Ruminal Fermentation and Nutrient Digestion by Dairy Cows Fed Varying Amounts of Soyhulls as a Replacement for Corn Grain

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ABSTRACT

Five multiparous Holstein cows cannulated in the rumen and duodenum that averaged 63 d in milk were used in a 5 × 5 Latin square design with 14-d periods to evaluate the incremental substitution of soyhulls for corn in the diet. Diets contained 23% alfalfa silage, 23% corn silage, and 54% concentrate on a dry matter (DM) basis. Pelleted soyhulls replaced corn in the concentrate to supply 0, 10, 20, 30, or 40% of the dietary DM. The intakes of DM and organic matter were unaffected by treatments. Intakes of acid detergent fiber and neutral detergent fiber increased linearly, but the intake of nonstructural carbohydrates decreased linearly as soyhulls increased from 0 to 40% of dietary DM. The amount of acid detergent fiber and neutral detergent fiber digested was increased whereas the amount of nonstructural carbohydrate digested was decreased in the rumen, in the lower digestive tract, and in the total digestive tract as soyhulls replaced corn in the diet. Passage to the duodenum of nonammonia N, microbial N, nonammonia nonmicrobial N, total essential amino acids, total nonessential amino acids, and total amino acids were not affected by treatments. Yield of milk (29.5 kg/d) was not affected by treatments in this experiment. In a companion experiment, cows fed the 40% SH diet produced 1.2 kg/day per cow less ($P < 0.07$) milk than cows fed the control diet which is similar to the 1.3 kg/day per cow less milk produced by cows fed the same 40% SH diet in this experiment. Differences in the source of energy (fiber vs. nonstructural carbohydrates), in the amount of fiber and nonstructural carbohydrates digested, and in the site of digestion in the gastrointestinal tract may cause a shortage of the source and/or amount of energy that is required for maximum milk production in high producing cows when more than 30% of the dietary DM that is supplied as corn is replaced with soyhulls.

(**Key words:** dairy cow, nutrient digestion, ruminal fermentation, soyhull)

Abbreviation key: EAA = essential amino acids, MUN = milk urea nitrogen, NANMN = nonammonia nonmicrobial N, NEAA = nonessential amino acids, NFC = nonfiber carbohydrates, SH = soyhulls.

INTRODUCTION

To achieve maximum milk production potential through means acceptable to consumers, feeding systems for dairy cows need to ensure, among other factors, high intake of energy. This goal might be accomplished by raising the dietary concentration of rapidly degradable NSC, like starch from cereal grains. Increasing the concentration of NSC in diets of dairy cows, however, can lead to undesirable ruminal fermentation, compromising the nutrient supply for production of milk and milk components. In fact, it is well documented that feeding large amounts of NSC or nonfiber carbohydrates (NFC) can enhance the production of acids, particularly lactic acid, in the rumen; this increases the incidence of ruminal acidosis (Nocek, 1997) and reduces ruminal pH, fiber digestibility, acetate to propionate ratio, and milk fat content (Erdman, 1988). Additionally, an excess of readily available NSC in the rumen might compromise the efficiency of microbial protein synthesis and the supply of microbial AA to the small intestine because of increased energy spilling by ruminal bacteria (Clark et al., 1992). To prevent ruminal upsets and health problems, the NRC (2001) recommended that the maximum NFC in diets for high producing dairy cows should range from 36 to 44% depending on the total and forage NDF content of the ration.

The partial replacement of cereal grains with low starch byproduct feeds, such as soyhulls (SH), represents a potential alternative to overcome this limitation (Ipharraguerre and Clark, 2002). For instance, the replacement of 12 and 25% of the DM in the ration supplied as high moisture corn with SH markedly reduced NFC in the diet from 41 to 34 and 29%, respectively, but still enhanced the total VFA concentration and the

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acetate to propionate ratio in the rumen of dairy cows during early lactation (Cunningham et al., 1993). In this study, diets that contained SH sustained milk yield and secretion of milk components. Similar shifts in ruminal fermentation were reported in a number of studies (Sarwar et al., 1992; Mansfield and Stern, 1994) in which SH were substituted for corn to supply up to about 30% of dietary DM. This response seems to result from increases in the amount of fiber digested in the rumen of cows fed diets that contained SH (Cunningham et al., 1993; Mansfield and Stern, 1994). Additionally, the enhancement in digestibility of NDF could be related to the digestible nature of fiber in SH and/or to the reduction of negative associative effects of NSC on ruminal digestion of fiber (Firkins, 1997; Titgemeyer, 2000). The mechanism by which feeding SH to replace grains in the diet caused a positive associative effect on fiber digestion remains unclear. Furthermore, there is a paucity of data describing the process of digestion of carbohydrate fractions other than fiber when SH are fed to dairy cows (Ipharraguerre and Clark, 2002).

Similar rates of substitution of SH for corn ($\leq 30\%$ of dietary DM) supported ruminal synthesis of microbial protein (Cunningham et al., 1993; Mansfield and Stern, 1994) and apparent digestibility of N in the total gastrointestinal tract of dairy cows (Pantoja et al., 1994). On the other hand, there is only one study (Nakamura and Owen, 1989) reported in which the replacement of corn with SH exceeded 40% of the dietary DM. In that trial, Nakamura and Owen (1989) observed that the complete replacement of corn with SH (48% of dietary DM) in diets that contained 50% forage and 50% concentrate reduced NSC concentration; increased ruminal turnover rate; and decreased milk production, milk protein output, nutrient digestion, and nutrient utilization by lactating dairy cows. However, lack of sufficient evidence from experiments in which SH constituted more than 25 to 30% of the dietary DM restricts any attempt to establish a maximum at which SH can be substituted for cereal grains so as to optimize the supply of nutrients for production of milk and milk components (Ipharraguerre and Clark, 2002).

The objectives of this study were: 1) to evaluate the effects of the incremental substitution of SH for ground corn in high grain diets on ruminal fermentation, site and extent of nutrient digestion, microbial protein synthesis, and passage of nutrients to the small intestine of lactating dairy cows; and 2) to relate differences in production of milk and milk components determined in a companion experiment (Ipharraguerre et al., 2002) to alterations in ruminal fermentation, passage of nutrients to the small intestine, and utilization of nutrients by dairy cows.

MATERIALS AND METHODS

Animal Management, Experimental Design, and Diets

Five multiparous Holstein cows that averaged 574 ± 61 kg in BW and 63 ± 12 DIM at the onset of the experiment were surgically fitted with ruminal and duodenal cannulas according to procedures approved by the University of Illinois Laboratory Animal Care Advisory Committee. The ruminal cannulas were constructed of soft plastic (Bar Diamond, Parma, ID) and measured 10.2 cm in diameter. The duodenal cannulas were an enclosed T-shaped design made of stainless steel (Berzins Vet Laboratory LTD, Edmonton, Alberta, Canada). They were placed proximal to the common bile and pancreatic duct, about 10 cm distal to the pylorus.

Cows were housed in individual stanchions equipped with water bowls and bedded with straw. With the exception of the last 3 d of each period, cows were allowed to exercise in a drylot from 0800 to 0900 h. Cows were fed a TMR for ad libitum intake and were milked daily at 0500 and 1700 h. The experimental design was a 5×5 Latin square with 14-d periods. The first 9 d of each period were used to adapt the cows to treatments and the remaining 5 d were used to collect data. Each cow was randomly assigned to one of five treatment sequences in which a treatment never followed the same treatment for all sequences. The control diet contained 46% forage, 54% concentrate, and no SH. For the other four dietary treatments pelleted SH replaced corn in the concentrate to supply 10, 20, 30, or 40% of the dietary DM (Table 1). All diets were formulated to contain 16% CP and to meet the NRC (1989) recommendations for other nutrients. Diets were adjusted weekly to reflect changes in DM of forages and concentrate mixtures by drying each component overnight in an oven at 105°C.

Sampling, Measurements, and Analyses

Dry matter intake and orts were measured and recorded daily. Samples of individual feed ingredients, TMR, and orts were collected for the last 5 d of each period. Samples of individual feedstuffs and TMR were dried at 55°C in an oven for 72 h, ground through a 2-mm screen in a Willy Mill (Arthur H. Thomas, Philadelphia, PA), composited on an equal weight basis by period, and ground through a 1-mm screen. Samples of orts were dried at 55°C in an oven for 72 h, ground through a 2-mm screen, composited by the amount and dry weight of the daily orts for each cow, and ground through a 1-mm screen. Samples of feeds, TMR, and orts were analyzed for DM, OM, Kjeldahl N (AOAC, 1990), ADF (Van Soest et al., 1991), NDF with heat-

Table 1. Ingredient and chemical composition of the experimental diets.

