Effects of altering alfalfa hay quality when feeding steam-flaked versus high-moisture corn grain on ruminal fermentation and lactational performance of dairy cows¹

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ABSTRACT

This experiment was performed to test a hypothesis that nutritive benefits of feeding high-moisture corn (HMC) would be different when fed with different qualities of alfalfa hay (AH) due to associative effects on ruminal fermentation and nutrient utilization efficiency. Eight multiparous lactating Holstein cows were used; 4 were surgically fitted with ruminal cannulas. Days in milk averaged 184 ± 10.7 at the start of the experiment. The experiment was performed in a duplicate 4×4 Latin square design. Within each square, cows were randomly assigned to a sequence of 4 diets during each of the four 21-d periods (14 d of treatment adaptation and 7 d of data collection and sampling). A 2×2 factorial arrangement was used; fair-quality AH [FAH; 39.6% neutral detergent fiber (NDF) and 17.9% crude protein (CP)] or high-quality AH (HAH; 33.6% NDF and 21.9% CP) was combined with steam-flaked corn (SFC) or HMC to form 4 treatments: FAH with SFC, FAH with HMC, HAH with SFC, and HAH with HMC. The AH was fed at 32% dry matter (DM) content, whereas SFC or HMC was included at 17% DM content. Quality of AH did not affect DM intake, whereas feeding HMC decreased DM intake, regardless of quality of AH. Digestibility of DM was greater for cows fed HAH compared with those fed FAH (70.1 vs. 67.6%). Digestibility of NDF increased by feeding HMC (67.6 vs. 58.4%), but not by quality of AH. Under FAH, starch digestibility decreased by feeding HMC compared with SFC (85.7 vs. 95.0%), but it was similar under HAH, resulting in an interaction between quality of AH and type of corn grain (CG). Feeding different qualities of AH did not affect milk yield; however, feeding HMC decreased milk yield in FAH diet, causing an AH $\times$ CG interaction. Efficiency of milk yield/DM intake was improved due to feeding HMC, regardless of

the quality of the AH. In addition, dietary N utilization for milk N tended to increase by feeding HMC, but it was not influenced by quality of AH. Yield of microbial protein increased by feeding HAH diets compared with FAH diets, whereas feeding the HMC diet increased microbial protein yield under the HAH diet, leading to an interaction between AH and CG. Overall results in this experiment indicate that feeding HMC in AH-based diets improved feed efficiency as well as N utilization efficiency, regardless of quality of AH.

Key words: dairy cow, high-moisture corn, alfalfa hay, feed efficiency, microbial protein yield

INTRODUCTION

Forage quality affects feed intake and energy density, lactational performance, cow health, and feed cost. In addition, recent increases in grain and protein supplement prices have been unprecedented, making forage quality of paramount importance for reducing purchased feed costs and improving income-over feed cost. Dairy producers in the western United States use alfalfa hay (AH) to make up the majority of the forage portion in dairy diets, and great emphasis has been placed on producing high-quality AH with an average chemical composition for CP, NDF, and ADF of 21.3, 38.3, and 26.7% DM, respectively (Holt et al., 2010). Feeding high-quality AH (HAH) provides enough CP and forage NDF to support potential milk production by dairy cows; however, ruminal microbes degrade alfalfa protein too rapidly, resulting in excessive excretion of nitrogenous waste by the animal. This process results in inefficient utilization of feed N with high CP degradability of AH in the rumen and limits optimal microbial CP (MCP) synthesis. It also increases energy cost to convert ruminal ammonia-N ($\text{NH}_3\text{-N}$) to urea and elevates N excretion into the environment (Holt et al., 2013). Consequently, the full benefit of alfalfa protein is not realized due to its poor N utilization by the animal. Feeding carbohydrates that are more extensively fermented in the rumen may improve utilization of the CP in HAH through stimulation of MCP synthesis.

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Ruminal starch digestibility, rate, and extent of VFA production, and postruminal starch flow and digestion vary in response to physiological status of the cow as well as to type and genotype of grain, growing conditions, and both physical and chemical processing methods of the grain (Nocek and Tamminga, 1991). The addition of highly digestible carbohydrate to the diet is a common method of increasing the energy available to the cow. Although ruminally fermentable carbohydrate can increase MCP yield (Nocek and Tamminga, 1991; Krause et al., 2002), high amounts of fermentable carbohydrate increase the risk of ruminal acidosis. High-moisture corn (**HMC**) has consistently greater starch digestion in the rumen, the small intestine, and the total tract compared with dry-rolled and steam-flaked corn (**SFC**; Wilkerson et al., 1997; Knowlton et al., 1998; Firkins et al., 2001). Several (Zogg et al., 1961; San Emeterio et al., 2000), but not all experiments (Clark et al., 1973) feeding HMC, have reported improved lactational performance of dairy cows. Inconsistent effects of HMC in lactation dairy diets have been caused by various factors, including cows differing in the physiological state and interactions with other forages and concentrates (Ekinci and Broderick, 1997). The objectives of this study were to investigate the effects of, and interaction between quality of AH [fair-quality AH (**FAH**) vs. HAH] and type of corn grain [**CG**; **SFC** vs. **HMC**] on nutrient digestibility, ruminal fermentation characteristics, and lactational performance in mid-lactation dairy cows. We hypothesized that nutritive benefits of feeding HMC would be different between FAH and HAH due to their associative effects on ruminal fermentation and nutrient utilization efficiency.

MATERIALS AND METHODS

The dairy cows used in this study were cared for according to the Live Animal Use in Research Guidelines of the Institutional Animal Care and Use Committee at Utah State University. The study was conducted at the Caine Dairy Research Center (Wellsville, UT), Utah State University from May to August, 2013.

