Replacement of starch from corn with nonforage fiber from distillers grains and soyhulls in diets of lactating dairy cows¹

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ABSTRACT

Forty Holstein cows were used in a completely randomized design with a 2-wk covariate period followed by a 6-wk experimental period to evaluate incremental substitution of nonforage fiber provided by dried distillers grains with solubles (DDGS) and soyhulls (SH) for starch provided by corn in the diet. Diets provided decreasing concentrations of starch: 29% starch with 0% DDGS; 26% starch with 7% DDGS; 23% starch with 14% DDGS; and 20% starch with 21% DDGS. Diets contained 27% corn silage, 22% alfalfa hay, and 51% concentrate mix and were formulated to be 17% crude protein, 4.7% fat, and 23% neutral detergent fiber from forage. Total neutral detergent fiber increased as DDGS and SH were included in the diet. Soyhulls were included in a linear fashion along with DDGS to replace soybean meal and expeller soybean meal, thereby maintaining a similar crude protein content across diets. Dry matter intake decreased linearly; consequently, feed efficiency tended to increase linearly as starch was replaced by nonforage fiber. There was no effect of diet on milk production or milk fat and protein percentage or yield. Milk fatty acid profiles were similar across diets. Other response variables, including 4% fat-corrected milk, total solids, and milk urea nitrogen, were unaffected by dietary treatments. Ruminal volatile fatty acid concentration did not differ between diets. Concentrations of blood glucose and β -hydroxybutyrate were similar across diets. Results from this research suggest that nonforage fiber from DDGS can partially substitute for starch from corn in dairy cow diets without affecting milk production and milk composition. Economic analysis of the diets showed that feeding DDGS and SH in substitution of corn was cost-effective. Results from this experiment indicate that DDGS and SH can replace corn as an energy source to decrease feed costs.

Key words: dried distillers grain with solubles, nonforage fiber, soyhull, starch

INTRODUCTION

Starch is a major source of energy in diets fed to high-producing dairy cows and accounts for 50 to 100% of the NSC in most feedstuffs (NRC, 2001). Dairy cow diets fed in the United States typically contain between 20 and 30% starch on DM basis. Corn is the most commonly used grain for providing starch in lactating dairy cow diets. Because of its high starch content, corn permits the formulation of energy-dense diets required by high-producing dairy cows and promotes microbial protein synthesis in the rumen. However, increasing dietary starch from corn grain at the expense of forage fiber has been demonstrated to negatively affect rumen function. Excess fermentation of starch to VFA in the rumen disturbs the buffering and absorptive capacity of cows, leading to decreased ruminal pH. Feeding less forage NDF also decreases chewing, which reduces saliva production and the passage of its buffers into the rumen. As a result, lower ruminal pH may decrease appetite, fiber digestion, microbial yield, and milk fat concentration (Mould et al., 1983; Strobel and Russell, 1986; Kalscheur et al., 1997).

Corn grain is used for food, feed, and the growing bio-fuel industry. This competition for corn has tightened the supply that is available for livestock feed and, as a result, has increased feed costs. The partial replacement of starch with cost-effective, low-starch, nonforage fiber sources represents a potential alternative to help overcome these issues. Previous research conducted on partial substitution of starch with nonforage fiber sources such as soyhulls (SH; Bernard and McNeill, 1991; Ipharraguerre et al., 2002; Aikman et al., 2006), beet pulp (Clark and Armentano, 1997; Voelker and Allen, 2003), and citrus pulp (Leiva et al., 2000) has led to the replacement of significant portions of starch from dairy cow diets.

Dried distillers grains with solubles (DDGS) are a coproduct of the ethanol industry and are traditionally fed as a protein supplement as an alternative to soybean meal. They have been recognized as an excellent source of energy, attributed to their high concentration of digestible NDF and fat (Schingoethe et al., 2009). Dried distillers grains with solubles have been fed suc-

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cessfully up to 20% of DM in lactating dairy cow diets, maintaining high milk production without impairing DMI (Anderson et al., 2006; Kleinschmit et al., 2006; Schingoethe et al., 2009). Utilization of DDGS as an energy source to replace starch supplied by corn has not been reported previously. We hypothesized that replacing starch with nonforage fiber from DDGS and SH as energy sources would not affect performance of lactating dairy cows. Therefore, the primary objective was to replace starch provided by corn with nonforage fiber provided by DDGS and SH in dairy cow diets in order to evaluate feed intake, milk production, and milk composition. A secondary objective was to determine the cost-effectiveness of feeding diets in which nonforage fiber replaced starch.

MATERIALS AND METHODS

Animals and Diets

This experiment was conducted at the Dairy Research and Training Facility at South Dakota State University (Brookings), and all procedures were approved by the South Dakota Institutional Animal Care and Use Committee. Forty Holstein cows [22 multiparous (77 ± 33 DIM) and 18 primiparous (79 ± 29 DIM)] were assigned to 4 treatments (10 cows each) in a completely randomized design. All cows were fed a common diet for 2 wk (covariate period) followed by the experimental diets for 6 wk (experimental period). Diets were formulated to meet or exceed NRC (2001) requirements for mature, lactating Holstein cows of 614 kg of BW, at 60 DIM, producing 41 kg of milk. Formulated diets were to provide decreasing concentrations of starch [29, 26, 23, and 20% (DM basis)]; ground corn, solvent-extracted soybean meal, and expeller soybean meal were replaced by increasing concentrations of DDGS and SH (Table 1). The DDGS were purchased from a South Dakota ethanol plant (Glacial Lakes Energy LLC, Watertown) as a single shipment to ensure similar composition throughout the experiment. Corn silage and alfalfa were forage sources and composed 27 and 22% of diet DM, respectively, in all diets. Ruminally inert fat (Energy Booster, Milk Specialties Co., Dundee, IL) was added to all diets to increase crude fat level and to maintain similar fat concentrations for all diets (4.7%). Inclusion of the ruminally inert fat decreased from 1.38 to 0.35% as DDGS increased from 0 to 21%. Forages were premixed in a vertical mixer and blended with concentrates in a Calan Data Ranger (American Calan Inc., Northwood, NH). Cows were fed diets as a TMR once daily (0800 h) using the Calan Broadbent feeder door system (American Calan Inc.). Diets were adjusted to allow for ad libitum intake (10% orts).

