Whole Linted Cottonseed as a Forage Substitute Fed with Ground or Steam-flaked Corn: Digestibility and Performance^{1, 2}

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ABSTRACT

Six ruminally and duodenally cannulated Holstein cows were used in a 6 × 6 Latin square design. The objective was to evaluate any potential interactions in site of nutrient digestion when neutral detergent fiber (NDF) from cottonseed was incrementally substituted for forage NDF (FNDF) from alfalfa silage and when starch availability was varied by feeding ground (G) or steam-flaked (SF) corn. Iso-NDF diets were forage control with G corn (21% FNDF), 5% whole cottonseed (WCS) with G or SF corn (18% FNDF), 10% WCS with G or SF corn (15% FNDF), and 15% WCS with G corn (12% FNDF). Ruminal or total tract digestibilities of organic matter (OM) or nonstructural carbohydrate (NSC) were unaffected, but efficiency of microbial protein synthesis decreased as WCS increased. Ruminal NDF digestibility was not affected despite a linear decrease in pH, but postruminal NDF digestibility decreased with increasing WCS. Ruminal digestibilities of OM and NSC were higher for SF than G corn but did not affect efficiency of microbial N synthesis. Dry matter intake increased quadratically with increasing level of WCS but decreased when SF replaced G corn. Milk yield did not differ across treatments. Milk fat percentage was affected quadratically and milk protein increased linearly with increasing WCS. Milk fat percentage decreased but milk protein was not affected when SF replaced G corn. Lack of an interaction between corn source and level of WCS substitution suggests that WCS was equally effective in maintaining ruminal fermentation and digestibility in diets varying in ruminal starch availability.

(**Key words:** corn processing, starch digestion, fiber digestion, whole cottonseed)

Abbreviation key: ADIN = acid detergent insoluble N, FCG = forage control with ground corn, FNDF = forage NDF, G = ground corn, HG = high cottonseed with ground corn, LG = low cottonseed with ground corn, LSF = low cottonseed with steam-flaked corn, MG = medium cottonseed with ground corn, MSF = medium cottonseed with steam-flaked corn, NDIN = neutral detergent insoluble N, NFFS = nonforage fiber source, SF = steam-flaked corn, WCS = whole cottonseed.

INTRODUCTION

Grain processing increases ruminal starch availability (Theurer et al., 1999). The combined effects of heat, steam, and pressure during steam-flaking increase starch availability by disrupting the protein matrix surrounding the starch granule and by gelatinizing the starch (Theurer et al., 1999). Increased ruminal starch availability has negatively affected NDF digestibility (Poore et al., 1993a; Plascencia and Zinn, 1996; Joy et al., 1997) and efficiency of microbial protein synthesis (Firkins, 1996) due to low ruminal pH (Russell, 1998). To maintain ruminal pH, the increased production of fermentative acids must be balanced with physically effective fiber to minimize negative associative effects from rapid ruminal starch degradability (Allen, 1997).

The previous NRC (1989) suggested that 75% of the dietary fiber should be provided as forage, which is equivalent to 21% of DM as forage NDF (FNDF). Although the current NRC (2001) suggests that minimum FNDF can be decreased when dietary NSC concentration is decreased, improved quantification of the effectiveness of forage and nonforage fiber sources (NFFS) would reduce variation in ration formulations. Replacement of NDF from NFFS for FNDF has reduced DMI when FNDF decreased below 14 to 16% (Firkins, 1997), but lactation performance was maintained in diets with 11 to 12% FNDF when whole cottonseed (WCS) replaced forage and when nonfiber carbohydrate was simultaneously reduced by WCS and other NFFS (Clark and Armentano, 1997; Slater et al., 2000). Replacing

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starch sources with NFFS increased ruminal pH (Swain and Armentano, 1994; Firkins, 1997), but some NFFS had low NDF digestibility when substituted for forage, apparently because of faster passage rates and slower digestion rates (Firkins, 1997). Despite the common usage of WCS as a forage substitute, site and extent of WCS digestion have not been extensively evaluated when WCS was fed as a forage replacement.

Although soybean hulls (Weidner and Grant, 1994) and wet corn gluten feed (Allen and Grant, 2000) interacted with forage to alter passage rate, NDF effectiveness, and digestibility, the potential interaction of WCS and forage have not been researched adequately. Because WCS appears to be the most effective NFFS source but its effectiveness varied inversely with the effectiveness of the forage (Mooney and Allen, 1997), high levels of WCS may not be effective enough to maintain ruminal pH and digestibility in diets higher in ruminal starch availability. Thus, our objectives were to evaluate potential interactions in site of nutrient digestion and lactation performance as WCS replaced forage and when steam-flaked (**SF**) or ground (**G**) corn was fed.

MATERIALS AND METHODS

Animals, Treatments, and Experimental Design

Six primiparous Holstein cows were fitted with ruminal and simple T duodenal cannulas as per approved animal care and use guidelines. At the start of the experiment, cows were 130, 134, 137, 140, 161, and 28 DIM. The sixth cow was used as a replacement for one cow that died of complications at calving, and one cow was removed from the final collection period due to duodenal cannula complications. Cows were injected with Posilac (Monsanto, St. Louis, MO), a synthetic bST, every 2 wk throughout the trial except for the replacement, which never received Posilac during the trial. The first Posilac injection was given 2 wk before the initiation of the trial.

All six experimental diets (Table 1) were alfalfa silage-based TMR included as treatments in a 6 × 6 Latin square. Diets were balanced to be equivalent in nutrient composition on a DM basis (28% NDF, 5.6% lipid, 19% CP, 12% RDP, and 1.67 Mcal/kg of NE_L based on reference values). The RDP concentration was balanced using estimates from Spartan Ration Evaluator (Vandehaar et al., 1992). The forage control diet (**FCG**) with no WCS addition contained the NRC (1989) recommendation of 21% FNDF. The WCS diets contained linted WCS at low, medium, or high concentrations (5, 10, and 15% of dietary DM, respectively). In a review, Arieli (1998) recommended a maximal WCS inclusion rate of 15% of dietary DM. In diets with G corn, alfalfa silage

