Performance, Ruminal Fermentation, and Site of Starch Digestion in Early Lactation Cows Fed Corn Grain Harvested and Processed Differently[1,2]

K. F. KNOWLTON,* B. P. GLENN,†,3 and R. A. ERDMAN*
*Department of Animal Sciences,
University of Maryland, College Park 20742
†Nutrient Conservation and Metabolism Laboratory,
Livestock and Poultry Sciences Institute, USDA,
Agricultural Research Service, Beltsville, MD 20705

ABSTRACT

Two experiments were conducted to assess the effects of corn grain processing on performance, ruminal fermentation, and starch digestion in early lactation dairy cows. Diets were based on wilted alfalfa silage and high moisture or dry corn grain that was either ground or rolled. Thirty-four cows (17 multiparous) were used to measure effects on intake and lactational performance in a free-stall environment during wk 2 to 15 postpartum. Grinding increased dry matter intake, particularly for cows fed diets containing dry corn, and tended to increase yields of milk, protein, lactose, and SNF. Cow performance was not affected by the moisture content of the corn grain.

In the digestion experiment, six cows (43 d of lactation) with ruminal, duodenal, and ileal cannulas were used to measure ruminal and intestinal digestion. Starch digestion in the rumen and small intestine was greater for high moisture corn, but disappearance of starch in the large intestine was greater for dry corn. Both the grinding process and the high moisture content of the corn increased starch digestibility in the total tract. Flow of microbial N in the duodenum was not affected by treatment. High moisture corn increased starch digestion in the rumen and total tract and enhanced ruminal fermentation as indicated by increased volatile fatty acids and decreased NH_3 concentrations in the rumen. In the production experiment, however, only grinding improved the value of corn; ensiling at high moisture content had little effect.

(**Key words**: corn processing, starch, intestinal digestion)

Abbreviation key: **DG** = dry ground corn, **DR** = dry rolled corn, **HMG** = high moisture ground corn, **HMR** = high moisture rolled corn.

INTRODUCTION

Typically, diets consumed by high producing dairy cows in the US contain high concentrations of starch. Starch degradability in the rumen, rate and extent of VFA production, postruminal starch flow, and digestion of starch can vary in response to the physiological status of the cow, grain type, genotype, growing conditions, and both physical and chemical processing methods (27, 32). The starch in similarly processed wheat, oats, and barley is generally more degradable than is the starch in corn, and the digestibility of starch from sorghum is the lowest of the commonly used grains (27). Within grain type, physical processing increases the rate of starch digestion in the rumen by breaking the outer coat of the kernel to increase access of ruminal microorganisms and enzymes. The application of heat, moisture, and pressure (high moisture or steam processed grains) increases the susceptibility of the starch to digestion by disrupting the protein matrix surrounding starch granules and gelatinizing the starch, which disrupts its crystalline structure (19). Recent studies with lactating dairy cows (1, 14, 21, 33) indicated that 1 to nearly 5 kg of starch may disappear postruminally in cows fed high starch diets.

Although the site of starch digestion can be manipulated, its effect on performance of lactating cows varies. Excess fermentation of starch to VFA in the rumen may overwhelm the buffering and absorptive capacity of the cow, leading to reductions in ruminal pH that may decrease the DMI of high

---

Received December 12, 1996.
Accepted March 2, 1998.

[1] Mention of trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the USDA and does not imply its approval to the exclusion of other products that may be suitable.

[2] Partial support for this project was provided by the Maryland Agricultural Experiment Station. Fellowship support for K. F. Knowlton was provided by the National Science Foundation and by Purina Mills, Inc. and is gratefully acknowledged.

[3] Reprint requests should be addressed to Barbara P. Glenn, 10300 Baltimore Boulevard, Building 200 Room 100, BARC-East, Beltsville, MD 20705.

producing dairy cows (18, 21, 36). The DMI of lactating cows have decreased when more rapidly available starch sources were fed (1, 21, 22, 25, 28). Other studies (6, 14, 29) have shown no change in intake as degradation of starch in the rumen increased. The effect of amount of ruminally degraded starch on milk production also varies. Increased milk production has been observed (6, 14, 17, 25, 33, 35) as the degradation of starch in the rumen increases. However, increased ruminally degradable starch did not affect the milk production or FCM yield of early lactation cows in several studies (22, 28, 29) and decreased milk production or FCM yield in other studies (1, 21, 37).

Although it is clear that increased starch digestion in the total tract improves performance (27), the optimal site of starch digestion is unclear. Much of the work on alteration of the site of starch digestion has been done to compare different grain sources. Although this information is useful and practical, more specific questions about starch digestion in those studies are difficult to address because of confounding factors, such as protein and fiber concentration and source. Studies with dairy cows that had both duodenal and ileal cannulas and yielded data on site of intestinal starch digestion are rare. Our objective was to examine the effect of altered ruminal degradability of starch on intake, milk production, and site of starch digestion in high producing lactating dairy cows without the confounding effects of differences in other dietary nutrients. A companion study to measure energy metabolism was conducted (42) using these same diets.

MATERIALS AND METHODS

Cows

Experiment 1. Six multiparous cows were cannulated in the rumen, duodenum, and ileum during the dry period preceding the onset of the experiment. Under local anesthetic, cows were fitted with 7.6-cm i.d. flexible ruminal cannulas. Two weeks later, under general anesthesia, cows were fitted with Komarek-type duodenal T cannulas approximately 15 cm posterior to the pylorus (barrel = 26 mm i.d. and 95 mm long, cannula in lumen of the intestine = 94 mm long; ANKOM, Spencerport, NY) and with gutter-type plastisol T cannulas in the terminal ileum, proximal to the cecum (25 mm i.d., cannula in lumen of the intestine = 150 mm long). All surgeries were completed at least 3 wk prior to parturition.

Cows averaged 43 d of lactation (SD = 20) at the start of the experiment and were assigned randomly to one of two incomplete 4 × 4 Latin squares. Two 4 × 4 squares were established and balanced for residual effects, and one row was selected randomly and removed from each square, leaving three cows in each of two squares (24 observations). This design ensured statistical power (one 4 × 4 square was insufficient) and minimized the number of surgeries conducted.

Experiment 2. Thirty-four lactating Holstein cows (17 multiparous) were blocked by calving date, not by parity, and assigned to four dietary treatments.

Diets and Management

Experiment 1. Diets were formulated to contain 45% forage (first-cutting, wilted alfalfa silage), 25% NDF, 40% starch, and 19% CP. Alfalfa was at the late bud stage at harvest; the alfalfa was wilted, chopped, and stored in a concrete stave upright silo. Corn grain was harvested at 160 d of maturity and was stored at 70% DM in an oxygen-limiting upright silo or dried to 85% DM before storage. Before diets were mixed into total mixed diets, both types of corn were either ground through a 6.4-mm screen in a hammer mill (Smalley Manufacturing Co., Manitowoc, WI) or rolled in a roller mill with an initial gap setting of 0.58 mm (model 400; Automatic Equipment Manufacturing Co., Pender, NE). Corn was processed no more than 36 h before feeding, and heating of the high moisture corn was not a problem during the experiment. Cows were assigned to treatment diets in a 2 × 2 factorial arrangement of treatments (dry corn or high moisture corn, ground or rolled). An analysis of the complete dietary ingredients is listed in Table 1,

TABLE 1. Ingredient composition of diets (Experiments 1 and 2).