Composition	Soyhulls in diet, ¹ %				
	0	10	20	30	40
	(% of DM)				
Ingredient					
Alfalfa silage	23.00	23.00	23.00	23.00	23.00
Corn silage	23.00	23.00	23.00	23.00	23.00
Soyhulls, pelleted	0.00	10.00	20.00	30.00	40.00
Ground shelled corn	40.32	30.48	20.75	10.88	1.00
Soybean meal, 49% CP	10.50	10.30	10.25	10.25	10.00
Sodium bicarbonate	1.00	1.00	1.00	1.00	1.00
Sodium chloride	0.25	0.25	0.25	0.25	0.25
Dicalcium phosphate	0.50	0.60	0.70	0.80	0.90
Limestone	0.63	0.55	0.22	0.00	0.00
Mineral and vitamin mix ²	0.25	0.25	0.25	0.25	0.25
Magnesium oxide	0.20	0.20	0.18	0.15	0.15
Sodium sulfate	0.35	0.37	0.40	0.42	0.45
Chemical					
DM	59.2	59.0	59.1	59.3	58.6
OM	93.0	92.8	92.7	92.6	92.2
CP	15.0	15.3	15.6	16.0	16.3
NDF	26.6	30.4	35.9	40.8	45.4
ADF	16.8	21.0	24.6	29.0	32.5
NSC	35.9	29.7	25.3	20.9	15.6
NE _L , Mcal/kg of DM ³	1.66	1.60	1.55	1.50	1.44

¹Soyhulls were substituted for corn in the experimental diets.

²Contained 5.0% Mg, 7.5% K, 10.0% S, 3.0% Zn, 3.0% Mn, 2.0% Fe, 0.5% Cu, 0.025% I, 0.015% Se, 0.004% Co, 2200 IU of vitamin A/g, 600 IU of vitamin D3/g, and 8 IU of vitamin E/g.

³Calculated using tabulated values from NRC (2001) and assuming an intake of 3 times maintenance.

stable α -amylase (Thermamyl 120L, Novo Nordisk Biochem, Franklinton, NC) and sodium sulfite (Van Soest et al., 1991), and NSC according to the enzymatic method of Smith (1981). Samples of feeds and TMR were prepared for AA determination, except Met, by acid hydrolysis with 6 N HCl (McCarthy et al., 1989). For Met determination, samples were first oxidized with performic acid, lyophilized after dilution with water to remove excess performic acid (Overton et al., 1995), and hydrolyzed with 6 N HCl as outlined by Moore (1963). Individual AA were then separated by ion exchange chromatography on a Beckman 126AA amino acid analyzer equipped with a Beckman 12-cm column (Beckman Instruments Inc., Palo Alto, CA).

Samples of ruminal fluid and duodenal digesta were collected every 3 h during the last 3 d of each period. The sampling time was adjusted ahead 1 h daily so that a sample was obtained for each 1-h interval of the day (24 total samples). Ruminal fluid samples were taken from multiple sites in the rumen and pH of ruminal fluid was measured immediately by glass electrode. After measurement of pH, a subsample of 50 ml was acidified to pH < 2 with 50% H₂SO₄ (v/v), centrifuged at 27,000 $\times$ g for 10 min at 4°C, and the supernatant was frozen at -20°C for later analyses. Following removal of the cap of the duodenal cannula, accumulated digesta was discarded, and when the flow appeared normal 500

ml of duodenal contents were collected. The volume of sample collected represented less than 4% of the estimated passage of digesta to the duodenum during the three days of collection. Samples were pooled by cow and stored frozen in 20 L buckets at -20°C until analyses.

After thawing, ruminal fluid samples were centrifuged at 27,000 $\times$ g for 20 min at 4°C and an aliquot of 4 ml was diluted with 25% metaphosphoric acid (4:1 ratio). These subsamples were used to determine VFA with a gas chromatograph (model 5890 Series II; Hewlett-Packard, Avondale, PA) equipped with a 1.8 m glass column packed with 10% SP 1200/1% H₃PO₄ on 80/100 chromosorb W AW (Supelco, 1975). Nitrogen was the carrier gas and the temperature of the injector port and column was 175°C and 125°C, respectively. Ruminal NH₃ N was determined according to the procedures outlined by Chaney and Marbach (1962) as modified by Cotta and Russell (1982).

Duodenal samples were thawed and homogenized for 5 min using a propeller-type mixer set at high speed. During continuous stirring, a representative subsample (1000 ml) of digesta was collected by vacuum. Samples then were poured into shallow pans, lyophilized, ground through a 1-mm screen, and analyzed for DM, OM, Kjeldhal N, ADF, NDF, NSC, and AA as described above. The duodenal content of NH₃ N was determined

by steam distillation with MgO (Bremner and Keeney, 1965) and purines, used as a bacterial marker, were measured by the method of Zinn and Owens (1986).

Ruminal bacteria were isolated from samples (1000 ml) of whole ruminal contents obtained from the reticulum near the reticulo-omasal orifice at six separate postfeeding times (0, 2, 4, 6, 8, and 10 h) during the last 3 d of each period. Ruminal contents were blended in a Waring blender (Waring Products Division, New Hartford, CT) for 1 min at low speed, strained through six layers of cheesecloth, and the effluents were used to prepare a bacteria-rich sample by differential centrifugation (Overton et al., 1995). Bacterial samples were pooled by cow within period and frozen at -20°C . These samples were lyophilized and analyzed for DM, OM, Kjeldhal N, AA, and purines by the methods described above.

During the last 5 d of each period, fecal grab samples were collected at 0700 and 1900 h, composited on an equal wet weight basis, dried at 55°C , ground through a 1-mm screen, and assayed for DM, OM, Kjeldhal N, ADF, NDF, and NSC as described above.

Chromic oxide (Cr_2O_3) was used as an indigestible marker to assess the passage of digesta to the duodenum and fecal excretion by the cows. Gelatin capsules that contained 10 g of Cr_2O_3 powder were administered via the ruminal cannula at 0800 and 2000 h during the last 10 d of each period. Concentration of Cr in duodenal and fecal samples was quantified by atomic absorption spectroscopy (air plus acetylene flame; Perkin-Elmer, Norwalk, CT) after preparation of samples by the procedure of Williams et al. (1962).

Passage of microbial N and OM to the duodenum was calculated from the passage of DM and from the proportion of N or OM of bacterial origin, respectively. These proportions were estimated by dividing the N to purine ratio or the OM to purine ratio of isolated bacteria by the N to purine ratio or the OM to purine ratio of duodenal digesta. Passage of nonammonia nonmicrobial N (**NANMN**) to the duodenum was calculated by subtracting passage of microbial N from passage of total NAN. Apparent digestibility of OM in the rumen was corrected for the passage of microbial OM to the duodenum to establish the amount of OM truly digested in the rumen.

Milk weights were recorded at each milking throughout the last 7 d of each period. Milk samples were taken at each milking during the last 7 d of each period, preserved with 2-bromo-2-nitropropane-1,3-diol, and stored at 4°C . Samples were sent to Dairy One Cooperative Inc. (Ithaca, NY) for analyses of fat, CP, true protein, total solids, and milk urea N (**MUN**) by infrared procedures (Foss 4000; Foss North America, Eden Prairie, MN).

Statistical Analyses

Data were analyzed using the MIXED procedure of SAS (2000), with cow treated as a random variable. With the exception of ruminal variables, data were analyzed as a 5×5 Latin square with the following model:

$$Y_{ijk} = \mu + C_i + P_j + T_k + \varepsilon_{ijk}$$

where:

- μ = overall mean,
- C_i = effect of cow i ($i = 1, 2, 3, 4, 5$),
- P_j = effect of period j ($j = 1, 2, 3, 4, 5$),
- T_k = effect of treatment k ($k = 1, 2, 3, 4, 5$), and
- ε_{ijk} = residual error.

The degrees of freedom for treatment were partitioned into four single-degree-of-freedom non-orthogonal contrasts: linear, quadratic, SH diets vs. control diet, and 40% SH diet vs. control diet. Linear and quadratic contrasts included the control and all SH diets.

Ruminal VFA, NH_3 N, and pH data were analyzed using the repeated measures approach of the MIXED procedure of SAS (Littell et al., 1996). Based on the largest value for the Akaike's information criterion (Littell et al., 1996), the compound symmetric structure type was selected as the appropriate covariance structure. The model was similar to the model described previously except for the addition of the effect of hour and the interaction of treatment and hour. Because the treatment by hour interaction was not significant ($P > 0.05$) for the ruminal parameters measured, treatment effects were compared across treatment sampling times using the contrasts described above.

Differences among treatments were considered to be significant when $P < 0.05$, whereas when $P > 0.05$ but < 0.10 differences were considered to indicate a trend towards a significant effect.

During the third period, one cow had abnormally low DMI and diarrhea because of heat stress. Veterinarians of the Ambulatory Service at the University of Illinois hydrated this cow with an electrolytic solution via the ruminal cannula and allowed her to recover during that period. Therefore, samples from that cow were not collected during the third period.

RESULTS AND DISCUSSION

Composition of Experimental Diets

The ingredient and chemical composition of diets is shown in Table 1. As expected, the incremental substitution of SH for corn markedly increased NDF and ADF in the diet. In contrast, as the percentage of SH in the

Table 2. Chemical composition of forages and soyhulls fed in the experimental diets.