Cows had unlimited access to feed and water, except during milking.

Measurements and Sampling Procedures

Feed offered and refused was recorded daily using a Calan Data Ranger (American Calan Inc.). Dry matter intake was measured individually for the 10 cows of each of the 4 treatment groups using data on daily feed offered and refused. Samples of corn silage, alfalfa, concentrate mixes, diets, and orts were collected on d 7 of each week of the experiment and stored at -20°C until analyzed. Samples of ground corn, soybean meal, expellers soybean meal (SoyPlus, West Central Soy, Ralston, IA), DDGS, SH, and a rumen-inert fat were collected 3 times when concentrates were mixed at the feed mill. All other feed samples were composited into 2-wk periods.

Cows were milked thrice daily at 0600, 1400, and 2100 h, and milk production was recorded. Milk samples were collected from each milking on 3 consecutive days at the end of the covariate period and during wk 6 of the experimental period and once each week from wk 1 to 5.

The BW and BCS of each cow were recorded on the last 3 d of the covariate period and on the last 3 d at the end of the experiment. Body condition scores were recorded independently by 3 individuals on a scale of 1 to 5, where 1 represented emaciated and 5 represented obese (Wildman et al., 1982).

Blood was collected by venipuncture of the coccygeal artery (arterial sample) approximately 3 h after feeding during the covariate period and wk 2, 4, and 6 of the experiment period. Blood was drawn into 10-mL evacuated tubes containing $\text{K}_3\text{-EDTA}$ anticoagulant (Becton Dickinson and Co., Rutherford, NJ).

Rumen fluid samples were aspirated with an esophageal tube and a hand-operated pump approximately 3 h after feeding on the last 2 consecutive days of wk 6 of the experimental period. After discarding the initial draw of 200 mL to minimize potential saliva contamination, a 10-mL aliquot of rumen fluid was acidified with 2 mL of 25% (wt/vol) metaphosphoric acid according to Erwin et al. (1961) and transported on ice to the laboratory. Samples were frozen at -20°C until analysis.

Laboratory Analyses

All feed samples were dried at 55°C for 48 h in a Despatch oven (style V-23, Despatch Oven Co., Minneapolis, MN). The dried composites were ground to 2-mm particle size (Wiley mill, model 3, Arthur H. Thomas Co., Philadelphia, PA) and then further ground

Table 1. Composition of ingredients, nutrients, and fatty acids of diets with decreasing concentrations of dietary starch fed to cows

Item	Diet ¹			
	29%	26%	23%	20%
Ingredient (% of DM)				
Corn silage	26.9	26.9	26.9	26.9
Alfalfa hay	22.1	22.1	22.1	22.1
Ground corn	35.0	29.3	23.6	17.9
Dried distillers grains with solubles	0	7.0	14.0	21.0
Soybean hulls	0	3.19	6.36	9.55
Soybean meal, 44% CP	4.53	3.21	1.89	0.56
Expellers soybean meal ²	8.43	5.61	2.82	0
Ruminally inert fat ³	1.38	1.04	0.70	0.35
Limestone	0.80	0.80	0.80	0.80
Salt	0.40	0.40	0.40	0.40
Dicalcium phosphate	0.30	0.30	0.30	0.30
Dairy micro premix ⁴	0.20	0.20	0.20	0.20
Nutrient (% of DM unless noted)				
DM (% of diet)	48.5	47.8	47.6	48.4
OM	93.0	93.1	93.1	93.2
CP	16.8	16.7	16.5	16.7
NDF	28.4	31.1	34.3	36.4
NDF from forage	22.9	22.9	22.9	22.9
ADF	16.1	17.5	19.6	20.5
NFC ⁵	43.5	40.2	36.9	34.6
Starch	29.0	26.0	23.1	19.9
Crude fat	4.35	5.07	5.37	5.48
Ash	6.99	6.95	6.88	6.83
Ca	0.93	0.93	0.94	0.97
P	0.37	0.38	0.39	0.40
Mg	0.27	0.29	0.29	0.30
K	1.26	1.26	1.26	1.26
S	0.16	0.17	0.19	0.21
NE _L ⁶ (Mcal/kg)	1.70	1.68	1.65	1.63
Fatty acid (g/100 g of total fatty acids)				
C14:0	0.86	0.73	0.79	0.82
C16:0	25.6	23.1	20.7	18.4
C16:1 <i>trans</i> -9	0.42	0.41	0.38	0.37
C16:1 <i>cis</i> -9	0.21	0.18	0.16	0.17
C17:0	0.70	0.55	0.41	0.29
C18:0	13.8	10.8	7.8	5.1
C18:1 total	15.4	17.7	18.6	20.1
C18:2 <i>trans</i> -9, <i>trans</i> -12	0.28	0.25	0.27	0.25
C18:2 <i>cis</i> -9, <i>cis</i> -12	27.1	31.2	35.1	38.3
C18:3n-3	7.6	7.2	7.5	7.4
C20:0	0.52	0.54	0.51	0.51
C20:1	0.14	0.14	0.14	0.17
C20:2	0.29	0.28	0.26	0.44
SFA ⁷	42.0	36.3	30.7	25.8
UFA ⁸	58.0	63.6	69.3	74.2
Total fatty acids (g/100 g of DM)	4.1	4.1	4.5	4.8

¹Diets provided decreasing concentrations of starch: 29% starch with 0% dried distillers grains with solubles (DDGS); 26% starch with 7% DDGS; 23% starch with 14% DDGS; and 20% starch with 21% DDGS.

²SoyPlus (West Central Soy, Ralston, IA).

³Energy Booster (Milk Specialties Co., Dundee, IL).

⁴Contained: 10% Mg; 2.6% Zn; 1.7 mg/kg of Mn; 4,640 mg/kg of Fe; 4,712 mg/kg of Cu; 396 mg/kg of I; 119 mg/kg of Co; 140 mg/kg of Se; 2,640,000 IU/kg of vitamin A; 528,000 IU/kg of vitamin D₃; and 10,560 IU/kg of vitamin E (Land O'Lakes, St. Paul, MN).