Cows and Experimental Design and Diets

Eight multiparous lactating Holstein cows were used; 4 were surgically fitted with ruminal cannulas. Days in milk averaged 184 ± 10.7 at the start of the experiment. Average BW was 741 ± 63.5 kg at the beginning of the experiment and 801 ± 70.6 kg at the end of the experiment, showing positive BW gain over all experimental periods.

The experiment was performed in a double 4×4 Latin square design. Within each square, cows were ran-

domly assigned to a sequence of 4 diets during each of the four 21-d periods (14 d of treatment adaptation and 7 d of data collection and sampling). A 2×2 factorial arrangement was used; FAH (39.6% NDF and 17.9% CP) or HAH (33.6% NDF and 21.9% CP; Table 1) was combined with SFC (8.26% CP and 61.6% starch) or HMC (8.66% CP and 65.4% starch; Table 1) to form 4 treatments: FAH with SFC (**FAH-SFC**), FAH with HMC (**FAH-HMC**), HAH with SFC (**HAH-SFC**), and HAH with HMC (**HAH-HMC**; Table 2). Diets were isonitrogenous across treatments, averaging 16.0% CP and are typical of high-producing dairy cows in the Intermountain West (i.e., Utah, Idaho, Wyoming, Montana, and parts of Arizona and Nevada) with 32% of the forage DM coming from AH and with the remaining forage considered to come from corn silage. Experimental diets contained 16.6 or 17.3% of corn grains (SFC or HMC) under FAH- or HAH-based TMR, respectively (Table 2).

Whole corn (Pioneer 3730; Pioneer Hi-bred International Inc., Johnston, IA) was processed with a mobile roller mill (model number ATG3600B; Automatic Equipment Manufacturing Co., Pender, NE), which resulted in a mean particle size of $1,017 \mu\text{m}$. The ground HMC was ensiled in a 2.4×9.0 -m bag (Ag-Bag International Ltd., Blair, NE). The SFC grain used in this study was supplied by Cache Commodities (Ogden, UT). The average thickness of the SFC was 2.0 mm, and its bulk density was averaged at 0.35 kg/L. Alfalfa was preserved as sun-cured hay and processed for approximately 15 min in a TMR wagon (model 455; Roto-Mix, Dodge City, KS).

Cows were housed in individual tie-stalls fitted with rubber mattresses, bedded with straw, and were fed a TMR for ad libitum intake with at least 10% of daily feed refusal. All cows were individually fed twice daily at 0830 and 1500 h with approximately 70 and 30% of total daily feed allocation at each feeding, respectively. Feed offered and refused was recorded daily, and daily samples were collected to determine DMI. Cows had free access to water.

Cows were milked twice daily at 0400 and 1600 h. Milk production was recorded daily throughout the experiment. Cows were turned outside to a dry lot for exercise for at least 1 h daily in the morning after being milked. Milk was sampled during the a.m. and p.m. milking on 3 consecutive days (d 16 to 18) in each period. Milk samples were preserved with Broad Spectrum Microtabs II (D&F Control Systems Inc., San Ramon, CA), and were stored at 4°C. Individual milk samples were analyzed for fat, true protein, lactose, and MUN by the Rocky Mountain DHIA Laboratory (Wellsville, UT). Milk composition was expressed on weighted milk yield of a.m. and p.m. samples. Milk fat

Table 1. Chemical composition (means $\pm$ SD) of forages and corn grains ($n = 4^1$)

Item, % of DM	Forage ²			Corn grain ³	
	FAH	HAH	Corn silage	SFC	HMC
DM, %	93.3 $\pm$ 0.94	94.4 $\pm$ 0.49	35.9 $\pm$ 1.01	89.1 $\pm$ 2.47	81.4 $\pm$ 2.20
OM	88.9 $\pm$ 0.99	88.4 $\pm$ 0.28	93.8 $\pm$ 0.28	98.1 $\pm$ 0.16	98.1 $\pm$ 0.05
CP	17.9 $\pm$ 0.26	21.9 $\pm$ 0.97	7.08 $\pm$ 0.290	8.26 $\pm$ 0.401	8.66 $\pm$ 0.810
NDF	39.6 $\pm$ 1.29	33.6 $\pm$ 1.55	41.8 $\pm$ 2.20	13.6 $\pm$ 0.35	13.0 $\pm$ 2.03
ADF	29.2 $\pm$ 0.49	23.9 $\pm$ 0.81	21.8 $\pm$ 0.61	3.52 $\pm$ 0.095	3.13 $\pm$ 0.544
Starch	ND ⁴	ND	33.4	61.6	65.4

¹Number of sample replicates.²FAH = fair-quality alfalfa hay; HAH = high-quality alfalfa hay.³SFC = steam-flaked corn; HMC = high-moisture corn.⁴ND = not determined.

and protein yields were calculated by multiplying milk yield from the respective day by fat and true protein concentration of the milk on an individual cow. To convert milk true protein to milk N, 6.38 was used as the

conversion factor (DePeters and Cant, 1992), and total milk N (kg/d) was calculated as milk true protein/6.38 + MUN, where milk true protein and MUN were expressed in kilograms per day. Calculation of 3.5% FCM

Table 2. Ingredients and chemical composition (means $\pm$ SD) of the experimental diets fed to lactating dairy cows ($n = 4^1$)