	Dry corn		High moisture corn	
	Ground	Rolled	Ground	Rolled
	(% of dietary DM)			
Dry ground corn	42.4	...	...	...
Dry rolled corn	...	42.4	...	...
High moisture ground corn	...	...	42.4	...
High moisture rolled corn	...	...	...	42.4
Alfalfa silage	45.3	45.3	45.3	45.3
SoyPass™ [1]	10.6	10.6	10.6	10.6
Mineral and vitamin mix[2]	1.7	1.7	1.7	1.7

[1] Soybean meal treated with lignosulfonate (Ligno-Tech USA, Fort Wayne, IN).

[2] Composition: 0.08% Ca, 6.32% P, 1.58% Mg, 26.46% Na, 14.0% Cl, 1.73% S, 14.7 ppm of Co, 97 ppm of Cu, 1174 ppm of Fe, 21 ppm of I, 592 ppm of Mn, 16 ppm of Se, 2275 ppm of Zn, 277 KIU/kg of vitamin A, 140 KIU/kg of vitamin D, and 25 IU/kg of vitamin E.

TABLE 2. Nutrient composition of diets (Experiments 1 and 2).[1]

	Dry corn		High moisture corn			Contrast[2]		
Nutrient	Ground	Rolled	Ground	Rolled	SE	D vs. HM	G vs. R	Interaction
	(% of dietary DM)					$P <$		
NDF	28.0	27.7	26.8	26.9	0.134	0.001	0.34	0.16
ADF	20.2	20.2	20.2	20.1	0.041	0.58	0.37	0.70
Lignin	4.91	4.92	4.87	4.84	0.007	0.001	0.23	0.03
Starch	34.1	34.4	36.0	35.8	0.581	0.02	0.93	0.70
Ash	7.49	7.47	7.53	7.52	0.016	0.02	0.35	0.51
CP	20.3	20.2	20.4	20.3	0.106	0.21	0.55	0.98
Forage NDF[3]	20.3	20.3	20.3	20.3	...	...	...	...

[1] Nutrient composition of diets (n = 4) was calculated from nutrient composition of individual ingredients.

[2] D = Dry, HM = high moisture, G = ground, and R = rolled; probabilities that effects were not different.

[3] Forage source and, therefore, forage NDF were constant among diets.

and diet nutrient analysis is listed in Table 2. Cows were housed in a climate-controlled barn (16°C, 65% relative humidity) in tie stalls with rubber mats bedded with wood shavings. Orts were weighed daily, and the amount of feed offered was adjusted to about 10% in excess of the intake of the previous day. Water was available for ad libitum consumption. Cows were milked at 0700 and 1900 h and fed at 0800 and 2000 h. Cows were allowed access to an exercise lot daily from 1000 to 1200 h. This experiment was conducted under approval from the Beltsville Area Institutional Animal Care and Use Committee and the University of Maryland Animal Care and Use Committee.

Experiment 2. Treatment diets were the same as in Experiment 1. Cows were housed in a free-stall barn and fed individually once daily at 1100 h for ad libitum intake through electronically controlled gates (American Calan, Inc., Northwood, NH). Orts were weighed daily. Water was available for ad libitum consumption. Cows were milked twice daily at 0800 and 2000 h. This experiment was conducted under approval from the Beltsville Area Institutional Animal Care and Use Committee.

Experimental Periods and Sample Collection

Experiment 1. Each experimental period lasted 21 d; the first 14 d were for dietary adjustment, and samples were collected on d 15 to 21. Milk weights were measured on d 15 to 21. Milk was sampled on d 15 and 16 and was analyzed for milk fat, CP, lactose, and SNF using infrared analysis (Environmental Systems Services, College Park, MD). Feed offered, grain, silage, and orts were sampled on d 15 to 21. Body weights were measured on d 20 and 21.

Ytterbium-labeled NDF was used as a marker for duodenal, ileal and, fecal DM flow (10). Ytterbium-labeled NDF was dosed into the rumen twice daily at feeding on d 10 to 18. Cows were dosed with 100 g of Yb-labeled NDF/d, approximately 100 mg of Yb/kg of DMI. Duodenal and ileal samples were taken every 4 h on d 17 and 18. Sample times were shifted forward by 2 h on the 2nd d so that samples were taken every 2nd h of a 24-h period. Samples were composited, homogenized, subsampled, lyophilized, and ground. Fecal grab samples were taken every 8 h on d 17 and 18 and were composited. Sample times were shifted forward by 2 h on the 2nd d to sample every 4th h of a 24-h period.

The pH of the ruminal fluid was measured by insertion of a pH electrode (UniFET, Inc., San Diego, CA) into the ventral rumen at 16 cm above the floor of the rumen every 2 h for 12 h on d 19 starting just before the a.m. feeding. Ruminal contents were sampled at the same time. Samples for VFA and NH_3 N analyses were filtered through eight layers of cheesecloth, acidified (0.5 ml of H_2SO_4/100 ml of ruminal fluid), and frozen immediately. For isolation of bacterial cells, sufficient contents were filtered through eight layers of cheesecloth to generate 250 ml of fluid, rinsed with 50 ml of 0.9% NaCl solution, and preserved in formaldehyde (final concentration, 0.5% HCHO); samples were composited for each cow and refrigerated at 4°C.

Experiment 2. All cows were fed a common diet during wk 2, 16, and 17 and were fed treatment diets during wk 3 through 15. Data from wk 2, 16, and 17 were used as covariates. Milk production was recorded at each milking. Individual milk samples were collected from consecutive milkings (p.m. and a.m.) once weekly. Body weights were recorded once weekly.

Analytical Procedures

Experiment 1. Samples of feces, total mixed diets, orts, grain, and silage were dried in a forced-air oven at 60°C to a constant weight for DM content. All samples were ground through a 1-mm screen in a Wiley mill (Arthur H. Thomas, Philadelphia, PA). Samples were analyzed in duplicate for DM, ash, N, starch, NDF, ADF, and lignin. Ash was determined following sample ignition at 500°C for 6 h. Samples were analyzed sequentially for NDF (40), ADF, and acid detergent sulfuric acid lignin (4). Samples were analyzed for total N by micro-Kjeldahl digestion with automated procedures (Technicon Instruments Corp., Tarrytown, NY). Total starch analysis was completed using a two-stage enzymatic hydrolysis method (15), and glucose release was quantified with immobilized glucose oxidase-peroxidase (model 2700 select biochemistry analyzer; Yellow Springs Instruments Inc., Yellow Springs, OH). To measure starch degradability, samples were gelatinized with $CaCl_2$ and incubated with amyloglucosidase for 0.5, 1, 2, 3, and 4 h at 60°C. Samples were centrifuged at $300 \times g$ for 10 min. The concentration of glucose in the supernatant was measured, and the amount of starch hydrolyzed as a fraction of the original was regressed against time; the slope of the line was equal to the relative rate of starch degradation (15).