⁵NFC = 100 - (% NDF + % CP + % crude fat + % ash) (NRC, 2001).

⁶Calculated according to NRC (2001) using analyzed feed values.

⁷SFA = total concentration of saturated fatty acids.

⁸UFA = total concentration of unsaturated fatty acids.

to 1-mm particle size using an ultracentrifuge mill (Brinkman Instruments Co., Westbury, NY). Ground samples were analyzed for DM, ash, CP, NDF, ADF, crude fat, starch, minerals, and fatty acid composition. Dry matter was determined at 105°C for 3 h (Shreve et al., 2006). Ash was determined at 450°C for 8 h (Undersander et al., 1993). Crude protein was determined using the Kjeldahl procedure as described in AOAC (2002). Concentrations of NDF (Van Soest et al., 1991) and ADF (Robertson and Van Soest, 1981) were determined sequentially using the Ankom fiber analysis system (Ankom Technology, Macedon, NY). α -Amylase (Ankom Technology) and sodium sulfite were used for the NDF procedure. Crude fat was analyzed with an Ankom^{X10} Extractor (Ankom Technology) using diethyl ether according to AOCS (2004) procedures. Starch concentrations were determined using an enzyme-based (thermostable α -amylase and amyloglucosidase) total starch assay (AOAC, 2002; Total Starch Assay Procedure, Megazyme International Ireland Ltd., Wicklow, Ireland). Composites of corn silage, alfalfa hay, DDGS, and diets were sent to Dairyland Laboratories Inc. (Arcadia, WI) for mineral analysis (Ca, P, K, Mg, and S). Minerals were quantified according to AOAC (2002) using an inductively coupled plasma spectrometer (Thermo Jarrell Ash, Franklin, MA). Feed fatty acids were prepared as butyl esters according to Abdelqader et al. (2009). Prepared samples were then analyzed using gas chromatography (model 6890, Hewlett-Packard, Palo Alto, CA). The injector port was at 230°C with a split ratio of 100:1. The column was 100 m in length with an inside diameter of 0.25 mm (Supelco 2560, Supelco Inc., Bellefonte, PA). Flow-rate was 2.0 mL/min of helium. Initial temperature of the column was 50°C and held for 5 min, then increased to 145°C at a rate of 5°C/min. It was held at 145°C for 30 min, then increased to 190°C at 10°C/min to hold the temperature for 30 min. Finally, the temperature was increased at 5°C/min to 210°C and held at this temperature for 40 min. Individual fatty acids were identified by order of elution and comparison to known, commercially prepared reference standards (GLC-606 and GLC-566, Nu-Chek Prep Inc., Elysian, MN).

The 4-screen Penn State Particle Size Separator (**PSPS**; Kononoff et al., 2003) was used to determine the particle size distribution of each diet andorts. The DM and NDF were determined on the particles retained on each sieve. The physical effectiveness factor (**pef**) was calculated as the proportion of particles retained (DM basis) on the top 2 screens ($\text{pef}_{\text{ps-2s}}$; Lammers et al., 1996) and on the top 3 screens ($\text{pef}_{\text{ps-3s}}$; Kononoff et al., 2003). Physically effective NDF (peNDF_{PS}) was calculated as dietary NDF multiplied by **pef**.

The collected milk samples were composited by day on a weight basis proportional to yield and separated into 2 aliquots. The first aliquot was sent to Heart of America DHIA Laboratory (Manhattan, KS) for milk composition analysis. Mid-infrared spectroscopy (Bentley 2000 Infrared Milk Analyzer, Bentley Instruments, Chaska, MN; AOAC, 2002) was used to analyze milk fat, protein, and lactose, whereas MUN concentration was determined using chemical methodology based on a modified Berthelot reaction (ChemSpec 150 Analyzer, Bentley Instruments). Somatic cell counts were determined using a flow cytometer laser (Somacount 500, Bentley Instruments; AOAC, 2002). Somatic cell counts were converted to SCS where $\text{SCS} = \log_{10}(\text{SCC})$. Energy-corrected milk was determined using the following equation: $\{[0.327 \times \text{milk yield (kg)}] + [12.95 \times \text{fat yield (kg)}] + [7.2 \times \text{protein yield (kg)}]\}$ (Orth, 1992). A second aliquot of milk samples collected at the end of the covariate period and wk 6 of the experimental period was analyzed for fatty acid composition. Milk fatty acids were prepared as described by Abdelqader et al. (2009) and analyzed by gas chromatography as described above.

The collected blood samples were immediately placed in ice and taken to the laboratory, where they were centrifuged ($500 \times g$) for 20 min to separate the plasma. The plasma was stored at -20°C until analysis. Plasma samples were thawed and analyzed for glucose using glucose oxidase (glucose kit, cat. no. G7521, Pointe Scientific, Canton, MI) according to Trinder (1969). Concentration of BHBA in plasma was determined (BHBA kit, cat. no. H7587-58, Pointe Scientific) following the methods of Williamson et al. (1962).

Ruminal samples were thawed and centrifuged at $30,000 \times g$ for 20 min. Concentrations of VFA were measured using an automated gas-liquid chromatograph (model 6890, Hewlett-Packard) using a flame-ionization detector. Volatile fatty acids were separated on a capillary column (15 m $\times$ 0.25 mm i.d.; Nukol, 17926-01C, Supelco Inc., Bellefonte, PA) using 2-ethylbutyrate as an internal standard. The split ratio of 100:1 in the injector port was at a temperature of 250°C with flow-rate of 1.3 mL/min of He. The column and detector temperature were maintained at 140°C and 250°C, respectively.

