Impact of corn vitreousness and processing on site and extent of digestion by feedlot cattle

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ABSTRACT: Eight cannulated Holstein steers (average BW: 251 kg) were used in 2 simultaneous 4 × 4 Latin squares in a split-plot arrangement to test the effects of processing method [dry-rolled (DR) vs. steam-flaked (SF); main plot] and vitreousness (V, %; subplot) of yellow dent corn (V55, V61, V63, and V65) on site of digestion of diets containing 73.2% corn grain. No vitreousness × processing method interactions were detected for ruminal digestion, but ruminal starch digestion was 14.4% lower ($P < 0.01$) for DR than for SF corn. Interactions were detected between vitreousness and processing method for postruminal ($P < 0.10$) and total tract digestion ($P < 0.05$). With DR, vitreousness tended to decrease (linear effect, $P < 0.10$) postruminal OM and starch digestion. With SF, vitreousness did not affect ($P \geq 0.15$) postruminal digestion of OM and starch. Postruminal N digestion tended to decrease (linear effect, $P = 0.12$) as vitreousness increased. Postruminal digestion was greater for SF than for DR corn OM (25.7%, $P < 0.05$), starch (94.3%, $P < 0.10$), and N (10.7%, $P < 0.01$). Steam flaking increased total tract digestion of OM (11%, $P < 0.05$), starch (16%, $P < 0.01$), and N (8.4%, $P < 0.05$) but decreased total tract ADF digestion (26.7%, $P < 0.01$). With DR, total tract starch digestion was lower for V65 (cubic effect, $P < 0.10$) than for the other hybrids. With SF, total tract starch digestion was not affected ($P \geq 0.15$) by vitreousness. Fecal starch and total tract starch digestion were inversely related (starch digestion, % = 101 – 0.65 × fecal starch, %; $r^2 = 0.94$, $P < 0.01$). Ruminal pH was greater for steers fed DR than for steers fed SF corn (6.03 vs. 5.62, $P < 0.05$). Steam flaking decreased ($P < 0.01$) the ruminal molar proportion of acetate (24%), acetate:propionate molar ratio (55%), estimated methane production (37.5%), and butyrate (11.3%, $P < 0.05$). There was a vitreousness × processing interaction ($P < 0.01$) for acetate:propionate. For DR, acetate:propionate tended to increase (linear effect; $P < 0.10$) with increasing vitreousness. With SF, acetate:propionate was greater (cubic effect, $P < 0.01$) for V65. Starch from more vitreous corn grain was less digested when corn grain was DR, but this adverse effect of vitreousness on digestion was negated when the corn grain was SF. Of the 19% advantage in energetic efficiency associated with flaked over rolled corn grain, about ¾ can be attributed to increased OM digestibility, with the remaining ¼ ascribed to reduced methane loss.

Key words: corn, cattle, digestion, processing, vitreousness

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INTRODUCTION

The structure and composition of cereal starches and the physical interactions between starch and grain protein can alter the digestibility and feeding value of grain for livestock (Rooney and Pflugfelder, 1986). Based on kernel characteristics, corn grain has been divided into 5 general classes: flint, popcorn, flour, dent, and sweet (Watson, 1987). Starch in the endosperm of "flint" corn is almost all hard (also called corneous, horny, or vitreous), whereas "flour" corn has virtually all of its starch as floury or soft endosperm (Pomeranz et al., 1984). Dent corn hybrids represent a cross of flint and floury types; hence, dent hybrids differ in their ratio of horny to floury endosperm. The vitreousness also varies with the position of kernels on the ear, and the growing environment (Watson, 1987). Digestibility of starch from corn grain is limited by the protein matrix that encapsulates starch granules and by the compact nature of the starch itself, particularly in the hard endosperm portion of kernels that prevents microbial colonization and retards penetration by amylolytic enzymes (McAllister et al., 1990). Disruption of the protein ma-

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trix can enhance the rate and extent of starch digestion. Increased kernel vitreousness has been associated with decreased in situ ruminal starch degradation (Philippeau et al., 1999a; Correa et al., 2002). Furthermore, Zinn et al. (1995) observed that steam flaking increased the digestibility of nonstarch OM of grain to an extent similar to the enhancement in starch digestion. The objective of this study was to evaluate the effect of corn vitreousness and grain processing on in vivo and in situ digestion using 4 samples of yellow dent corn grain that differed in vitreousness.

MATERIALS AND METHODS

Corn Hybrids

Samples of yellow dent grain from 4 hybrids (Pioneer Hi-Bred International, Inc., Johnston, IA) were used to evaluate the effect of processing method [dry rolled (**DR**) vs. steam flaked (**SF**)] and vitreousness (**V**, vitreous endosperm as a percentage of total endosperm DM) on site and extent of digestion by steers. These 4 commercial, single-cross, dent corn grain hybrids were grown with irrigation in isolated plots (minimum of 33 m from the nearest hybrid) near York, Nebraska, in 2002. Such isolation helps to reduce cross-pollination; the pollen source affects all 12 sets of triploid genes of the kernel endosperm that dictate specific characteristics (e.g., soft, brittle, waxy, sugary) of the starch.

First, chemical composition and in vitro enzymatic starch digestion were examined in laboratory studies. All samples were ground through a Wiley mill (1-mm screen) for compositional analysis. Corn vitreousness was determined according to Dombrink-Kurtzman and Bietz (1993) by manual dissection of 50 randomly selected, whole kernels from each grain sample. After the kernels were soaked in distilled water for 2 min and dried with a paper towel, the pericarp, tip cap, and germ were removed with a scalpel. Kernels were dried overnight at 90°C and the total endosperm that remained was weighed before separating the endosperm fractions. The floury endosperm was removed using a grinder drill; weight of the remaining vitreous endosperm was expressed as a percentage of the total endosperm (vitreousness) DM. All samples were analyzed for total starch (Zinn, 1990) and for amylose content (Gibson et al., 1997). Based on this physical separation procedure and starch analysis, the fraction of DM of the grain that was not removed from the kernel as floury endosperm was considered the vitreous endosperm. Consequently, the 4 samples of hybrids that were processed were designated V55, V61, V63, and V65. However, as a percentage of total endosperm starch, starch of the vitreous endosperm accounted for 59, 61, 64, and 67%, respectively, whereas as a fraction of starch in the total kernel, starch of the vitreous endosperm accounted for 49, 53, 63, and 72%, respectively.

