24.5	20.1	21.7	21.7
ADL	2.0	2.5	2.5	1.7	2.5	2.2
CP	15.3	15.6	15.1	15.2	15.9	15.0
NDICP ²	2.71	3.92	2.99	3.04	3.96	3.11
ADICP ³	0.76	0.16	0.38	0.21	0.84	0.46
Ash	6.7	6.9	6.8	6.9	7.4	7.2
Ether extract	3.10	2.84	2.66	2.83	2.80	2.70
Starch	17.1	18.3	18.1	16.8	16.7	16.6
Sugar	3.7	3.7	4.0	4.2	4.4	3.9
NFC ⁴	41.3	37.9	35.6	38.3	35.9	37.2
NE _L ⁵ (Mcal/kg of DM)	1.55	1.59	1.56	1.57	1.57	1.58
Ca	0.83	1.05	0.83	0.78	0.87	0.80
P	0.48	0.49	0.44	0.56	0.54	0.51
Mg	0.26	0.28	0.27	0.29	0.30	0.29
K	1.21	1.24	1.30	1.28	1.28	1.32
S	0.20	0.23	0.20	0.23	0.24	0.22
Particle distribution by PSPS ⁶ (% of total)						
TMR						
19 mm	7.0	6.4	10.7	6.5	8.2	9.3
8 mm	30.5	24.1	24.4	30.8	24.2	22.2
Pan	62.5	69.5	64.9	62.7	67.6	68.5
Orts						
19 mm	22.3	23.2	33.3	19.7	27.8	31.6
8 mm	39.7	30.0	28.7	37.5	28.6	31.9
Pan	38.0	46.7	38.0	42.9	43.6	36.5

¹Corn-milling product (CMP) with corn silage (CS) only or with CS partially substituted with alfalfa hay (AH) or grass hay (GH).

²Neutral detergent-insoluble CP from NDF prepared without sodium sulfite.

³Acid detergent-insoluble CP from ADF prepared without sodium sulfite.

⁴Nonfiber carbohydrate = 100 – NDF – CP – ash – ether extract.

⁵Net energy of lactation predicted by NRC (2001) equations.

⁶Penn State Particle Size (PSPS) separator (The Pennsylvania State University, University Park; Lammers et al., 1996), on an as-is basis.

more coarsely than typical before ensiling. To compensate, the CS was delivered in a Jaylor self-propelled mixer (Jaylor Fabricating, East Garafraxa, Ontario, Canada) with a flat knife and was allowed to mix to reduce the size as much as possible before inclusion in our TMR. Based on the particle distribution of Orts, all diets were sorted against coarse particles after feeding. However, no treatment $\times$ hour interactions ($P > 0.69$) were detected for particle distributions at 0 (TMR), 2, and 8 h (data not shown). Main effects of hour ($P < 0.01$) existed for the top screen and the pan (more long particles and fewer short particles for GH vs. AH), but all treatment contrasts were $P \geq 0.15$ for 8 h after feeding (data not shown). Because the values for Orts in Table 3 must be considered within the context of restriction of DMI to $\leq 103\%$ of ad libitum intake, we did not report treatment means separated by time or their statistical inferences.

Total-Tract and Estimated Rumen Digestibilities

Treatments did not significantly affect NDF, apparent N, or apparent OM digestibilities in the total tract (Table 4). A trend ($P = 0.10$) existed for increased N digestibility when cows were fed the 30% CMP diets compared with when they were fed diets with 20% CMP (67.2 vs. 65.3% for main-effect means). This trend probably reflects a higher N digestibility of CMP than the other protein sources it replaced.