Data Analyses

Weekly means for feed intake, milk yield, milk composition, and particle size were used for statistical analysis. All data were analyzed by the MIXED procedure in SAS (SAS, 2001) in a completely randomized design. The model for feed intake, milk yield, milk composi-

tion, and blood parameters was $Y = \text{covariate period} + \text{treatment} + \text{parity} + \text{week} + (\text{treatment} \times \text{parity}) + (\text{treatment} \times \text{week}) + (\text{parity} \times \text{week}) + (\text{treatment} \times \text{parity} \times \text{week})$, where the random effect was cow nested within treatment and parity. The model for the particle size data was $Y = \text{treatment} + \text{week} + (\text{treatment} \times \text{week})$. The model for fatty acid data was $Y = \text{covariate period} + \text{treatment} + \text{parity} + (\text{treatment} \times \text{parity})$, where the random effect was cow nested within treatment and parity. The same model was used for rumen measures, BW change, and BCS change, except that there was no covariate period. Week was used as repeated measures when included in the model with the covariance structure corresponding to the lowest value according to the Akaike's information criterion being selected (Littell et al., 2006). Nonsignificant interactions were sequentially dropped from the model. Significant interactions are identified in the results and tables. Least squares means are reported for each variable. Polynomial orthogonal contrasts were used to test the linear, quadratic, and cubic effects of decreasing inclusion of dietary starch. Statistical significance of main effects was declared at $P \leq 0.05$, and tendencies were discussed at $0.05 \leq P \leq 0.10$.

An economic analysis was conducted to compare the income over feed cost (IOFC) of diets using the following formula: $\text{IOFC} = (\$/\text{cow per d}) = \text{all-milk price } (\$/\text{kg}) \times \text{daily average milk production } (\text{kg}/\text{cow per day}) - \text{daily feed cost } (\$/\text{cow per day})$. Six-year average prices (2003–2008) were used for corn silage (\$31.50/t), alfalfa hay (\$128.00/t), ground corn (\$0.12/kg), soybean meal (\$0.26/kg), expellers soybean meal (\$0.34/kg), DDGS (\$0.13/kg), SH (\$0.10/kg), rumen-inert fat (\$1.21/kg), dicalcium phosphate (\$0.36/kg), dairy micro premix (\$0.82/kg), limestone (\$0.05/kg), and salt (\$0.16/kg). Price of corn silage was calculated as the price of corn grain/bushel $\times 10$. Prices of corn grain and alfalfa hay were obtained from Economic Research Service (USDA, 2009), and prices of all other ingredients were obtained from the South Dakota State University Feed Processing Unit (Brookings). Milk component prices were calculated from South Dakota State University Dairy Research and Training Facility from 2003 to 2008. Six-year average prices of milk fat, protein, and other solids were \$3.47/kg, \$6.27/kg, and \$0.24/kg, respectively.

RESULTS AND DISCUSSION

Dietary Nutrient Composition

The chemical composition of all diets, concentrate mixes, corn silage, alfalfa hay, DDGS, ground corn, and SH used in the experiment are presented in Tables 1

and 2. Crude protein concentration was similar across diets, and all values were similar to the formulated CP concentration of 17.0%. As expected, NDF and ADF concentration increased numerically with higher DDGS and SH in the diets. Starch concentration in the diets decreased from 29 to 20% as corn was removed. Diets were also formulated to have similar concentrations of crude fat (4.7%), but crude fat increased from 4.35 to 5.48% of the diet DM as DDGS was included in the diets. This resulted from DDGS having a slightly greater concentration of fat (13.8%) than the value used in the original formulation (10.3%). Mineral concentrations were similar except for S, which numerically increased from 0.16 to 0.21% as DDGS were included.

Total fatty acids numerically increased from 4.1 to 4.8%, the result of ingredient changes as starch decreased from 29 to 20% in the diets (Table 1). Fatty acid composition changed across diets (Table 1); C16:0 and C18:0 numerically decreased and C18:1 and C18:2 increased as corn was replaced with DDGS and SH. Changes in fatty acid composition can be explained by reviewing the fatty acid profiles of individual dietary ingredients. Ruminally inert fat and DDGS were the main ingredients that affected fatty acid profiles of diets. Because ruminally inert fat contained a greater proportion of saturated fatty acids, particularly C16:0 and C18:0, a greater concentration of saturated fatty acids was observed in the higher starch diets. Conversely, unsaturated fatty acid concentration was greater in DDGS; therefore, more unsaturated fatty acids were observed in diets with greater DDGS inclusion.

Dietary Particle Size

Feed particles separation using the PSPS (Table 3) showed that, for all diets, the top screen retained an average of 9.1% on as-fed basis and 8.0% when corrected for DM. The separations based on as-fed basis demonstrated that, on one hand, the proportion of particles retained on the top 2 screens linearly decreased as diets increased in nonforage NDF and decreased in starch concentration. On the other hand, particles retained on the third screen increased when the concentration of nonforage fiber increased, but there was no difference across diets for particles remaining in the bottom pan. On a DM basis, particles retained on the top screen were similar across all diets, probably because all diets contained similar amounts of forage. Particles retained on the second screen increased quadratically ($P = 0.05$) when starch from corn was removed from the diets. The portion of the diet remaining on the third screen increased linearly ($P < 0.001$) and on the bottom pan decreased linearly ($P < 0.001$) as nonforage fibers replaced starch. This evolution contributed to an increase

Table 2. Composition of nutrients and fatty acids of concentrate mixes, corn silage, alfalfa hay, dried distillers grains with solubles (DDGS), ground corn, soy hulls, and ruminally inert fat used in diets during the lactation study