Each hybrid sample was processed to form DR and SF (8 samples) corn. Preparation of DR corn was as follows: cleaned, dry corn from the 2 hybrids grown at the same location in the same year was coarsely rolled (6 to 8 particles per kernel) through a 2-stack roller mill (Automatic Equipment Co., Pender, NE). Identical roller settings were used for both hybrids. Preparation of SF corn was as follows: 2 d before flaking, cleaned grain was placed in 2,000-kg plastic tote bags and transported from Lynnville, Iowa, to the Animal Science Feed Mill (Manhattan, KS). At the feed mill, on the day before the grain was flaked, it was removed from tote bags, and cold water containing Sartemp surfactant (0.156 mL/kg of grain; SarTec Corp., Anoka, MN) was added to the grain to achieve 19% moisture; the wetted grain was mixed for at least 10 min in a horizontal ribbon mixer at the Kansas State University feed mill, transported by truck to the Grain Science mill at Kansas State University, and augered into plastic-lined tote bags holding approximately 1,816 kg of grain. The next day, approximately 17 h after water was added to the grain, the moistened grain was passed over a shaking bed to remove fine particles and was flaked to a hot-flake density of 0.373 kg/L (29 pounds per bushel). Flaking rolls (RossKamp 30.5 × 45.7-cm rolls) were adjusted to maintain the same flake density for both hybrids. Steam chamber temperature was maintained at 99°C; holding time in the steam chamber was approximately 7 min. After flaking, hot flakes were immediately dropped onto the belt of a 2-pass grain drier at the mill, where flakes were cooled and dried with warm air. Cooled, dried flakes were placed in totes holding approximately 908 kg for transport to the University of California Desert Research Center (El Centro, CA).

A subsample of each of the 4 grain treatments was ground through a Wiley mill (1-mm screen) and analyzed for chemical composition and in vitro enzymatic starch digestion. Amyloglucosidase-reactive starch (**AGR**) was determined (Zinn, 1990), with the incubation time extended to 4 h. Enzymatic reactivity of insoluble starch was determined as described by Rodríguez et al. (2001). Insoluble reactive starch (**IRS**, %) was calculated as: IRS = (RS – AGR)/6, where 6 represents the number of hours of the in vitro incubation. Insoluble starch digestion (**ISD**, %) in the rumen was calculated as: ISD = (100 – AGR) × [IRS/(IRS + 0.05)], where 0.05 is an estimate of the passage rate (fraction per hour) of grain from the rumen. Finally, an equation was used to predict ruminal starch digestion (**PRSD**): PRSD = 1.32 (AGR) + 0.93 (ISD). Particle size distribution of DR and SF corn hybrids as received in bulk tote bags (as-is basis) was determined according to ASAE (1969).

Metabolism Trial

Animals and Sampling. Animal care and handling techniques were approved by the University of California Animal Care and Use Committee. Eight Holstein steers (average BW: 251 kg) with cannulas in the rumen and proximal duodenum (Zinn and Plascencia, 1993) were used in 2 studies in which a 4 × 4 Latin square

Table 1. Composition of experimental diets

	Treatments	
	Dry-rolled corn	Steam-flaked corn
Ingredients, % of DM		
Alfalfa hay	4.00	4.00
Sudan hay	8.00	8.00
Steam-flaked corn	—	73.20
Dry-rolled corn	73.20	—
Cane molasses	7.50	7.50
Yellow grease	3.50	3.50
Limestone	1.40	1.40
Dicalcium phosphate	0.25	0.25
Magnesium oxide	0.20	0.20
Urea	1.00	1.00
Trace mineral salt[1]	0.95	0.95
Chromic oxide	0.30	0.30
Analyzed composition, DM basis		
NE,[2] Mcal/kg		
Maintenance	2.12	2.23
Gain	1.46	1.56
CP,%	12.07	12.07
NDF, %	14.76	13.44
Ca, %	0.75	0.75
P, %	0.33	0.33

[1]Trace mineral salt contained 0.052% KI; 0.68% $CoSO_4$; 1.04% $CuSO_4$; 1.07% $MnSO_4$; 1.24% ZnO_4; 3.57% $FeSO_4$; and 92.96% NaCl.
[2]Based on tabular NE values for individual feed ingredients (NRC, 1996), with the exception of supplemental fat, which was assigned NE_m and NE_g values of 6.0 and 4.85 Mcal/kg, respectively.

with a split-plot design was used to test the effects of processing method (DR vs. SF corn; main plot), and vitreousness (subplot) of yellow dent corn (V55, V61, V63, and V65) within each processing method on site and extent of digestion. The composition of the experimental diets is shown in Table 1. Chromic oxide (0.3% of diet DM) was included in each diet as an indigestible marker. The composition of each sample of the corn grain hybrids used is shown in Table 2.

Steers were individually maintained in concrete slatted-floor pens (3.9 m^2) and had access to water at all times. The DMI was restricted to 2.2% of BW, with equal portions provided at 0800 and 2000. Experimental periods consisted of 10 d for diet adjustment followed by 4 d for collection. During the collection period, duodenal and fecal samples were taken from all steers twice daily as follows: d 1, 0750 and 1350; d 2, 0900 and 1500; d 3, 1050 and 1650; and d 4, 1200 and 1800. Individual samples consisted of approximately 750 mL of duodenal chyme and 200 g (wet basis) of feces. Samples from each steer and within each collection period were composited for analysis. During the final day of each collection period, ruminal samples were obtained from each steer approximately 4 h postprandially via the ruminal cannula. Ruminal fluid pH was determined; subsequently, 10 mL of freshly prepared 25% (wt/vol) metaphosphoric acid was added to 40 mL of strained ruminal fluid. Acidified samples were centrifuged (17,000 × *g* for 10 min) and the supernatant fluid was stored at –20°C for later VFA analysis. Upon completion of the trial, ruminal fluid obtained from each steer was composited across steers for isolation of ruminal bacteria via differential centrifugation (Bergen et al., 1968).

Sample Analysis and Calculations. Samples were subjected to all or part of the following analyses: DM (oven drying at 105°C until no further weight loss); ash, Kjeldahl N, NH_3-N (AOAC, 1986); purines (Zinn and Owens, 1986); ADF (Goering and Van Soest, 1970); NDF (ash-corrected; Chai and Uden, 1998); Cr (Hill and Anderson, 1958), starch (Zinn, 1990), and VFA concentrations of ruminal fluid (gas chromatography; Zinn 1988). Duodenal flow and fecal excretion of DM and individual nutrients were calculated based on marker ratios using Cr. Microbial OM and microbial N leaving the abomasum were calculated using purines as a microbial marker (Zinn and Owens, 1986). Organic matter fermented in the rumen was considered equal to OM intake minus the difference between the amounts of total OM reaching the duodenum and microbial OM reaching the duodenum. Apparent feed N that escaped to the small intestine was considered equal to total N leaving the abomasum minus NH_3-N and microbial N, and included endogenous contributions. Methane production was calculated based on the theoretical fermentation balance, considering the molar distribution of VFA at 4 h postfeeding and measured OM apparently fermented in the rumen (Wolin, 1960).