Analysis of VFA in the ruminal fluid was completed using a gas chromatograph (model 5890A; Hewlett Packard, Inc., Avondale, PA). The NH_3 N in ruminal fluid was analyzed by automated procedures using the hypochlorite method (Technicon industrial method 339-01; Technicon Instruments Corp.). Bacterial cells were isolated from composited, refrigerated ruminal fluid by centrifugation immediately following each period (12). Purine analysis and calculation of microbial N flow was according to Zinn and Owens (43). Microbial DM flow was calculated as microbial N flow at the duodenum (grams per day) divided by the N content (grams per gram of DM) of isolated bacterial cells from ruminal fluid. Duodenal, ileal, and fecal samples were wet-ashed with nitric acid and analyzed for Yb content via atomic absorption. Duodenal, ileal, and fecal flows and digestibilities were calculated using Yb as a marker (10, 39).

Corn grain particle size was measured by dry-sieving through eight sieves (sieve apertures, 4750, 2360, 1190, 600, 300, 149, and 75 μm and the bottom pan; sieve shaker model RX-86; W. S. Tyler, Inc., Gastonia NC) for about 15 min until the weight of the bottom pan was constant (2). Mean particle size of corn and variance were calculated by fitting the data to a log normal distribution (41). Data for particle size are shown in Table 3. As expected, the grinding process significantly reduced mean particle size by about 60%, but moisture had no effect on particle size.

Experiment 2. All sample analyses were conducted as in Experiment 1.

TABLE 3. Particle size of corn grain.[1]

	Dry corn		High moisture corn			Contrast[2]		
	Ground	Rolled	Ground	Rolled	SE	D vs. HM	G vs. R	Interaction
							$P <$	
Log mean[3]	2.79	3.22	2.69	3.24	0.037	0.34	0.001	0.12
Log standard deviation	0.256	0.343	0.287	0.389	0.017	0.05	0.001	0.70
Mean particle size,[4] μm	618	1725	489	1789	167	0.85	0.001	0.58

[1] Data presented are least squares means (n = 4).

[2] D = Dry, HM = high moisture, G = ground, and R = rolled; probabilities that effects were not different.

[3] Log normal distribution of the particle size data was assumed. Statistical analyses were performed on log of means and log of standard deviations.

[4] Data for log mean particle size were transformed and then analyzed.

Statistical Analysis

Experiment 1. All data were statistically analyzed using PROC MIXED of SAS (38). The data were analyzed as replicated (n = 2) incomplete 4 × 4 Latin squares. Data were analyzed with the model

$$\begin{aligned} Y_{ijkl} = {} & \mu + S_i + C_{j(i)} + P_k + M_l + G_m \\ & + (M \times G)_{lm} + e_{ijklm} \end{aligned}$$

where

μ = overall mean;
S_i = random effect of square (i = 1 to 2);
$C_{j(i)}$ = random effect of cow within square (j = 1 to 3);
P_k = effect of period (k = 1 to 4);
M_l = effect of corn grain moisture (l = 1 to 2);
G_m = effect of corn grain processing (m = 1 to 2);
$(M \times G)_{lm}$ = effect of interaction of M_l and G_m; and
e_{ijklm} = residual error, assumed to be normally distributed.

Ruminal pH and VFA concentrations were analyzed with time as a subplot using the model

$$\begin{aligned} Y_{ijkl} = {} & \mu + S_i + C_{j(i)} + P_k + M_l + G_m \\ & + (M \times G)_{lm} + (S \times C \times P \times M \times G)_{ijklm} \\ & + T_n + (M \times T)_{ln} + (G \times T)_{mn} \\ & + (T \times M \times G)_{lmn} + e_{ijklmn} \end{aligned}$$

where

μ = overall mean;
S_i = random effect of square (i = 1 to 2);
$C_{j(i)}$ = random effect of cow within square (j = 1 to 3);
P_k = fixed effect of period (k = 1 to 4);
M_l = fixed effect of corn grain moisture (l = 1 to 2);
G_m = fixed effect of corn grain processing (m = 1 to 2);
$(P \times G)_{lm}$ = effect of interaction of M_l and G_m;
$(S \times C \times P \times M \times G)_{ijklm}$ = error term for all whole-plot sources of variation;
T_n = fixed effect of time postfeeding (n = 1 to 7);
$(M \times T)_{ln}$ = effect of interaction of M_l and T_n;
$(G \times T)_{mn}$ = effect of interaction of G_m and T_n;
$(M \times G \times T)_{lmn}$ = effect of interaction of M_l, G_m, and T_n; and
e_{ijklmn} = error term for all time sources of variation.

For all parameters, model effects were declared significant at $P < 0.05$, unless otherwise noted.

Experiment 2. All data were statistically analyzed using PROC MIXED (38). The data were analyzed as replicated (n = 5) randomized complete blocks. Data were analyzed with the model

$$\begin{aligned} Y_{ijkl} = {} & \mu + B_i + C_{j(i)} + M_k + P_l + (M \times P)_{kl} \\ & + A_m + (M \times A)_{km} + (P \times A)_{lm} \\ & + (M \times P \times A)_{klm} + W_n + (A \times W)_{mn} \\ & + COV_o + e_{ijklmno} \end{aligned}$$

where

μ = overall mean;
B_i = random effect of block (i = 1 to 5);
$C_{j(i)}$ = random effect of cow within block (j = 1 to 15);
M_k = fixed effect of corn grain moisture (k = 1 to 2);
P_l = fixed effect of corn grain processing (l = 1 to 2);
$(M \times P)_{kl}$ = interaction of M_k and P_l;
A_m = fixed effect of age (parity 1 vs. ≥2; m = 1 to 2);
$(M \times A)_{km}$ = interaction of M_k and A_m;
$(P \times A)_{lm}$ = interaction of P_l and A_m;
$(M \times P \times A)_{klm}$ = interaction of M_k, P_l, and A_m;
W_n = fixed effect of week (n = 3 to 16);
$(A \times W)_{mn}$ = interaction of A_m and W_n;
COV_o = covariate (using data from wk 2, 16, and 17); and
$e_{ijklmno}$ = residual error, assumed to be normally distributed.

Model effects were declared significant at $P < 0.05$, unless otherwise noted. An expanded model with all possible interactions was tested, and three- and four-way interactions that were nonsignificant ($P > 0.10$) for all parameters were removed to generate the reduced model detailed previously. Data regarding BW change were summarized across the entire experimental period and analyzed without a covariate.