was replaced with WCS on an NDF basis to achieve diets with 18% FNDF (**LG**), 15% FNDF (**MG**), and 12% FNDF (**HG**). Linted cottonseed hulls were added to the diets in slightly different amounts during each period to balance NDF from forage and WCS and to enable the direct substitution of alfalfa silage NDF with cotton products (WCS plus cottonseed hulls) NDF, allowing NFC to be equivalent and reducing the potential effect of a grain dilution response (Armentano and Pereira, 1997). To evaluate the potential interaction of starch availability and level of forage substitution, the G in the LG and MG diets was replaced with SF (**LSF** and **MSF** diets). Steam-flaked corn (7.94% CP, 9.96% NDF, and 2.72% FA on DM bases) was provided by Pennfield Feeds, Lancaster, Pennsylvania. The density according to the manufacturing specifications (0.360 to 0.386 kg/L of 85% DM corn) was slightly lower than our measurement (0.393 kg/L on DM basis) probably because of corn fracture during handling and storage. Ground corn (7.56% CP, 13.1% NDF, and 4.66% FA on DM bases) had a mean particle size of 1.05 mm. Mean particle size was determined according to log-normal distribution procedures after dry sieving (Kerley et al., 1985). Cotton Incorporated, Cary, North Carolina, provided the WCS (23.6% CP, 48.7% NDF, and 18.4% FA) and cottonseed hulls (6.31% CP, 84.2% NDF, and 2.88% FA). Roasted soybeans were heated as described by Tice et al. (1993) and cracked. Alfalfa silage (19.2% CP and 40.6% NDF) had a mean particle size of 5.64 mm, with 38.5, 53.9, 66.5, and 72.8% retained on screens with pore sizes of 9.5, 4.75, 2.36, and 1.18 mm, respectively, after wet sieving (Kerley et al., 1985).

Sampling and Laboratory Analysis

Periods consisted of 21 d, with d 1 through 9 serving as an adjustment period; and d 10 through 21, as the data collection period. Diets were prepared once daily as a TMR and fed twice daily in equal proportions at 0600 and 1800 h ad libitum. Orts were weighed daily at 1600 h to adjust feed offered for 10% refusal. Feed offered and individual dietary components were sampled on d 13 through 17, and Orts were sampled on d 14 through 18. Samples were composited by cow, sample type, and period and were lyophilized.

Cows were housed in a conventional tie-stall barn with mattresses. They were allowed access to a concrete lot before milking, except on days when chewing activity was being monitored (Harvatine et al., 2002). Cows were milked at 0530 and 1600 h daily, with milk yield recorded at each milking. Milk samples were taken at a.m. and p.m. milkings on d 14 to 16 of each period and analyzed by DHI Cooperative Inc. (Powell, OH) for milk fat and CP by infrared spectroscopy and for milk urea

Table 1. Ingredient composition of experimental diets.

Ingredient	Diets ¹					
	FCG	LG	MG	HG	LSF	MSF
	% of DM					
Alfalfa silage	53.00	44.70	38.00	30.27	44.70	38.00
Whole linted cottonseed	...	5.00	10.00	15.00	5.00	10.00
Cottonseed hulls	...	0.65	0.93	1.43	0.65	0.93
Corn, ground shelled	27.72	30.44	32.59	35.19	...	...
Corn, steam-flaked	...	...	...	...	30.44	32.59
Soybean meal, 48% CP	...	3.63	7.36	11.16	3.63	7.36
Roasted soybeans, cracked	14.41	9.89	4.94	...	9.89	4.94
Soybean hulls	2.13	2.64	2.86	3.35	2.64	2.86
Soybean hull pellets ²	1.10	1.10	1.10	1.10	1.10	1.10
Trace-mineralized salt ³	0.48	0.49	0.49	0.50	0.49	0.49
Monosodium phosphate	0.64	0.66	0.66	0.67	0.66	0.66
Magnesium oxide	0.09	0.09	0.09	0.09	0.09	0.09
Limestone	0.32	0.59	0.86	1.12	0.59	0.86
Vitamin premixes ⁴	0.11	0.12	0.12	0.12	0.12	0.12

¹FCG = Forage control with ground corn; LG = low cottonseed with ground corn; MG = medium cottonseed with ground corn; HG = high cottonseed with ground corn; LSF = low cottonseed with steam-flaked corn, and MSF = medium cottonseed with steam-flaked corn.

²Contained 5% chromic oxide.

³Contained 0.10% Mg, 38.0% Na, 58.0% Cl, 0.04% S, and (mg/kg) 5000, Fe; 7500, Zn; 2500, Cu; 6000, Mn; 100, I; 60, Se, and 50, Co.

⁴Supplied approximately 136 kIU of vitamin A, 27 kIU of vitamin D, and 500 IU of vitamin E per day.

N using a Skalar SAN Plus segmented flow analyzer (Skalar, Inc., Norcross, GA). Daily milk fat and protein yields were calculated and averaged by cow per period. Cows were weighed prior to the p.m. milking on d 7, 14, and 21 of each period; BW were averaged per period.

Core samples (approximately 600 ml) of ruminal contents from three different sites in the rumen were removed at 3, 6, 9, and 12 h after the a.m. feeding on d 14 of each period. Contents were strained through two layers of cheesecloth, and pH of the fluid was measured immediately. A 50-ml aliquot of the filtered ruminal fluid was acidified with 3 ml of 6 N HCl to stop fermentation and frozen. After thawing, the acidified ruminal fluid was mixed, centrifuged at 15,000 × *g* at 4°C for 15 min, and then filtered through Whatman number 1 filter paper (Whatman, Clifton, NJ). The supernatant was analyzed for VFA concentrations by GLC (Pantoja et al., 1994) and for NH₃N (Chaney and Marbach, 1962).

Digestibility was measured on d 14 to 17 of each period. A pellet (equivalent to 1.1% of daily DMI) containing 5% Cr₂O₃ and 95% soybean hulls was dosed through the rumen cannula twice daily on d 8 through 17. Fecal grab samples were taken on d 14 to 17 of each period so that every 3 h in a 24-h period were represented (eight samples total). Samples were dried in a forced-air oven at 40°C for 48 to 60 h. Samples were composited on an air-dry basis by cow within period. Duodenal samples (250 ml) were taken on d 14 to 17 of each period so that every 90 min in a 24-h period were represented (16 samples total), combined by cow

within period, and frozen immediately. After thawing, a 1000-ml subsample of the composited duodenal contents was lyophilized.

The samples of feed offered, orts, individual dietary components, and duodenal contents were ground to pass through a 2-mm screen (Wiley Mill; Arthur H. Thomas, Philadelphia, PA). The chromic oxide pellets were composited by period and ground manually using a mortar and pestle. Samples of feed, orts, chromic oxide pellets, duodenal contents, and fecal contents were analyzed for DM, OM, and N (AOAC, 1990). The NDF concentration of feed, orts, chromic oxide pellets, duodenal samples, and fecal samples was determined according to Van Soest et al. (1991) using hot ethanol, 8 M urea, and heat stable α -amylase (Sigma A3306; Sigma Chemical Co., St. Louis, MO). The ADF and acid-detergent lignin concentrations of feed offered and chromic oxide pellets were determined sequentially; 72% H₂SO₄ was used for lignin quantification (Van Soest et al., 1991). Feed, orts, chromic oxide pellets, duodenal, and fecal samples were analyzed for total fatty acids by GLC (Sukhija and Palmquist, 1988). Chromic oxide pellets and duodenal and fecal samples were analyzed for Cr by atomic absorption spectroscopy (Williams et al., 1962). Duodenal samples were analyzed for NH₃N content (Bremner and Keeney, 1965) and total purine concentration (Zinn and Owens, 1986) as modified by Ushida et al. (1985) for use as a microbial flow marker. Neutral detergent insoluble N (NDIN) and ADIN concentrations of feed offered were determined by the NDF or

ADF procedure described previously (without urea addition) followed by Kjeldahl N analysis.