Item	Corn silage	Alfalfa silage	Soyhulls
		(% of DM)	
CP	8.0	23.4	11.9
NDF	38.2	37.5	67.2
ADF	22.0	29.8	46.9
NSC	33.6	8.2	12.8

diets increased up to 40%, the concentration of NSC decreased by about 57%. These differences resulted because of the chemical composition of SH that are high in fiber and low in other carbohydrate fractions, such as NSC (Table 2; NRC, 2001). The CP percentage of the diets increased as additional increments of pelleted SH were substituted for corn (Table 1). The increase in CP content of the diets occurred because the CP content of the pelleted SH was slightly greater than expected and the CP content of corn was slightly lower. All diets, however, met or exceeded the requirements (NRC, 2001) for CP, RUP, and RDP of cows used in this experiment.

Intakes and Digestibilities of DM and OM

The average intake of DM for all treatments was 21.6 kg/d, and differences among treatments were not significant (Table 3). In a companion experiment (Ipharraguerre et al., 2002), however, DMI of midlactation dairy cows decreased linearly ($P < 0.06$) as incremental additions of SH were substituted for corn. Similar trends for DMI by cows in early lactation also were observed when SH replaced about 14% of the total DM in the diet supplied as high moisture corn (Stone, 1996). In contrast, the use of SH as a cereal grain replacement in diets of dairy cattle failed to alter DMI when SH provided less than 35% of the total DM in the diet (Sarwar et al., 1992).

The percentage of DM apparently digested in the total gastrointestinal tract was unaffected by dietary treatments (Table 3). However, compared with the control diet, feeding the diet that contained 40% SH tended to depress the amount of DM digested in the total tract by 1.6 kg/d. In an earlier study (Nakamura and Owen, 1989), the largest decrease in apparent DM digestibility in the total tract (i.e. nine percentage units) occurred when SH replaced corn to supply 48%, but not 25%, of the total dietary DM. Because in our experiment the percentage of DM digested did not change significantly, the decrease in the amount of DM digested can be attributed, at least partially, to the numerically lower DMI of cows fed the 40% SH diet.

The average intake of OM for all treatments was 20.0 kg/d and differences among treatments were not significant (Table 3). The amount of OM apparently and truly digested in the rumen was unaffected by the feeding of diets that contained SH. However, the percentage of OM intake that was apparently or truly digested in the rumen tended to be higher for the 40% SH diet compared with the control diet (Table 3). Mansfield and Stern (1994) reported that similar amounts and proportions of OM intake were apparently and truly digested in the rumen of lactating dairy cows fed diets in which SH replaced corn to supply 30% of the total DMI. To our knowledge, experiments that aimed to assess the site of nutrient digestion in dairy cows fed diets that contained more than 30% SH (DM basis) have not been conducted.

The amount of OM that passed to and was digested in the intestines decreased significantly for diets that contained SH. Compared with the control diet, the diet that contained 40% SH significantly decreased OM digestibility as a percentage of OM intake and tended to decrease OM digestibility as a percentage of OM that passed to the small intestine. The amount and the percentage of OM apparently digested in the total gastrointestinal tract were not affected by treatments. These results support previous findings, which indicate that replacing 12 to 34% of the total DM in the diet supplied as cereal grains with SH, does not affect digestibility of OM in the total gastrointestinal tract (Sarwar et al., 1992; Cunningham et al., 1993).

DMI, rate of passage from the rumen, and the supply of NSC in relation to fiber from SH are at least three factors that might explain why there were differences in digestibility of OM in the rumen and intestines, but not in the total tract. Nakamura and Owen (1989) reported that the replacement of corn with SH to supply 25 and 48% of the total dietary DM did not affect DMI, but enhanced the rate of passage of SH and decreased the proportion of DM apparently digested in the total tract. Because starch from corn has a similar or even slower (3.6 to 4.0%/h; Nocek and Tamminga, 1991) rate of ruminal disappearance than fiber from SH (3.3 to 10.3%/h; Ipharraguerre and Clark, 2002), it is possible that ruminal turnover rate might have increased as SH were increased in the diet, decreasing ruminal digestibility of OM when SH provided 30% or less of the dietary DM. In contrast, when SH provided 40% of the dietary DM the numerically lower intake of OM might have offset any increase in the rate of passage, in turn improving OM digestibility in the rumen. These observations are in agreement with other findings (Cunningham et al., 1993; Feng et al., 1993), indicating that ruminal fermentation of OM might be maintained or even improved if dietary NSC are reduced by replacing cereal

Table 3. Least squares means for intakes and digestibilities of DM and OM in various segments of the gastrointestinal tract of lactating dairy cows fed diets containing incremental amounts of soyhulls.

Item	Soyhulls in diet, ¹ %					SEM	Contrast			
	0	10	20	30	40		SH vs. C ²	Linear	Quadratic	40 SH vs. C ²
	(P <)									
DM										
Intake, kg/d	22.1	21.1	21.7	22.0	20.9	1.3	NS ³	NS	NS	NS
ADTT ⁴										
kg/d	16.1	15.4	15.8	16.0	14.5	0.9	NS	NS	NS	0.09
%	72.6	73.0	73.0	71.2	69.4	1.6	NS	NS	NS	NS
OM										
Intake, kg/d	20.6	19.6	20.1	20.3	19.3	1.3	NS	NS	NS	NS
Apparently digested in the rumen										
kg/d	4.6	5.8	5.2	4.3	5.6	1.4	NS	NS	NS	NS
% of Intake	22.4	28.8	25.9	21.2	28.2	6.2	NS	NS	NS	0.07
Truly digested in the rumen										
kg/d	7.5	8.5	8.1	7.7	8.6	1.6	NS	NS	NS	NS
% of Intake	36.8	42.6	40.0	38.0	43.5	7.0	NS	NS	NS	0.06
Passage to duodenum, kg/d	16.0	13.8	14.9	16.0	13.8	1.4	0.03	NS	NS	0.008
Apparently digested postruminally										
kg/d	10.5	8.7	9.8	10.6	8.1	1.2	0.04	0.08	NS	0.004
% of Intake	51.0	45.3	48.6	52.7	42.6	6.0	NS	NS	NS	0.02
% of Passage to duodenum	64.8	62.4	64.6	65.6	58.2	4.3	NS	NS	NS	0.07
ADTT										
kg/d	15.1	14.4	15.0	15.0	13.7	1.0	NS	NS	NS	NS
%	73.4	74.1	74.5	73.5	70.9	1.9	NS	NS	NS	NS

¹Soyhulls were substituted for corn in the experimental diets.²SH vs. C = Soyhull diets vs. control diet, 40 SH vs. C = 40% soyhull diet vs. control diet.³Nonsignificant ($P > 0.10$).⁴Apparently digested in the total gastrointestinal tract.

grains with fermentable nonforage fiber sources in the diet.

Intakes and Digestibilities of NSC

The intake of NSC decreased linearly as SH replaced corn in the diet, being 4.8 kg/d per cow greater for the control diet compared with the diet that contained 40% SH (Table 4). The linear decrease in intake of NSC was caused mainly by the decreasing concentration of NSC in the diets (Table 1) when SH replaced corn. Other researchers also reported a lower intake of NSC (Feng et al., 1993; Mansfield and Stern, 1994) from diets in which the percentage of NSC was altered by varying the dietary concentration of fibrous byproducts and cereal grains.

The amount and percentage of NSC apparently digested in the rumen decreased linearly as SH were substituted for corn (Table 4). Previous data indicate that reduced intake of NSC can depress the amount (Stokes et al., 1991) or both the amount and percentage (Feng et al., 1993) of NSC fermented in the rumen.

Because the content of starch in SH normally is negligible (NRC, 2001), we expect that as corn grain was removed from the diets the proportion of total NSC intake supplied as starch may have decreased progres-

sively and markedly. This implies that a proportionally greater intake of NSC from carbohydrate sources other than starch must have occurred as SH partially replaced corn in the diet. These sources of carbohydrates were probably simple sugars and pectin, because SH contain high concentrations of these constituents. Simple sugars and pectin are degraded in the rumen at a faster rate than starch (Mertens, 1992). Even though SH contain these rapidly degradable simple sugars and pectin, there was a tendency for decreased ruminal digestibility of NSC in the diets that contained SH. This trend for decreased ruminal digestibility of NSC for the diets that contained SH might have occurred because of a faster rate of passage of SH than corn from the rumen. These observations are consistent with other findings (Lykos et al., 1997), which indicate that diets formulated to contain NSC with different rates of ruminal degradability (6.04, 6.98, and 7.94%/h) did not differ among treatments for apparent ruminal digestibility of NSC because of different rates of passage of the NSC sources from the rumen.