TABLE 4. Starch digestibility of diets containing corn grain (Experiment 1).[1]

	Dry corn		High moisture corn			Contrast[2]		
	Ground	Rolled	Ground	Rolled	SE	D vs. HM	G vs. R	Interaction
						$P <$		
In vitro starch degradability, %/h	8.08	5.91	13.1	10.9	0.470	0.001	0.002	0.95
Starch intake, kg/d	7.93	7.94	8.80	8.30	0.23	0.03	0.33	0.34
Ruminal starch digestibility, %	60.9	69.2	86.8	81.2	3.23	0.001	0.71	0.08
Duodenal starch flow, g/d	3109	2484	1138	1578	359	0.002	0.79	0.16
Ileal starch flow, g/d	2696	2858	470	575	269	0.001	0.61	0.92
Starch disappearance in the SI[3], g/d	412	–374	668	1003	375	0.04	0.53	0.16
Starch digestibility in the SI, %	9.11	–20.4	58.9	56.6	18.7	0.005	0.38	0.48
Fecal starch flow, g/d	878	1986	147	377	240	0.001	0.03	0.13
Starch disappearance in the LI[4], g/d	1819	872	323	198	240	0.001	0.04	0.11
Postruminal starch disappearance, g/d	2231	498	990	1201	333	0.41	0.04	0.02
Total tract starch digestibility, %	88.9	76.4	98.2	95.7	2.57	0.001	0.01	0.08

[1] Data presented are least squares means (n = 6).

[2] D = Dry, HM = high moisture, G = ground, and R = rolled; probabilities that effects were not different.

[3] Small intestine.

[4] Large intestine.

RESULTS AND DISCUSSION

Digestibility and Nutrient Flows

Ground corn increased the in vitro rate of starch digestion compared with rolled corn (Table 4). In vivo ruminal starch digestion, duodenal starch flow, ileal starch flow, and starch disappearance from the small intestine were not affected by particle size of the corn grain. The grinding of corn decreased fecal starch flow and increased starch digestion in the total tract because of increased starch disappearance from the large intestine. Thus, particularly with the diets containing dry ground corn (**DG**), postruminal digestion of starch in dry corn was associated with digestion in the large intestine rather than in the small intestine. Similarly, DM digestibility in the rumen and small intestine was not affected by grinding (Table 5), but DM digestion in the total tract increased.

The ensiling of high moisture corn increased in vitro starch digestion (Table 4) and also increased ruminal starch digestion in vivo compared with dry corn. For diets containing high moisture corn, starch flow in the duodenum was decreased, starch flow in the ileum was decreased, and starch disappearance from the small intestine was increased. Digestibility in the small intestine of duodenal starch flow averaged 58% for the high moisture corn. Starch digestion in the total tract increased from 83% for dry corn to 97% for high moisture corn. Digestion of DM in the total tract also was increased for high moisture corn, and ileal DM flow was decreased because of a slight increase in the digestion of DM in the rumen and small intestine (Table 5). Total tract fiber digestion (Table 5) tended to decrease for diets containing high moisture corn, as would be expected with the observed increase in starch digestion in the rumen (13). Fiber digestibility was low for all treatment diets in this experiment, averaging 31.7% for the diets containing dry corn and 26% for the diets containing high moisture corn.

In our experiment, corn grain moisture apparently affected the accessibility of starch in corn to enzymatic digestion in the small intestine. The process of ensiling exposes the corn grain to combinations of heat, moisture, and pressure that degrade the endosperm structure, exposing starch granules and causing some degree of starch gelatinization (19). Amylose and amylopectin are normally deposited in starch granules in a semicrystalline arrangement, and gelatinization releases them from this arrangement. Kreikemeier et al. (20) found that dextrin (pure corn starch pretreated with acid and heat to degrade the crystalline structure) had much higher digestibility in the small intestine at each of three levels of infusion than did untreated pure corn starch. At the highest level of infusion (60 g/h), 81% of the dextrin infused into the abomasum disappeared in the small intestine versus 58% of the pure corn starch. We inferred from these two data files that starch that has been gelatinized to disrupt the crystalline arrangement of amylose and amylopectin polymers (i.e., high

TABLE 5. Dry matter and fiber digestibility of diets containing corn grain fed to six cows (Experiment 1).[1]

	Dry corn		High moisture corn			Contrast[2]		
	Ground	Rolled	Ground	Rolled	SE	D vs. HM	G vs. R	Interaction
						$P <$		
True ruminal DM digestibility,[3] %	57.0	57.3	64.7	60.2	4.40	0.24	0.63	0.61
Duodenal DM flow, kg/d	15.8	14.6	13.5	15.8	1.08	0.57	0.60	0.13
Ileal DM flow, kg/d	12.4	11.5	9.68	9.13	0.730	0.004	0.31	0.81
DM Disappearance in the SI[4], kg/d	3.40	3.07	3.80	6.65	1.15	0.09	0.26	0.19
Total tract DMD,[5] %	62.0	58.9	67.5	65.0	0.91	0.001	0.008	0.73
Total tract NDF digestion, %	30.4	33.0	26.3	25.7	2.94	0.06	0.73	0.60

[1] Data presented are least squares means (n = 6).

[2] D = Dry, HM = high moisture, G = ground, and R = rolled; probabilities that effects were not different.

[3] Corrected for bacterial DM flow.

[4] Small intestine.

[5] DM digestibility.

moisture grains or steam-flaked or rolled grains) is much more digestible, not only in the rumen, but also in the small intestine, than is ungelatinized starch in dry grains.

Most published reports on the site of starch digestion in lactating cows have involved duodenally but not ilealy cannulated cows. Some of the very high postruminal starch disappearances observed when dry grains were fed (1, 21, 29, 34) might have been more associated with fermentation in the large intestine than digestion in the small intestine. Digestion of starch in the large intestine (as much as 11% of starch intake) has been reported in steers fed an 80% corn diet (16). In our experiment, 23% of the starch consumed from the DG diet was digested in the large intestine. Fermentation of starch in the large intestine results in a loss of microbial N in feces, although the VFA produced are available for absorption and use by the cow.

The increase in starch digestibility in the total tract that was observed when grains were ground and when high moisture corn was fed in this experiment correlates well with the values for net energy for lactation derived in the companion calorimetry experiment (42). In that experiment, NE_L values of the diets were 1.63, 1.65, 1.84, and 1.72 Mcal/kg for the DG diet and the diets containing dry rolled corn (**DR**), high moisture ground corn (**HMG**), and high moisture rolled corn (**HMR**), respectively. The NE_L values of the corn grain [substitution calculation with the NRC (26) value for DG as the base (3)] were 1.96, 2.01, 2.46, and 2.17 Mcal/kg for the DG, DR, HMG, and HMR diets, respectively. This substitution calculation assumes constant dietary interaction between alfalfa silage and corn. In a digestion experiment, NE_L values can be estimated from DM digestibility (24). In Experiment 1, estimated NE_L values of the entire diet were 1.53, 1.45, 1.68, and 1.61 Mcal/kg for the DG, DR, HMG, and HMR diets, respectively, which were lower than NE_L values measured by Wilkerson et al. (42). In Experiment 1, NE_L values of the corn grain based on substitution calculation were 1.96, 1.77, 2.31, and 2.15 Mcal/kg for the DG, DR, HMG, and HMR diets, respectively, indicating that dry corn had 84% of the energy value of high moisture corn. In comparison, according to the NRC (26) calculations, NE_L values for dry corn are 96% of NE_L values for high moisture corn. These relative energy values were specific to our conditions. Under commercial conditions, relative energy concentrations of dry and high moisture corn likely vary by relative maturity and moisture of the corn grain at harvest. The type of forage in the diet and maturity of that forage may affect relative grain energy values as well.