Table 2. Kernel component weight distribution of yellow corn treatments

	Vitreousness[1]				
Part of kernel,[2] %	V55	V61	V63	V65	SD
Pericarp	3.57	3.98	3.76	3.51	0.2
Tip cap	2.55	3.35	2.87	3.90	0.5
Germ	8.90	8.60	9.11	7.84	0.5
Total endosperm	84.99	84.07	84.26	84.75	0.37

[1]Vitreousness = proportion of the horny endosperm in the degermed grain, where V55 = 55% vitreous endosperm.
[2]Average of 50 kernels per sample determined by manual dissection (DM basis).

Statistical Analysis

Statistical relationships (vitreousnness vs. predicted ruminal starch digestion; in vivo ruminal starch digestion vs. predicted ruminal starch digestion; fecal starch concentration vs. total starch digestion; and vitreousness vs. fecal starch excretion) were determined using regression analysis (Statistix, Version 8.0, Analytical Software, Tallahassee, FL). Data from the metabolism trial were analyzed using a split-plot design (Hicks, 1973). The statistical model for the trial was as follows: $Y_{ijkl} = \mu + G_j + S_{j(i)} + P_k + V_l + GV_{il} + \varepsilon_{ijkl}$, where μ is the common experimental effect, G is grain processing (whole plot), S is the steer within corn processing effect (whole-plot error), P is the period effect, V is the corn vitreousness effect, GV is the interaction of corn pro-

Table 3. Starch and amylose content of hard and soft corn endosperm[1]

	Starch type, % of total starch		Amylose,[2] %		Amylopectin, %	
Vitreousness[3]	Hard	Soft	Hard	Soft	Hard	Soft
V55	48.98	51.02	23.60	27.40	76.40	72.60
V61	49.11	50.89	23.10	32.00	76.90	68.00
V63	48.77	51.43	24.00	32.00	76.00	68.00
V65	50.40	49.40	23.80	29.2	76.20	70.80

[1]DM basis.
[2]Amylose/amylopectin assay kit (K-AMYL, Megazyme International Ireland Ltd., Dublin, Ireland). Amylose, % of starch in respective fraction; amylopectin, % of starch in respective fraction.
[3]Vitreousness = proportion of the horny endosperm in the degermed grain, where V55 = 55% vitreous endosperm.

cessing and corn vitreousness, and ε is the residual error. The effects of vitreousness on characteristics of digestion were tested by means of orthogonal polynomials. Coefficients for polynomial contrasts (linear, quadratic, and cubic) with unequal spacing were determined according to SAS (Version 9.1, SAS Inst., Inc., Cary, NC). Where processing × vitreousness interactions were detected, subplots were evaluated separately for the vitreousness effect within processing by using orthogonal polynomials.

RESULTS AND DISCUSSION

Weight distribution of principal kernel components of the samples of corn hybrids tested (Table 2) averaged 3.7 ± 0.2, 3.2 ± 0.5, 8.6 ± 0.5, and 84.5 ± 0.37% for pericarp, tip cap, germ, and total endosperm, respectively. These values were consistent with estimates from the Food and Agricultural Organization (1992) and Watson (1987). Starch and amylose contents of the endosperm fractions are shown in Table 3. Starch (% of total starch) was similar for soft endosperm (50.69%) and hard endosperm (49.32%) fractions. Amylose content of the cornstarch was similar between hybrids, averaging 30.2 ± 2.0, and 23.6 ± 0.3% for soft and hard endosperm, respectively. These values were in the range (24 to 30% amylose) reported by Rooney and Pflugfelder (1986). In contrast with our results, Dombrink-Kurtzman and Knutson (1997) reported that amylose content was slightly lower for the soft than the hard endosperm (20.5 vs. 23.0%) for the 3 hybrids that they evaluated.

Because raw amylopectin has a greater ruminal digestibility than amylose (Mohd and Wootton, 1984), corn hybrids with a greater proportion of amylopectin may have greater feeding value when fed dry-processed. Accordingly, waxy corn hybrids (greater content of amylopectin) have a greater rate and extent of starch digestion than nonwaxy corn hybrids when fed as DR grain (Mohd and Wootton, 1984; Huntington, 1997). Likewise, corn hybrids with high amylose content are poorly digested by dogs, even after the grain is extruded (Gajda et al., 2005). The lower digestibility of amylose starch has been ascribed to tighter intermolecular bonding between starch molecules. However, Wang et al. (1999) suggested that amylose digestion also might be restricted to a limited array of bacterial strains in the human colon.

Effects of corn processing and vitreousness on the physical characteristics of corn are shown in Table 4. Particle size greater than 4 mm as percentage of the total ranged from 51.8 (V63) to 71.6 (V65) for DR, and from 58.9 (V61) to 73.4 (V65) for SF corn. The hybrid with the greatest vitreousness had fewer fines (particles ≤2 mm, % of total = 97.44 − 1.013 vitreousness; r^2 = 0.39). The geometric mean diameter of processed grain tended to be lower for the corn samples that were intermediate in vitreousness, both for DR and SF grain. The number of particles per gram of corn was 2.7 to 4.7 times greater for the samples intermediate in vitreousness (Table 4). Thus, surface area per gram was 24 to 35% greater for these intermediate samples than for the most and least vitreous grain samples, respectively.

Chemical composition of corn samples averaged 87.9 ± 0.8; 8.3 ± 0.3; 74.4 ± 1.8; 6.6 ± 0.9; 1.89 ± 0.20; and 1.11 ± 0.12% for DM, CP, starch, NDF, ADF and ash, respectively (Table 5). Observed values were notably lower than tabular values (NRC, 1996) for CP (9.8%), NDF (10.8%), and ADF (3.3%) reflecting genetic selection and environmental conditions for yielding grain with a high starch content. The starch content was greater (5%) than the average (71%) reported for 46 modern yellow dent hybrids (Zinn et al., 2002). Compared with DR corn samples within each hybrid, SF samples had lower ($P < 0.01$) concentrations of CP, NDF, ADF, and insoluble starch digestion as well as ash ($P < 0.06$), but greater ($P < 0.01$) concentration of starch, AGR, and predicted ruminal starch digestion. Because physical destruction of specific nutrients during flaking is unlikely, these differences are probably associated with production of fine particles during flaking; separation of small particles from the large flakes results in underrepresentation of the tip cap and germ in samples of flaked grain.