The decreased intakes of NSC resulted in smaller quantities of these carbohydrates passing to the small intestine of cows fed diets that contained SH, even though their ruminal digestibilities were depressed (Table 4). Once in the lower digestive tract, the amount

Table 4. Least squares means for intakes and digestibilities of NSC in various segments of the gastrointestinal tract of lactating dairy cows fed diets containing different amounts of soyhulls.

Item	Soyhulls in diet, ¹ %					SEM	Contrast			
	0	10	20	30	40		SH vs. C ²	Linear	Quadratic	40 SH vs. C ²
<i>(P <)</i>										
NSC										
Intake, kg/d	8.5	6.7	6.0	5.0	3.7	0.4	0.0001	0.0001	NS ³	0.0001
Apparently digested in the rumen										
kg/d	1.8	2.1	1.0	0.6	0.3	0.9	NS	0.009	NS	0.03
% of Intake	21.6	29.8	17.2	10.7	4.5	17.1	NS	0.1	NS	NS
Passage to duodenum, kg/d	6.7	4.6	5.0	4.5	3.4	0.9	0.0003	0.0002	NS	0.0001
Apparently digested postruminally										
kg/d	6.0	4.2	4.6	4.1	3.0	0.9	0.0006	0.0004	NS	0.0002
% of Intake	70.5	63.8	75.9	81.4	83.0	17.3	NS	NS	NS	NS
% of Passage to duodenum	89.2	89.5	89.9	89.1	80.0	4.6	0.1	NS	NS	0.07
ADTT ⁴										
kg/d	7.8	6.3	5.6	4.6	3.3	0.4	0.0001	0.0001	NS	0.0001
%	92.1	93.6	93.2	92.2	87.6	0.7	NS	0.0002	0.0002	0.0003

¹Soyhulls were substituted for corn in the experimental diets.

²SH vs. C = Soyhull diets vs. control diet, 40 SH vs. C = 40% soyhull diet vs. control diet.

³NS = Nonsignificant ($P > 0.10$).

⁴Apparently digested in the total gastrointestinal tract.

of NSC apparently digested was greater for cows fed corn and decreased linearly as SH replaced corn in the diet. Mansfield and Stern (1994) reported that replacing ground corn with SH to supply 30% of the total dietary DM significantly reduced the amount of NSC passing to and digested in the small intestine.

In our experiment, the NSC digestibility as percentage of passage to duodenum tended to decrease when SH were fed, being about nine percentage units lower for the diet that contained 40% SH than for other treatments (Table 4). The depressed postruminal digestibility of NSC probably occurred because the proportions of highly digestible NSC that would be fermented in the rumen increased as SH replaced corn in the diet, leaving a proportionally larger fraction of less digestible NSC that was more likely to escape postruminal digestion. Recent data of Lykos et al. (1997) indicate that postruminal digestibility of NSC in dairy cows was increased almost four-fold when similar amounts of NSC with dissimilar rates of ruminal degradability passed to the lower digestive tract.

The quantity of NSC apparently digested in the total tract declined with the incremental substitution of SH for corn in the diets (Table 4), which was caused largely by the lower intake of these carbohydrate fractions when cows were fed SH. The substitution of SH for corn in the diet resulted in a quadratic response for digestibility of NSC in the total digestive tract when expressed as a percentage of intake, which was lowest for the diet that contained 40% SH. The largest depression in digestibility was obtained for the diet that contained 40% SH and occurred because of a lower intake

and decreased digestibility in both the rumen and lower digestive tract.

Digestibilities of NSC were lower in the rumen and were higher in the lower digestive tract than values previously reported for diets that contained similar concentrations of NSC (Stokes et al., 1991; Feng et al., 1993; Mansfield and Stern, 1994; Lykos et al., 1997), in which corn was the predominant source of NSC. Potential sources of variation that might explain these discrepancies include decreasing precision of the methodology used in the determination of NSC as their concentration in the collected samples decreased to low levels, especially for the samples from the treatment that contained 40% SH, and/or segregation of digesta particles, particularly pieces of corn kernel that were high in starch, during sampling, processing, or both.

Intakes and Digestibilities of ADF and NDF

Intakes of ADF and NDF were smallest for cows fed the control diet and increased linearly in response to the incremental substitution of SH for corn (Table 5). These responses were obtained because of the higher concentration of ADF and NDF in the SH diets (Table 1), which agree with results from other experiments in which SH were added to the diet without the diets being made equal in fiber (Cunningham et al., 1993; Ipharraguerre et al., 2002).

The quantities of ADF and NDF fermented in the rumen, passed to the duodenum, digested in the lower tract, and digested in the total tract were greater for cows fed SH than for cows fed the control diet and

Table 5. Least squares means for intakes and digestibilities of ADF and NDF in various segments of the gastrointestinal tract of lactating dairy cows fed diets containing different amounts of soyhulls.

Item	Soyhulls in diet, ¹ %					SEM	Contrast			
	0	10	20	30	40		SH vs. C ²	Linear	Quadratic	40 SH vs. C ²
							(P <)			
ADF										
Intake, kg/d	3.7	4.4	5.3	6.5	6.7	0.4	0.0001	0.0001	NS ³	0.0001
Apparently digested in the rumen										
kg/d	1.7	2.2	2.5	2.7	3.1	0.5	0.002	0.0004	NS	0.0006
% of Intake	44.5	47.4	48.3	41.2	45.6	6.5	NS	NS	NS	NS
Passage to duodenum, kg/d	2.0	2.2	2.7	3.8	3.7	0.3	0.0006	0.0001	NS	0.0001
Apparently digested postruminally,										
kg/d	0.2	0.4	0.4	1.1	0.8	0.3	0.08	0.02	NS	0.08
% of Intake	6.9	10.8	7.7	15.9	10.7	5.3	NS	NS	NS	NS
% of Passage to duodenum	10.2	18.0	13.7	28.6	18.8	8.7	NS	NS	NS	NS
ADTT ⁴										
kg/d	2.0	2.6	3.0	3.7	3.8	0.4	0.0006	0.0001	NS	0.0002
%	51.5	58.2	56.0	56.1	56.3	4.3	NS	NS	NS	NS
NDF										
Intake, kg/d	5.9	6.3	7.7	8.9	9.4	0.6	0.0001	0.0001	NS	0.0001
Apparently digested in the rumen										
kg/d	2.6	2.6	3.6	3.6	4.2	0.6	0.008	0.0005	NS	0.0004
% of Intake	43.2	39.2	46.9	39.6	44.4	5.5	NS	NS	NS	NS
Passage to duodenum, kg/d	3.3	3.7	4.1	5.4	5.3	0.5	0.003	0.0001	NS	0.0007
Apparently digested postruminally										
kg/d	0.6	0.9	0.9	1.6	1.4	0.4	0.09	0.04	NS	0.09
% of Intake	8.9	16.8	11.4	18.2	14.5	6.2	NS	NS	NS	NS
% of Passage to duodenum	15.0	25.3	19.9	30.4	25.1	9.3	NS	NS	NS	NS
ADTT										
kg/d	3.2	3.5	4.5	5.2	5.5	0.5	0.001	0.0001	NS	0.0002
%	52.0	56.0	58.3	57.6	58.9	4.1	NS	NS	NS	NS

¹Soyhulls were substituted for corn in the experimental diets.²SH vs. C = Soyhull diets vs. control diet, 40 SH vs. C = 40% soyhull diet vs. control diet.³NS = Nonsignificant ($P > 0.10$).⁴Apparently digested in the total gastrointestinal tract.

increased linearly as additional SH replaced corn in the diet (Table 5). Cunningham et al. (1993) and Mansfield and Stern (1994) also reported that large intakes of NDF that resulted from the replacement of corn with SH in diets for dairy cows ($\geq 50\%$ concentrate) enhanced the amount of NDF apparently digested in the rumen and total digestive tract. However, the passage of NDF to the duodenum increased significantly only when 30% of the dietary DM (Mansfield and Stern, 1994), but not 25% or less (Cunningham et al., 1993), was supplied from SH.

The proportions of ADF and NDF that were apparently digested in the rumen as a percentage of intake, digested in the lower tract as a percentage of intake and as a percentage of passage to the duodenum, and digested in the total digestive tract were similar among treatments (Table 5). Inclusion of SH in diets for dairy cows increased ruminal digestibility of NDF in one experiment (Cunningham et al., 1993) but failed to affect it in another (Mansfield and Stern, 1994). Apparent digestibility of NDF in the total digestive tract of lactating cows was numerically (Nakamura and Owen, 1989)

or significantly (Cunningham et al., 1993; Pantoja et al., 1994) improved when SH replaced cereal grains (SH ranged from 12 to 48% of dietary DM) in the diet. Compared with the control diet, the average increase in digestibility of NDF in the total tract for diets that contained SH was 11% (Table 5), which is in close agreement with the 14% improvement estimated by Firkins (1997). Firkins (1997) suggested that the replacement of concentrate with sources of nonforage fiber might have positive associative effects on fiber digestibility but only when the NFC concentration of the control diet was equal to or greater than 45%; moreover, the largest response in digestibility occurred when the reduction in NFC of the control diet was from 45 to 35%. Therefore, in our trial, the highest concentration of readily fermentable carbohydrates (35.9% NSC) might already be too low to negatively affect ruminal fiber digestibility, which might explain why NDF digestibilities were similar for all dietary treatments. Additionally, an accelerated rate of ruminal outflow for diets that contain large quantities of SH might also have contributed to equalize NDF digestibilities among

Table 6. Least squares means for ruminal characteristics of lactating dairy cows fed diets containing different amounts of soyhulls.