Item	Concentrate mix ¹				Corn silage ²	Alfalfa hay ³	DDGS ⁴	Ground corn	Soy hulls	Ruminally inert fat
	29%	26%	23%	20%						
Nutrient (% of DM unless noted)										
DM (%)	87.6	88.5	89.0	90.0	22.0	87.9	89.9	86.8	93.2	96.7
CP	19.1	18.9	18.5	18.9	8.8	21.2	30.8	8.0	13.5	0
NDF	10.8	16.0	22.3	26.5	56.8	33.5	32.6	8.1	58.0	0
ADF	3.3	6.0	10.1	12.0	33.9	24.0	9.3	2.0	39.6	0
Starch	50.6	44.6	38.9	32.8	9.8	2.5	9.7	74.4	2.1	0
Crude fat	4.52	5.20	6.50	7.89	5.13	2.55	13.8	2.83	3.05	100
Ash	5.23	5.50	5.45	5.49	5.14	10.7	3.96	1.32	5.22	0
Fatty acid (g/100 g of total fatty acids)										
C14:0	1.8	1.1	0.23	0.23	6.4	1.4	0.42	—	—	3.5
C16:0	32.7	26.6	22.8	18.1	19.3	22.8	14.7	—	—	40.7
C16:1 <i>trans</i> -9	0.06	0.07	0.05	0.06	0.86	2.10	0.06	—	—	0.04
C16:1 <i>cis</i> -9	0.18	0.18	0.16	0.15	0.12	0.15	0.13	—	—	0.33
C17:0	1.02	0.71	0.52	0.27	0.31	0.26	0.11	—	—	1.8
C18:0	22.0	14.4	11.0	5.3	2.3	3.0	1.9	—	—	40.4
C18:1 total	16.9	21.8	23.2	25.7	11.3	4.1	26.9	—	—	9.4
C18:2 <i>trans</i> -9, <i>trans</i> -12	0.04	0.06	0.07	0.06	0.25	1.3	0.15	—	—	0
C18:2 <i>cis</i> -9, <i>cis</i> -12	19.6	29.7	35.5	43.4	26.8	17.4	50.7	—	—	0.63
C18:3n-3	1.1	1.4	1.7	1.8	20.1	25.5	1.6	—	—	0
C20:0	0.49	0.44	0.46	0.41	0.58	1.1	0.39	—	—	0
C20:1	0.15	0.18	0.19	0.20	0.11	0.06	0.22	—	—	0.06
C20:2	0.01	0.02	0.03	0.03	0.26	1.8	0.03	—	—	0
SFA ⁵	58.4	43.6	35.5	24.8	29.9	30.0	18.0	—	—	87.3
UFA ⁶	41.6	56.4	64.5	75.2	70.1	70.0	82.0	—	—	12.7
Total fatty acids (g/100 g of DM)	4.1	5.3	5.7	6.8	2.1	1.9	11.6	—	—	97.4

¹Concentrate mixes of diets that provided decreasing concentrations of starch: 29% starch with 0% DDGS; 26% starch with 7% DDGS; 23% starch with 14% DDGS; and 20% starch with 21% DDGS.

²Mineral analysis of corn silage: 0.26% Ca, 0.23% P, 0.26% Mg, 1.11% K, and 0.10% S.

³Mineral analysis of alfalfa hay: 1.55% Ca, 0.28% P, 0.35% Mg, 2.02% K, and 0.18% S.

⁴Mineral analysis of DDGS: 0.06% Ca, 0.69% P, 0.30% Mg, 0.86% K, and 0.51% S.

⁵SFA = total concentration of saturated fatty acids.

⁶UFA = total concentration of unsaturated fatty acids.

in the proportion of particles greater than the critical value of 1.18 mm; this was probably the result of SH inclusion because DDGS typical mean particle size is smaller than 1.18 mm (Kleinschmit et al., 2007).

The NDF concentrations for each fraction from PSPS showed that it was greatest in the fraction obtained from the top 2 screens. The NDF concentrations of the fractions obtained from the third screen and bottom pan linearly increased as starch decreased in the diets. The physical effectiveness factor ($\text{pef}_{\text{ps-2s}}$) was similar across all diets when calculated using the fractions obtained from the top and second screens. However, there was a linear increase ($P < 0.001$) for the $\text{pef}_{\text{ps-3s}}$ as DDGS and SH replaced corn in the diets. A similar pattern was observed for peNDF . Physically effective NDF increased linearly ($P < 0.001$) as DDGS and SH replaced corn in the diets. Differences in calculated pef across diets further explained the effective fiber contribution of the byproduct's fiber portion. The particle size distribution, pef , and peNDF were also determined on the orts of each diet (data not shown for particle size distribution of orts). Measurements for the orts samples

were very similar to the numbers reported for the TMR diets, indicating no significant sorting occurred during the experiment. This indicated that diets used in this experiment were properly mixed and that nutrient intake was not influenced by particle size.

Rumen Fluid and Blood Analysis

Decreasing dietary starch concentration did not change total VFA concentration (Table 4). Molar proportions of acetate linearly decreased ($P = 0.03$) when dietary starch was replaced with nonforage fiber; however, molar proportions of other VFA, including propionate, butyrate, valerate, isobutyrate, and isovalerate, were similar across all diets. The observed linear decrease of acetate concentration with greater DDGS and SH concentrations in the diets was probably attributable to decreased forage NDF intake or greater concentration of unsaturated fatty acids in the diets with greater DDGS concentration. There was a linear decrease ($P = 0.04$) in the acetate:propionate ratio, resulting primarily from the linear decrease in acetate

Table 3. Particle size distribution, physical effectiveness factor (pef), and physically effective NDF of diets with decreasing concentrations of dietary starch

Item	Diet ¹				SEM	Contrast (<i>P</i> -value)		
	29%	26%	23%	20%		Linear	Quadratic	Cubic
PSPS distribution ²								
% retained (as-fed basis)								
Top screen (19 mm)	9.7	9.6	8.6	8.5	0.32	0.003	0.95	0.22
Second screen (8 mm)	38.3	36.6	35.0	35.0	0.45	<0.001	0.06	0.48
Third screen (1.18 mm)	34.7	36.5	38.9	39.5	0.38	<0.001	0.16	0.17
Bottom pan	17.3	17.3	17.5	17.0	0.30	0.60	0.34	0.56
% retained (DM basis)								
Top screen (19 mm)	7.8	8.6	7.8	7.7	0.36	0.51	0.20	0.13
Second screen (8 mm)	27.3	30.6	29.7	29.8	0.81	0.08	0.05	0.16
Third screen (1.18 mm)	33.0	39.5	41.9	42.7	0.79	<0.001	0.001	0.49
Bottom pan	31.9	21.2	20.6	19.8	1.57	<0.001	0.003	0.16
% NDF retained (DM basis)								
Top screen (19 mm)	47.5	47.7	46.5	47.0	0.33	0.72	0.41	<0.001
Second screen (8 mm)	46.6	48.1	47.7	48.6	0.18	<0.001	0.004	0.51
Third screen (1.18 mm)	20.0	24.8	29.3	33.2	0.10	<0.001	0.05	<0.001
Bottom pan	13.7	17.8	21.4	23.8	0.18	<0.001	0.17	0.61
pef _{ps-2s}	35.1	39.2	37.5	37.5	1.02	0.25	0.05	0.11
pef _{ps-3s}	68.1	78.8	79.4	80.2	1.56	<0.001	0.003	0.16
peNDF _{ps-2s} (% of DM)	10.0	12.2	12.8	13.6	0.32	<0.001	0.03	0.24
peNDF _{ps-3s} (% of DM)	19.3	24.5	27.2	29.2	0.43	<0.001	0.001	0.41

¹Diets provided decreasing concentrations of starch: 29% starch with 0% dried distillers grains with solubles (DDGS); 26% starch with 7% DDGS; 23% starch with 14% DDGS; and 20% starch with 21% DDGS.