Item	Experimental diet ²			
	FAH		HAH	
	SFC	HMC	SFC	HMC
Ingredient, % of DM				
Fair-quality alfalfa hay	32.4	32.4	—	—
High-quality alfalfa hay	—	—	30.8	30.8
Corn silage	25.9	25.9	26.9	26.9
Steam-flaked corn	16.6	—	17.3	—
High-moisture corn	—	16.6	—	17.3
Corn DDGS ³	6.47	6.47	6.73	6.73
SBMCM ⁴	8.50	8.50	7.70	7.70
Beet pulp, shred	7.39	7.39	7.69	7.69
Sodium bicarbonate	0.55	0.55	0.58	0.58
Vitamin and mineral mix ⁵	2.22	2.22	2.31	2.31
Chemical composition, % of DM				
DM, %	59.3 $\pm$ 3.12	58.2 $\pm$ 3.07	60.0 $\pm$ 1.75	58.9 $\pm$ 1.19
OM	91.0 $\pm$ 1.17	91.3 $\pm$ 0.45	90.3 $\pm$ 0.68	90.8 $\pm$ 0.57
CP	15.4 $\pm$ 0.63	16.0 $\pm$ 0.71	16.6 $\pm$ 0.19	16.3 $\pm$ 0.91
RDP ⁶	8.74	9.05	9.13	9.12
RUP ⁶	6.95	6.87	7.47	7.14
NDF	36.4 $\pm$ 1.32	35.7 $\pm$ 1.76	33.6 $\pm$ 1.52	33.2 $\pm$ 0.97
ADF	22.3 $\pm$ 1.31	21.8 $\pm$ 1.42	19.5 $\pm$ 0.95	19.3 $\pm$ 0.53
Starch	17.0 $\pm$ 0.79	20.4 $\pm$ 1.02	17.5 $\pm$ 1.14	19.5 $\pm$ 1.39
Ether extract	2.41 $\pm$ 0.404	2.35 $\pm$ 0.527	2.68 $\pm$ 0.542	2.49 $\pm$ 0.452
NFC ⁷	36.7 $\pm$ 0.99	37.2 $\pm$ 1.91	37.1 $\pm$ 1.56	38.8 $\pm$ 1.85
NE _L ⁶ Mcal/kg	1.56	1.56	1.65	1.65

¹Number of sample replicates.²FAH-SFC = fair-quality alfalfa hay (FAH) and steam-flaked corn (SFC) diet; FAH-HMC = FAH and high-moisture corn (HMC) diet; HAH-SFC = high-quality alfalfa hay (HAH) and SFC diet; HAH-HMC = HAH and HMC diet.³DDGS = dried distillers grains with solubles.⁴Mixture of soybean meal and canola meal at a ratio of 50:50 on a DM basis.⁵Formulated to contain (per kg of DM): 226.7 mg of Se (from sodium selenite), 9,278.7 mg of Cu (from copper amino acid complex), 40,537.4 mg of Zn (from zinc amino acid complex), 38,653.4 mg of Mn (from manganese amino acid complex), 552.6 mg of Co (from cobalt carbonate), 1,234,585.2 IU of vitamin A, 152,808.1 IU of vitamin D, 3,815.1 IU of vitamin E, and 295 mg of Rumensin (Elanco Animal Health, Greenfield, IN).⁶Based on tabular values (NRC, 2001).⁷NFC = 100 – CP – NDF – ether extract – ash.

was done using the equation $0.4324 \times \text{milk yield (kg/d)} + 16.216 \times \text{fat yield (kg/d)}$, whereas ECM was calculated using the equation $0.327 \times \text{milk yield (kg/d)} + 12.95 \times \text{fat yield (kg/d)} + 7.65 \times \text{true protein yield (kg/d)}$ (DRMS, 2014).

Feed Sampling and Analysis

Corn silage, AH, and HMC were sampled weekly to determine DM concentration and composited for each period. Diets were adjusted weekly to account for changes in DM concentration. Samples of the TMR fed and orts for individual cows were collected daily during the data collection period, dried at 60°C for 48 h, ground to pass a 1-mm screen (standard model 4; Arthur H. Thomas Co., Swedesboro, NJ), and stored for subsequent analyses.

Analytical DM concentration of samples was determined by oven drying at 135°C for 3 h (AOAC International, 2000; method 930.15), and OM content was determined by ashing at 550°C for 5 h (AOAC International, 2000; method 942.05). The concentration of N was determined using a N analyzer (Flash 2000; CE Elantech Inc., Lakewood, NJ; AOAC International, 2000; method 990.03). The NDF and ADF concentrations were sequentially determined using a fiber analyzer (200/220; Ankom Technology, Macedon, NY) according to the methodology supplied by the company, which is based on the methods described by Van Soest et al. (1991). Sodium sulfite was used in the procedure for NDF determination and pretreatment with heat-stable amylase (type XI-A from *Bacillus subtilis*; Sigma-Aldrich Corp., St. Louis, MO). Ether extract was measured (AOAC International, 2000; method 2003.05) using a fat analyzer (XT20; Ankom Technology). In addition, samples of corn grain (SFC and HMC), TMR, orts, and fecal samples were analyzed for starch by the Dairyland Laboratories Inc. (Arcadia, WI) according to Knudsen (1997).