Ruminal NDF digestibility was calculated using the pool and flux method as described in Harvatine et al. (2002b), with k_p assumed to be equivalent for both iNDF and pdNDF. This assumption leaves some room for error because those authors reported that the fractional k_p of iNDF is not always equivalent to the rate of passage of pdNDF. However, all diets primarily comprised pdNDF from mostly CS and CMP, which

Table 4. Apparent total-tract digestibility, rumen NDF digestibility predicted by the pool and flux method, and in situ disappearance kinetics for NDF and protein for cows fed diets with 2 concentrations of corn-milling product and 3 forage sources

Item	Diet ¹						SEM	Contrast ² (<i>P</i> -value)				
	20% CMP			30% CMP				(1) 20 vs. 30% CMP	(2) CS vs. AH + GH	(3) AH vs. GH	(4) Interaction CMP vs. 2	(5) Interaction CMP vs. 3
	CS	AH	GH	CS	AH	GH						
Total-tract digestibility												
NDF (%)	41.8	39.6	44.4	44.5	45.1	42.6	2.87	NS ³	NS	NS	NS	NS
N (%)	65.9	63.7	64.0	68.6	66.6	66.4	1.85	0.10	NS	NS	NS	NS
OM (%)	66.2	64.3	65.4	67.8	66.2	65.8	1.58	NS	NS	NS	NS	NS
Rumen NDF ⁴												
iNDF k _p (/h)	0.024	0.024	0.027	0.026	0.027	0.029	0.002	0.07	NS	NS	NS	NS
k _d (/h)	0.040	0.041	0.036	0.035	0.041	0.035	0.003	NS	NS	0.08	NS	NS
NDFD (%)	49.6	49.3	43.9	45.2	47.4	41.9	2.24	NS	NS	0.02	NS	NS
Disappearance in situ ⁵												
NDF in forage												
A fraction (%)	2.21	4.12	0.94	1.02	2.95	1.23	1.25	NS	NS	0.06	NS	NS
B fraction (%)	58.1	50.2	49.5	59.8	54.0	55.0	3.8	NS	0.06	NS	NS	NS
C fraction (%)	39.3	41.9	38.8	32.9	45.0	39.4	6.2	NS	NS	NS	NS	NS
k _d (/h)	0.025	0.030	0.028	0.023	0.028	0.026	0.004	NS	NS	NS	NS	NS
Lag (h)	10.1	8.5	3.5	6.9	4.2	8.5	2.6	NS	NS	NS	NS	NS
NDFD (%)	11.7	17.6	12.8	12.6	17.4	14.6	1.8	NS	0.03	0.04	NS	NS
Disappearance in situ ⁵												
NDF in CMP												
A fraction (%)	4.74	3.61	4.50	4.79	3.83	5.96	1.17	NS	NS	NS	NS	NS
B fraction (%)	91.8	92.4	84.9	89.4	88.4	91.9	3.4	NS	NS	NS	NS	NS
C fraction (%)	3.29	4.14	9.11	5.62	3.25	2.15	2.24	NS	NS	NS	NS	NS
k _d (/h)	0.021	0.023	0.023	0.021	0.025	0.021	0.003	NS	NS	NS	NS	NS
Lag (h)	0.92	2.65	2.06	1.59	5.76	2.38	1.52	NS	0.09	NS	NS	NS
NDFD (%)	24.9	23.2	22.5	22.5	23.1	24.7	1.7	NS	NS	NS	NS	NS
N in CMP												
A fraction (%)	52.1	52.5	51.7	50.3	52.6	52.3	1.5	NS	NS	NS	NS	NS
B fraction (%)	33.6	36.0	35.8	38.2	31.1	32.6	3.8	NS	NS	NS	NS	NS
C fraction (%)	14.4	11.5	12.5	11.5	16.3	11.5	3.8	NS	NS	NS	NS	NS
k _d (/h)	0.020	0.029	0.029	0.024	0.040	0.051	0.011	NS	NS	NS	NS	NS
RDP (%)	59.4	61.7	59.9	57.9	60.8	60.3	1.3	NS	0.08	NS	NS	NS

¹Corn-milling product (CMP) with corn silage (CS) only or with CS partially substituted with alfalfa hay (AH) or grass hay (GH).