For the DR diet, ileal starch flow was greater than duodenal starch flow, resulting in negative starch digestibility in the small intestine, a biological impossibility (Table 4). There are at least two possible explanations for this observation; both are related to limitations in the methodology used to research intestinal nutrient flow. The first possibility is segregation of the sample in subsampling of DR diets. These samples were collected, composited, homogenized, subsampled, and lyophilized. Duodenal samples from cows fed the DR diet contained large pieces of corn, and these samples did not homogenize well. These large pieces of corn likely segregated during subsampling, causing an underestimation of duodenal starch flow. Ileal samples are drier and are, therefore, more homogenous; particle segregation is less of a problem. In hindsight, it would have been better to lyophilize the entire sample rather than a subsample.

TABLE 6. Ruminal fluid pH and VFA concentrations sampled for 12 h following the feeding of diets containing corn grain (Experiment 1).[1]

	Dry corn		High moisture corn			Main plot[2]			Time effects[3]			
	Ground	Rolled	Ground	Rolled	SE	D vs. HM	G vs. R	Interaction	Time	T × M	T × P	T × M × P
						$P <$						
Ruminal fluid pH	6.14	6.27	6.14	6.16	0.077	0.43	0.25	0.43	0.21	0.80	0.66	0.85
Acetate (A), mol/100 mol	62.9	62.1	60.8	61.2	1.17	0.10	0.78	0.52	0.24	0.78	0.41	0.26
Propionate (P), mol/100 mol	21.1	20.7	22.7	22.4	1.47	0.14	0.77	0.93	0.05	0.87	0.26	0.81
Isobutyrate, mol/100 mol	1.38	1.52	1.41	1.35	0.066	0.15	0.39	0.07	0.001	0.99	0.67	0.13
Butyrate, mol/100 mol	10.1	10.7	9.81	9.91	0.529	0.16	0.39	0.56	0.62	0.28	0.65	0.76
Isovalerate, mol/100 mol	2.45	2.71	2.67	2.75	0.161	0.41	0.27	0.58	0.001	0.93	0.23	0.63
Valerate, mol/100 mol	2.08	2.33	2.64	2.46	0.137	0.03	0.77	0.14	0.001	0.87	0.58	0.52
BCFA,[4] mol/100 mol	3.83	4.23	4.07	4.09	0.217	0.80	0.30	0.36	0.001	0.96	0.35	0.45
Total VFA, mol	105	111	115	124	7.78	0.09	0.22	0.80	0.01	0.91	0.30	0.98
A:P	3.06	3.02	2.78	2.79	0.226	0.13	0.90	0.89	0.03	0.90	0.34	0.91

[1] Data presented are least squares means (n = 6).

[2] D = Dry, HM = high moisture, G = ground, and R = rolled; probabilities that effects were not different.

[3] Effect of time postfeeding and the interaction of time (T), moisture (M), and processing (P).

[4] Branched-chain fatty acids.

A second possible explanation for this underestimation is that the value assigned to starch disappearance from the small intestine for DR was within the standard error for that parameter. Marker problems and sampling problems are the primary sources of this error. Sampling at both the duodenum and ileum makes these errors more obvious than sampling at the duodenum only. These problems are a reminder that, with intestinal flow research, relative differences among treatments may be of more value than the absolute numbers reported (31). In this experiment, high moisture corn was clearly more digestible in both the rumen and small intestine than was dry corn. Fermentation of starch in the large intestine appeared to be high for DG diets, and digestion of DR diets was low throughout the total tract (Table 4).

Ruminal Fermentation

No interactions of time and treatment were observed for ruminal VFA concentrations and ruminal pH (Table 6). Ground corn did not affect ruminal pH or VFA concentrations, and ruminal NH_3 concentrations were not affected by the grinding of corn (Table 7). These data in combination with data regarding ruminal starch digestion in vivo indicate that the grinding process did not affect the ruminal fermentation of corn as much as one might have expected from the difference observed in in vitro rates of starch degradation. Grinding has been shown to increase the rate of passage of grain from the rumen as well as rate of digestion within the rumen (11). Rate of passage and rate of digestion have opposing effects on ruminal starch digestion. The effect of the grinding process on grains on in vivo starch digestion in the rumen may, therefore, be less than expected in animals with high intakes and high rates of passage, such as high producing dairy cows.

High moisture corn did not affect mean ruminal pH but increased valerate concentrations and tended to increase total VFA concentrations ($P < 0.09$; Table 6). High moisture corn also tended to decrease acetate concentrations ($P < 0.10$) and the acetate to propionate ratio ($P < 0.13$). Concentrations of ruminal NH_3 tended to decrease for cows fed diets containing high moisture corn ($P < 0.08$; Table 7). All of these findings indicate increased in vivo ruminal fermentation of diets containing high moisture corn compared with diets containing dry corn.

N Digestion

Microbial N flow in the duodenum was not significantly affected by the main effects of moisture and processing, although there was a trend for the interaction of moisture and particle size ($P < 0.12$; Table 7). Microbial N efficiency (grams of microbial N per kilogram of OM truly digested in the rumen) was affected by this interaction of moisture and processing. For diets containing dry corn, grinding tended to increase microbial N efficiency, but for diets containing high moisture corn, rolling tended to increase this efficiency. No effect of treatment on undegraded feed N flow or microbial N flow as a fraction of total duodenal N flow was observed. Digestion of total N in the small intestine averaged 59% and was not affected by treatment diet.

In Experiment 1, there was no consistent change in microbial N flow when carbohydrate digestion in the rumen was increased. Similarly, data in the literature show mixed effects of ruminally degraded starch on microbial N flow. One of the biggest effects demonstrated was between steam-flaked sorghum and dry-rolled sorghum (34). With steam-flaking, ruminally digested starch increased by 1.5 kg, and microbial N flow to the duodenum increased by 92 g/d (34). In another study (33), steam-flaked corn increased ruminally digested starch by 0.8 kg and increased microbial N flow to the duodenum by 37 g/d. Barley diets that increased ruminal starch digestion by 1.3 kg tended to increase microbial N flow to the duodenum (+ 20 g/d) (21). Those studies suggest that energy availability is a major determinant of microbial growth in the rumen.