Feed, orts, chromic oxide pellets, and duodenal and fecal samples were reground to pass through a 1-mm screen and analyzed for total NSC concentration by GLC (Callison et al., 2001). Area under the curve was used to calculate individual sugar concentrations, which were corrected for area of the myo-inositol internal standard. Individual sugar concentrations were summed to yield total hydrolyzed sugar content. Pure corn starch was used to check recovery, which averaged 103% (SD = 10).

Core samples of ruminal concentration (approximately 1000 ml) were taken on four consecutive days (d 14 through 17) at 3, 6, 9, or 12 h after the a.m. feeding for harvesting and isolating particulate-associated bacteria by blending (Callison et al., 2001). The bacterial cells were lyophilized and analyzed for DM, OM, N, FA, and purines as described previously.

Calculations

The NE_L concentration of the diet was calculated using the equation of Weiss (1993). The NFC concentration of the diet was determined by difference [OM – NDF – CP – (FA+1) + (NDIN * 6.25)]. The NFC component of the TDN equation used to calculate NE_L was adjusted for NSC digestibility in the SF diets. An adjustment factor for each SF diet (LSF and MSF) was calculated by dividing the apparent total tract NSC digestibility for the SF diet by the NSC digestibility for the FCG diet.

The average amount of Cr dosed daily was divided by the concentration of Cr in the duodenal and fecal samples to determine daily flow of DM to the duodenum and rectum. Digestibility coefficients were then calculated based on the intake (adjusted for orts) and the duodenal and fecal flows of each nutrient (OM, NDF, NSC, and N). Microbial N, OM, or NSC flows were calculated by multiplying the bacterial N:purine, OM:purine, or NSC:purine ratios by total purine flow at the duodenum. The NSC content of the bacterial sample was determined by difference [NSC = OM – (N * 6.25) – (FA + 1)]. True OM and NSC flows to the duodenum were corrected for bacterial contributions. Efficiency of microbial protein synthesis was expressed per unit of OM or unit of carbohydrate (NDF plus NSC) digestion on apparent and true bases.

Statistical Analyses

Data were analyzed using the MIXED procedure of SAS (1999) with the following model:

$$Y_{ijk} = \mu + T_i + C_j + P_k + e_{ijk} \quad [1]$$

where μ = overall population mean, T_i = fixed effect of i th treatment, C_j = random effect of j th cow, P_k = fixed effect of k th period, and e_{ijk} = residual error. Preplanned contrasts compared the linear, quadratic, and cubic effects of increasing WCS in the diet when G corn was used as the corn source (FCG, LG, MG, and HG). An additional contrast compared the effect of corn source (LG and MG vs. LSF and MSF). The final contrast evaluated the interaction of corn source and level of WCS for LG, MG, LSF, and MSF treatments. Significant differences were declared at $P < 0.05$ unless otherwise stated. When the MIXED procedure would not converge for a few datasets (ruminal FA disappearance expressed as percentage of total FA intake, percentage of total C_{18} intake, and percentage of unsaturated FA intake), data were analyzed using Proc GLM (SAS, 1999). Individual pH, VFA, and NH_3N concentrations were analyzed over time using the repeated measures analysis of the MIXED procedure of SAS (1999). Cow was designated as the only random effect. First-order autoregressive [AR(1)] was used as the covariance structure for pH, acetate:propionate, total VFA concentration, and most individual VFA concentrations. Heterogeneous compound symmetry (CSH) was used as the covariance structure for valerate. Heterogeneous first-order autoregressive [ARH(1)] was used as the covariance structure for ruminal NH_3N concentration. When interactions for treatment $\times$ time were not deemed to be significant ($P \geq 0.10$), averages over all times were reported.

RESULTS AND DISCUSSION

The chemical composition of the diets is shown in Table 2. Total NDF concentrations were higher than the formulated values of 28% for each diet due to variations in NDF in WCS and the grain mix. The FNDF concentration was determined and adjusted before each collection period. Cottonseed hulls were added to the diets in slightly different amounts during each period to balance NDF and enable the direct substitution of alfalfa silage NDF with cotton product (WCS plus linted cottonseed hulls) NDF on a one-to-one basis as alfalfa silage NDF varied. The ratio of WCS to cottonseed hulls was, on average, 10:1.

The NFC concentrations of the diets (Table 2) were similar to the values used in ration balancing. The enzymatic procedure used to determine NSC concentration was based on total hydrolyzed sugar concentrations. Several of the feeds used in this study (alfalfa silage, soybean meal, and soybean hulls) contain greater than 10% soluble fiber (Hall et al., 1997). The soluble fiber

Table 2. Chemical composition of experimental diets.

Item	Diets ¹					
	FCG	LG	MG	HG	LSF	MSF
DM, %	58.4	61.3	64.3	67.9	62.0	64.0
	% of DM					
NDF	30.9	31.3	31.3	31.4	31.1	31.6
Forage NDF	21.5	18.3	15.4	12.3	18.1	15.4
ADF	21.5	21.4	21.7	21.5	21.6	21.8
ADL ²	4.54	4.47	4.57	4.72	4.62	4.79
CP	18.4	18.8	18.6	18.8	18.6	18.9
NDIN ³	0.61	0.52	0.50	0.44	0.58	0.54
ADIN ⁴	0.23	0.22	0.22	0.21	0.26	0.24
Ash	7.67	7.50	7.13	6.71	7.49	7.28
Fatty acids	4.39	4.57	4.68	4.97	4.33	4.44
NFC ⁵	42.0	40.6	40.8	40.3	41.7	40.7
NSC ⁶	22.8	26.3	25.9	28.9	25.8	24.9
TDN ⁷	68.3	70.1	70.6	68.7	70.2	70.8
NE _L , Mcal/kg of DMI ⁷	1.69	1.69	1.70	1.72	1.72	1.73

¹FCG = Forage control with ground corn; LG = low cottonseed with ground corn; MG = medium cottonseed with ground corn; HG = high cottonseed with ground corn; LSF = low cottonseed with steam-flaked corn, and MSF = medium cottonseed with steam-flaked corn.

²ADL = Acid detergent lignin.

³NDIN = Neutral detergent insoluble nitrogen.

⁴ADIN = Acid detergent insoluble nitrogen.