²20 vs. 30% CMP = main effect of CMP concentration; CS vs. AH + GH = main effect of corn silage (CS diets with 20 and 30% CMP vs. AH and GH diets with 20 and 30% CMP); AH vs. GH = main effect of AH vs. GH averaged over CMP percentage; interaction CMP vs. 2 = interaction between CMP concentration and contrast 2 [(20% CMP-CS and 30% CMP-AH and 30% CMP-GH) vs. (30% CMP-CS and 20% CMP-AH and 20% CMP-GH)]; CMP vs. 3 = interaction between CMP concentration and contrast 3 [(20% CMP-AH and 30% CMP-GH) vs. (30% CMP-AH and 20% CMP-GH)].

³NS = nonsignificant at $P > 0.15$.

⁴The indigestible NDF (iNDF) passage rate (k_p) was estimated using the pool and flux method (iNDF intake/iNDF rumen pool size). By assuming the k_p of iNDF equals the k_p of potentially digestible NDF (pdNDF), the NDF digestibility (NDFD; % of original NDF) can be estimated as (pdNDF, % of total NDF)[$k_d/(k_p + k_d)$], where k_d = degradation rate (Harvatine et al., 2002b).

⁵A = washout; B = potentially digestible; C = indigestible; lag = discrete lag time; NDFD = $A + B[(k_d)(e^{-k_p \times t})/(k_d + k_p)]$; RDP = $A + B[k_d/(k_d + k_p)]$. The k_p were estimated from Seo et al. (2006) and averaged 7.97, 5.41, and 5.20%/h for CMP, CS, and hays, respectively.

were at relatively similar inclusion rates among treatments (and have relatively little opportunity for varying treatment bias) compared with the increasing inclusion of whole cottonseed in the study of Harvatine et al. (2002b). Kammes and Allen (2012b) noted no significant difference between iNDF and pdNDF when using duodenal flow to correctly calculate the k_p of pdNDF.

Using the pool and flux method, a trend ($P = 0.07$) existed for faster k_p for the main effect means of treatments with the higher concentration of CMP (Table 4). By-product feeds generally have a greater functional specific gravity than forages (Bhatti and Firkins, 1995) and might pass from the rumen at a more rapid rate than fNDF sources. A trend ($P = 0.08$) also existed for a faster rate of NDF digestion and increased ($P = 0.02$) NDF digestibility in the rumen with the AH diets compared with the GH diets ($k_d = 0.041$ vs. 0.036 ; 48.4 vs. 42.9% NDF digestibility, respectively; main-effect means not shown). Alfalfa hay typically has a faster rate of NDF digestibility than GH (Kammes and Allen, 2012a), supporting our results.

Kinetics of Disappearance In Situ

The A fraction (i.e., NDF washing out of the Dacron bags), tended ($P = 0.06$) to be higher in the AH diets when compared with the GH (Table 4). The potentially digestible (B) fraction tended ($P = 0.06$) to be higher for cows fed the corn silage diets than those fed the diets containing either hay. Corn silage had a higher concentration of pdNDF than hay (Kammes and Allen, 2012b). The NDF digestibility increased ($P = 0.03$) for the average of the AH and GH treatments compared with the CS treatments (12.2 vs. 15.6% for the main-effect means of CS vs. AH and GH), mostly resulting from the NDF digestibility being greater ($P = 0.04$) for cows fed AH than GH diets (17.5 and 13.8% , respectively). Although the k_d of AH in situ was not affected ($P > 0.10$) by treatment, the k_d of the total ruminal pdNDF calculated by the pool and flux method was faster for cows fed AH than GH (see previous discussion). The AH was expected to have of a lower extent of NDF disappearance than GH (Kammes and Allen, 2012b), but the C fraction was not affected by forage source in our study.

A trend ($P = 0.09$) existed for a shorter lag time for NDF disappearance in CMP by cows fed the CS diets compared with those fed the diets containing AH and GH (Table 4). A trend ($P = 0.08$) also existed for lower RDP percentage in CMP when CMP was incubated in cows fed CS compared with AH or GH treatments. However, this result was likely a reflection of the estimation of k_p using the Seo et al. (2006) correction

of the NRC (2001) model because no other differences existed in disappearance kinetics.