Crude protein concentrations were greater for V65 and less for V55. The average N content of 100 commercial yellow dent corn kernels was 1.52 and 0.91% for

Table 4. Influence of corn processing and vitreousness[1] on physical characteristics of corn

	Dry-rolled corn				Steam-flaked corn			
Item	V55	V61	V63	V65	V55	V61	V63	V65
Flake thickness, mm	—	—	—	—	0.134	0.116	0.180	0.139
Corn particle size (mm),[2] % total								
8	0	0	0	0	16.50	15.04	18.01	16.99
4 to 8	58.42	54.04	51.83	71.63	47.62	43.85	44.66	56.40
2 to 4	29.94	26.21	28.63	18.13	27.04	21.63	20.54	17.56
1 to 2	5.55	9.23	9.14	3.72	6.13	10.71	9.26	5.39
0.5 to 1	2.71	5.51	5.58	2.70	1.43	5.23	4.41	2.12
0.25 to 0.5	2.56	3.74	3.88	3.00	0.65	2.85	2.50	1.23
<0.25	0.82	1.28	0.95	0.82	0.63	0.69	0.62	0.31
Geometric mean particle size, μm	3,851	3,386	3,341	4,235	4,766	3,987	4,310	5,068
Surface area, cm^2/g	15	18	18	14	12	16	15	11
Particles/g	121	437	382	98	61	371	252	49
Geometric standard deviation	2.01	2.29	2.24	2.04	2.00	2.40	2.35	1.99

[1]Vitreousness = proportion of the horny endosperm in the degermed grain, where V55 = 55% vitreous endosperm.
[2]Physical characteristics of dry rolled and steam-flaked corn as received in bulk tote bags (as-is basis).

hybrids with a hard and soft endosperm, respectively (R. A. Zinn, unpublished data). A correlation between endosperm hardness and total kernel protein concentration has been noted previously, presumably related to increased deposition of zeins in hard endosperm (Hamilton et al., 1951). Also, Dorsey-Redding et al. (1991) observed that the relationship between corn protein level and kernel hardness (Stenvert hardness test) was moderately low but still positive (r^2 = 0.64 and 0.41, $P < 0.001$ for 2 different years).

In vitro-predicted ruminal starch digestion averaged 67.5 and 82.9% for DR and SF, respectively (Table 5). These estimates are in reasonably close agreement with the average of in vivo measurements for DR and SF (71.6 and 83.6%, respectively; Table 6) in this trial. Corn vitreousness and PRSD were closely associated, both for DR (r^2 = 0.95, $P < 0.01$), and SF (r^2 = 0.88, $P < 0.06$; Table 5; Figure 1). Previously, Philippeau et al. (1999a) observed (r^2 = 0.89) less ruminal starch digestion as vitreousness increased. Regardless, within the range of vitreousness evaluated in this study, the impact of vitreousness on in vitro ruminal starch digestion was not significant (P = 0.60). Furthermore, the relationship between vitreousness and in vivo ruminal starch digestion was small, indicating that although vitreousness per se may impede the rate of enzymatic attack, other overriding factors limit in vivo ruminal starch digestion that are not considered in the in vitro assay. However, overall, the relationship between in vivo and predicted ruminal starch digestion was high (r^2 = 0.90, $P < 0.01$, Figure 2). Philippeau et al. (1999a) observed that most of the increased starch disappearance from floury corn samples measured by the in situ technique occurs before ruminal incubation begins (0 h). This can be attributed to greater prevalence of very small particles generated during fine grinding (1- or 2-mm screens) of floury than of vitreous corn samples that readily wash through the pores of Dacron bags.

Table 5. Chemical composition and in vitro enzymatic starch digestion of corn treatments[1]

	Dry-rolled corn				Steam-flaked corn			
Item	V55	V61	V63	V65	V55	V61	V63	V65
DM, %	89.22	87.90	87.57	87.71	89.00	87.57	87.05	86.84
CP (N × 6.25), % of DM	8.1	8.7	8.4	8.6	7.7	8.4	8.2	8.3
Starch, % of DM	73.1	73.2	73.6	71.4	76.8	75.6	76.9	74.5
NDF, % of DM	6.63	7.55	8.01	7.38	5.39	5.89	6.19	5.71
ADF, % of DM	1.89	2.07	2.23	2.02	1.58	1.73	1.89	1.70
Ash, % of DM	0.99	1.18	1.27	1.30	0.96	1.03	1.14	1.03
Soluble starch (AGR),[2] %	9.61	10.29	10.47	8.89	36.98	36.04	33.57	31.90
Digestible insoluble starch (ISD),[3] %	59.98	58.33	57.17	58.08	38.11	37.72	41.00	43.17
Predicted ruminal starch digestion,[4] %	68.46	67.84	66.99	66.68	84.26	82.65	82.44	82.26

[1]Vitreousness = proportion of the horny endosperm in the degermed grain, where V55 = 55% vitreous endosperm.
[2]AGR = Amyloglucosidase reactivity, a measure of starch solubilization. Grains were ground to pass through a 20-mesh screen before 4-h enzymatic digestion (Zinn, 1990).
[3]ISD = Insoluble starch digestible, amylase reactivity of insoluble starch. Grains were ground to pass through a 20-mesh screen before 6-h enzymatic digestion (Rodríguez et al., 2001).
[4]Predicted ruminal starch digestion (1.32AGR + 0.93ISD).

Table 6. Main effects and interactions of corn vitreousness and processing on characteristics of digestion in cattle