Item	Soyhulls in diet, ¹ %					SEM	Contrast			
	0	10	20	30	40		SH vs. C ²	Linear	Quadratic	40 SH vs. C ²
							(P <)			
pH	6.11	6.00	6.09	5.96	6.09	0.08	0.07	NS ³	0.08	NS
VFA, mM	122.8	124.8	127.1	130.7	130.6	3.39	0.01	0.0006	NS	0.005
Acetate, mol/100 mol	63.7	65.0	64.5	65.5	66.2	1.32	0.0009	0.0001	NS	0.0001
Propionate, mol/100 mol	20.4	19.6	20.2	19.6	19.3	0.94	0.10	0.10	NS	0.06
Acetate:propionate	3.20	3.38	3.32	3.44	3.48	0.20	0.008	0.006	NS	0.004
Isobutyrate, mol/100 mol	1.0	1.0	0.9	0.9	1.0	0.07	NS	NS	NS	NS
Butyrate, mol/100 mol	11.3	11.1	10.6	10.6	10.3	0.35	0.05	0.008	NS	0.02
Isovalerate, mol/100 mol	1.7	1.7	1.7	1.6	1.6	0.09	NS	NS	NS	NS
Valerate, mol/100 mol	1.9	1.7	2.0	1.8	1.6	0.28	NS	NS	NS	NS
NH ₃ N, mg/dl	12.6	15.8	15.7	16.3	17.8	1.33	0.0001	0.0001	NS	0.0001

¹Soyhulls were substituted for corn in the experimental diets.

²SH vs. C = Soyhull diets vs. control diet, 40 SH vs. C = 40% soyhull diet vs. control diet.

³NS = Nonsignificant ($P > 0.10$).

treatments, as was suggested by Nakamura and Owen (1989).

Ruminal Environment

Ruminal pH tended to decrease when SH partially replaced corn in the diet, and replacing incremental quantities of corn with SH resulted in a trend for a quadratic decrease in pH (Table 6); however, these effects probably were not biologically significant. Generally, the use of SH as a replacement for grain has not altered ruminal pH (Mansfield and Stern, 1994; Elliott et al., 1995) but, in some trials, numerical trends similar to those in our trial were observed (Cunningham et al., 1993; Pantoja et al., 1994). In part, this effect could be associated with the amount of NSC in the diets fed in our experiment, which might be less than the quantity required to induce major changes in the environment of the rumen (Nocek, 1997). Sarwar et al. (1992) reported that reducing NSC in the diet from 50 to 37 and 27% through partial substitution of SH for corn in diets that contained 57% concentrate decreased the characteristic postfeeding decline in ruminal pH, although the decline was only significant at 9 h postfeeding.

The concentration of VFA in ruminal fluid was lowest when the control diet was fed and increased linearly as corn was replaced with SH (Table 6). These findings agree with data from a number of studies (Cunningham et al., 1993; Mansfield and Stern, 1994; Pantoja et al., 1994), reflecting the highly fermentable nature of fiber in SH. As SH were substituted for corn at incremental rates, the molar proportion of acetate increased and that of propionate tended to decline, resulting in a significantly higher acetate-to-propionate ratio (Table 6). Ruminal fluid from cows fed the control diet had the highest concentration of butyrate, and increasing the

amount of SH in the diet linearly reduced the molar percentage of butyrate, but the molar percentages of isobutyrate, isovalerate, and valerate were not affected by treatments (Table 6). Similar alterations in the pattern of VFA in ruminal fluid have been reported when SH partially or totally replaced cereal grains in diets of dairy cattle (Sarwar et al., 1991; 1992) and beef cattle (Grigsby et al., 1993). Mansfield and Stern (1994) suggested that such changes in the molar proportions of ruminal VFA reveal a shift in the type of carbohydrate (NSC vs. fiber) being fermented in the rumen. This interpretation of the VFA concentrations agrees with our data because as the amount of corn replaced with SH increased from 0 to 40% the amount of NSC digested in the rumen declined by about 83% (Table 4) and the amount of NDF digested increased by approximately 62% (Table 5). Even though the changes in digestibility of NSC and NDF were rather large and the changes in total concentrations and molar proportions of VFA were significantly different, the magnitude of the changes in concentrations and molar proportions of VFA was small and changes probably were not biologically significant. The molar proportion of propionate and the acetate to propionate ratio were in the range for the production of milk with a normal fat content (Erdman, 1988).

The concentration of NH₃ N in ruminal fluid was greater for cows fed SH than for cows fed corn and increased linearly from 12.6 to 17.8 mg/dl as increments of SH replaced corn in the diet (Table 6). This linear increase in NH₃ N probably occurred because the CP concentration of the diet increased as SH replaced corn (Table 1). Partial replacement of cereal grains with SH in diets of dairy cows has depressed concentrations of NH₃ N in ruminal fluid in two trials (Mansfield and Stern, 1994; Sarwar et al., 1992) but had no effect in another experiment (Cunningham et al., 1993). In our

Table 7. Least squares means for intake and digestibility of N in various segments of the gastrointestinal tract of lactating dairy cows fed diets containing different amounts of soyhulls.

Item	Soyhulls in diet, ¹ %					SEM	Contrast			
	0	10	20	30	40		SH vs. C ²	Linear	Quadratic	40 SH vs. C ²
							(P <)			
N intake, g/d	523	514	541	566	546	40.3	NS ³	NS	NS	NS
Passage to duodenum										
Total N										
g/d	562	563	601	660	608	47.1	0.10	NS	NS	NS
% of N intake	108.5	109.9	111.4	115.1	111.6	6.8	NS	NS	NS	NS
NAN										
g/d	542	538	576	631	582	45.9	NS	NS	NS	NS
% of N intake	104.6	105.0	107.0	110.3	106.6	6.4	NS	NS	NS	NS
NANMN ⁴										
g/d	250	265	285	275	273	21.5	NS	NS	NS	NS
% of NAN	46.1	49.9	49.7	43.5	47.7	3.6	NS	NS	NS	NS
% of N intake	48.3	52.5	52.7	48.1	50.7	4.7	NS	NS	NS	NS
Microbial N, g/d	292	273	291	353	309	38.2	NS	NS	NS	NS
% of NAN	53.9	50.1	50.3	56.1	52.3	3.6	NS	NS	NS	NS
g/kg of OMAD ⁵	68.4	51.7	55.7	75.7	59.8	13.3	NS	NS	NS	NS
g/kg of OMTD ⁶	39.4	33.8	35.8	46.5	36.8	4.5	NS	NS	NS	NS
g/kg of OMADTT ⁷	19.4	18.8	19.5	23.3	22.3	1.9	NS	0.02	NS	NS
N digested postruminally										
g/d	390	386	427	497	424	42.7	NS	NS	NS	NS
% of N intake	75.4	75.6	79.3	85.3	77.6	7.2	NS	NS	NS	NS
% of N passage to duodenum	69.0	68.9	70.5	73.9	69.5	2.6	NS	NS	NS	NS
N ADTT ⁸										
g/d	350	337	368	398	361	32.4	NS	NS	NS	NS
%	66.8	65.7	67.9	69.6	66.1	2.4	NS	NS	NS	NS

¹Soyhulls were substituted for corn in the experimental diets.²SH vs. C = Soyhull diets vs. control diet, 40% SH vs. C = 40% soyhull diet vs. control diet.³NS = Nonsignificant ($P > 0.10$).⁴Nonammonia nonmicrobial N.⁵Organic matter apparently digested in the rumen.⁶Organic matter truly digested in the rumen.⁷Organic matter apparently digested in the total gastrointestinal tract.⁸Apparently digested in the total gastrointestinal tract.

experiment and in these cited experiments, the concentration of NH_3 N in ruminal fluid from cows fed all diets was greater than the minimum concentration of 5 mg/dl recommended for maximum microbial growth (Satter and Slyter, 1974). These data suggest that there was not a deficiency of NH_3 N in ruminal fluid for maximizing microbial protein synthesis.