Low predicted digestibility of NDF for the forages and CMP could be attributed to errors associated with incubations in situ or measurement of residual NDF. A biofilm from degradation could have blocked the pores in the Dacron bags, and this gummy residue was especially notable in bags containing corn silage. However, the use of Dacron bags might underestimate ruminal digestibility as a cumulative result of overestimating lag time, potentially underestimating k_d because of insufficient removal of degradation end products, and overestimating k_p (Firkins, 1997). Effective ruminal degradability (i.e., RDP) using Dacron bags also might not reflect potential treatment differences in the k_p of CMP compared with its predicted k_p .

Ruminal Fermentation Characteristics

No treatment $\times$ time interactions were detected for ruminal fermentation characteristics (Table 5). Neither mean pH nor total VFA concentration was affected by treatment. The interaction ($P = 0.04$) of CMP concentration with forage source (contrast 4) was a result of acetate molar percentage being higher for CS than AH or GH with 20% CMP included but was lower for CS than AH or GH when 30% CMP was fed. The opposite results were noted for propionate for contrast 4 ($P = 0.08$), so the acetate:propionate ratio followed similar responses as for acetate molar percentage. Isovalerate molar percentage was greater for main-effect means of 20 than 30% CMP ($P = 0.02$) and for CS than the average of AH and GH ($P = 0.01$). The greater corn silage in the diet would provide a greater proportion of corn protein, which has a higher percentage of leucine than that of grass and alfalfa proteins (NRC, 2001), the deamination and decarboxylation of which yields isovalerate (Russell, 2002). The lower isobutyrate percentage for 30 than 20% CMP might indicate lower leucine degradability of corn protein in that product compared with other protein sources used. Ruminal $\text{NH}_3\text{-N}$ concentration was not affected by treatment, but all means are high enough to be nonlimiting for ruminal microbial needs (Russell, 2002).

Rumen Pools

The whole-rumen contents increased ($P = 0.03$) for cows fed the GH diets compared with those fed the AH treatments (Table 6). This result was largely from increased fluid weight, both in the liquid calculated from subtraction of rumen DM from the total weight of rumen evacuations ($P = 0.04$) and from the weight of

Table 5. Ruminal fermentation characteristics from cows fed diets with 2 concentrations of corn-milling product and 3 forage sources

Item	Diet ¹						Contrast ² (P-value)				
	20% CMP			30% CMP			(1) 20 vs. 30% CMP	(2) CS vs. AH + GH	(3) AH vs. GH	(4) Interaction CMP vs. 2	(5) Interaction CMP vs. 3
	CS	AH	GH	CS	AH	GH					
Mean pH	6.03	5.93	5.99	6.00	5.98	6.03	NS ³	NS	NS	NS	NS
Total VFA (mM)	91.7	93.5	85.6	94.8	88.9	87.8	NS	NS	NS	NS	NS
VFA (mol/100 mol)											
Acetate	63.5	63.0	62.6	62.2	63.0	63.5	NS	NS	NS	0.04	NS
Propionate	22.2	22.7	23.0	23.6	22.6	22.5	NS	NS	NS	0.08	NS
Butyrate	10.8	10.8	11.0	10.8	11.1	10.7	NS	NS	NS	NS	NS
Isobutyrate	0.695	0.722	0.669	0.663	0.686	0.675	NS	NS	NS	NS	NS
Isovalerate	1.77	1.60	1.67	1.65	1.50	1.53	NS	0.01	NS	NS	NS
Valerate	1.09	1.10	1.07	1.12	1.16	1.07	NS	NS	0.10	NS	NS
Acetate:propionate	2.90	2.80	2.73	2.66	2.80	2.85	NS	NS	NS	0.05	NS
NH ₃ -N (mg/dL)	13.0	11.1	12.7	13.1	13.5	14.5	NS	NS	NS	NS	NS