⁵NFC = Nonfiber carbohydrates [OM – NDF – CP – (FA + 1) + (NDIN * 6.25)].

⁶NSC = Nonstructural carbohydrates; analyzed by enzymatic determination.

⁷Calculated using the equation from Weiss et al. (1993); corrected for total tract starch digestibility of diets containing steam-flaked corn (LSF and MSF) relative to FCG.

would be included in NFC, but not NSC, explaining the difference between values for NFC and NSC.

St-Pierre and Jones (1999) suggested that, if the interest of a researcher is to use a given set of research animals to make inferences to a larger population, the effect of cow should be considered random. On this basis, data were analyzed using the MIXED procedure of SAS (1999) with cow as a random effect. The SE for data presented in this paper using Proc MIXED are approximately 15 to 25% larger than those obtained using GLM because the MIXED model considers the variance of cow in addition to the residual variance. However, the choice of procedure (MIXED vs. GLM) had little effect on the significance of the contrasts.

As the proportion of dietary WCS increased, OM intake increased quadratically (Table 3). Ruminal and total tract OM digestibilities were not affected by level of WCS substitution, despite a linear increase in apparent ruminal NSC digestibility. However, when duodenal flows were adjusted to account for bacterial NSC flows, true ruminal NSC digestibility did not differ. Additionally, WCS addition did not affect total tract NSC digestibility considerably, although there was a quadratic trend.

Steam-flaking decreased OM intake but increased true ruminal OM digestibility compared with grinding (Table 3). No differences were observed for apparent

total tract OM digestibility between corn sources. Compensatory postruminal digestion of starch or NDF tended to minimize differences in apparent total tract OM digestibility among grain processing methods (Firkins et al., 2001).

Apparent and true ruminal NSC digestibilities were higher for SF corn diets compared with G corn diets (77.6 and 96.1% for SF vs. 55.1 and 70.7 for G, respectively). Apparent ruminal NSC digestibilities were substantially lower than true ruminal NSC digestibilities (average measured values of 21% NSC in bacteria). Despite compensatory intestinal NSC digestibility in G corn diets, total tract NSC digestibility was slightly lower for G than SF corn. Callison et al. (2001) observed slightly higher apparent ruminal and total tract NSC digestibilities (70.1 and 98.0%, respectively) when finely ground corn of similar particle size (1.15 mm) was fed. Approximately 96% of the NSC in SF corn was truly digested in the rumen; consequently, apparent total tract NSC digestibility for SF corn (99.4 and 99.8% for LSF and MSF, respectively) was slightly higher than the average of 94.2% reported by Firkins et al. (2001). This may be a result of our NSC procedure or attributed to the density of the SF corn used in the current study (0.360 to 0.386 kg/L), which should be optimal (Theurer et al., 1999).

Table 3. Least squares means for OM, NSC,¹ and NDF digestibilities by cows fed diets in which whole cottonseed replaced alfalfa silage and was fed with ground or steam-flaked corn.

Item	Diets ²						SE ³		P ⁴				
	FCG	LG	MG	HG	LSF	MSF	n = 5	n = 6	L	Q	C	Corn	Intx
OM intake, kg/d	16.4	18.2	19.0	18.9	17.8	17.4	0.7	0.7	<0.01	0.02	NS	0.02	0.16
OM digestibility, %													
Apparent ruminal	39.2	41.8	41.1	43.9	44.7	46.9	3.3	3.0	NS	NS	NS	0.10	NS
True ruminal	56.2	58.6	57.3	61.6	64.7	66.8	3.6	3.3	NS	NS	NS	0.01	NS
Total tract	70.7	71.3	72.1	69.3	72.3	72.6	1.3	1.1	NS	0.13	NS	NS	NS
NSC intake, kg/d	4.00	4.97	5.13	5.68	4.87	4.59	0.31	0.30	<0.01	0.20	0.11	0.05	0.18
NSC digestibility, %													
Apparent ruminal	49.5	56.7	54.1	66.4	75.8	79.4	6.5	5.9	0.05	NS	NS	<0.01	NS
True ruminal	69.6	72.6	68.8	78.8	95.2	97.0	6.5	5.9	NS	NS	NS	<0.01	NS
Total tract	95.1	96.8	97.0	96.5	99.4	99.8	0.7	0.6	0.11	0.09	NS	<0.01	NS
NDF intake, kg/d	5.54	6.21	6.51	6.46	6.02	5.95	0.25	0.23	<0.01	0.04	NS	0.03	NS
NDF intake, % of BW	1.01	1.11	1.15	1.15	1.08	1.08	0.04	0.04	<0.01	0.04	NS	0.03	NS
NDF digestibility, %													
Ruminal	39.4	39.1	37.5	38.8	37.8	36.9	2.8	2.6	NS	NS	NS	NS	NS
Total Tract	58.5	55.2	54.8	48.3	53.9	53.3	2.3	2.1	<0.01	NS	NS	NS	NS

¹Nonstructural carbohydrates analyzed by enzymatic determination.

²FCG = Forage control with ground corn; LG = low cottonseed with ground corn; MG = medium cottonseed with ground corn; HG = high cottonseed with ground corn; LSF = low cottonseed with steam-flaked corn, and MSF = medium cottonseed with steam-flaked corn.

³For the LG treatment n = 5; for all other treatments n = 6.

⁴Probability of a treatment response; NS = not significant ($P > 0.20$). Contrasts compared the linear (L), quadratic (Q), and cubic (C) effects of increasing level of whole cottonseed in the diet when ground corn was used as the corn source (FCG, LG, MG and HG). Contrast Corn compared the effect of corn source (ground vs. steam-flaked) when low or medium levels of cottonseed were fed (LG and MG vs. LSF and MSF). Contrast Intx evaluated the interaction of corn source (ground or steam-flaked) and level of cottonseed (low or medium) in LG, MG, LSF, and MSF treatments.

Intake of NDF increased quadratically as the proportion of WCS in the diet increased (Table 3). Because the NDF concentration of the diets was similar (Table 2), this response was a result of increased DMI. There was no effect of level of WCS substitution on ruminal NDF digestibility (Table 3). During diet formulation, the estimated FA concentration from oilseeds was limited to approximately 3% of dietary DM (Table 1) to prevent depression in ruminal fiber digestion (Jenkins, 1994; Palmquist, 1995).

The amount of postruminal NDF digestion decreased as the concentration of WCS increased (Table 3), suggesting that NDF from WCS was not as digestible in the large intestine as was NDF from alfalfa silage. Cottonseed hulls contained more digestible NDF (54.2% of original NDF) compared with alfalfa (41.3% of original NDF), but ground alfalfa had a higher rate of digestion (0.0547 h^{-1}) than ground cottonseed hulls (0.0208 h^{-1}) in vitro (Bhatti and Firkins, 1995). A lower digestion rate and higher proportion of digestible NDF from WCS should promote passage and compensatory digestion of WCS NDF in the large intestine. However, the opposite effect occurred in our study, apparently because of increased negative associative effects as forage decreased (Firkins, 1997).