Nitrogen Intake and Metabolism

The intake of N was similar among treatments, averaging 538 g/d per cow for all diets (Table 7). The amount of total N that passed to the duodenum tended to be greater for cows fed diets that contained SH but this trend was not evident when passage of N was expressed as a percentage of N intake (Table 7). Because the passage of NAN to the duodenum (expressed as amount and percentage of N intake) was not altered by treatments (Table 7), the trend for increased passage of total N to the duodenum indicates that the amount of NH_3

N that passed to the duodenum also was slightly greater for diets that contained SH than corn (average 26 vs. 20 g/d). On average, passage of total N and NAN were 11 and 7% greater than N intake, respectively (Table 7). Likewise, the inclusion of a fibrous byproduct in high grain diets has resulted in passage of N and NAN that was greater than N intake even though N intake was similar to that in our experiment (Feng et al., 1993). Our data agree with those of Mansfield and Stern (1994), indicating that the amount of NAN that passed to the duodenum did not differ when SH replaced corn in diets fed to dairy cows, but Cunningham et al. (1993) reported that NAN passage to the duodenum tended to be decreased. Likewise, passage of NANMN to the duodenum was not significantly different among treatments when expressed as an absolute amount, as a percentage of NAN, or as a percentage of N intake (Table 7). This agrees with data from a number of other experiments in which SH were used to replace grain in

diets of dairy cows (Cunningham et al., 1993; Mansfield and Stern, 1994; Pantoja et al., 1994).

Replacing corn in the diet of dairy cows with SH did not significantly affect the amount of microbial N that passed to the duodenum (Table 7), which averaged 304 g/d for all treatments. This value is slightly greater than the mean of 265 g/d calculated by Clark et al. (1992) from a summary of 152 dietary treatments, many of which had a lower DMI than was observed in our trial. Passage of microbial N to the duodenum as a percentage of NAN passage to the duodenum also was not significantly affected by treatments. Our data agree with those from other studies in that the complete or partial replacement of corn with SH did not affect (Mansfield and Stern, 1994) or increased (Grigsby et al., 1993) microbial protein synthesis.

Efficiency of microbial protein synthesis expressed as grams of microbial protein synthesized per kilogram of OM apparently digested in the rumen, or as grams of microbial protein synthesized per kilogram of OM truly digested in the rumen, was not different among treatments. Other researchers also reported that replacing corn with SH in diets for dairy cows (Cunningham et al., 1993; Mansfield and Stern, 1994; Pantoja et al., 1994) did not affect the efficiency of microbial protein synthesis.

Recently, the NRC (2001) concluded that the use of OM apparently digested in the total tract provides a more accurate estimation of the efficiency of microbial protein synthesis than the use of ruminally fermentable OM. In our experiment, the calculation of efficiency of microbial protein synthesis using grams of microbial N that passed to the duodenum per kilogram of OM apparently digested in the total tract resulted in less variable estimations, and efficiency increased linearly as SH replaced corn in the diet (Table 7). Because OM digestibility in the total tract was similar among treatments, it appears that the nonsignificant increase in microbial N synthesis for the SH diets was sufficient to cause this response. Therefore, enhanced efficiency of microbial protein synthesis might have arisen from the increased intake of AA by cows fed the diets that contained SH (Table 8). These observations are in general agreement with data indicating that microbial growth or efficiency of growth improved when ruminal microbes were able to derive a greater proportion of their N requirements from AA or peptides (Cotta and Russell, 1982; Griswold et al., 1996).

Postruminal digestibility of N expressed as grams per day, percentage of N intake, and as a percentage of N passage to the duodenum was unaffected by treatments (Table 7). Likewise, digestibility of N in the total gastrointestinal tract did not differ among treatments and averaged 67.2% (Table 7). Similar to results from

this experiment, other researchers have reported no change in digestibility of N when SH replaced cereal grains in diets fed to lactating dairy cows (Sarwar et al., 1992; Cunningham et al., 1993; Pantoja et al., 1994).

Amino Acid Intake and Passage to Duodenum

The incremental substitution of SH for corn linearly increased the intake of most individual AA, except for Leu, Phe, Val, Ala, Glu, and Pro, causing a linear increase in the ingestion of total essential AA (EAA), total nonessential AA (NEAA), and total AA (Table 8). However, the differences for His, Ile, Leu, Phe, Val, Ala, Glu, Pro, total EAA, total NEAA, and total AA between the corn-based control diet and the average of the four diets that contained SH were not significant. Because the content of Lys, Arg, Asp, Gly, and Ser is usually larger in protein from SH than from corn (Ipharraguerre and Clark, 2002), enhanced intake of these AA, or at least some of them, might be expected when SH replace relatively large proportions of corn and that is what we observed (Table 8). Data from another report (Cunningham et al., 1993) suggest that the intake of other AA, particularly Met, should not increase or might even decrease, as was reported by Mansfield and Stern (1994). Therefore, our results can be explained by the differences in the AA composition of the corn and soy proteins and by the slightly greater N intake by cows fed the diets that contained 20, 30, and 40% SH.

The amount of total EAA, total NEAA, and total AA of NANMN origin that passed to the duodenum was not affected by dietary treatments (Table 9). Although the intake of several individual EAA increased when diets that contained SH were fed, Lys was the only EAA of NANMN origin to increase in passage to the duodenum (Table 9). Among the individual NEAA of NANMN origin, only the passage to the duodenum of Gly increased and passage to the duodenum of Asp and Ser tended to increase for cows fed diets that contained SH (Table 9).

Passage to the duodenum of individual AA, total EAA, total NEAA, and total AA of microbial origin did not differ among diets (Table 10). The replacement of corn with SH resulted in a linear increase for passage to the duodenum of total Lys and Gly from NANMN plus microbial N and a trend for a linear increase for total Asp and Ser (Table 11). This effect was probably due to the larger intakes of these AA when diets that contained SH were fed and because of the nonsignificant but numerical increase in passage to the duodenum of these AA in microbial CP.

Our data agree with previous data (Cunningham et al., 1993; Mansfield and Stern, 1994) indicating that

Table 8. Least squares means for intakes of AA by lactating dairy cows fed diets containing different amounts of soyhulls.

AA	Soyhulls in diet, ¹ %					SEM	Contrast			
	0	10	20	30	40		SH vs. C ²	Linear	Quadratic	40 SH vs. C ²
	(g/d)						(P <)			
Essential										
Arg	134	143	150	159	172	9.8	0.02	0.001	NS ³	0.002
His	71	73	77	81	83	4.9	NS	0.02	NS	0.04
Ile	140	143	151	160	164	9.4	NS	0.01	NS	0.03
Leu	297	291	298	303	300	18.5	NS	NS	NS	NS
Lys	151	163	182	200	224	12.5	0.002	0.0001	NS	0.0001
Met	42	47	45	50	49	2.4	0.02	0.02	NS	NS
Phe	157	158	162	167	170	10.3	NS	NS	NS	NS
Thr	121	127	136	148	149	9.4	0.03	0.005	NS	0.01
Val	178	175	184	190	193	10.9	NS	NS	NS	NS
Total	1278	1297	1362	1430	1475	86.7	NS	0.03	NS	0.05
Nonessential										
Ala	268	261	265	274	264	17.9	NS	NS	NS	NS
Asp	323	327	355	376	394	22.0	0.05	0.003	NS	0.008
Glu	463	460	479	485	494	30.0	NS	NS	NS	NS
Gly	155	168	189	212	223	11.8	0.0006	0.0001	NS	0.0001
Pro	229	222	236	230	235	13.6	NS	NS	NS	NS
Ser	163	166	177	187	195	11.5	0.09	0.008	NS	0.02
Tyr	84	92	98	111	124	7.1	0.003	0.0001	NS	0.0001
Total	1684	1696	1798	1875	1929	109.4	NS	0.03	NS	0.06
Total AA	2962	2993	3160	3304	3403	195.9	NS	0.03	NS	0.05

¹Soyhull were substituted for corn in the experimental diets.²SH vs. C = Soyhulls diets vs. control diet, 40 SH vs. C = 40% soyhull diet vs. control diet.³NS = Nonsignificant ($P > 0.10$).**Table 9.** Least squares means for passage of nonammonia nonmicrobial AA to the duodenum of lactating dairy cows fed diets containing different amounts of soyhulls.

AA	Soyhulls in diet, ¹ %					SEM	Contrast			
	0	10	20	30	40		SH vs. C ²	Linear	Quadratic	40 SH vs. C ²
	(g/d)						(P <)			
Essential										
Arg	72	68	64	65	56	10.8	NS ³	NS	NS	NS
His	36	38	40	42	40	3.7	NS	NS	NS	NS
Ile	60	66	67	70	68	7.0	NS	NS	NS	NS
Leu	153	150	151	154	136	16.3	NS	NS	NS	NS
Lys	84	102	101	118	112	10.1	0.01	0.01	NS	0.02
Met	18	12	15	23	12	4.8	NS	NS	NS	NS
Phe	77	81	79	84	77	9.4	NS	NS	NS	NS
Thr	61	66	67	69	65	6.6	NS	NS	NS	NS
Val	69	80	76	80	78	8.1	NS	NS	NS	NS
Total	621	664	650	684	632	70.0	NS	NS	NS	NS
Nonessential										
Ala	89	96	95	94	88	9.9	NS	NS	NS	NS
Asp	125	145	149	154	152	15.6	0.08	NS	NS	NS
Glu	238	236	240	242	217	24.5	NS	NS	NS	NS
Gly	78	90	94	108	111	9.9	0.02	0.004	NS	0.007
Pro	108	108	115	111	100	13.6	NS	NS	NS	NS
Ser	76	86	93	95	91	9.1	0.08	0.10	NS	NS
Tyr	31	45	36	39	38	8.5	NS	NS	NS	NS
Total	745	806	821	844	797	84.7	NS	NS	NS	NS
Total AA	1366	1470	1471	1527	1430	154.0	NS	NS	NS	NS

¹Soyhulls were substituted for corn in the experimental diets.²SH vs. C = Soyhull diets vs. control diet, 40 SH vs. C = 40% soyhull diet vs. control diet.³NS = Nonsignificant ($P > 0.10$).