¹Corn-milling product (CMP) with corn silage (CS) only or with CS partially substituted with alfalfa hay (AH) or grass hay (GH).
²20 vs. 30% CMP = main effect of CMP concentration; CS vs. AH + GH = main effect of corn silage (CS diets with 20 and 30% CMP vs. AH and GH diets with 20 and 30% CMP); AH vs. GH = main effect of AH vs. GH averaged over CMP%; interaction CMP vs. 2 = interaction between CMP concentration and contrast 2 [(20% CMP-CS and 30% CMP-AH and 30% CMP-GH) vs. (30% CMP-CS and 20% CMP-AH and 20% CMP-GH)]; interaction CMP vs. 3 = interaction between CMP concentration and contrast 3 [(20% CMP-AH and 30% CMP-GH) vs. (30% CMP-AH and 20% CMP-GH)]. No treatment × time interactions were detected ($P > 0.15$).
³NS = nonsignificant at $P > 0.15$.

fluids pressed with the wine press ($P = 0.04$). Increasing NDF fill is associated with increased fluid volume (Allen, 2000). Karnati et al. (2007) reasoned that the fluid expressed from the wine press represented fluid that readily distributes in the rumen milieu. Water-holding capacity was positively correlated with increased fiber content of feeds, largely the cellulose and hemicellulose fractions (Ramanzin et al., 1994). Because the predicted NDF digestibility in the rumen based on the pool and flux method also was lower for GH than for AH treatments (Table 4), we assume that a greater pool of fluid was, therefore, associated with the greater amount and structure of undegraded GH. Grass hay should be even more physically effective than AH (Kammes and Allen, 2012a,b) and should, therefore, increase ruminal mat consistency more than AH.

Ruminal DM pool increased ($P = 0.04$) in cows fed the CS diets when the concentration of CMP was increased from 20 to 30% (contrast 4 of Table 6). As explained previously, the CS was actually coarser than typical and had a larger percentage of particles retained on the 8-mm screen (Table 3). Had the CS had a particle size distribution more typical (fewer large particles), we would have expected increased particle entanglement of the smaller CMP particles when part of the CS was substituted for hay (Weidner and Grant, 1994). Allen and Grant (2000) evaluated rumen mat density using a counterweight system and reported that adding chopped hay slowed the rate of ascension, indicating a denser rumen mat. We did not measure ruminal mat consistency in the current experiment because of its difficulty to reach statistical significance in our prior study (Harvatine et al., 2002b). However, no differences ($P > 0.20$) existed in iNDF (Table 6). Harvatine et al. (2002b) suggested that increased ruminal pools of DM and INDF can compensate for varying forage percentage. Therefore, mat consistency is probably controlled to a given physical fill (i.e., treatments were not different), and rumination (and associated ruminal fluid pool size) probably increased as a compensatory mechanism to help clear that retained fill. Dado and Allen (1995) demonstrated this principle in their landmark paper.

Chewing Activity

Time spent ruminating ($P = 0.07$) and total chewing time ($P = 0.03$) were greater when cows were fed GH than AH diets (Table 6). As explained above, increased rumination probably helped to clear ruminal particles and prevent bulk fill limitation of feed intake. A trend ($P = 0.08$) and a numerical response ($P = 0.15$) existed for ruminating time and total chewing time, respectively, for interactions between CMP concentration and hay source (contrast 5). Thus, when CMP was at 30%,

Table 6. Rumen pool characteristics, chewing activity, and mean particle size of TMR and rumen contents from cows fed diets with 2 concentrations of corn-milling product and 3 forage sources