	Main effects								Treatments[1]									
									DRC					SFC				
	Vitreousness[2]					Processing			Vitreousness					Vitreousness				
Item	V55	V61	V63	V65	SEM[3]	DRC	SFC	SEM[3]	V55	V61	V63	V65	SEM[3]	V55	V61	V63	V65	SEM[3]
Intake, g/d																		
DM	5,015	5,011	5,013	5,002		5,036	4,984		5,038	5,034	5,045	5,027		4,991	4,987	4,980	4,977	
OM	4,766	4,773	4,755	4,752		4,786	4,737		4,793	4,777	4,793	4,782		4,739	4,770	4,716	4,723	
ADF	249	237	257	254		263	236		254	259	273	265		244	216	241	244	
Starch	2,584	2,647	2,549	2,631		2,467	2,738		2,482	2,483	2,523	2,381		2,686	2,811	2,574	2,881	
N	78.3	82.0	80.0	82.2		80.5	80.8		77.7	80.5	81.0	82.7		79.0	83.5	79.0	81.8	
Flow to duodenum, g/d																		
OM	2,605	2,361	2,480	2,452	88.96	2,562	2,386	112.4	2,706	2,493	2,502	2,549	136.4	2,505	2,229	2,457	2,354	99.3
ADF[4,5,6,7]	180.8	151.3	165.9	156.6	9.43	149.2	178.1	12.34	152.6	145.7	153.7	144.9	9.61	209.1	156.9	178.1	168.2	12.67
Starch[8]	597.4	524.9	579.6	589.0	43.83	699.5	445.9	31.14	751.8	675.6	670.7	700.1	70.14	443.1	374.1	488.4	477.9	59.79
Nonammonia N	97.7	94.9	95.4	94.2	2.04	90.1	100.9	5.35	90.3	89.5	89.9	90.9	2.05	105.1	100.3	100.9	97.4	1.88
Microbial N[5,9]	68.6	68.7	70.2	69.5	1.78	65.2	73.3	3.81	61.8	65.7	67.8	65.4	1.01	75.4	71.7	72.5	73.6	2.72
Feed N[10]	29.1	26.2	25.2	24.7	1.83	25.0	27.6	4.14	28.5	23.8	22.1	25.5	2.25	29.8	28.7	28.4	23.8	1.60
Ruminal digestion, %																		
OM	59.7	64.9	63.1	62.5	1.80	60.1	65.0	2.38	56.4	61.5	61.9	60.3	2.83	63.0	68.2	63.1	65.8	1.74
ADF[10,11]	26.9	35.3	34.7	38.3	3.74	43.2	24.4	5.40	40.0	43.7	43.7	45.3	3.70	13.7	27.0	25.7	31.3	5.69
Starch[8]	76.6	79.7	77.1	77.1	1.76	71.6	83.6	1.33	69.7	72.8	73.4	70.6	2.89	83.5	86.6	80.8	83.5	2.26
Feed N[10]	62.9	68.1	68.4	69.8	2.29	68.9	65.7	5.09	63.4	70.4	72.7	69.1	2.77	62.5	65.8	64.0	70.6	2.01
Microbial efficiency[12]	24.2	22.6	23.8	23.3	1.10	22.9	24.0	0.93	23.2	22.9	22.9	22.7	1.35	25.2	22.2	24.6	23.9	1.41
Protein efficiency[10,13]	1.25	1.16	1.19	1.14	0.03	1.12	1.25	0.05	1.16	1.11	1.11	1.10	0.03	1.33	1.20	1.28	1.19	0.03
Fecal excretion, g/d																		
OM[11,14,15]	1,061	995	1,061	1,081	44.79	1248	850.9	93.43	1,208	1,238	1,207	1,339	71.73	915	752	914	823	37.54
ADF[8,14,15]	145.8	129.3	144.5	133.4	5.09	129.0	147.5	3.46	129.2	128.0	133.9	125.0	7.34	162.3	130.7	155.0	141.9	7.36
Starch[8]	162.6	189.1	172.1	222.6	23.02	354.5	18.7	51.07	309.4	355.3	326.9	426.5	38.73	15.9	22.9	17.2	18.8	3.99
N[11]	27.7	27.1	30.7	28.6	1.32	30.6	26.4	1.19	30.7	30.2	30.5	31.0	0.72	24.8	24.0	30.8	26.2	2.73
Postruminal digestion, %																		
OM[5,17,18]	59.2	57.6	57.2	56.0	2.13	51.0	64.1	3.40	55.2	49.2	51.8	47.7	2.00	63.3	66.0	62.6	64.3	1.97
ADF	16.5	12.6	10.8	11.8	4.73	11.4	14.4	5.75	14.0	10.4	9.8	11.5	4.78	19.0	14.8	11.8	12.0	6.02
Starch[5,8,17,18]	77.2	70.5	74.0	68.4	3.40	49.3	95.8	6.13	58.1	46.8	51.5	40.8	4.00	96.2	94.2	96.6	96.0	0.97
N[5,10,11]	72.2	71.9	68.9	70.2	1.32	67.2	74.4	1.98	67.3	67.2	67.3	66.9	0.818	77.1	76.6	70.6	73.4	2.47

Continued

Table 6 (Continued). Main effects and interactions of corn vitreousness and processing on characteristics of digestion in cattle

	Main effects								Treatments[1]									
									DRC					SFC				
	Vitreousness[2]					Processing			Vitreousness					Vitreousness				
Item	V55	V61	V63	V65	SEM[3]	DRC	SFC	SEM[3]	V55	V61	V63	V65	SEM[3]	V55	V61	V63	V65	SEM[3]
Total tract digestion, %																		
OM[11,14,19]	77.8	79.1	77.7	77.3	0.93	73.9	82.0	1.99	74.8	74.1	74.8	72.0	1.51	80.7	84.1	80.5	82.6	7.72
ADF[8]	41.3	44.7	43.0	47.3	2.16	50.9	37.3	2.49	49.2	50.5	51.0	52.8	2.85	33.4	38.9	35.1	41.8	3.46
Starch[8,14,20]	93.5	92.4	93.2	90.7	0.94	85.6	99.3	2.08	87.5	85.7	87.0	82.1	1.59	99.4	99.2	99.3	99.3	0.15
N[11,16]	64.6	66.8	61.7	65.2	1.62	62.0	67.2	1.37	60.5	62.5	62.3	62.5	0.90	68.6	71.2	61.1	67.9	3.34

[1]DRC = Dry-rolled corn-based diet, SFC = steam-flaked corn-based diet.
[2]Vitreousness = proportion of the horny endosperm in the degermed grain, where V55 = 55% vitreous endosperm.
[3]For vitreousnous main effect, n = 8, with 15 degrees of freedom for error. For processing main effects, n = 16, with 6 degrees of freedom for error. For vitreousness within processing effects, n = 4, with 6 degrees of freedom for error.
[4]Quadratic effect, vitreousness, $P < 0.10$.
[5]Vitreousness × processing interaction, $P < 0.10$.
[6]Linear effect, vitreousness in steam-flaked corn, $P < 0.10$.
[7]Quadratic effect, vitreousness in steam-flaked corn, $P < 0.10$.
[8]Corn processing effect, $P < 0.01$.
[9]Linear effect, vitreousness in dry rolled corn, $P < 0.01$.
[10]Linear effect, vitreousness, $P < 0.10$.
[11]Corn processing effect, $P < 0.05$.
[12]Microbial N g/kg of OM fermented.
[13]Nonammonia N flow to the small intestinal/N intake.
[14]Vitreousness × processing interaction, $P < 0.05$.
[15]Quadratic effect, vitreousness in steam-flaked corn, $P < 0.05$.
[16]Quadratic effect vitreousness, $P < 0.05$.
[17]Linear effect, vitreousness in dry-rolled corn, $P < 0.10$.
[18]Quadratic effect, vitreousness in dry-rolled corn, $P < 0.10$.
[19]Quadratic effect, vitreousness in steam-flaked corn, $P < 0.01$.
[20]Cubic effect, vitreousness in dry-rolled corn, $P < 0.10$.