Feed DM and nutrient digestibility were measured during the last week in each period using acid-insoluble ash (AIA) as an internal marker (Van Keulen and Young, 1977). Fecal samples (approximately 100 g, wet weight) were collected for each cow from the rectum twice daily (a.m. and p.m.) every 12 h, moving ahead 2 h each day for the 5-d sampling of feces beginning on d 15. This schedule provided 12 representative samples of feces for each cow. Samples were composited across sampling times for each cow, dried at 60°C for 72 h, ground to pass a 1-mm screen (standard model 4; Arthur H. Thomas Co.), and stored for chemical analysis. Apparent total-tract DM and nutrient digestibilities were calculated from concentrations of AIA and nutrients in diets fed, orts, and feces. Intake of digested

NDF was calculated from NDF intake and concentrations of AIA and NDF in diets fed, orts, and feces using the following equation: intake of digested NDF (kg/d) = intake of NDF (kg/d) $\times \{100 - [100 \times (\text{AIA}_d/\text{AIA}_f) \times (\text{NDF}_f/\text{NDF}_d)]\}$, where AIA_d = AIA concentration in the diet actually consumed, AIA_f = AIA concentration in the feces, NDF_f = concentration of the NDF in the feces, and NDF_d = concentration of the NDF in the diet actually consumed. Intake of undigested NDF was calculated from the following equation: intake of undigested NDF (kg/d) = intake of NDF (kg/d) – intake of digested NDF (kg/d) (Eun and Beauchemin, 2005).

Measurements of Ruminal pH and Fermentation Characteristics

Ruminal pH was continuously measured for 2 consecutive days starting on d 18, using the Lethbridge Research Centre Ruminal pH Measurement System (LRCpH; Dascor Inc., Escondido, CA) as described by Penner et al. (2006). Readings in pH buffers 4 and 7 were recorded before placing the LRCpH system in the rumen. Ruminal pH readings were taken every 30 s and stored by the data logger. After about 48 h of continuous pH measurement, the LRCpH was removed from the rumen, washed in 39°C water, and millivolt readings were recorded in pH buffers 4 and 7. The daily ruminal pH data was averaged for each minute and summarized as minimum pH, mean pH, and maximum pH. In addition, daily episodes, duration (h/d), and area (pH $\times$ min) when ruminal pH was less than 5.8 were calculated. The threshold 5.8 was assigned because it has been defined by others (Nocek, 1997; Maekawa et al., 2002; Beauchemin and Yang, 2005) to cause sub-clinical ruminal acidosis.

Ruminal contents were sampled 0, 3, and 6 h after the a.m. feeding of ruminally cannulated cows in one square on d 20 and 21. Approximately 1 L of ruminal contents was obtained from the anterior dorsal, anterior ventral, medial ventral, posterior dorsal, and posterior ventral locations within the rumen, composited by cow, and strained through a polyester screen (pore size: 355 μm ; B. & S. H. Thompson, Ville Mont-Royal, QC, Canada). Five milliliters of the filtered ruminal fluid was added to 1 mL of 1% sulfuric acid and samples were retained for $\text{NH}_3\text{-N}$ determination. Concentration of $\text{NH}_3\text{-N}$ in the ruminal contents was determined as described by Rhine et al. (1998). Another 5 mL of the filtered ruminal fluid was taken at 3 h after the a.m. feeding and added to 1 mL of 25% of meta-phosphoric acid, and the samples were retained for VFA determination. The VFA were quantified using a gas chromatograph (model 5890; Hewlett-Packard Labs, Palo Alto, CA) with a capillary column (30 m $\times$ 0.32 mm i.d.,

1- μ m phase thickness, Zebtron ZB-FAAP; Phenomenex Inc., Torrance, CA) and flame-ionization detection. The oven temperature was 170°C held for 4 min, which was then increased by 5°C/min to 185°C, and then by 3°C/min to 220°C, and held at this temperature for 1 min. The injector temperature was 225°C, the detector temperature was 250°C, and the carrier gas was helium (Eun and Beauchemin, 2007).

Urine Sampling and Analysis for MCP Production

On d 15 to 17, spot urine samples were collected from each cow at 0600 and 1800 h for a total of 6 samples per cow (Holt et al., 2013). Urine samples were acidified using 4 M HCl to pH <4.0 and composited by cow per period. Samples were frozen and stored at -40°C. Samples were thawed at a later date for analysis and diluted with 39 parts diluent to 1 part urine. Diluent consisted of 0.202% sodium 1-heptane sulfonic acid and 0.086% ammonium dihydrogen phosphate ($\text{NH}_4\text{H}_2\text{PO}_4$), and the solution was brought to a pH of 2.1 using 4 M HCl. Using the ratio of urinary purine derivatives (PD) to creatinine is an accepted way to estimate the MCP flow to the duodenum (Shingfield and Offer, 1998). The PD and creatinine were analyzed using an HPLC instrument (Waters Corp., Milford, MA) according to the procedures of Shingfield and Offer (1999). Supply of MCP was estimated based on estimates of urinary excretion of PD according to the method of Chen and Gomes (1992) and Janicek et al. (2008).

Statistical Analyses

Data were summarized for each cow by measurement period. All data were statistically analyzed using the mixed-model procedure in SAS (SAS Institute, 2013). Data for intake, digestibility, milk production, pH and VFA profiles, and MCP yield were analyzed with a model that included the effects of quality of AH in the diet (FAH vs. HAH), type of CG (SFC vs. HMC), and their interaction. Cow and period were the terms of the random statement. Data for $\text{NH}_3\text{-N}$ concentration were analyzed using the model described above, except that the fixed effect of time after feeding was included using the repeated option. For each variable analyzed, cow nested within treatment was subjected to 3 covariance structures: compound symmetry, autoregressive order 1, and unstructured covariance. The covariance structure that resulted in the lowest values for the Akaike information criterion and the Schwartz Bayesian criterion was used (Littell et al., 1998). Residual errors were used to test main effects and interactions. Differences were considered significant at $P \leq 0.05$, and trends were discussed at $P > 0.05$ to $P < 0.10$.