Table 10. Least squares means for passage of microbial AA to the duodenum of lactating dairy cows fed diets containing different amounts of soyhulls.

AA	Soyhulls in diet, ¹ %					SEM	Contrast			40 SH vs. C ²
	0	10	20	30	40		SH vs. C ²	Linear	Quadratic	
	(g/d)						(P <)			
Essential										
Arg	73	65	71	90	74	10.6	NS ³	NS	NS	NS
His	29	26	28	34	29	4.1	NS	NS	NS	NS
Ile	83	76	81	100	87	11.3	NS	NS	NS	NS
Leu	125	113	121	150	128	16.7	NS	NS	NS	NS
Lys	108	101	110	133	117	17.1	NS	NS	NS	NS
Met	22	28	25	22	27	4.4	NS	NS	NS	NS
Phe	82	74	80	98	86	11.1	NS	NS	NS	NS
Thr	79	75	79	97	84	11.5	NS	NS	NS	NS
Val	90	82	88	108	92	12.1	NS	NS	NS	NS
Total	715	655	706	870	746	101.1	NS	NS	NS	NS
Nonessential										
Ala	117	106	113	140	119	16.1	NS	NS	NS	NS
Asp	189	175	189	233	200	27.0	NS	NS	NS	NS
Glu	200	182	196	240	206	27.8	NS	NS	NS	NS
Gly	87	79	87	106	92	12.0	NS	NS	NS	NS
Pro	68	60	66	80	66	9.1	NS	NS	NS	NS
Ser	86	79	85	107	90	12.2	NS	NS	NS	NS
Tyr	89	81	91	108	97	13.0	NS	NS	NS	NS
Total	835	762	826	1016	870	116.7	NS	NS	NS	NS
Total AA	1550	1417	1532	1886	1616	217.6	NS	NS	NS	NS

¹Soyhulls were substituted for corn in the experimental diets.²SH vs. C = Soyhull diets vs. control diet, 40 SH vs. C = 40% soyhull diet vs. control diet.³NS = Nonsignificant ($P > 0.10$).**Table 11.** Least squares means for passage of AA to the duodenum of lactating dairy cows fed diets containing different amounts of soyhulls.

AA	Soyhulls in diet, ¹ %					SEM	Contrast			
	0	10	20	30	40		SH vs. C ²	Linear	Quadratic	40 SH vs. C ²
	(g/d)						(P <)			
Essential										
Arg	144	133	135	154	130	16.3	NS ³	NS	NS	NS
His	64	64	67	77	69	6.0	NS	NS	NS	NS
Ile	142	142	148	170	155	13.2	NS	NS	NS	NS
Leu	278	263	272	304	264	21.9	NS	NS	NS	NS
Lys	192	203	211	251	228	21.2	NS	0.04	NS	NS
Met	41	40	40	45	39	3.1	NS	NS	NS	NS
Phe	159	156	159	182	163	14.3	NS	NS	NS	NS
Thr	140	141	146	166	150	13.1	NS	NS	NS	NS
Val	159	162	164	187	170	14.6	NS	NS	NS	NS
Total	1336	1319	1356	1553	1379	121.8	NS	NS	NS	NS
Nonessential										
Ala	206	202	208	234	207	17.3	NS	NS	NS	NS
Asp	314	320	337	388	352	31.2	NS	0.08	NS	NS
Glu	437	418	436	482	423	35.2	NS	NS	NS	NS
Gly	165	169	180	214	203	16.8	0.08	0.001	NS	0.05
Pro	176	168	181	191	166	16.5	NS	NS	NS	0.06
Ser	162	164	178	202	181	16.2	NS	0.08	NS	NS
Tyr	120	126	126	147	135	14.2	NS	NS	NS	NS
Total	1580	1569	1647	1860	1667	142.7	NS	NS	NS	NS
Total AA	2915	2887	3004	3413	3046	264.2	NS	NS	NS	NS

¹Soyhulls were substituted for corn in the experimental diets.²SH vs. C = Soyhull diets vs. control diet, 40 SH vs. C = 40% soyhull diet vs. control diet.³NS = Nonsignificant ($P > 0.10$).

Table 12. Least squares means for production and composition of milk from lactating dairy cows fed diets containing different amounts of soyhulls.

Item	Soyhulls in diet, ¹ %						Contrast			
	0	10	20	30	40	SEM	SH vs. C ²	Linear	Quadratic	40 SH vs. C ²
<i>(P <)</i>										
Milk, kg/d	30.0	29.1	29.3	30.2	28.7	2.3	NS ³	NS	NS	NS
3.5% FCM, ⁴ kg/d	28.3	27.8	27.3	28.4	27.7	1.9	NS	NS	NS	NS
Fat %	3.21	3.25	3.10	3.18	3.36	0.26	NS	NS	NS	NS
kg/d	0.95	0.94	0.91	0.95	0.94	0.07	NS	NS	NS	NS
Crude protein %	3.16	3.05	2.88	2.91	3.02	0.19	NS	NS	NS	NS
kg/d	0.93	0.88	0.84	0.87	0.86	0.06	NS	NS	NS	NS
True protein %	2.78	2.71	2.76	2.75	2.68	0.09	NS	NS	NS	NS
kg/d	0.83	0.79	0.81	0.83	0.77	0.06	NS	NS	NS	NS
Total solids %	11.60	11.65	11.49	11.66	11.70	0.25	NS	NS	NS	NS
kg/d	3.46	3.38	3.36	3.51	3.35	0.25	NS	NS	NS	NS
MUN, ⁵ mg/dl	12.6	14.0	13.9	15.2	16.1	0.96	0.04	0.008	NS	0.01

¹Soyhulls were substituted for corn in the experimental diets.²SH vs. C = Soyhull diets vs. control diet, 40 SH vs. C = 40% soyhull diet vs. control diet.³NS = Nonsignificant ($P > 0.10$).⁴3.5% FCM = 0.4324(kilograms of milk) + 16.216(kilograms of fat).⁵Milk urea nitrogen.

the replacement of 12 to 30 percentage units of corn with SH successfully sustained microbial growth and passage of total AA to the duodenum of dairy cows. However, it has been suggested that feeding large amounts of soyhulls to lactating dairy cows (> 30% of dietary DM; Mansfield and Stern, 1994) might limit animal performance because of an inadequate supply of Met. According to the NRC (2001), contents of Met and Lys in metabolizable protein delivered to the duodenum of dairy cows should be 2.4 and 7.2%, respectively, to assure an optimal AA supply for maintenance and milk protein production. Model estimations (NRC, 2001) revealed that the concentrations of both Met and Lys in metabolizable protein were below those values for all diets in this experiment. The concentration of Met ranged from 1.90 to 1.75% of metabolizable protein for the control and 40% SH diets, respectively. The concentration of Lys ranged from 6.85% to 6.55% of metabolizable protein for the 40% SH and control diets, respectively. These data indicate that, under these experimental conditions, the availability of Met in duodenal contents appears to be more limiting than Lys (−27% vs. −9%).

Production of Milk and Milk Composition

Yields of milk and 3.5% FCM were not affected significantly by treatments (Table 12). However, milk production was numerically decreased by 1.3 kg/d per cow in this trial when the 40% SH diet was fed and milk

production was decreased by 1.2 kg/d per cow ($P < 0.07$) in a companion study (Ipharraguerre et al., 2002) in which the same diet was fed to midlactation cows. In other trials, when SH replaced corn in the diet of dairy cows to provide 30% or more of the dietary DM, production of milk (Mansfield and Stern, 1994; Nakamura and Owen, 1989) or FCM (Nakamura and Owen, 1989) decreased.

Milk fat percentage and yield did not differ among treatments (Table 12); however, in a companion trial (Ipharraguerre et al., 2002), feeding the same diets linearly increased milk fat percentage and yield. In previous trials, milk fat percentage was either unaltered (Cunningham et al., 1993; Mansfield and Stern, 1994) or increased (Nakamura and Owen, 1989; Pantoja et al., 1994) by the replacement of cereal grain with SH.