Corn processing decreased NDF intake because of reduced OM intake but did not affect NDF digestibility (Table 3). The effects of corn processing on NDF digest-

ibility have been variable; increasing ruminal starch availability has decreased (Poore et al., 1993a; Plascencia and Zinn, 1996; Joy et al., 1997), increased (Chen et al., 1994), or had no effect (Poore et al., 1993b; Knowlton et al., 1998) on NDF digestibility.

As the level of WCS substitution increased, the average ruminal pH decreased linearly from 6.28 for cows fed the FCG diet to 5.93 for cows fed the HG diet (Table 4). The decreased pH could be a result of increased OM and NSC intakes increasing ruminally fermentable substrate, decreasing salivary buffer secretion, or to decreased cation exchange capacity as alfalfa silage decreased. Because total chewing time was not affected by treatment (Harvatine et al., 2002) and cottonseed meal had a similar cation exchange capacity as alfalfa (Van Soest et al., 1991), the former reason seems more likely. The lack of pH effect for corn source explains why ruminal NDF digestibility was not decreased when SF corn replaced G corn.

Although there were no differences among diets in total VFA concentration, the acetate:propionate ratio decreased linearly with increasing level of WCS substitution (Table 4). Change in acetate:propionate is a reflection of the linear increase in propionate concentration and the linear decrease in acetate concentration with increasing level of WCS. Ruminal VFA concentrations responded in a similar manner when NDF from WCS replaced FNDF (Clark and Armentano, 1993).

Table 4. Least squares means for ruminal fluid characteristics of cows fed diets in which whole cottonseed replaced alfalfa silage and was fed with ground or steam-flaked corn.

Item	Diets ¹						SE ²		P ³				
	FCG	LG	MG	HG	LSF	MSF	n = 5	n = 6	L	Q	C	Corn	Intx
Ruminal pH	6.28	6.13	6.12	5.93	6.07	6.02	0.08	0.07	<0.01	NS	NS	NS	NS
Total VFA, mM	102	107	108	110	108	108	5	4	0.16	NS	NS	NS	NS
VFA, mol/100 mol													
Acetate	67.7	66.4	65.0	63.9	63.8	61.9	1.01	0.98	<0.01	NS	NS	<0.01	NS
Propionate	17.5	18.7	20.7	21.9	21.6	23.3	1.26	1.23	<0.01	NS	NS	<0.01	NS
Butyrate	11.1	11.2	10.5	10.6	11.2	11.3	0.53	0.48	0.18	NS	NS	NS	NS
Valerate	1.38	1.38	1.37	1.39	1.40	1.56	0.06	0.06	NS	NS	NS	0.02	0.06
Isovalerate	1.37	1.42	1.52	1.43	1.34	1.23	0.07	0.07	0.14	0.13	NS	<0.01	0.03
Isobutyrate	0.88	0.90	0.89	0.85	0.76	0.73	0.05	0.05	NS	0.16	NS	<0.01	NS
Acetate:propionate	3.98	3.59	3.21	3.01	2.98	2.77	0.22	0.21	<0.01	NS	NS	<0.01	NS
NH ₃ N, mg/dl	10.28	12.41	15.22	17.62	8.35	9.70	1.29	1.24	<0.01	NS	NS	<0.01	NS

¹FCG = Forage control with ground corn; LG = low cottonseed with ground corn; MG = medium cottonseed with ground corn; HG = high cottonseed with ground corn; LSF = low cottonseed with steam-flaked corn, and MSF = medium cottonseed with steam-flaked corn.

²For the LG treatment n = 5; for all other treatments n = 6.

³Probability of a treatment response; NS = not significant ($P > 0.20$). Contrasts compared the linear (L), quadratic (Q), and cubic (C) effects of increasing level of whole cottonseed in the diet when ground corn was used as the corn source (FCG, LG, MG, and HG). Contrast Corn compared the effect of corn source (ground vs. steam-flaked) when low or medium levels of cottonseed were fed (LG and MG vs. LSF and MSF). Contrast Intx evaluated the interaction of corn source (ground or steam-flaked) and level of cottonseed (low or medium) in LG, MG, LSF, and MSF treatments.

Cows fed the diets with G corn had a higher acetate:propionate than did cows fed the diets with SF corn, resulting from a decrease in acetate concentration and an increase in propionate concentration. Other researchers have observed a decrease in acetate:propionate and an increase in propionate concentration when rapidly degradable NSC was fed (Ekinici and Broderick, 1997; Joy et al., 1997; Dann et al., 1999). When SF corn replaced G corn, there was an increase in concentration of valerate and a decrease in concentrations of isovalerate and isobutyrate (Table 4). Additionally, there was an interaction between corn source and level of WCS for valerate and isovalerate concentrations. An explanation for these observations is not clear.

Ruminal NH₃N concentrations have been used as a measure of the ruminal availability of N and the efficiency of protein utilization in the rumen. Ruminal NH₃N concentrations in the current study (Table 4) all were above the minimum concentration of 6.2 to 8.0 mg/dl suggested to maintain NDF digestion (Hoover, 1986). The diets were balanced to contain higher RDP than required (Table 1).

As expected from the linear increase in ruminal NH₃N concentration (Table 4), the duodenal flow of NH₃N increased linearly (Table 5) as WCS addition increased. However, nonmicrobial nonammonia N flow (% of N intake) decreased linearly with increasing WCS addition (Table 5). Diets were balanced to be equivalent in estimated RDP (64% of CP and 12% of DM). As NDF from WCS replaced FNDF, the concentration of roasted soybeans was reduced to maintain similar FA concentrations from oilseeds (roasted soybeans plus WCS) (Ta-

ble 1). The RDP concentration of WCS (43.0% of CP) from Spartan Ration Evaluator (VandeHaar et al., 1992), which was used in diet formulation, was higher than that previously reported (30.4% of CP) for raw WCS (Pires et al., 1997). As a result, nonmicrobial nonammonia N (% of intake) ranged from 45.7% for FCG to 30.0% for HG (Table 5). Total tract N digestibility increased linearly with increasing WCS, which also indicates that heating of roasted soybeans might have been greater than planned.