RESULTS AND DISCUSSION

Nutrient Profiles of Forages, CG, and Experimental Diets

Chemical compositions of AH are similar to those with comparable quality reported by Mertens (2002) and Holt et al. (2013), with concentrations greater for CP and less for NDF in HAH versus FAH (21.9 vs. 17.9% and 33.6 vs. 39.6%, respectively; Table 1). Nutrient profiles were similar between SFC and HMC, except that HMC contained 3.8 percentage units greater starch concentration, which resulted in slight increases in starch and NFC concentrations in experimental diets containing HMC (Table 2).

Intake and Digestibility of DM and Nutrients

Intakes of DM and nutrients were not affected due to quality of AH, except that ADF intake decreased by feeding HAH-based diets (Table 3). In contrast, cows fed HMC decreased or tended to decrease ($P = 0.06$) intakes of DM, OM, CP, and fiber compared with those fed SFC. Feeding different types of CG did not influence starch intake. No AH $\times$ CG interaction was observed in intakes of DM and nutrients. Feeding HAH-based diets increased total-tract digestibility of DM and tended to increase OM and CP digestibilities ($P = 0.08$). However, total-tract digestibilities of NDF and ADF were not different between FAH- and HAH-based diets. Feeding different types of CG resulted in similar digestibilities of DM and OM. In contrast, feeding HMC-containing diets caused increased total-tract digestibilities of CP, NDF, and ADF. Total-tract digestibility of starch decreased when feeding FAH-based diets compared with HAH diets, which resulted from the sizable reduction of starch digestibility by feeding HMC-containing diet with FAH, but not HAH, resulting in an AH $\times$ CG interaction.

The overall results of feeding different qualities of AH in the diets observed in this study were generally expected, based on a previous study performed with similar diets using the same experimental design (double 4×4 Latin square; Holt et al., 2013). We reported no difference in intakes and digestibilities of DM, CP, NDF, and ADF in response to feeding FAH vs. HAH (Holt et al., 2013). Hence, the discussion of these effects is limited in this paper, because the focus of the current study was to understand the interaction between quality of AH and CG processing in the diets, rather than the effects of quality of AH per se.

Given similar concentrations of major nutrients (CP, NDF, and NFC) between SFC- and HMC-containing diets, the negative effects of feeding HMC-containing

Table 3. Intake of DM and nutrient and total-tract digestibility of lactating dairy cows fed different qualities of alfalfa hay and types of corn grain

Item	Diet ¹				SEM	Significance of effect ²		
	FAH		HAH			AH	CG	AH × CG
	SFC	HMC	SFC	HMC				
Intake, kg/d								
DM	27.4	24.5	27.4	25.7	2.54	0.56	0.04	0.56
OM	24.9	22.4	24.7	23.4	2.30	0.67	0.05	0.52
CP	4.23	3.93	4.57	4.17	0.064	0.11	0.06	0.79
NDF	9.84	8.65	9.12	8.50	0.911	0.22	0.02	0.42
ADF	6.03	5.26	5.31	4.96	0.577	0.04	0.02	0.37
Starch	4.73	4.97	4.83	5.03	0.29	0.65	0.59	0.78
Intake of NDF, kg/d								
Digested	5.59	5.05	5.18	5.37	0.464	0.82	0.39	0.08
Undigested	4.26	3.60	3.94	3.13	0.512	0.16	0.02	0.77
Digestibility, %								
DM	67.4	67.8	68.6	71.5	1.56	0.05	0.17	0.29
OM	69.9	70.4	70.9	73.6	1.53	0.08	0.17	0.33
CP	63.9	68.3	67.1	69.8	1.70	0.08	0.02	0.52
NDF	57.1	59.8	57.5	63.5	2.35	0.27	0.03	0.39
ADF	57.0	59.7	57.5	63.6	2.26	0.23	0.03	0.36
Starch	95.0 ^a	85.7 ^b	93.9 ^a	92.4 ^a	1.78	0.03	0.02	0.02

^{a,b}Means within a row with different superscripts differ ($P < 0.05$).

¹FAH-SFC = fair-quality alfalfa hay (FAH) and steam-flaked corn (SFC) diet; FAH-HMC = FAH and high-moisture corn (HMC) diet; HAH-SFC = high-quality alfalfa hay (HAH) and SFC diet; HAH-HMC = HAH and HMC diet.

²AH = quality of alfalfa hay in the diet (FAH vs. HAH); CG = type of corn grain in the diet (SFC vs. HMC); AH × CG = interaction between AH and CG.

diets on intakes of DM and nutrients observed in the current study was unexpected, and the mechanism whereby feeding HMC decreased the intakes is difficult to explain. Allen (2000) suggested that DMI will continue to increase until gut fill is no longer a limiting factor and then decrease with an excess of metabolic fuels. Because NDF intake decreased due to feeding HMC in both FAH and HAH diets in the current study, differences in physical fill were not likely responsible for differences in intakes of DM and nutrients. The amount of rumen-degraded starch consumed must be maintained to an adequate concentration to maximize the NE_L density while decreasing the risk of ruminal acidosis and feed intake associated with excessive rumen degraded starch intake (Firkins, 2008). However, increasing ruminal fermentability of CG can decrease average meal size for cows, implying that increasing the concentration of rumen-degraded starch in a diet above a threshold would be expected to decrease DMI proportionately (Firkins, 2008). Oba and Allen (2003) observed that HMC treatment decreased DMI by 1.7 kg compared with dry-ground corn treatment when fed in high-starch diets, but had no effect when fed in low-starch diets. Consistent with the treatment effects on DMI, meal size was greater for the dry-ground corn treatment compared with the HMC treatment when cows were fed high-starch diets (Oba and Allen, 2003). Similarly, Harvatine et al. (2002) reported a decrease in