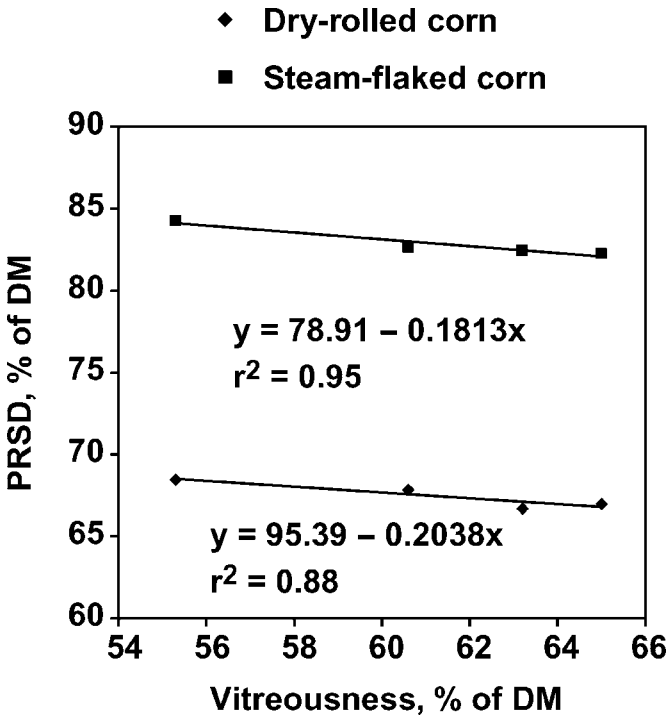

Figure 1. Relationship between vitreousness and predicted ruminal starch digestion (PRSD, % of DM).

Treatment effects on ruminal and total tract digestion of OM, ADF, N, and starch, and ruminal microbial efficiency are shown in Table 6. There were no vitreousness × processing method interactions on measures of ruminal digestion. Ruminal starch digestion was greater with SF than with DR grain (83.6 ± 2.1 vs. 71.6 ± 1.5). Consistent with previous studies (Cole et al., 1976; Zinn et al., 1995; Barajas and Zinn, 1998), steam flaking increased ($P < 0.01$) ruminal starch digestion by 17% but decreased ($P < 0.05$) ruminal ADF digestion by 43.5%. The decrease in ruminal fiber digestion may be associated with decreased ruminal pH in steers fed SF corn-based diets (Table 7). Growth of ruminal fibrolytic bacteria is inhibited by lowering ruminal pH (Hoover, 1986; Russell and Wilson, 1996).

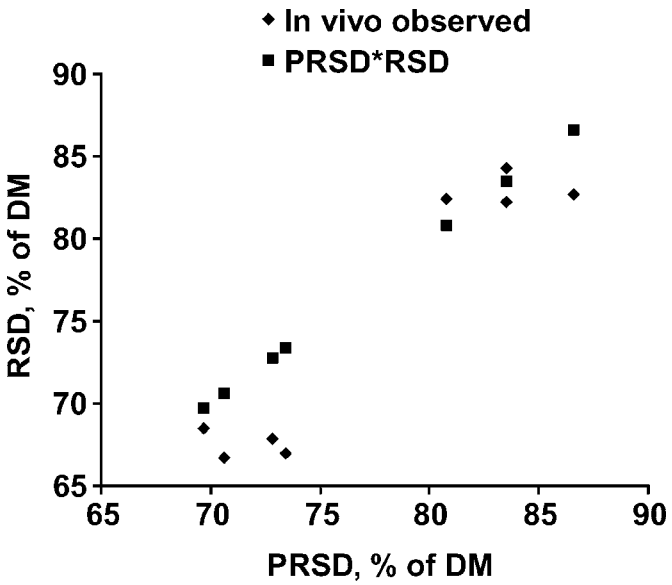

Figure 2. Relationship between in vivo ruminal starch digestion (RSD) and predicted ruminal starch digestion (PRSD; $r^2 = 0.90$, $P < 0.01$).

Across hybrids, ruminal starch digestion for SF corn averaged 83.6%; this agrees closely with values reported previously (80%; Zinn et al., 2002). In contrast, the ruminal starch digestion from DR corn at 71.6% was markedly greater (18%) than the average of values reported previously (61%; Zinn et al., 2002). The reason for the greater ruminal starch digestion with DR corn in this trial is not certain. As mentioned previously, the average in vivo ruminal starch digestion in this trial agrees well with that predicted from the in vitro enzymatic digestion procedure (68%; Table 5).

Steam flaking increased postruminal digestion of starch (94.3%, $P < 0.10$) and N (10.7%, $P < 0.01$). Greater postruminal starch digestion due to SF corn grain was consistent with previous studies (Zinn et al., 1995; Barajas and Zinn, 1998). Postruminal starch digestion was considerably lower (28%) than expected (68%; Zinn et al., 2002) for diets containing DR corn, a compensatory reflection of the 18% greater-than-expected ruminal starch digestion. Total tract starch digestion for DR corn was similar to that reported for other studies (Zinn et al., 2002).

In agreement with previous studies (Johnson et al., 1968; Zinn 1987; Zinn et al., 1995), SF increased total tract digestion of OM (11%, $P < 0.05$), starch (16%, $P < 0.01$), and N (8.4%, $P < 0.05$) but decreased total tract ADF digestion (26.7%, $P < 0.01$). In a summary of published trials, Owens and Zinn (2005) noted that total tract starch digestion averaged 99.1 and 89.3%, respectively, for SF and DR. The value for SF is consistent with the average value in this trial of 99.3 ± 0.07% (Table 6), but the value from this trial for DR corn (85.6 ± 2.1) was less than the 89.3% expected.

Adjusting for endogenous contributions to N flow to the small intestine (0.195 g/kg of $BW^{0.75}$; Ørskov et al., 1986), true ruminal degradation of fed N was 82.6%. Ruminal degradation of dietary nonurea CP was 44.8%, in close agreement with the tabular degradable intake protein (DIP) values based on dietary components of 43.8% (NRC, 1996).