Item	Diet ¹						SEM	Contrast ² (<i>P</i> -value)				
	20% CMP			30% CMP				(1) 20 vs. 30% CMP	(2) CS vs. AH + GH	(3) AH vs. GH	(4) Interaction CMP vs. 2	(5) Interaction CMP vs. 3
	CS	AH	GH	CS	AH	GH						
Rumen pool (kg)												
Total	57.7	56.8	60.1	59.0	55.4	58.6	3.5	NS ³	NS	0.03	NS	NS
DM	8.04	7.97	8.37	8.65	7.92	8.05	0.64	NS	NS	NS	0.04	NS
Liquid ⁴	49.7	48.9	51.7	50.4	47.5	50.6	2.9	NS	NS	0.04	NS	NS
Fluid, pressed ⁵	32.9	30.5	34.0	32.4	31.0	33.0	2.0	NS	NS	0.04	NS	NS
iNDF ⁶	1.95	2.09	2.13	1.98	2.07	2.00	0.21	NS	NS	NS	NS	NS
Chewing activity (min/d)												
Ruminating	398	388	388	408	369	416	21	NS	NS	0.07	NS	0.08
Eating	360	361	368	342	342	356	18	0.15	NS	NS	NS	NS
Standing	650	632	647	632	619	621	24	NS	NS	NS	NS	NS
Total chewing ⁷	758	747	758	747	710	770	22	NS	NS	0.03	NS	0.15
Particle size ⁸ (mm)												
TMR												
Mean	1.39	1.32	1.22	1.41	1.37	1.45	0.07	NS	NS	NS	NS	NS
Log ₁₀ SD	1.04	1.00	1.10	0.99	1.11	1.10	0.06	NS	NS	NS	NS	NS
Rumen contents (mm)												
Mean	0.55	0.53	0.71	0.51	0.57	0.66	0.07	NS	0.14	0.06	NS	NS
Log ₁₀ SD	1.12	1.19	1.09	1.21	1.11	1.07	0.04	NS	<0.01	0.06	NS	NS

¹Corn-milling product (CMP) with corn silage (CS) only or with CS partially substituted with alfalfa hay (AH) or grass hay (GH).

²20 vs. 30% CMP = main effect of CMP concentration; CS vs. AH + GH = main effect of corn silage (CS diets with 20 and 30% CMP vs. AH and GH diets with 20 and 30% CMP); AH vs. GH = main effect of AH vs. GH averaged over CMP%; interaction CMP vs. 2 = interaction between CMP concentration and contrast 2 [(20% CMP-CS and 30% CMP-AH and 30% CMP-GH) vs. (30% CMP-CS and 20% CMP-AH and 20% CMP-GH)]; interaction CMP vs. 3 = interaction between CMP concentration and contrast 3 [(20% CMP-AH and 30% CMP-GH) vs. (30% CMP-AH and 20% CMP-GH)].

³NS = nonsignificant at *P* > 0.15.

⁴Liquid volume = total weight – DM weight (kg at 55°C).

⁵Fluid fraction of rumen contents, separated by wine press during rumen evacuations.

⁶Indigestible NDF.

⁷Total chewing = rumination + eating (min/d).

⁸Particle size by wet-sieving and fitting to a log-normal distribution for calculating the mean particle size and the logarithm of its SD.

GH increased time spent ruminating compared with AH, but when CMP was at 20%, no difference existed between hays. Amounts of time spent standing and eating were not significantly affected by treatment.

Mean Particle Size

Mean particle sizes (MPS) of TMR and rumen solids (Table 6) were analyzed using linear fits of log-normal distributions to condense the data from wet sieving with laboratory sieves. No significance of treatment on MPS of the TMR was detected. However, the MPS of the rumen solids from cows fed GH tended ($P = 0.06$) to be 0.13 mm larger than the rumen solids from cows fed the diets with AH, even though the logarithm of the standard deviation tended ($P = 0.06$) to be lower for GH than AH (Table 6). Ruminal mean particle size actually was decreased by substitution of 10% long AH for corn silage (without effect on $\log_{10}$ SD) when ruminal DM fill was at its minimum (before feeding) but had no effect when fill was increased after feeding (Woodford and Murphy, 1988). Kammes and Allen (2012b) discussed that grasses tend to be less fragile than alfalfa, which could allow GH to maintain a larger, more physically effective particle size for longer in the rumen compared with AH particles, particularly if the GH would decrease NDF digestibility (Table 4). Thus, the increases in total and liquid pools of rumen contents, rumination activity, and the larger mean particle size of the GH in the rumen likely all are related to a more consistent rumen mat and greater retention of small particles (Kammes and Allen, 2012b), which we would expect to help retain CMP particles for better digestibility and improved chemical effectiveness in rations with GH than AH and especially than CS. Moreover, this greater rumination by cows fed GH apparently compensated to prevent the ruminal iNDF pool from being greater and more filling for GH than AH.