DMI by 1.1 kg/d when cows were fed SFC compared with those fed dry-ground corn. Collectively, the effects on feed intake reported across a broad range of corn processing is primarily due to a change in ruminal starch degradability. Cows fed HMC in the current study may have received all necessary nutrients from lower feed intakes, decreasing the DMI. Because of increased digestibilities of CP and NDF in response to feeding HMC, calculated digestible intakes of CP (2.89 vs. 2.80 kg/d) and NDF (5.43 vs. 5.29 kg/d) between SFC- and HMC-containing diets were similar, implying that cows tested in this study may have consumed a similar level of nutrients for metabolism. Another possibility is that shifts in energy metabolism due to feeding HMC may have contributed to the downward regulation of intakes of cows fed HMC. Further research needs to be done to determine the mechanism of regulation of feed intake when early-lactation cows are fed high-forage diets with CG that are processed differently.

Fiber digestion by ruminants can be altered by grain processing. Total-tract digestion of NDF was lower for HMC than for dry-rolled, flaked, or whole corn with both lactating cows and feedlot cattle (Owens and Soderlund, 2006). This depression in NDF digestion may have resulted from reduced ruminal fiber digestion coupled with low ruminal pH. Ekinci and Broderick (1997) and Valadares Filho et al. (2000) reported that increased intake of NFC from HMC reduced ruminal pH

and, thus, depressed NDF digestibility. However, feeding different types of CG did not affect overall ruminal pH patterns in the current study as will be discussed later, and so overall ruminal fermentative conditions were not interfered with by feeding HMC. Calsamiglia et al. (2008) reported that the effect of ruminal pH on NDF digestibility was relatively small above pH 6.0, but digestibility of NDF decreased sharply below this pH threshold. Therefore, feeding HMC in AH-based diets can increase ruminal NDF digestion without interfering with ruminal physiological conditions.

Milk Production, BW, and Caloric Efficiency

Cows fed HAH increased milk yield compared with those fed with FAH (30.0 vs. 28.8 kg/d; Table 4), whereas dietary treatments did not affect yields of 3.5% FCM and ECM. Type of CG did not influence milk yield. However, feeding HMC decreased milk yield under FAH, but not under HAH, leading to an AH $\times$ CG interaction. Feeding FAH-based diets increased milk fat concentration compared with HAH-based diets (3.52 vs. 3.32%), whereas type of CG did not influence milk fat concentration, resulting in an AH $\times$ CG interaction. Increased milk fat concentration due to feeding

HMC under FAH can be associated with decreased DMI; Firkins et al. (2001) stated that increased milk fat concentration coupled with decreased DMI below 25.8 kg/d was likely associated with increased lipolysis of adipose tissue with decreasing DMI. Milk fat yield was similar across dietary treatments. In addition, milk true protein concentration and yield was not different between treatments. Feeding different qualities of AH resulted in inconsistent effects on feed efficiency; based on yield of milk as well as ECM, the feed efficiency was not affected, whereas feeding FAH-based diets increased the efficiency based on 3.5% FCM yield compared with HAH. Cows fed HMC increased all feed efficiencies compared with those fed SFC, regardless of quality of AH. In addition, dietary N utilization efficiency for milk N tended to increase due to feeding HMC ($P = 0.07$), but it was not affected by quality of AH.

Feed efficiencies are used to evaluate herd productivity and profitability, and increased feed efficiencies are associated with greater milk yield, loss in body condition, high-quality forages, and improved feed digestibilities (Britt et al., 2003). The greatest factor affecting energy availability to the lactating dairy cow is digestibility (NRC, 2001). Feeding HMC-containing diets increased NDF digestibility regardless of quality

Table 4. Milk production and composition and efficiencies of DM and N use for milk production of lactating dairy cows fed different qualities of alfalfa hay and types of corn grain

Item	Diet ¹				SEM	Significance of effect ²		
	FAH		HAH			AH	CG	AH × CG
	SFC	HMC	SFC	HMC				
Yield, kg/d								
Milk	29.4 ^a	28.1 ^b	29.6 ^a	30.4 ^a	2.93	0.02	0.62	0.05
3.5% FCM	29.7	30.3	29.4	29.9	2.94	0.56	0.34	0.95
ECM	30.3	30.7	30.0	30.8	2.96	0.80	0.32	0.73
Milk composition, %								
Fat	3.43 ^b	3.61 ^a	3.39 ^b	3.24 ^b	0.137	0.02	0.86	0.04
True protein	3.10	3.09	3.08	3.10	0.078	0.90	0.94	0.62
Lactose	4.69 ^a	4.57 ^b	4.65 ^{ab}	4.66 ^{ab}	0.066	0.46	0.14	0.06
Milk component yield, kg/d								
Fat	1.03	1.08	1.02	1.01	0.110	0.18	0.50	0.36
True protein	0.93	0.92	0.92	0.97	0.092	0.52	0.50	0.25
Lactose	1.41 ^{ab}	1.37 ^b	1.38 ^{ab}	1.46 ^a	0.135	0.27	0.56	0.07
Efficiency								
Milk yield/DMI	1.11	1.25	1.10	1.18	0.075	0.43	0.05	0.61
3.5% FCM yield/DMI	1.10 ^b	1.28 ^a	1.08 ^b	1.12 ^b	0.070	0.05	0.02	0.10
ECM yield/DMI	1.12	1.29	1.10	1.16	0.070	0.18	0.05	0.28
Milk N:N intake	0.22	0.23	0.21	0.23	0.014	0.43	0.07	0.35
BW								
Initial, kg	765	764	764	769	22.8	0.50	0.46	0.36
Mean, kg	784	781	778	779	23.7	0.23	0.68	0.45
Gain, kg/d	0.91	0.76	0.67	0.48	0.230	0.08	0.26	0.84

^{a,b}Means within a row with different superscripts differ ($P < 0.05$).