Ruminal microbial efficiency averaged 23.5 g of N/kg of OM fermented and was not affected by dietary treatments. The expected microbial efficiency based on NRC (1996) Level 1 was 22.4 g of N/kg of OM fermented (21.8 vs. 23.0 for DR vs. SF, respectively). Estimated net microbial N flow to the small intestine based on Level 1 calculations (65.3 g; NRC, 1996) also agrees closely with our measured mean (64.2 g/d; Table 6). This consistency in estimation of microbial efficiency and net microbial and feed N supply to the small intes-

Table 7. Main effects and interactions of corn vitreousness and processing on ruminal pH, VFA concentrations, and estimated methane production

	Main effects								Treatments[1]									
									DRC					SFC				
	Vitreousness[2]					Processing			Vitreousness					Vitreousness				
Item	V55	V61	V63	V65	SEM[3]	DRC	SFC	SEM[3]	V55	V61	V63	V65	SEM[3]	V55	V61	V63	V65	SEM[3]
pH[4]	5.79	5.76	5.80	5.96	0.11	6.03	5.62	0.11	6.06	5.92	6.05	6.10	0.09	5.51	5.59	5.55	5.81	0.23
Total VFA, m*M*	109.4	109.8	109.4	104.0	6.60	101.2	115.1	5.86	101.2	102.6	102.6	98.4	5.89	117.6	116.9	116.3	109.7	13.39
mol/100 mol																		
Acetate[5,6,7,8]	52.3	51.8	54.4	55.1	0.68	60.7	46.1	1.60	57.9	61.0	62.7	61.2	1.09	46.7	42.5	46.1	49.0	0.83
Propionate[5,6,9]	32.5	32.9	30.2	28.6	1.29	23.6	38.5	1.35	26.2	22.6	22.1	23.7	1.56	38.8	43.3	38.4	33.6	1.87
Butyrate[4]	9.6	9.6	9.7	10.7	0.80	10.6	9.4	0.35	10.7	10.8	10.4	10.3	0.60	8.4	8.4	9.6	11.1	1.18
Acetate/propionate[5,6,9,10]	1.72	1.89	2.07	2.13	0.12	2.66	1.25	0.16	2.24	2.79	2.98	2.63	0.22	1.21	0.99	1.27	1.51	0.10
Methane production[5,6,8,10,11]	0.44	0.43	0.47	0.49	0.01	0.56	0.35	0.02	0.53	0.58	0.59	0.57	0.02	0.35	0.29	0.35	0.41	0.02

[1]DRC = Dry-rolled corn-based diet, SFC = steam-flaked corn-based diet.
[2]Vitreousness = proportion of the horny endosperm in the degermed grain, where V55 = 55% vitreous endosperm.
[3]For vitreousness main effects, n = 8, with 15 degrees of freedom for error. For processing main effects, n = 16, with 6 degrees of freedom for error. For vitreousness within processing effects, n = 4, with 6 degrees of freedom for error.
[4]Corn processing effect, $P < 0.05$.
[5]Corn processing effect, $P < 0.01$.
[6]Vitreousness × processing interaction, $P < 0.01$.
[7]Linear effect, vitreousness in dry rolled corn, $P < 0.05$.
[8]Cubic effect, vitreousness in steam-flaked corn, $P < 0.01$.
[9]Cubic effect, vitreousness in steam-flaked corn, $P < 0.05$.
[10]Linear effect vitreousness in dry rolled corn, $P < 0.10$.
[11]Methane, mol/mol of glucose equivalent fermented.

tine supports the practicality of the generalized (Level 1) approach.

The concomitant increase in postruminal digestion of nonstarch OM and of N with starch is often overlooked when considering the advantages of steam flaking. Indeed, Zinn et al. (1995) observed that the digestibility of nonstarch OM was increased by flaking to the same degree (10%) that starch digestibility was increased.

An inverse relationship between fecal starch (**FS**, %) and total tract starch digestion was apparent: total tract starch digestion, % = 101.14 − 0.649 FS (n = 32, $r^2 = 0.94$, $P < 0.01$). This close association between percentage fecal starch and starch digestion agrees closely with a 64-trial summary by Zinn et al. (2002; total tract starch digestion, % = 100.5 − 0.649 FS; $r^2 = 0.91$).

Effects of corn processing on ruminal pH, VFA concentrations, and estimated methane production (based on VFA concentrations 4 h postprandially) are shown in Table 7. There were no processing × vitreousness interactions on ruminal pH. Consistent with previous trials (Johnson et al., 1968; Zinn, 1987), ruminal pH was greater (7.3%, $P < 0.05$) with diets based on DR corn than on SF corn. Total ruminal VFA concentration tended to be greater ($P = 0.14$) with SF than with DR corn diets. In agreement with previous studies (Johnson et al., 1968; Zinn, 1987; Zinn et al., 1995), SF diets lowered the ruminal molar proportion of acetate (24%, $P < 0.01$) and butyrate (11.3%, $P < 0.05$), acetate:propionate molar ratio (55.5%, $P < 0.01$), and estimated methane production (37.5%, $P < 0.01$). These responses are consistent with a greater molar proportion of propionate (61.9%, $P < 0.01$). As a percentage of fermented energy, loss of methane would account for a mean of 17.7% with diets based on DR corn vs. 11.0% with SF corn despite having more OM truly digested in the rumen. As a fraction of dietary energy, methane loss was reduced from 10.6 ± 0.92 to 7.1 ± 1.01% by flaking corn grain. This corresponds to an increase of 3.4 ± 1.4% in available energy from the diet due to flaking corn grain that can be attributed to methane reduction, a difference that would not be detected through measurement of digestion alone. The magnitude of this advantage from flaking might be affected by others factors that influence total methane production; for example, use of ionophores, greater feed intakes, or including more fat in the diet.

Across processing method, increasing corn vitreousness from V55 to V65 tended to increase (linear effect, $P < 0.10$) ruminal digestion of feed N, ADF, and postruminal N digestion. Total tract apparent N digestion was lower (quadratic effect, $P < 0.05$) for the V63. Increasing vitreousness increased (linear effect, $P < 0.05$) the acetate:propionate molar ratio. The hybrid with greater vitreous endosperm (V65) showed greater (cubic effect, $P < 0.05$) molar proportions of acetate and estimated methane production (linear effect, $P < 0.10$) and lesser (cubic effect, $P < 0.10$) molar proportion of propionate.

To provide more applicable results within each processing method, the effects of vitreousness on site and extent of digestion and on ruminal measurements were examined separately for DR and SF corn-based diets; responses were subdivided into linear, quadratic, and cubic effects of the percentage of endosperm considered vitreous. Vitreousness of DR corn did not affect ($P \geq 0.15$) ruminal digestion of OM, starch, ADF, or N, but with SF corn, ruminal disappearance of ADF tended to increase (linear effect, $P < 0.10$) with grain vitreousness. With the more extreme differences in vitreousness (38.5 to 79.1%) associated with dent vs. flint genotypes, Philippeau et al. (1999a) observed a markedly lower calculated effective ruminal starch degradation based on in situ measurements (61.9 vs. 36.2%) for dent vs. flint genotypes. The majority of this difference was apparent at time zero and thus, may reflect greater loss of finely ground particles through the pores of Dacron bags from finely ground floury grain.