Flow of microbial N to the duodenum increased linearly with WCS addition (Table 5), probably because OM intake increased (Table 3). However, the efficiency of microbial N synthesis (calculated per unit of carbohydrate degraded) decreased linearly as WCS addition increased (Table 5). Because branched-chain VFA concentrations (Table 4) did not differ across treatments and NH₃N concentrations should have been adequate, RDP did not appear to limit microbial growth. Therefore, the difference in microbial N synthesis appears to be related to ruminal pH. As ruminal pH decreased linearly (Table 4), the efficiency of microbial N synthesis per unit of carbohydrate digested also decreased linearly (Table 5). Russell (1998) suggested that, when excess carbohydrates are available in the rumen, microorganisms expend extra nongrowth energy in a process termed energy spilling. Although not measured in this study, increased lactate concentration might have contributed to observed pH differences as WCS increased. Additionally, the decreased efficiency of microbial protein synthesis could potentially be a result of the linear decrease in the passage rate of potentially digestible

Table 5. Least squares means for N digestibility and efficiency of bacterial growth by cows fed diets in which whole cottonseed replaced alfalfa silage and was fed with ground or steam-flaked corn.

Item ⁴	Diets ¹						SE ²		P ³				
	FCG	LG	MG	HG	LSF	MSF	n = 5	n = 6	L	Q	C	Corn	Intx
N intake, g/d	521	595	608	607	570	568	26	25	<0.01	0.03	NS	0.06	NS
Duodenal flow, g/d													
Ammonia N	11.5	14.3	15.1	18.2	10.7	12.3	1.4	1.2	<0.01	NS	NS	0.01	NS
Microbial N	247	267	271	295	319	301	16	15	0.01	NS	NS	<0.01	NS
Nonmicrobial NAN	234	227	212	182	197	164	31	28	0.14	NS	NS	0.14	NS
Nonmicrobial NAN, % of N intake	45.7	36.9	34.3	30.0	34.5	28.6	4.5	4.0	0.01	NS	NS	NS	NS
Efficiency of microbial N synthesis													
g N/ kg OM apparently digested	43.0	37.4	37.8	37.1	41.6	38.6	3.9	3.6	NS	NS	NS	NS	NS
g N/ kg OM truly digested	27.6	25.4	25.6	25.6	27.5	25.7	1.7	1.5	NS	NS	NS	NS	NS
Efficiency of microbial N synthesis													
g N/ kg CHO apparently digested	78.4	57.4	59.4	48.6	55.3	53.8	10.5	9.5	0.04	NS	NS	NS	NS
g N/ kg CHO truly digested	57.8	47.5	49.8	43.4	46.9	46.2	5.4	4.9	0.05	NS	NS	NS	NS
Apparent total tract N digestibility, % of intake	62.5	66.5	68.6	69.9	66.0	69.6	1.1	1.0	<0.01	0.20	NS	NS	NS

¹FCG = forage control with ground corn; LG = low cottonseed with ground corn; MG = medium cottonseed with ground corn; HG = high cottonseed with ground corn; LSF = low cottonseed with steam-flaked corn, and MSF = medium cottonseed with steam-flaked corn.

²For the LG treatment n = 5; for all other treatments n = 6.

³Probability of a treatment response; NS = not significant ($P > 0.20$). Contrasts compared the linear (L), quadratic (Q), and cubic (C) effects of increasing level of whole cottonseed in the diet when ground corn was used as the corn source (FCG, LG, MG, and HG). Contrast Corn compared the effect of corn source (ground vs. steam-flaked) when low or medium levels of cottonseed were fed (LG and MG vs. LSF and MSF). Contrast Intx evaluated the interaction of corn source (ground or steam-flaked) and level of cottonseed (low or medium) in LG, MG, LSF, and MSF treatments.

⁴NAN = Nonammonia N; CHO = carbohydrate (NDF + non-structural carbohydrate).

NDF (Harvatine et al., 2001). Because of the extensive attachment of ruminal microbes to feed particles, Firkins (1996) explained that a slower particulate passage rate could increase the proportion of energy spent on cell maintenance.

Substituting SF corn for G corn decreased ruminal NH_3N concentration (Table 4) and duodenal flow of NH_3N (Table 5). Additionally, duodenal flow of microbial N increased by about 15% with the use of SF corn. In a recent review, Firkins et al. (2001) determined that microbial N flow to the duodenum was greater for cows fed SF compared with dry-rolled or G corn. Ruminally fermentable NSC intake (NSC intake $\times$ true ruminal NSC digestibility) increased by over 1 kg/d when SF corn was fed (data not shown; see Table 3), which provided more substrate for microbial growth. Increased NSC availability combined with a lack of pH differences (Table 4), probably increased NH_3N utilization by ruminal microorganisms. As a result, method of corn processing did not affect efficiency of microbial protein synthesis.

Intakes of total FA, C_{16} , $\text{C}_{18:1}$, and $\text{C}_{18:2}$ increased linearly and $\text{C}_{18:3}$ intake decreased quadratically with increasing WCS addition (Table 6). Although diets were balanced to contain equivalent crude fat concentrations, the FA concentration of the diet increased from 4.39 to 4.97% with increasing WCS inclusion (Table 2). Alfalfa silage has fewer lipids in the form of FA than WCS (Van Soest, 1994). By design, as the dietary pro-

portion of WCS increased, the proportion of alfalfa silage and whole roasted soybeans decreased (Table 1). Typical alfalfa silage contains 39.0% $\text{C}_{18:3}$ (as a percentage of total FA), whereas soybeans and WCS contain 6.8% and less than 0.5%, respectively (Van Soest, 1994). Additionally, WCS contain 25.3% C_{16} (as a percentage of total FA), but soybeans contain 10.7% C_{16} , explaining the linear increase in C_{16} intake as WCS increased and roasted soybeans decreased.

There were negative FA disappearances for total FA and total C_{18} FA for FCG (Table 6). In past trials, an average of 87% of dietary FA was recovered at the duodenum; however, de novo FA synthesis by ruminal microbes can result in a net gain of FA across the rumen (Jenkins, 1994). Thus, it is likely that de novo FA synthesis contributed to the increase in FA flow at the duodenum for cows fed FCG. There were linear increases in ruminal disappearance of total FA, total C_{18} FA, and unsaturated FA with increasing WCS addition (Table 6). To our knowledge, the ruminal disappearance of FA from WCS has not been compared with that of roasted soybeans in a single trial. Palmquist (1995) noted that the in situ disappearance of FA was higher for whole roasted soybeans (36.6%) compared with WCS (-5.86%). He attributed differences in FA disappearance to the physical structure of the oilseed; the hull of the soybean is more digestible than the hull of WCS, so the digestion and utilization of WCS might be more dependent on rumination and mastication to provide

Table 6. Least squares means for fatty acid (FA) digestibility by cows fed diets in which whole cottonseed replaced alfalfa silage and was fed with ground or steam-flaked corn.