The results of our experiment were in contrast to the results of those studies, because high moisture corn increased ruminally degraded starch by 2 kg/d, but microbial N flow was not consistently higher. Similarly, Aldrich et al. (1) observed an increase (1 kg/d) in ruminally digested starch when high moisture shelled corn was fed than when dry ground ear corn was fed, but microbial N flow to the duodenum was not affected by the main effect of ruminal starch availability. In the study of Aldrich et al. (1), the amount of ruminally available nonstructural carbohydrate interacted with the amount of ruminally available protein for microbial N flow. Those researchers (1) suggested that asynchrony between ruminally digested starch and ruminally digested protein might have caused the lack of response in microbial N flow to their treatment diet, which was high in ruminally available nonstructural carbohydrates and low in ruminally available protein. In our experiments, soybean meal treated with lignosulfonate was the protein supplement, and dietary CP was 58% degradable and 42% undegradable (26). With the exclusion of the observations for the DR diet because of our sampling problems, the HMG diet depressed microbial N flow and efficiency. Because ruminal starch digestion was highest for the HMG diets (Table 4), one possible explanation was asynchrony between ruminally digested starch and ruminally digested protein. Microbial yield is also affected by source of carbohydrate, and, in Experiment 1, fiber digestion was impaired for high moisture corn, which reduced cell-wall availability for microbial growth (Table 5).

Nitrogen digestibility in the total tract was lower for diets containing dry corn than for diets containing high moisture corn (Table 7). These data and the

TABLE 7. Nitrogen metabolism in cows fed diets containing corn grain (Experiment 1).[1]

	Dry corn		High moisture corn			Contrast[2]		
	Ground	Rolled	Ground	Rolled	SE	D vs. HM	G vs. R	Interaction
						$P <$		
N Intake, g/d	782	788	855	831	26.0	0.05	0.72	0.59
Ruminal NH_3 N, mg/dl	15.5	16.6	13.2	13.0	1.65	0.08	0.78	0.71
Duodenal N flow								
Microbial, g/d	443	359	385	471	48.8	0.58	0.99	0.12
Undegraded feed, g/d	269	349	318	333	49.3	0.73	0.34	0.53
Total, g/d	713	696	704	805	43.9	0.25	0.33	0.20
Microbial N, % of total	60.5	50.6	55.3	58.0	5.83	0.85	0.54	0.31
Microbial N, g/kg of OMTD[3]	32.5	26.9	25.1	34.0	3.13	0.96	0.60	0.05
Fecal N flow								
Microbial, g/d	191	150	139	148	20.3	0.20	0.44	0.24
Total, g/d	336	334	292	313	23.1	0.17	0.67	0.63
LI[4] Microbial N,[5] g/d	88.9	68.6	57.7	74.7	16.7	0.46	0.92	0.30
Total tract N digestibility	57.5	57.3	65.4	62.0	2.16	0.01	0.37	0.47

[1] Data presented are least squares means (n = 6).

[2] D = Dry, HM = high moisture, G = ground, and R = rolled; probabilities that effects were not different.

[3] OM truly digested in the rumen.

[4] Large intestine.

[5] Calculated as fecal microbial N – ileal microbial N.

TABLE 8. Intake, BW, milk production, and milk composition of cows fed diets containing corn grain (Experiment 1).[1]

	Dry corn		High moisture corn			Contrast[2]		
	Ground	Rolled	Ground	Rolled	SE	D vs. HM	G vs. R	Interaction
							$P <$	
DMI, kg/d	23.4	23.4	24.4	23.7	0.735	0.40	0.69	0.63
BW, kg	564	569	568	561	7.61	0.82	0.88	0.45
Milk production, kg/d	35.2	33.4	35.0	35.2	1.23	0.52	0.53	0.48
Milk fat								
%	4.36	4.36	4.10	4.46	0.105	0.48	0.12	0.14
kg/d	1.56	1.47	1.48	1.60	0.071	0.74	0.84	0.20
Protein								
%	3.19	3.27	3.18	3.25	0.060	0.82	0.26	0.98
kg/d	1.15	1.09	1.14	1.16	0.053	0.56	0.74	0.53
Lactose								
%	4.86	4.85	4.87	4.84	0.038	0.94	0.62	0.83
kg/d	1.73	1.63	1.75	1.73	0.078	0.46	0.49	0.66
SNF								
%	8.77	8.88	8.75	8.82	0.080	0.62	0.32	0.84
kg/d	3.13	2.99	3.16	3.16	0.139	0.52	0.63	0.64

[1] Data presented are least squares means (n = 6).

[2] D = Dry, HM = high moisture, G = ground, and R = rolled; probabilities that effects were not different.

numerical, although nonsignificant, increase in microbial N flow in feces and in microbial N produced in the large intestine for DG diets support the observation that starch digestion in the large intestine increases for DG diets. The increase in N lost as starch fermentation increased in the large intestine can be caused by microbes that incorporate N arriving from the small intestine that would normally be digested and absorbed as NH_3. Also, N from urea recycled from the blood to the large intestine may be incorporated into microbial N and excreted (30). In agreement with our results, the companion calorimetry experiment (42) demonstrated decreased N digestibility in the total tract for diets containing dry corn than for diets containing high moisture corn, because high moisture corn decreased fecal N losses by 7.5% (278 vs. 257 g/d; $P < 0.01$).

Performance (Experiments 1 and 2)

In Experiment 1 (the digestion experiment), neither corn grain moisture nor processing affected DMI, BW, milk production, or milk composition (Table 8). In Experiment 2, there was an interaction of corn grain moisture and particle size for DMI (Table 9). Within diets containing dry corn, grinding increased DMI to a much greater extent than it did within diets containing high moisture corn. Overall, the main effect of ground corn was an increase in DMI and ground corn also tended to increase milk production by 2.2 kg/d ($P < 0.08$). Neither BW nor change in BW was affected by treatment diet. Concentration of milk components was unaffected by treatment diet (Table 9). The grinding process increased milk lactose yield (+130 g/d) and tended to increase milk protein yield (+67 g/d; $P < 0.08$) and SNF yield (+210 g/d; $P < 0.06$). In lower producing, midlactation cows, the grinding of corn also increased DMI (23), but, in another experiment with early lactation cows (17), ground corn had no effect on DMI. In those experiments, increases in milk production were related to increases in nutrient digestibility in the total tract (17).