²Particle size distribution of diets was measured using Penn State Particle Separator (PSPS; Kononoff and Heinrichs, 2003); pef_{ps-2s} and pef_{ps-3s} = physical effectiveness factor determined as the proportion of particles retained on 2 sieves (Lammers et al., 1996) and 3 sieves (Kononoff and Heinrichs, 2003), respectively; peNDF_{ps-2s} and peNDF_{ps-3s} = physically effective NDF determined as dietary NDF content multiplied by pef_{ps-2s} and pef_{ps-3s}, respectively.

concentration, when starch was replaced with nonforage fiber in the diets. There was no treatment effect on either the plasma glucose or BHBA (Table 4). Average concentration of plasma glucose and BHBA concentrations were 64.7 and 8.5 mg/dL, respectively.

Intake, BW, and BCS

Nutrient intakes, BW, and BCS of cows during the experiment are presented in Table 5. Dry matter in-

take decreased linearly ($P = 0.005$) when DDGS and SH replaced corn, with the highest DMI recorded for the 29% starch diet (25.6 kg/d) and the lowest for the 20% starch diet (22.9 kg/d). Previous experiments have reported a variety of DMI responses to the substitution of nonforage fiber for starch. In agreement with our findings, DMI was reduced with increasing SH in Ipharraguerre et al. (2002) and Aikman et al. (2006). Conversely, DMI was not affected by increasing SH, with dietary NDF increasing from 31 to 57.6% and

Table 4. Ruminal volatile fatty acids (VFA) concentrations and plasma metabolites of cows fed diets with decreasing concentrations of dietary starch

Item	Diet ¹				SEM	Contrast (<i>P</i> -value)		
	29%	26%	23%	20%		Linear	Quadratic	Cubic
Total VFA (mM)	77.9	76.0	75.8	78.8	6.22	0.92	0.70	0.96
VFA (mmol/100 mmol)								
Acetate	61.8	61.9	61.9	60.7	0.30	0.03	0.06	0.46
Propionate	17.1	17.0	17.1	18.0	0.42	0.12	0.74	0.45
Butyrate	11.5	11.4	11.5	11.6	0.13	0.41	0.36	0.83
Isobutyrate	3.28	3.25	3.24	3.23	0.13	0.78	0.96	0.99
Valerate	3.23	3.27	3.26	3.31	0.11	0.66	0.95	0.82
Isovalerate	3.08	3.00	3.03	2.98	0.12	0.63	0.88	0.71
Acetate:propionate	3.63	3.67	3.63	3.37	0.09	0.04	0.11	0.72
Plasma metabolites								
Glucose (mg/dL)	65.7	63.0	65.7	64.2	2.3	0.87	0.79	0.31
BHBA (mg/dL)	8.5	8.6	8.1	8.7	0.4	0.92	0.55	0.41

¹Diets provided decreasing concentrations of starch: 29% starch with 0% dried distillers grains with solubles (DDGS); 26% starch with 7% DDGS; 23% starch with 14% DDGS; and 20% starch with 21% DDGS.

Table 5. Nutrient intake, BW, BCS, milk yield, milk composition, and feed efficiency of cows fed diets with decreasing concentrations of dietary starch

Item	Diet ¹				SEM	Contrast (<i>P</i> -value)		
	29%	26%	23%	20%		Linear	Quadratic	Cubic
Intake (kg/d)								
DM	25.6	25.0	23.4	22.9	0.72	0.005	0.90	0.52
CP	4.34	4.18	3.91	3.80	0.12	0.006	0.83	0.60
NDF (total)	7.20	7.64	7.94	8.34	0.24	0.001	0.94	0.84
NDF (forage)	5.84	5.64	5.35	5.23	0.17	0.006	0.81	0.73
NDF (nonforage)	1.40	1.98	2.66	3.11	0.07	<0.001	0.56	0.50
ADF	4.12	4.28	4.57	4.60	0.13	0.003	0.59	0.49
Starch	7.32	6.29	5.32	4.62	0.18	<0.001	0.34	0.79
BW (kg)	691	678	681	689	18	0.99	0.57	0.91
BCS	3.49	3.27	3.23	3.38	0.12	0.49	0.12	0.98
BW change (kg)	10.1	12.9	9.3	4.2	5.5	0.37	0.46	0.84
BCS change	0.27	0.22	0.19	0.10	0.07	0.08	0.74	0.85
Production (kg/d)								
Milk ²	39.4	37.4	37.7	38.3	1.03	0.51	0.21	0.63
ECM ²	37.3	36.3	36.5	36.1	1.08	0.48	0.77	0.72
Milk composition								
Fat (%)	3.14	3.23	3.29	3.24	0.11	0.46	0.51	0.84
Fat ² (kg/d)	1.24	1.23	1.22	1.22	0.05	0.75	0.94	0.96
Protein (%)	2.97	2.96	3.01	2.94	0.04	0.89	0.43	0.30
Protein ² (kg/d)	1.17	1.11	1.10	1.13	0.04	0.37	0.28	0.94
Lactose (%)	4.96	4.91	4.90	4.99	0.03	0.47	0.01	0.65
Lactose ² (kg/d)	1.95	1.85	1.83	1.90	0.06	0.50	0.12	0.99
Total solids (%)	12.0	12.0	12.1	12.1	0.12	0.43	0.93	0.83
Total solids ² (kg/d)	4.73	4.54	4.55	4.58	0.13	0.46	0.40	0.78
MUN (mg/dL)	11.7	12.2	11.6	12.2	0.38	0.64	0.85	0.18
Feed efficiency ² (ECM/DMI)	1.47	1.47	1.54	1.61	0.06	0.07	0.57	0.81
SCS	4.08	4.08	3.96	4.18	0.39	0.92	0.79	0.79

¹Diets provided decreasing concentrations of starch: 29% starch with 0% dried distillers grains with solubles (DDGS); 26% starch with 7% DDGS; 23% starch with 14% DDGS; and 20% starch with 21% DDGS.