¹FAH-SFC = fair-quality alfalfa hay (FAH) and steam-flaked corn (SFC) diet; FAH-HMC = FAH and high-moisture corn (HMC) diet; HAH-SFC = high-quality alfalfa hay (HAH) and SFC diet; HAH-HMC = HAH and HMC diet.

²AH = quality of alfalfa hay in the diet (FAH vs. HAH); CG = type of corn grain in the diet (SFC vs. HMC); AH $\times$ CG = interaction between AH and CG.

of AH in the current study as discussed earlier. Oba and Allen (1999) reported that a one percentage unit increase in NDF digestibility (measured in vitro or in situ) was associated with a 0.25 kg/d increase in 4% FCM yield. The increased NDF digestion due to feeding HMC observed in the current study resulted in similar milk yield even with reduced DMI, causing the overall improvement in feed efficiencies in this study. Additionally, feeding HMC increased CP digestibility in our study, leading to a similar digestible CP intake between SFC- and HMC-containing diets. Thus, higher dietary CP intake by feeding SFC-containing diets could reduce ME allowable milk due to additional energy required to convert excess protein into urea (NRC, 2001; Abdoun et al., 2006). This would result in decreased feed efficiencies coupled with less efficient ME utilization when cows were fed SFC.

No difference in mean BW existed between treatments (Table 4). Cows tested in this study gained 0.71 kg/d, on average, while on trial, and cows fed FAH tended to increase BW gain ($P = 0.08$) compared with those fed HAH. However, type of CG did not influence BW gain. The relatively low values of feed efficiencies in our current study reported earlier may have resulted from sizable energy partitioning toward BW gain. Numerically decreased BW gain due to feeding HMC compared with SFC (0.62 vs. 0.79 kg/d, respectively; $P = 0.26$) may have contributed to the increased feed and N utilization efficiencies because of feeding HMC by channeling more ME toward milk production rather than BW gain.

Ruminal Fermentation Characteristics

Minimum and mean pH in the rumen were similar across dietary treatments (Table 5), and mean pH of at least 6.30 was maintained. This provides evidence of minimal negative effects on physiological conditions in the rumen by feeding HMC discussed earlier in this paper. In addition, the pattern of diurnal fluctuation of the ruminal pH was similar among treatments, with the highest pH values observed just before morning feeding and the lowest pH values around 8 h after the feeding (Figure 1), which is very similar to the patterns from cows fed 20 or 40% HMC reported by Vagnoni and Broderick (1997). The ruminal pH averaged on an hourly basis was maintained above 6.0 in the current study, although there were some daily episodes of pH <5.8. Therefore, some effects of statistical tendencies due to feeding HMC and interaction effects would have biologically minor consequences on microbial physiology. Vagnoni and Broderick (1997) observed that mean ruminal pH was 6.12 and 6.05 when cows were fed 24% HMC + 75% AH and 44% HMC + 50% AH,

respectively. Although fermentation acids or proteolysis degrade prolamin-zein proteins during the ensiling process of HMC and lead to greater and more rapid ruminal starch fermentation in HMC (Hoffman et al., 2011), its effects on ruminal pH would not be detrimental when cows are fed HMC in an appropriate forage proportion in their diets.

Total VFA concentration, molar proportions of acetate and propionate, and acetate-to-propionate ratio were not affected by quality of AH and processing of corn grain (Table 5). The products of ruminal fermentation are related to the composition of the diet (Eun et al., 2004). In general, increasing ruminal fermentability of grain typically yields increased VFA concentration with a greater propionate proportion. However, decreased DMI due to feeding HMC in our study may have moderated the potential effects of feeding HMC on ruminal VFA profiles.

Ruminal $\text{NH}_3\text{-N}$ concentration tended to be greater ($P = 0.09$) for HAH compared with FAH, whereas feeding the HMC diet decreased the $\text{NH}_3\text{-N}$ concentration under the HAH diet, resulting in an AH $\times$ CG interaction. This result was likely due to greater fermentability of CP from HAH compared with FAH (Holt et al., 2013). Yield of MCP increased by feeding HAH diets compared with FAH diets, whereas feeding the HMC diet increased the MCP yield under the HAH diet, leading to an interaction between AH and CG. The lower ruminal $\text{NH}_3\text{-N}$ concentration observed for HMC under the HAH diet can be attributed to increased utilization of ruminally degraded N for MCP synthesis due to feeding HMC. Rumen bacteria can utilize more $\text{NH}_3\text{-N}$ for MCP synthesis in the presence of readily available energy (NRC, 2001). As the ensiling process of HMC increases fermentability of grain starch, the utilization of $\text{NH}_3\text{-N}$ for MCP synthesis could have been greater in the HMC diet compared with the SFC diet, resulting in less $\text{NH}_3\text{-N}$ concentration in the HMC diet than in the SFC diet. Others reported a similar reduction in ruminal $\text{NH}_3\text{-N}$ concentration when feeding HMC (Agca and Broderick, 1995; Vagnoni and Broderick, 1997), implying that the inclusion of HMC in dairy diets can stimulate the uptake of ruminal $\text{NH}_3\text{-N}$ and increase N utilization for milk production. These results suggest that enhancing the availability of ruminal fermentable energy can be an effective strategy to increase microbial capture of RDP from HAH. Supplementation of alfalfa silage with HMC increased milk protein yield by 260 g/d (Cadorniga and Satter, 1993), presumably through enhanced ruminal MCP synthesis. The reduction of $\text{NH}_3\text{-N}$ concentration with feeding HMC under the HAH diet was likely due to greater fiber digestion in the rumen, and cellulolytic bacteria such as *Ruminococcus albus*, *Ruminococcus flavefaciens*, and *Fibrobacter*