DMI and Milk Production

A trend ($P = 0.09$) existed for decreased DMI (averaging about 5%) in cows fed the 30% CMP treatment diets compared with those fed the 20% CMP diets (Table 7). When CMP replaced forage, DMI numerically increased; however, when it replaced concentrate or both forage and concentrate, DMI decreased (Boddugari et al., 2001). Ruminal mat consistency was lower when CMP replaced forage (but not measured when it replaced concentrate) in that study. When wet corn gluten feed (similar to CMP) replaced both forage and concentrate, DMI increased (Mullins et al., 2010). The DMI decreased when CMP replaced concentrate, but when CMP replaced both forage and concentrate, DMI

increased (Weiss, 2012). In that study, NSC concentration was higher than in ours. Both the third trial of Boddugari et al. (2001) and the study of Weiss (2012) replaced CMP for both forage and concentrate, but the former was in early-lactation cows and the latter was in mid-lactation cows. Filling mechanisms and differences in DMI might be greater with increasing nutrient demand by cows (Kammes and Allen, 2012a).

On average, diets containing 30% CMP were higher in NDF concentration than diets with 20% CMP. However, NDF and OM digestibility were not affected by treatment, and the k_p of iNDF was faster for 30 versus 20% CMP (Table 4). If the trend for decreased DMI noted for cows fed the higher CMP concentrations was attributed to increased bulk fill, the k_p of iNDF from the rumen would be expected to increase to compensate for the increased ruminal distension. The lack of difference in rumen pool characteristics for the main effect of CMP (Table 6) would actually support the latter mechanism. That is, the lower DMI for cows fed the 30% CMP diets resulted from the lack of ability to increase the rumen volume (i.e., ruminal fill was restricting DMI). In support, no differences existed among treatments for iNDF intake.

A trend ($P = 0.07$; contrast 4) existed for an interaction between CMP concentration and corn silage versus the average of AH and GH for milk production (Table 7). This interaction can be explained by the increased milk production by cows fed the diets containing CS versus the average of AH and GH when CMP was 30%, but milk production was lower for CS versus the average of AH and GH when diets had 20% CMP. This interaction tended ($P = 0.09$) in the opposite directions for milk fat percentage, resulting in no net effect on milk fat production. No effect of treatment was detected for protein percentage, protein production, or 3.5% FCM.

A trend ($P = 0.10$) existed for improved efficiency of FCM production in the diets containing AH or GH compared with the diets in which CS was the only forage source (Table 7). Main effect means of BW also tended ($P = 0.07$) to be lower for the treatments with AH and GH compared with CS, which could be a result of mobilizing body fat. Because of the short-term duration of our study (21-d periods), feed efficiency probably has a greater inference from continuous designs of longer term. In the 9-wk study of Boddugari et al. (2001), FCM/DMI improved with CMP without treatment response for BCS change. Weiss (2012) reported a decreasing milk fat yield as dietary starch:iNDF ratio increased from about 1.2 to 1.5, coinciding with replacement of both concentrate and forage in their study with 28-d periods. Although our diets had moderately low iNDF concentrations, the lower dietary starch:iNDF ratio (about 1.0) in our study probably helped maintain

Table 7. Production data from cows fed diets with 2 concentrations of corn-milling product and 3 forage sources