The inconsistency between results of Experiments 1 and 2 with respect to the effect of grinding on DMI can be explained by the duration of the experiments and the difference in cow numbers. The digestion experiment, with periods of just 3 wk and a total of six cows, had less power to detect differences caused by treatment diets. Maturity of the cows might also have influenced the results, because half of the cows in the long-term production experiment were primiparous, and all cows in the digestion experiment were multiparous. The interaction of moisture, processing, and age was significant for DMI in Experiment 2 (data not shown). In multiparous cows, the grinding process increased intake of diets containing dry corn but decreased intake of diets containing high moisture corn. In primiparous cows, the grinding

TABLE 9. Intake, BW, milk production, and milk composition of cows fed diets containing corn grain (Experiment 2).[1]

	Dry corn		High moisture corn			Contrast[2]		
	Ground	Rolled	Ground	Rolled	SE	D vs. HM	G vs. R	Interaction
						$P <$		
Cows, no.								
Total	9	8	8	9	...	...	...	...
Multiparous	4	4	4	5	...	...	...	...
DMI, kg/d	22.9	20.7	22.0	21.8	0.618	0.84	0.03	0.04
BW, kg	544	547	544	545	6.8	0.87	0.67	0.84
BW Change, kg	22.1	10.2	51.5	19.9	16.5	0.18	0.15	0.49
Milk production, kg/d	37.6	35.1	37.8	35.9	1.34	0.66	0.08	0.78
4% FCM, kg/d	33.2	32.9	32.7	31.4	1.49	0.36	0.49	0.66
Milk fat								
%	3.24	3.46	3.20	3.14	0.156	0.11	0.50	0.20
kg/d	1.22	1.25	1.19	1.13	0.078	0.15	0.86	0.42
Protein								
%	3.01	3.03	3.06	3.05	0.063	0.40	0.90	0.76
kg/d	1.12	1.05	1.15	1.09	0.041	0.34	0.08	0.85
Lactose								
%	4.99	4.95	5.02	5.00	0.042	0.32	0.48	0.85
kg/d	1.86	1.72	1.88	1.77	0.060	0.56	0.05	0.79
SNF								
%	8.72	8.66	8.80	8.80	0.090	0.12	0.63	0.65
kg/d	3.25	3.02	3.29	3.12	0.108	0.49	0.06	0.75

[1] Data presented are least squares means (n = 34).

[2] D = Dry, HM = high mositure, G = ground, and R = rolled; probabilties that effects were not different.

process increased intake of both dry and high moisture corn. Therefore, overall improvement in DMI when corn was ground in Experiment 2 was largely due to responses by the primiparous cows.

In Experiment 2, corn grain moisture did not affect milk production (Table 9). In the literature, milk production responses to high moisture corn are mixed. No significant difference in milk production was observed between cows fed high moisture and dry corn in one study (5), increased milk production was observed for cows fed high moisture corn in another study (7), and a slight decrease in milk production was observed for cows fed high moisture corn in another study (9). Milk composition was unaffected by the corn grain moisture in Experiment 2, but increases in milk fat concentration have been observed when cows were fed high moisture corn relative to dry corn (5). Moisture content of the corn did not affect DMI in Experiment 2. However, there was an interaction of parity and moisture for DMI ($P < 0.03$). Multiparous cows had a higher intake (1 kg/d) of diets containing dry corn than of diets containing high moisture corn, but primiparous cows had a higher intake of diets containing high moisture corn than of diets containing dry corn. Other studies (5, 7, 9) have indicated no significant difference in DMI between cows fed diets containing high moisture and dry corn, although depressed intake was observed for cows fed high moisture shell corn in diets based on corn silage (8). When fed with hay, there was no difference in DMI between cows fed dry and high moisture corn.

When the results of Experiment 2 are compared with the results of the companion calorimetry experiment (42), it appears that ambient temperature might have affected milk response to dietary treatment. In the calorimetry experiment (42), milk production tended to increase for cows fed high moisture corn (39.7 vs. 41.7 kg/d; $P < 0.10$) but was not affected by corn grain moisture in the production experiment. The DMI was not affected by grain moisture in either experiment [24.5 vs. 23.9 kg/d in the calorimetry experiment (42); 21.8 vs. 21.9 kg/d in Experiment 2]. Experiment 2 was conducted in a freestall barn at ambient temperatures during the spring and summer months. The calorimetry experiment (42) was conducted in a climate-controlled barn (16°C, 65% relative humidity; eight cows, 4-wk periods) and indicated that heat production increased when high moisture corn was fed (35.01 vs. 36.96

Mcal/d; $P < 0.01$). One possibility is that the benefits of high moisture corn were limited when fed under production conditions in the summer months because of increased heat production associated with this treatment.

CONCLUSIONS

Increased digestion of starch primarily in the rumen and small intestine was largely responsible for the increased net energy values observed for a total mixed diet containing high moisture corn and based on alfalfa (42). Increases in ruminal VFA concentrations mirrored the increase in ruminal starch digestion when high moisture corn was fed. In these two experiments, improved milk production was not observed when high moisture corn was fed, although milk production was increased in a companion calorimetry study (42). Increased heat production when high moisture corn was fed and different environmental conditions in the production experiment might explain this contradiction. The grinding process increased the starch digestibility in the total tract, and this treatment did increase milk production. Much of the increase in total tract starch digestion when DG was fed was due to increased starch disappearance from the large intestine rather than to increased digestion in the rumen or small intestine. Although the VFA produced from fermentation of starch in the large intestine are available to the cow, the microbial protein produced is lost in feces. This loss has both nutritional and environmental consequences. Diets containing DR clearly lagged behind the other treatment diets in both starch digestion and its effect on milk production. Dry-rolling is inadequate as a corn processing method for cows in early lactation. Corn processing not only influences ruminal starch digestion but also site of postruminal starch digestion. Improvements in digestion, metabolism, and milk production can be obtained with the processing of corn grain.

ACKNOWLEDGMENTS

The authors acknowledge the technical support provided by L. Colbert, T. Dawson, T. Jacobs, K. Sarratt, B. Stroud, and E. Zetina.

REFERENCES

1 Aldrich, J. M., L. D. Muller, G. A. Varga, and L. C. Griel, Jr. 1993. Nonstructural carbohydrate and protein effects on rumen fermentation, nutrient flow, and performance of dairy cows. J. Dairy Sci. 76:1091.–1105.

2 American Society of Agricultural Engineers. 1968. Method of determining and expressing fineness of feed material by sieving. ASAE Stand. S319. Am. Soc. Agric. Eng., St. Joseph, MI.

3 Andrew, S. M., H. F. Tyrrell, C. K. Reynolds, and R. A. Erdman. 1991. Net energy for lactation of calcium salts of long-chain fatty acids for cows fed silage-based diets. J. Dairy Sci. 74: 2588–2600.

4 Association of Official Analytical Chemists. 1984. Official Methods of Analysis, 14th ed. AOAC, Arlington, VA.

5 Chandler, P. T., C. N. Miller, and E. Jahn. 1975. Feeding value and nutrient preservation of high moisture corn ensiled in conventional silos for lactating dairy cows. J. Dairy Sci. 58: 682–688.

6 Chen, K. H., J. T. Huber, J. Simas, C. B. Theurer, P. Yu, S. C. Chan, F. Santos, Z. Wu, R. S. Swingle, and E. J. DePeters. 1995. Effect of enzyme treatment or steam-flaking of sorghum grain on lactation and digestion in dairy cows. J. Dairy Sci. 78: 1721–1727.

7 Clark, J. H., R. A. Frobish, K. E. Harshbarger, and R. G. Derrig. 1973. Feeding value of dry corn, ensiled high moisture corn and propionic acid treated high moisture corn fed with hay or haylage for lactating cows. J. Dairy Sci. 56:1531–1539.