²Interaction of parity $\times$ week ($P < 0.05$).

NSC decreasing from 47 to 22% in Nakamura and Owen (1989), Sarwar et al. (1992), and Mansfield and Stern (1994). Nakamura and Owen (1989) hypothesized that SH dietary inclusion may improve the digestion or the passage rate or a combination of both. This effect could have counteracted the increase of NDF above 32%, which is suggested to be the limit above which NDF depresses DMI (Mertens, 1994).

The reasons for the decrease of DMI with increasing nonforage fiber as observed in the present results are varied. Factors such as total NDF, fiber effectiveness, forage NDF concentration, source of nonforage fiber, and other characteristics (i.e., water-holding capacity, specific gravity, rumen degradability, or fatty acid composition of the diet) might affect DMI. Firkins (1997) suggested that decreasing the forage NDF concentration to less than 14 to 16% of the total DM might also decrease DMI when fibrous byproducts are included in the diets. This decrease in DMI could be attributed to a factor such as decreasing the effectiveness of those diets to stimulate rumination and salivation. In addition, an accumulation of acids and decreased pH of ruminal fluid caused by rapid fermentation of the

more-digestible fiber from nonforage sources could also decrease DMI (Harmison et al., 1997).

Dietary NDF and DMI are inversely and strongly correlated (Mertens, 1994), but NDF from SH may not restrict DMI to the same extent as NDF from forages (Ipharraguerre and Clark, 2003). On one hand, DMI and NDF correlate negatively when forages are the main or sole source of NDF. On the other hand, SH contain a pool of potentially degradable NDF greater than that of most forages. Finally, the smaller particle size and higher specific gravity of SH could double the rumen passage rate compared with forages (Ipharraguerre and Clark, 2003). The decrease in DMI observed in the present experiment when substituting grain with high-fiber byproducts may physically limit the rumen fill (Forbes, 1995). In fact, forage NDF was higher than recommended (NRC, 2001) and VFA concentrations were not altered, which cannot relate decreased DMI with changes in VFA. Moreover, DMI should not have been reduced by DDGS in this study because the DMI depression with dietary inclusion of DDGS does not typically occur until their inclusion exceeds 20 to 30% (Kalscheur, 2005; Anderson et al., 2006; Kleinschmit

et al., 2006; Sasikala-Appukuttan et al., 2008; Schingoethe et al., 2009). In the present study, the decrease in DMI began with the lowest inclusion of byproducts (7% of DDGS + 3.1% of SH) and continued as additional nonforage fiber replaced starch. The dietary NDF content was 31.1% or higher for all the diets with byproducts inclusion, which is close to the 32% level suspected to affect DMI (Mertens, 1994). Consequently, the increased dietary NDF content resulting from the inclusion of byproducts may have filled the rumen, which in turn reduced DMI.

In the present study, inclusion of DDGS in the diets increased the dietary fat concentration from 4.35 to 5.48% on DM basis, and this led to increased unsaturated fatty acid concentration from 58 to 74.2% on DM basis. Greater dietary fat concentration can be another possible reason to decrease DMI. Allen et al. (2005) demonstrated that an increase in unsaturated long-chain fatty acids has a hypophagic effect that could decrease intake. Therefore, greater unsaturated fatty acid concentration might have stimulated the satiety receptors and decreased DMI. Similar linear decreases in DMI when wet distillers grains and SH replaced corn and soybean meal have been observed in a study conducted on growing Holstein heifers (Anderson et al., 2009).

All the diets contained the same dietary amounts of CP (17%) and forage NDF (22.9%), but as shown in Table 5, the decrease in DMI also linearly decreased CP and forage NDF intakes ($P = 0.006$). Conversely, total NDF, nonforage NDF, and total ADF intakes increased linearly ($P < 0.01$). As expected, starch intake decreased linearly ($P < 0.001$) according to diet formulation. Starch intake decreased 2.7 kg/d when dietary starch decreased from 29 to 20%. Average BW of cows during the experiment was 685 kg, and there was no treatment effect on BW. Average BCS varied from 3.27 to 3.49, but no differences were observed for BCS when diets varied in starch concentration. There were no observed BW changes during the experimental period, but there was a tendency ($P = 0.08$) for change in BCS for cows fed diets containing lower starch concentrations.

Milk Production and Composition

Milk production averaged 38.2 kg/d per cow for all treatments (Table 5) and was not affected by starch replacement with nonforage fiber in the diets. A parity $\times$ week interaction ($P < 0.05$) was observed for milk yield because primiparous cows were more persistent in production for the duration of the 6-wk experiment, whereas multiparous cows decreased at a greater weekly rate. Similarly, yields for ECM and 4% FCM did not change. Ipharraguerre et al. (2002) showed there was

no effect on milk and FCM when SH was included up to 30% in the diet as a replacement for corn. Decreasing dietary starch from 30.2 to 14.0% by replacing wheat with SH also had no effect on milk and FCM yields (Aikman et al., 2006). Several studies in which SH replaced ground corn up to maximum of 25% DM also observed no effect of SH inclusion on milk yield (Bernard and McNeill, 1991), but inclusion of SH beyond 30% decreased milk yield and ECM (Nakamura and Owen, 1989; Ipharraguerre et al., 2002). Inclusion of SH up to 40% of the dietary DM to replace corn might have decreased milk production by restricting both amount and source of energy available (Ipharraguerre et al., 2002). This could have been attributed to decreased DMI and to a decreased amount of NSC digested in the rumen and intestine.