Interactions were detected ($P < 0.10$) between vitreousness and processing method on postruminal digestion of OM, starch, and N digestion. With DR, postruminal OM and starch digestion tended to decrease (linear effect, $P < 0.10$) with increasing vitreousness, but with SF grain, no effect of grain vitreousness on starch digestion was detected. Philippeau et al. (1999b) evaluated site of digestion of 2 corn hybrids that differed in vitreousness (51.7 and 68.8%) but were similar to the extremes used in our study. In contrast with our results, they observed a markedly decreased ruminal starch digestion for the more vitreous hybrid (35 vs. 61%), but postruminal starch digestion exhibited a compensatory increase (46 vs. 22%) so that total tract starch digestion of the dry-processed hybrids was not different between their 2 hybrids. In our study, the more vitreous (V65) grain when fed as DR grain was not different from the other hybrids in ruminal starch digestion, but it had lower postruminal and total tract starch digestion (41 vs. 58% and 82 vs. 88%, respectively; $P < 0.10$). We expect that additional factors beyond vitreousness (including intermolecular association, granular size, and the nature of the protein matrix) would have appreciable, if not overriding, influences on rate and extent of digestion when hybrids of very diverse genetic background (flint vs. dent) or maturity are compared.

Although vitreousness of grain did not affect ($P \geq 0.15$) postruminal digestion of OM and starch when grain was SF, postruminal N digestion tended to decrease (linear effect, $P = 0.12$) as vitreousness increased. Vitreousness did not affect ($P \geq 0.15$) postruminal N digestion with DR corn.

In a parallel way to treatment effects on postruminal digestion, interactions ($P < 0.05$) between vitreousness and processing method were detected for total tract digestion of OM, starch, and N. With SF corn, vitreousness did not affect ($P \geq 0.15$) total tract starch digestion. In contrast, with DR corn, total tract starch digestion was lower (cubic effect, $P < 0.10$) for V65. With DR grain, vitreousness of the grain before grinding could explain 55% of the variation in total starch digestion (total starch digestion = 111.93 − 0.4642 vitreousness;

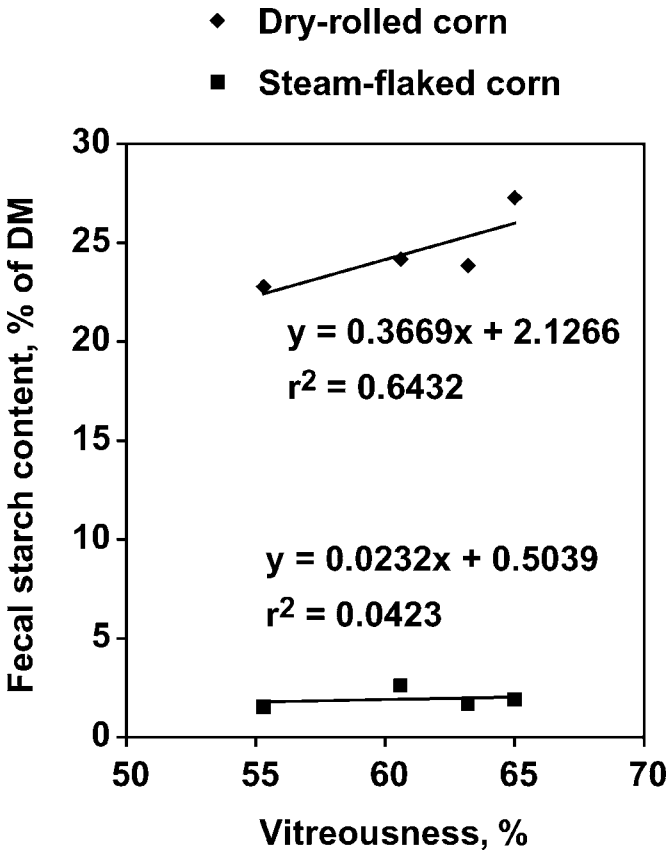

Figure 3. Relationship between vitreousness and fecal starch excretion.

r^2 = 0.55, P = 0.25) and 64% of the variation in fecal starch excretion (fecal starch excretion = 2.1266 + 0.3669 × vitreousness). But with flaked grain, the difference in total starch digestibility among these same hybrids was only 0.2 percentage units (99.2 to 99.4%). Flaking corn grain obliterated any impact of vitreousness on starch digestibility.

Vitreousness reflects the association between starch and protein in the endosperm. In the vitreous endosperm, starch granules are surrounded by protein bodies and are embedded in a dense matrix that limits the accessibility of hydrolytic enzymes to starch. In contrast, starch granules in floury endosperm are more accessible to ruminal bacteria because the granules are less compact and the protein matrix is discontinuous (Kotarski et al., 1992). Our results indicate that corn vitreousness primarily affects postruminal digestion for DR corn, explaining 64% of the variation in fecal starch excretion (fecal starch excretion = 2.1266 + 0.3669 × vitreousness; Figure 3). The effect of vitreousness on starch digestion with SF corn is minimal because starch in the horny endosperm that surrounds the kernel is denatured by exposure to shear at elevated temperatures. The difference among hybrids in digestibility was minimized when corn was flaked. From a grain-handling viewpoint, the most vitreous hybrid tested may have an advantage with respect to flake quality (fewer fines and broken flakes; Table 4). Furthermore, considering trends in ruminal pH, site of starch digestion (greater proportions of digestible starch digested postruminally), and ruminal fiber digestion, more vitreous hybrids may be preferable when corn grain is to be flaked.

In this study, flaking corn hybrids to a density of 0.373 kg/L increased total tract digestibility of starch (from 85.6 to 99.3%) and OM (from 73.9 to 82%), and decreased loss of energy as methane (from 10.6 to 7.1% of gross energy). Taken together, increased OM digestion (11.0% improvement, of which a mere 5.8% can be attributed to starch) and methane reduction (3.4%) equal an improved energetic efficiency of diets containing flaked grain of 14.4%. If this full difference is attributed to the corn grain that comprised 73.2% of the diet, then energetic efficiency in this trial was increased by 19.7% by flaking compared with dry rolling of corn grain. This advantage is similar to the 18% observed in performance trials (Zinn et al., 2002).

IMPLICATIONS

Compared with diets containing dry-rolled corn grain, diets with steam-flaked grain had greater ruminal, postruminal, and total tract starch digestion in finishing steers. When fed as dry-rolled corn, less vitreous (more floury) corn samples had greater total tract starch digestion, primarily due to greater postruminal starch digestion. However, adverse effects of more vitreous grain on digestion were obliterated when the grain was steam flaked. Of the 19% energetic efficiency advantage of steam-flaked over dry-rolled corn grain, ¾ can be attributed to increased total tract digestibility not only of starch, but also of nonstarch organic matter and protein. One-fourth can be ascribed to decreased methane loss at some sacrifice in fiber digestibility.

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