Item	Diet ¹						SEM	Contrast ² (<i>P</i> -value)				
	20% CMP			30% CMP				(1) 20 vs. 30% CMP	(2) CS vs. AH + GH	(3) AH vs. GH	(4) Interaction CMP vs. 2	(5) Interaction CMP vs. 3
	CS	AH	GH	CS	AH	GH						
DMI (kg/d)	16.1	15.0	15.3	14.8	14.9	14.7	0.8	0.09	0.11	NS ³	NS	NS
iNDFI ⁴ (kg/d)	1.10	1.16	1.34	1.19	1.23	1.32	0.08	NS	0.06	0.06	NS	NS
Milk (kg/d)	22.2	22.3	22.6	23.2	22.7	22.1	1.0	NS	NS	NS	0.07	NS
Fat (%)	4.82	4.52	4.59	4.59	4.91	4.69	0.19	NS	NS	NS	0.09	NS
Protein (%)	3.65	3.63	3.65	3.62	3.64	3.63	0.05	NS	NS	NS	NS	NS
Fat (kg/d)	1.08	1.05	1.03	1.06	1.11	1.03	0.07	NS	NS	NS	NS	NS
Protein (kg/d)	0.81	0.84	0.83	0.84	0.83	0.80	0.04	NS	NS	NS	0.15	NS
MUN (mg/dL)	16.0	16.2	16.0	17.1	16.4	16.0	0.49	NS	NS	NS	NS	NS
3.5% FCM (kg/d)	27.1	27.1	26.5	27.2	27.8	26.3	1.5	NS	NS	NS	NS	NS
FCM/DMI	1.70	1.82	1.75	1.79	1.88	1.86	0.05	0.13	0.10	0.02	0.15	NS
BW (kg)	403	402	401	407	403	399	13	NS	0.07	NS	NS	NS
DMI (% of BW)	3.71	3.69	3.66	3.96	3.72	3.86	0.17	NS	0.11	NS	NS	NS

¹Corn-milling product (CMP) with corn silage (CS) only or with CS partially substituted with alfalfa hay (AH) or grass hay (GH).
²20 vs. 30% CMP = main effect of CMP concentration; CS vs. AH + GH = main effect of corn silage (CS diets with 20 and 30% CMP vs. AH and GH diets with 20 and 30% CMP) AH vs. GH = main effect of AH vs. GH averaged over CMP%; interaction CMP vs. 2 = interaction between CMP concentration and contrast 2 [(20% CMP-CS + 30% CMP-AH + 30% CMP-GH) vs. (30% CMP-CS + 20% CMP-AH + 20% CMP-GH)]; interaction CMP vs. 3 = interaction between CMP concentration and contrast 3 [(20% CMP-AH + 30% CMP-GH) vs. (30% CMP-AH + 20% CMP-GH)].
³NS = nonsignificant at *P* > 0.15.
⁴Indigestible NDF intake.

ruminal conditions (e.g., pH; Table 5) and probably FA biohydrogenation profiles (which were not measured) conducive for milk fat secretion. The differences in FCM/DMI for CS versus AH plus GH might be an artifact of the short-term nature of our trial.

Cows fed the AH treatment diets also had improved ($P = 0.02$) feed efficiency compared with those fed the GH diets (Table 7). Although the decreasing estimates of k_d and digestibility for ruminal NDF using the rumen-evacuation data support improved fiber digestibility as the reason, the lack of differences in total-tract NDF digestibility or other production responses preclude a clear explanation for this result.

CONCLUSIONS

Total-tract digestibility of protein, NDF, and OM were not affected by treatment. A trend existed for increased rate of passage of iNDF from the rumen when CMP increased from 20 to 30%. Because CMP has little iNDF, this result is not likely from faster passage of the smaller CMP particles but is likely more indicative of increased restriction by fill resulting from accumulating DM in the ruminal pool, as evidenced by the same ruminal pool characteristics, despite a trend for lower DMI. However, increasing dietary concentrations of CMP from 20 to 30% maintained production of milk and milk components. The diets containing GH were the most physically effective, as evidenced by the increased particle size of the rumen pool, total chewing activity, and mean particle size of the rumen contents. In contrast, total feed efficiency (a summation of results, although ignoring BW change) supported the usage of AH in the short term. We conclude that CMP can readily be used at 20% but also can be successfully incorporated into rations at 30% of the DM without affecting production, as long as attention is paid to having moderate fNDF to prevent bulk fill while retaining appropriate ruminal mat characteristics and also to limiting starch to reduce risk for negative associative effects.

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