Item	Diets ¹						SE ²		P ³				
	FCG	LG	MG	HG	LSF	MSF	n = 5	n = 6	L	Q	C	Corn	Intx
FA intake, g/d													
Total FA	770	890	946	1008	825	826	49	45	<0.01	NS	NS	0.01	NS
Total C ₁₆	111	145	184	224	141	167	8	8	<0.01	NS	NS	0.08	NS
Total C ₁₈	578	665	686	717	607	588	38	35	<0.01	NS	NS	<0.01	NS
C _{18:0}	26.3	28.5	26.9	26.3	27.6	25.0	1.6	1.5	NS	NS	NS	NS	NS
C _{18:1}	123	148	152	162	128	124	9.2	8.5	<0.01	NS	NS	<0.01	NS
C _{18:2}	331	402	436	480	365	375	24	22	<0.01	NS	NS	0.01	NS
C _{18:3}	97.4	86.8	70.3	48.3	86.0	63.9	3.9	3.6	<0.01	0.04	NS	0.18	NS
FA flow to the duodenum, g/d													
Total FA	806	874	893	926	776	749	41	38	<0.01	NS	NS	<0.01	NS
Total C ₁₆	133	157	174	197	142	148	9	8	<0.01	NS	NS	<0.01	NS
Total C ₁₈	610	657	664	682	576	549	30	28	0.03	NS	NS	<0.01	NS
C _{18:0}	352	417	439	481	358	349	20	19	<0.01	NS	NS	<0.01	NS
Total C _{18:1}	142	139	138	135	129	127	11	10	NS	NS	NS	0.19	NS
<i>trans</i> C _{18:1}	32.1	32.9	42.1	41.7	31.1	38.7	4.5	3.9	0.04	NS	NS	NS	NS
C _{18:2}	101	86	76	57	76	63	11	10	<0.01	NS	NS	0.19	NS
C _{18:3}	15.8	13.0	11.0	7.6	12.6	10.6	1.2	1.1	<0.01	NS	NS	NS	NS
Ruminal FA disappearance													
Total FA, % of intake	-8.0	1.9	5.4	8.4	6.0	9.2	4.8	4.2	0.01	NS	NS	NS	NS
Total C ₁₈ FA, % of intake	-9.5	1.3	2.8	5.2	4.7	6.6	5.6	4.9	0.05	NS	NS	NS	NS
Unsaturated C ₁₈ FA, % of intake	51.7	62.5	66.1	70.9	62.6	64.4	2.9	2.5	<0.01	NS	NS	NS	NS
Apparent total tract FA digestibility, % of intake	67.8	70.9	73.0	73.0	72.4	75.4	2.5	2.3	0.09	NS	NS	NS	NS
Biohydrogenation ⁴	56.1	61.9	64.0	67.1	56.9	56.6	3.8	3.5	0.01	NS	NS	0.05	NS
Biohydrogenation ⁵	65.9	70.8	72.5	75.6	67.1	67.5	3.2	2.9	<0.01	NS	NS	0.10	NS

¹FCG = Forage control with ground corn; LG = low cottonseed with ground corn; MG = medium cottonseed with ground corn; HG = high cottonseed with ground corn; LSF = low cottonseed with steam-flaked corn, and MSF = medium cottonseed with steam-flaked corn.

²For the LG treatment n = 5; for all other treatments n = 6.

³Probability of a treatment response; NS = not significant ($P > 0.20$). Contrasts compared the linear (L), quadratic (Q), and cubic (C) effects of increasing level of whole cottonseed in the diet when ground corn was used as the corn source (FCG, LG, MG, and HG). Contrast Corn compared the effect of corn source (ground vs. steam-flaked) when low or medium levels of cottonseed were fed (LG and MG vs. LSF and MSF). Contrast Intx evaluated the interaction of corn source (ground or steam-flaked) and level of cottonseed (low or medium) in LG, MG, LSF, and MSF treatments. ($P = 0.10$) D Slightly lower, biohydrogenation for SF than G corn was likely result of lower FA concentration (Table 2).

⁴Equation from Wu et al. (1991).

⁵Equation 2 from Tice et al. (1994).

microbial access to seed contents (Coppock et al., 1985). When WCS was replaced with a combination of whole raw soybeans and soybean hulls on a FA and NDF basis, the diet with WCS stimulated more chewing and ruminating activity than the diet containing soybean products (Abel-Caines et al., 1997). In our study, total tract FA digestibility tended to increase linearly with increasing WCS use, apparently because of increased availability of FA from WCS compared with that from roasted soybeans.

Biohydrogenation of C₁₈ FA and duodenal flow of *trans* C_{18:1} increased linearly with increasing inclusion of WCS (Table 6), despite pH decreasing linearly to 5.93 (Table 4). Kalscheur et al. (1997) suggested that decreased ruminal pH interfered with complete biohydrogenation. When the effects of pH on lipolysis and biohydrogenation were compared in vitro, lipolysis and biohydrogenation were not significantly inhibited until pH declined below 6.0 (Van Nevel and Demeyer, 1996).

As WCS replaced alfalfa silage and roasted soybeans, the proportion of C_{18:2} increased from 43.0 to 47.6% and C_{18:3} decreased from 12.6 to 4.8% of total FA (data not shown). The C_{18:3} is probably primarily from alfalfa in the form of glycolipids. *Anaerovibrio lipolytica*, a prominent lipolytic bacterium, is apparently incapable of hydrolyzing glycolipids such as galactolipids (Harfoot and Hazlewood, 1988) because the sugar group needs to be removed before lipolysis. Therefore, although these lipids are rapidly hydrolyzed, lipolysis might have been more rate limiting as a higher proportion of lipids were from alfalfa silage.

Dry matter intake increased quadratically as the proportion of WCS in the diet increased (Table 7), explaining similar responses in intakes of OM, NSC, and NDF (Table 3); N (Table 5); and FA (Table 6). Although with fewer treatments to detect a nonlinear response, substituting WCS for forage typically increases DMI (Clark and Armentano, 1997; Mooney and Allen, 1997;

Table 7. Least squares means for lactation performance by cows fed diets in which whole cottonseed replaced alfalfa silage and was fed with ground or steam-flaked corn.