Figure 1. Effects of quality of alfalfa hay [fair-quality (FAH) vs. high-quality alfalfa hay (HAH)] and type of corn grain [(steam-flaked (SFC) vs. high-moisture corn (HMC)] on diurnal variation of ruminal pH. The pH values were recorded every 30 s over a 48-h period. Least squares means for culture pH were 6.33, 6.31, 6.30, and 6.31 for FAH-SFC, FAH-HMC, HAH-SFC, and HAH-HMC, respectively.

succinogenes require $\text{NH}_3\text{-N}$ as an N source for growth (Russell et al., 1992).

Energy spilling can occur when ruminal pH is low (Strobel and Russell, 1986), and under these conditions, MCP yield would decrease due to less energy available for microbial growth. However, this did not appear in the current study for the MCP yield observed for HMC

compared with SFC treatment, because feeding HMC did not negatively influence ruminal pH profiles.

CONCLUSIONS

Our current study investigated if forage type interacted with grain processing, and whether the addition of highly digestible carbohydrate to an AH-based diet increased the energy available in ruminal fermentation and to the cow. Our hypothesis was confirmed in ruminal $\text{NH}_3\text{-N}$ concentration and MCP yield, but not in feed and N utilization efficiencies, as feeding HMC improved the efficiencies of feed and N for milk production, regardless of the quality of AH. We found that feeding HMC depressed DM and nutrient intakes, regardless of quality of AH, which partially contributed to the increased feed and N efficiencies. Contrary to previously reported results, we did not observe any negative results of feeding HMC on ruminal fermentation. Rather, we observed that feeding HMC increased fiber and CP digestibilities. These positive effects may have resulted from effective utilization of forage NDF in the diets, which could maintain favorable fermentative conditions of rumen microbes for N and energy metabolism. Thus, feeding HMC in AH-based diets can be a good approach to formulate an optimal dairy feeding program for improving feed efficiency and nutrient

Table 5. Ruminal fermentation characteristics of lactating dairy cows fed different qualities of alfalfa hay and types of corn grain

Item	Diet ¹				SEM	Significance of effect ²		
	FAH		HAH			AH	CG	AH × CG
	SFC	HMC	SFC	HMC				
Minimum pH	5.64	5.56	5.56	5.66	0.058	0.90	0.88	0.15
Mean pH	6.33	6.31	6.30	6.31	0.051	0.70	0.85	0.80
Maximum pH	7.13 ^a	6.88 ^b	6.99 ^a	6.99 ^a	0.074	0.71	0.02	0.02
pH <5.8								
Daily episodes	5.50 ^b	6.75 ^b	15.0 ^a	5.25 ^b	3.362	0.15	0.13	0.06
Duration, h/d	1.64	1.19	1.80	0.50	0.535	0.58	0.10	0.38
Area, pH × min	11.99	7.58	13.32	3.74	4.031	0.71	0.07	0.46
Total VFA, mM	147	148	140	146	6.55	0.12	0.21	0.39
Individual VFA ³								
Acetate (A)	63.8	63.2	63.1	63.1	1.34	0.50	0.63	0.63
Propionate (P)	21.9	22.5	22.2	21.6	1.11	0.57	0.93	0.24
A:P	2.96	2.87	2.91	2.94	0.205	0.91	0.75	0.52
NH ₃ -N, ⁴ mg/100 mL	6.58 ^b	6.44 ^b	9.76 ^a	7.55 ^b	0.585	0.09	0.38	0.03
MCP, ⁵ g/d	2,484 ^{bc}	2,183 ^c	2,608 ^b	2,894 ^a	145.2	<0.01	0.52	0.02

^{a-c}Means within a row with different superscripts differ ($P < 0.05$).

¹FAH-SFC = fair-quality alfalfa hay (FAH) and steam-flaked corn (SFC) diet; FAH-HMC = FAH and high-moisture corn (HMC) diet; HAH-SFC = high-quality alfalfa hay (HAH) and SFC diet; HAH-HMC = HAH and HMC diet.

²AH = quality of alfalfa hay in the diet (FAH vs. HAH); CG = type of corn grain in the diet (SFC vs. HMC); AH × CG = interaction between AH and CG.

³Expressed as mol/100 mol.

⁴Ruminal $\text{NH}_3\text{-N}$.

⁵Microbial protein production (g/d) = $(\{[\text{purine derivatives production} - (0.385 \times \text{BW}^{0.75})]/0.85\} \times 70 \times 6.25)/(0.13 \times 0.83 \times 1,000)$ (Janicek et al., 2008).

utilization, but its effect on depressed DMI should be considered. It is possible that if this study were repeated with early-lactation cows under negative energy balance conditions and more limited DMI, then different results might be found, showing increased DMI and milk production when the greater quality, earlier maturity AH was fed. If this study is repeated, it would be good to use corn of one variety with similar protein concentration to compare between the 2 physical forms as SFC and HMC to confirm the main finding in this study that conservation method and not varietal differences was the reason that the HMC was utilized so much more efficiently and beneficially in this study.

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