8 Clark, J. H., and K. E. Harshbarger. 1972. High moisture corn versus dry corn in combination with either corn silage or hay for lactating cows. J. Dairy Sci. 55:1474–1480.

9 DeBrabander, D. L., B. G. Cottyn, and C. V. Boucque. 1992. Substitution of concentrates by ensiled high moisture maize grain in dairy cattle diets. Anim. Feed Sci. Technol. 39:57–67.

10 Ellis, W. C., and D. E. Beever. 1984. Methods for binding rare earths to specific feed particles. Occas. Publ. No. 1. Can. Soc. Anim. Sci., Edmonton, Alberta, Canada.

11 Ewing, D. L., D. E. Johnson, and W. V. Rumpler. 1986. Corn particle passage and size reduction in the rumen of beef steers. J. Anim. Sci. 63:1509–1515.

12 Glenn, B. P., G. A. Varga, G. B. Huntington, and D. R. Waldo. 1989. Duodenal nutrient flow and digestibility in Holstein steers fed formaldehyde and formic acid-treated alfalfa or orchardgrass silage at two intakes. J. Anim. Sci. 67:513–528.

13 Grant, R. J., and D. R. Mertens. 1992. Influence of buffer pH and raw corn starch addition on in vitro fiber digestion kinetics. J. Dairy. Sci. 75:2762–2768.

14 Herrera-Saldana, R., and J. T. Huber. 1989. Influence of varying protein and starch degradabilities on performance of lactating cows. J. Dairy Sci. 72:1477–1483.

15 Herrera-Saldana, R. E., J. T. Huber, and M. H. Poore. 1990. Dry matter, crude protein and starch degradability of five cereal grains. J. Dairy Sci. 73:2386–2393.

16 Karr, M. R., C. O. Little, and G. E. Mitchell, Jr. 1966. Starch disappearance from different segments of the digestive tract of steers. J. Anim. Sci. 26:652–654.

17 Knowlton, K. F., M. S. Allen, and P. S. Erickson. 1996. Lasalocid and particle size of corn grain for dairy cows in early lactation. 1. Effect on performance, serum metabolites, and nutrient digestibility. J. Dairy Sci. 79:557–564.

18 Knowlton, K. F., M. S. Allen, and P. S. Erickson. 1996. Lasalocid and particle size of corn grain for dairy cows in early lactation. 2. Effect on ruminal measurements and feeding behavior. J. Dairy Sci. 79:565–574.

19 Kotarski, S. F., R. D. Waniska, and K. K. Thurn. 1992. Starch hydrolysis by the rumen microflora. J. Nutr. 122:178–190.

20 Kreikemeier, K. K., D. L. Harmon, R. T. Brandt, Jr., T. B. Avery, and D. E. Johnson. 1991. Small intestinal starch digestion in steers: effect of various levels of abomasal glucose, corn starch, and corn dextrin infusion on small intestinal disappearance and net glucose absorption. J. Anim. Sci. 69:328–338.

21 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.

22 Mitzner, K. C., F. G. Owen, and R. J. Grant. 1994. Comparison of sorghum and corn grains in early and midlactation diets for dairy cows. J. Dairy Sci. 77:1044–1051.

23 Moe, P. W., and H. F. Tyrrell. 1976. Effects of feed intake and physical form on energy value of corn in timothy hay diets for lactating cows. J. Dairy Sci. 60:752–758.

24 Moe, P. W., and H. F. Tyrrell. 1976. Estimating metabolizable and net energy of feeds. Pages 232–237 *in* Proc. 1st Int. Symp. Feed Composition, Anim. Nutr. Requirements, and Computerization of Diets, Utah State Univ., Logan. P. V. Fonnesbeck, L. E. Harris, and L. C. Kearl, ed. Utah State Univ., Logan.

25 Moore, J. A., M. H. Poore, T. P. Eck, R. S. Swingle, J. T. Huber, and M. J. Arana. 1992. Sorghum grain processing and buffer addition for early lactation cows. J. Dairy Sci. 75:3465–3472.

26 National Research Council. 1989. Nutrient Requirements of Dairy Cattle. 6th rev. ed. Natl. Acad. Sci., Washington, DC.

27 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.

28 Oliveira, J. S., J. T. Huber, D. Ben-Ghedalia, R. S. Swingle, C. B. Theurer and M. Pessarakli. 1993. Influence of sorghum grain processing on performance of lactating dairy cows. J. Dairy Sci. 76:575–581.

29 Oliveira, J. S., J. T. Huber, J. M. Simas, C. B. Theurer, and R. S. Swingle. 1995. Effect of sorghum grain processing on site and extent of digestion of starch in lactating dairy cows. J. Dairy Sci. 78:1318–1327.

30 Ørskov, E. R. 1982. Protein Nutrition in Ruminants. Acad. Press, New York, NY.

31 Owens, F. N., and C. F. Hanson. 1992. External and internal markers for appraising site and extent of digestion in ruminants. J. Dairy Sci. 75:2605–2617.

32 Owens, F. N., R. A. Zinn, and Y. K. Kim. 1986. Limits to starch digestion in the ruminant small intestine. J. Anim. Sci. 63: 1634–1648.

33 Plascencia, A., and R. A. Zinn. 1996. Influence of flake density on the feeding value of steam-processed corn in diets for lactating cows. J. Anim. Sci. 74:310–316.

34 Poore, M. H., J. A. Moore, T. P. Eck, R. S. Swingle, and C. B. Theurer. 1993. Effect of fiber source and ruminal starch degradability on site and extent of digestion in dairy cows. J. Dairy Sci. 76:2244–2253.

35 Poore, M. H., J. A. Moore, R. S. Swingle, T. P. Eck, and W. H. Brown. 1993. Response of lactating Holstein cows to diets varying in fiber source and ruminal starch degradability. J. Dairy Sci. 76:2235–2243.

36 Robinson, P. H., and J. J. Kennelly. 1988. Influence of ammoniation of high moisture barley on its *in situ* rumen degradation and influence on rumen fermentation in dairy cows. Can. J. Anim. Sci. 68:839–851.

37 Robinson, P. H., and J. J. Kennelly. 1989. Influence of ammoniation of high moisture barley on digestibility, kinetics of rumen ingesta turnover, and milk production in dairy cows. Can. J. Anim. Sci. 69:195–203.

38 SAS® User's Guide. Release 6.11 Edition. 1991. SAS Inst., Inc., Cary, NC.

39 Teeter, R. G. 1981. Indigestible markers: methodology and application in ruminant nutrition. Ph.D. Diss., Oklahoma State Univ., Stillwater.

40 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.

41 Waldo, D. R., L. W. Smith, E. L. Cox, B. T. Weinland, and H. L. Lucas. 1971. Logarithmic normal distribution for seived forage materials. J. Dairy Sci. 54:1465–1469.

42 Wilkerson, V. A., B. P. Glenn, and K. R. McLeod. 1997. Energy and nitrogen balance in lactating cows fed diets containing dry or high moisture corn in either rolled or ground form. J. Dairy Sci. 80:2487–2496.

43 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.