	Diets ¹						SE ²		P ³				
Item	FCG	LG	MG	HG	LSF	MSF	n = 5	n = 6	L	Q	C	Corn	Intx
DMI, kg/d	17.8	19.8	20.5	20.3	19.2	18.8	0.8	0.7	<0.01	0.02	NS	0.02	0.18
DMI, % of BW	3.25	3.51	3.61	3.59	3.43	3.40	0.11	0.10	<0.01	0.05	NS	0.04	NS
Milk, kg/d	26.4	25.8	28.3	27.5	28.5	27.8	2.7	2.6	NS	NS	NS	NS	NS
Milk protein, %	3.04	3.16	3.12	3.26	3.08	3.19	0.11	0.11	<0.01	NS	0.08	NS	0.09
Milk protein, g/d	802	812	880	894	881	874	75	72	0.08	NS	NS	NS	NS
Milk fat, %	3.37	3.67	3.57	3.41	3.15	3.19	0.17	0.16	NS	0.06	NS	<0.01	NS
Milk fat, g/d	894	951	1004	925	898	882	85	79	NS	NS	NS	0.18	NS
3.5% FCM, kg/d	25.9	26.5	28.5	26.9	26.9	26.3	2.5	2.3	NS	NS	NS	NS	NS
MUN, mg/dl ⁴	11.9	12.7	14.6	15.5	11.9	11.8	0.8	0.8	<0.01	NS	NS	0.01	0.13
BW, kg	546	563	565	568	561	556	19	18	0.01	NS	NS	NS	NS

¹FCG = Forage control with ground corn; LG = low cottonseed with ground corn; MG = medium cottonseed with ground corn; HG = high cottonseed with ground corn; LSF = low cottonseed with steam-flaked corn, and MSF = medium cottonseed with steam-flaked corn.

²For the LG treatment n = 5; for all other treatments n = 6.

³Probability of a treatment response; NS = not significant ($P > 0.20$). Contrasts compared the linear (L), quadratic (Q), and cubic (C) effects of increasing level of whole cottonseed in the diet when ground corn was used as the corn source (FCG, LG, MG, and HG). Contrast Corn compared the effect of corn source (ground vs. steam-flaked) when low or medium levels of cottonseed were fed (LG and MG vs. LSF and MSF). Contrast Intx evaluated the interaction of corn source (ground or steam-flaked) and level of cottonseed (low or medium) in LG, MG, LSF, and MSF treatments.

⁴Milk urea nitrogen.

Slater et al., 2000). Lower fill should increase DMI in the short term (Allen, 2000), but increased ruminal carbohydrate availability could decrease DMI in the long term if acidosis or other metabolic disturbances develop.

When SF corn replaced G corn, DMI decreased. Although Yu et al. (1998) observed an increase in DMI when SF corn was compared to finely ground corn, most researchers reported no difference in DMI between cows fed dry-rolled or SF corn (Dann et al., 1999; Theurer et al., 1999). In practice, rations with high concentrations of ruminally degradable NSC, such as in the SF corn diets (LSF and MSF), would not likely be used because SF corn and dietary NFC concentrations would probably be lower than in our trial. The LSF and MSF diets had lower concentrations of forage than most of the studies comparing SF to G corn, perhaps explaining the impact of chemostatic regulation of DMI in the current study (Allen, 2000).

No differences were observed for yields of milk, milk fat, or 3.5% FCM (Table 7). There was a trend ($P = 0.06$) for a quadratic response for milk fat percentage with increasing substitution of forage with WCS (Table 7), with milk fat percentage being higher for the LG and MG diets. Milk fat percentage was not decreased despite the lower ruminal pH, which has been associated with milk fat depression (Allen, 1997). Milk fat percentages were also not highly related to *trans* C_{18:1}. Although this lack of effect does not seem to coincide with current theory (Kalscheur et al., 1997), our fatty acid procedure could not separate various *trans* C_{18:1} isomers, which has recently been documented to be crit-

ical (Griinari et al., 2000). In two previous studies, replacing alfalfa silage NDF with NDF from WCS did not affect milk fat percentage (Clark and Armentano, 1993; Mooney and Allen, 1997) but increased (Clark and Armentano, 1993) or did not affect (Mooney and Allen, 1997) fat yield. However, replacing forage and concentrate with a combination of soybean hulls and WCS in 9.4% FNDF diets decreased milk fat percentage in another study (Slater et al., 2000). The ability to maintain milk fat percentage in this study supports the calculated 0.84 physical effectiveness factor for cottonseed NDF (Harvatine et al., 2002).

Milk protein percentage increased linearly and protein yield tended ($P < 0.08$) to increase with increasing WCS substitution (Table 7). Replacing FNDF with NDF from WCS increased milk protein percentage in one study (Clark and Armentano, 1993) but had no effect in another (Mooney and Allen, 1997). The increased supply of microbial protein N was offset by decreased nonmicrobial nonammonia N as WCS increased (Table 5), so increased intake of digestible OM and increased propionate concentration could have spared amino acids for milk protein synthesis (Theurer et al., 1999).

Processing method did not affect milk yield or milk protein (yield or percentage) in the present study (Table 7). In a review, Theurer et al. (1999) noted an increase in milk and milk protein yields when SF corn was fed. However, Firkins et al. (2001) reported that milk protein percentage and milk yield were not different for SF versus G corn. The regression procedure used by the latter authors accounted for differences in DMI or

other dietary factors rather than to total effect of grain processing attributed to starch digestibility.

Milk fat percentage was significantly decreased when SF corn replaced G corn (Table 7). Steam-flaking corn linearly increased apparent ruminal NSC digestibility (Table 3), which resulted in higher ruminal propionate concentrations in cows fed SF corn compared with G corn (Table 4). Decreased milk fat percentage can be explained by the glucogenic theory of milk fat depression for which increased propionate production causes metabolic changes that lead to decreased milk fat percentage (Gaynor et al., 1995). The lack of a corn effect on duodenal *trans*-C_{18:1} flow (Table 6) does not support the theory of *trans* fatty acids in milk fat depression (Kalscheur et al., 1997) or is a result of our inability to differentiate *trans* isomers (as discussed earlier). Steam-flaking often depresses milk fat percentage (Theurer et al., 1999), although decreasing DMI associated with higher ruminal starch availability (as for SF vs. G corn diets) can help reduce the milk fat depression (Firkins et al., 2001).

As the level of WCS increased, there was a linear increase in MUN (Table 7). Gustafsson and Palmquist (1993) have shown a positive relationship between MUN and ruminal NH₃ N concentration, which also increased linearly (Table 4). Similarly, the lower MUN concentration for SF corn than that for G corn paralleled a decreased ruminal NH₃ N concentration with SF corn. Ekinci and Broderick (1997) and Dann et al. (1999) have also shown decreased MUN concentrations when processed grains were compared with those with a lower degree of processing.

CONCLUSIONS

Alfalfa silage can be replaced with WCS in low forage diets in the short term without adversely affecting DMI, milk production, and ruminal digestion, although efficiency of microbial protein synthesis might be reduced. Replacing G corn with SF corn is an effective means to increase ruminal nutrient digestibility, although the improvements for total tract digestibility are not as substantial. The lack of an interaction between corn source and level of WCS substitution suggests that WCS was equally effective in maintaining ruminal fermentation and digestibility in diets varying in ruminal starch availability. Replacing forage with WCS at up to 15% of dietary DM is a viable alternative for producers when forage quality or quantity is limiting. However, the long-term effects of feeding similar diets need further investigation.

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