The concentration and yield of CP, true protein, and total solids in milk did not differ among dietary treatments (Table 12). Secretion of urea in milk (i.e., MUN) increased for cows fed SH, increasing linearly as SH replaced corn in the diet (Table 12). This is consistent with the higher concentration of NH_3N in ruminal fluid of cows fed SH, suggesting that the amount of NH_3N absorbed from the rumen into the blood, converted to urea in the liver, and released back into the blood increased as additional SH replaced corn in the diets.

CONCLUSIONS

These data suggest that SH can replace corn to supply up to 30% of the DMI of midlactation cows in diets that

contain about 50% forage without depressing energy, protein, or amino acid availability for milk production. Replacing corn with SH in diets that contain about 50% forage increases the intake of NDF and ADF and decreases the intake of NSC when the diet contains SH in excess of 30% of the total dietary DM. Increasing the intake of NDF and ADF increases the amounts digested in the rumen and lower gastrointestinal tract, and decreasing the intake of NSC decreases the amount digested in the rumen and lower gastrointestinal tract. These differences in the source of energy (fiber vs. NSC), in the amounts of fiber and NSC digested, and in the site of digestion in the gastrointestinal tract may cause a shortage in the source and/or amount of energy that is required for maximum milk production in high producing cows when more than 30% of the dietary DM that is supplied as corn is replaced with SH.

REFERENCES

- Association of Official Analytical Chemists. 1990. Official Methods of Analysis. Vol. I, 15th ed. AOAC, Arlington, VA.
- Bremner, J. M., and D. R. Keeney. 1965. Steam distillation methods for determination of ammonium, nitrate, and nitrite. *Anal. Chim. Acta* 32:485–495.
- Chaney, A. L., and E. P. Marbach. 1962. Modified reagents for determination of urea and ammonia. *Clin. Chem.* 8:130–132.
- Clark, J. H., T. H. Klusmeyer, and M. R. Cameron. 1992. Microbial protein synthesis and flows of nitrogen fractions to the duodenum of dairy cows. *J. Dairy Sci.* 75:2304–2323.
- Cotta, M. A., and J. B. Russell. 1982. Effects of peptides and amino acids on efficiency of rumen bacterial protein synthesis in continuous culture. *J. Dairy Sci.* 65:226–234.
- Cunningham, K. D., M. J. Cecava, and T. R. Johnson. 1993. Nutrient digestion, nitrogen, and amino acid flows in lactating cows fed soybean hulls in place of forage or concentrate. *J. Dairy Sci.* 76:3523–3535.
- Elliott, J. P., J. K. Drackley, G. C. Fahey, Jr., and R. D. Shanks. 1995. Utilization of supplemental fat by dairy cows fed diets varying in content of nonstructural carbohydrates. *J. Dairy Sci.* 78:1512–1525.
- Erdman, R. A. 1988. Dietary buffering requirements of the lactating dairy cow. *J. Dairy Sci.* 71:3246–3266.
- Feng, P., W. H. Hoover, T. K. Miller, and R. Blauweikel. 1993. Interactions of fiber and nonstructural carbohydrates on lactation and ruminal function. *J. Dairy Sci.* 76:1324–1333.
- Firkins, J. L. 1997. Effects of feeding nonforage fiber sources on site of fiber digestion. *J. Dairy Sci.* 80:1426–1437.
- Grigsby, K. N., M. S. Kerley, J. A. Paterson, and J. C. Weigel. 1993. Combinations of starch and digestible fiber in supplements for steers consuming a low-quality bromegrass hay diet. *J. Anim. Sci.* 71:1057–1064.
- Griswold, K. E., W. H. Hoover, T. K. Miller, and W. V. Thayne. 1996. Effect of form of nitrogen on growth of ruminal microbes in continuous culture. *J. Anim. Sci.* 74:483–491.
- Ipharraguerre, I. R., and J. H. Clark. 2002. Soyhulls as an alternative feed for lactating dairy cows: A review. *J. Dairy Sci.* (Accepted).
- Ipharraguerre, I. R., R. R. Ipharraguerre, and J. H. Clark. 2002. Performance of lactating dairy cows fed varying amounts of soyhulls as a replacement for corn grain. *J. Dairy Sci.* 85:2917–2924.
- Littell, R. C., G. A. Milliken, W. W. Stroup, and R. D. Wolfinger. 1996. SAS system for mixed models. SAS Institute Inc., Cary, NC.
- Lykos, T., G. A. Varga, and D. Casper. 1997. Varying degradation rates of total nonstructural carbohydrates: Effects on ruminal fermentation, blood metabolites, and milk production and composition in high producing Holstein cows. *J. Dairy Sci.* 80:3341–3355.
- Mansfield, H. R., and M. D. Stern. 1994. Effects of soybean hulls and lignosulfonate-treated soybean meal on ruminal fermentation in lactating dairy cows. *J. Dairy Sci.* 77:1070–1083.
- McCarthy, R. D., Jr., T. H. Klusmeyer, J. L. Vicini, J. H. Clark, and D. R. Nelson. 1989. Effects of source of protein and carbohydrate on ruminal fermentation and passage of nutrients to the small intestine of lactating cows. *J. Dairy Sci.* 72:2002–2016.
- Mertens, D. R. 1992. Nonstructural and structural carbohydrates. Pages 219–235 in *Large Dairy Herd Management*. pp. 219–235. H. H. Van Horn, and C. J. Wilcox, ed. American Dairy Science Association, Champaign, IL.
- Moore, S. 1963. On the determination of cystine as cysteic acid. *J. Biol. Chem.* 238:235–237.
- Nakamura, T., and F. G. Owen. 1989. High amounts of soyhulls for pelleted concentrate diets. *J. Dairy Sci.* 72:988–994.
- Nocek, J. E. 1997. Bovine acidosis: Implications on laminitis. *J. Dairy Sci.* 80:1005–1028.
- Nocek, J. E., and S. Tamminga. 1991. Site of digestion of starch in the gastrointestinal tract of dairy cows and its effect on milk yield and composition. *J. Dairy Sci.* 74:3598–3629.
- National Research Council. 1989. Nutrient Requirements of Dairy Cattle. 6th rev. ed. Natl. Acad. Sci., Washington, DC.
- National Research Council. 2001. Nutrient Requirements of Dairy Cattle. 7th rev. ed. Natl. Acad. Sci., Washington, DC.
- Overton, T. R., M. R. Cameron, J. P. Elliott, J. H. Clark, and D. R. Nelson. 1995. Ruminal fermentation and passage of nutrients to the duodenum of lactating cows fed mixtures of corn and barley. *J. Dairy Sci.* 78:1981–1998.
- Pantoja, J., J. L. Firkins, M. L. Eastridge, and B. L. Hull. 1994. Effects of fat saturation and source of fiber on site of nutrient digestion and milk production by lactating dairy cows. *J. Dairy Sci.* 77:2341–2356.
- Sarwar, M., J. L. Firkins, and M. L. Eastridge. 1991. Effect of replacing neutral detergent fiber of forage with soyhulls and corn gluten feed for dairy heifers. *J. Dairy Sci.* 74:1006–1017.
- Sarwar, M., J. L. Firkins, and M. L. Eastridge. 1992. Effects of varying forage or concentrate carbohydrates on nutrient digestibilities and milk production by dairy cows. *J. Dairy Sci.* 75:1533–1542.
- SAS. 2000. The SAS System for Windows. Release 8.1 (TS1 MO). SAS Institute, Inc. Cary, NC.
- Satter, L. D., and L. L. Slyter. 1974. Effect of ammonia concentration on rumen microbial protein production in vitro. *Br. J. Nutr.* 32:199–208.
- Smith, D. 1981. Removing and analyzing carbohydrates from plant tissue. Wisconsin Agric. Exp. Stn. Rep. No. R 2107, Madison, WI.
- Stokes, S. R., W. H. Hoover, T. K. Miller, and R. Blauweikel. 1991. Ruminal digestion and microbial utilization of diets varying in type of carbohydrates and protein. *J. Dairy Sci.* 74:871–881.
- Stone, W. C. 1996. Applied topics in dairy cattle nutrition. I. Soyhulls as either forage or concentrate replacement. Ph.D. Thesis. Cornell Univ., Ithaca, NY.
- Supelco, Inc. 1975. GC Separation of VFA C2–C5. Tech. Bull. 749D. Supelco, Inc., Bellefonte, PA.
- Titgemeyer, E. C. 2000. Soy byproducts as energy sources for beef and dairy cattle. Pages 238–256 in *Soy in Animal Nutrition*. J. K. Drackley, ed. Fed. Anim. Sci. Soc., Savoy, IL.
- Van Soest, P. J., J. B. Robertson, and B. A. Lewis. 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. *J. Dairy Sci.* 74:3583–3597.
- Williams, C. H., D. J. David, and O. Iismaa. 1962. The determination of chromic oxide in faeces samples by atomic absorption spectrophotometry. *J. Agric. Sci.* 59:381–385.
- Zinn, R. A., and F. N. Owens. 1986. A rapid procedure for purine measurement and its use for estimating net ruminal protein synthesis. *Can. J. Anim. Sci.* 66:157–166.