Milk component yields, including fat, protein, lactose, and total solids, were also not affected by diet. Interactions of parity $\times$ week ($P < 0.05$) were observed for yields of FCM, fat, protein, lactose, and total solids resulting from differences observed in milk yield. Percentages of fat, protein, lactose, and total solids followed the same pattern, where no significant differences were observed. Milk fat percentage was unaffected when lactating dairy cows were fed diets with 30% or less SH on DM basis in place of starch (Mansfield and Stern, 1994; Aikman et al., 2006). Mansfield and Stern (1994) suggested that similar molar percentages of total lipogenic VFA (acetate and butyrate) may have resulted in similar milk fat percentage compared with diets with high concentrations of corn. However, milk fat percentage or yield normally increases when SH replaces more than 30% of corn in high-grain diets (Nakamura and Owen, 1989; Sarwar et al., 1992; Ipharraguerre et al., 2002). No dietary effect on milk protein composition and yield in the present study agrees with previous research by Ipharraguerre et al. (2002). However, Aikman et al. (2006) reported that milk protein concentration decreased linearly as SH replaced wheat starch concentration in lactating dairy cow diets. These authors postulated that the lower milk protein concentration could be attributed to limited mammary protein synthesis because inclusion of SH may decrease the concentration of specific AA (methionine) and low degradability of SH protein. Milk urea nitrogen was not affected by reducing dietary starch. Feed efficiency, defined as ECM/DMI, tended to increase linearly ($P < 0.07$) as starch from corn was replaced with nonforage NDF from DDGS and SH (Table 5). The greatest feed efficiency was observed for the diet with the lowest starch concentration. This could possibly be attributable to lower availability of fat and protein from DDGS in the rumen and increased passage to the small intestine, where they are directly utilized by the animal with

Table 6. Fatty acid composition of milk from cows fed diets with decreasing concentrations of dietary starch

Fatty acid (g/100 g of total fatty acids)	Diet ¹				SEM	Contrast (<i>P</i> -value)		
	29%	26%	23%	20%		Linear	Quadratic	Cubic
<C16:0	28.5	27.4	27.8	27.0	0.86	0.29	0.88	0.48
C16:0	29.9	31.3	29.3	30.3	1.06	0.90	0.85	0.19
Total C18	36.6	35.7	37.1	37.4	1.62	0.60	0.71	0.64
C18:1 total	22.3	22.1	23.0	23.4	1.03	0.37	0.81	0.74
C18:1 <i>trans</i> -9	0.21	0.21	0.25	0.22	0.03	0.72	0.59	0.50
C18:1 <i>trans</i> -10	0.51	0.49	0.46	0.49	0.05	0.68	0.64	0.66
C18:1 <i>trans</i> -11	1.03	1.05	0.99	0.94	0.10	0.45	0.75	0.82
C18:1 <i>cis</i> -9	18.8	19.0	19.3	19.8	0.79	0.36	0.88	0.97
Other C18:1 <i>cis</i>	1.52	1.66	1.63	1.76	0.16	0.35	0.96	0.67
C18:2 <i>cis</i> -9, <i>cis</i> -12	3.28	3.00	3.11	2.94	0.20	0.31	0.79	0.47
CLA ² (<i>trans</i> -10, <i>cis</i> -12)	0.01	0.02	0.02	0.02	0.01	0.35	0.39	0.60
CLA (<i>cis</i> -9, <i>trans</i> -11)	0.51	0.56	0.52	0.50	0.05	0.76	0.53	0.64
C18:3n-3	0.58	0.51	0.55	0.58	0.03	0.66	0.09	0.29

¹Diets provided decreasing concentrations of starch: 29% starch with 0% dried distillers grains with solubles (DDGS); 26% starch with 7% DDGS; 23% starch with 14% DDGS; and 20% starch with 21% DDGS.

²CLA = conjugated linoleic acid.

a greater efficiency (Klopfenstein et al., 2008; Anderson et al., 2009). In contrast to DDGS, fat and protein from corn and soybeans are subjected to greater degradation and fermentation in the rumen, resulting in lower feed efficiency.

Milk fatty acid profiles are shown in Table 6. Reducing dietary starch concentration by replacing it with nonforage fiber had no effect on any of the fatty acids or fatty acid classes across diets. Even though dietary unsaturated fatty acids increased from 58.0 to 74.2% and, more specifically, linoleic acid increased from 27.1 to 38.3% of the total fatty acids as dietary starch decreased across diets (Table 1), there was no effect on milk fatty acid composition (Table 6). No differences in milk fat and milk fatty acid composition across all treatments leads to speculation that all cows maintained normal rumen function during the study and that ruminal biohydrogenation by rumen microorganism was not affected by dietary treatments. Therefore, in this study, adequate physically effective fiber resulted in normal rumen function even though unsaturated fat from DDGS was substantially increased as nonforage fiber replaced starch.

Economic Analysis of the Diets

Average price for class III milk used for all calculations was \$0.31/kg, and the same value was used when calculating IOFC because there were no differences observed for milk components. Calculated feed costs (\$/cow per day) were 4.91, 4.53, 3.94, and 3.49 for 29, 26, 23, and 20% starch diets, respectively. Calculated IOFC (\$/cow per day) were 7.02, 7.40, 7.98, and 8.44 for 29, 26, 23, and 20% starch diets, respectively. The

economic analysis of the present study showed that there was a decrease in feed cost when corn starch was replaced with DDGS and SH. This was attributable to replacing corn, soybean meal, and expellers soybean meal with lower cost, nonforage fiber sources, in combination with greater feed efficiency demonstrated by cows fed lower-starch diets. The economic advantage gained from feeding DDGS and SH by replacing starch was reflected in IOFC. According to IOFC analysis, an economic advantage of \$1.42/cow per day was observed in this study when feeding the 20% starch diet compared with the 29% starch diet.

CONCLUSIONS

Replacing starch from corn with nonforage NDF from DDGS and SH in lactating dairy cow diets did not affect milk production or composition. Dry matter intake decreased as nonforage fiber replaced starch in the diets. There was a tendency to increase feed efficiency as DMI was decreased at higher nonforage fiber concentrations. Moreover, increased feed efficiency and the replacement of higher cost starch and protein feedstuffs with lower cost nonforage fiber and protein feedstuffs decreased diet feed costs. Greater conversion of feed to milk combined with lower cost diets could increase profitability from cows fed diets formulated with greater amounts of nonforage feedstuffs at lower dietary starch concentrations.

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