CORN GRAIN PROCESSING AND DIGESTION

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SUMMARY

Grains are fed to livestock primarily to supply energy, and the major energy source in cereal grains is starch. For maximum starch digestion, corn and sorghum grain must be processed. For non-ruminants, starch from finely ground grain is fully digested, but for ruminants fed concentrate diets, finely ground grain can cause metabolic diseases. Hence, steam rolling or flaking and fermentation (high moisture storage) rather than fine grinding are used for grains fed to ruminants to increase the extent of starch digestion. Such processing methods increase starch digestion both in the rumen (of dietary starch) and postruminally (of starch reaching the small intestine). The lower the density of corn flakes, the greater the digestibility of starch, particularly in the small intestine. For maximum ruminal starch digestion, a thinner flake is needed for lactating cows than for feedlot cattle because particles spend less time in the rumen for digestion in lactating cows than in feedlot cattle. This shortened ruminal residence time can explain why ruminal and total tract starch digestibility is lower for lactating cows than for finishing cattle. Contrary to popular belief, digestion of starch reaching the small intestine does not decrease as abomasal supply of starch increases. However, neither dry rolled or whole corn is digested well post-ruminally. Due to reduced loss of methane and heat, available energy supply for the animal is greater for starch digested in the small intestine than for starch fermented in either the rumen or large intestine. Different hybrid characteristics are desired for different processing methods. For whole and dry rolled corn, very fine grinding of grain with a floury endosperm, a thin or loose pericarp, and a low amylose:amylopectin ratio all will help to maximize starch digestion. For fermented corn grain with adequate moisture content and for adequately processed steam flaked corn, starch digestion usually exceeds 97%. Therefore, the remaining differences among various corn samples in digestibility (1 to 3%) must be attributed to differences in digestibility of components other than starch (NDF, protein). For maximum feed efficiency, energy digestibility must be maximized. For dry rolled or ground corn, incomplete starch digestibility is of primary concern, but with more extensively processed grain, corn grain richer in starch (and thereby lower in NDF and protein) will provide more digestible energy.

BACKGROUND

For poultry and swine, corn grain typically is processed through a grinder or roller to reduce particle size. If processed particles have a mean diameter of 500 to 700 microns, this means that each corn kernel is being subdivided into 4,000 to 10,000 pieces! With finely ground corn, total tract starch digestion by non-ruminants exceeds 99%. Because total tract starch digestion is so high, starch digestibility by non-ruminants has been largely ignored even though as much as 7% of gross energy from corn grain may be digested from the large intestine (Lin et al., 1987; Pascual-Reas, 1997) and over 4% of dietary starch and over 20% of non-structural polysaccharides from corn grain-based diets may enter the large intestine of pigs (Morales et al., 2002). Grains are less extensively processed for ruminants than non-ruminants. Indeed, some sheep and calves are fed whole (unprocessed) corn grain. Such animals chew and ruminate the whole grain so it need not be processed. For mature cattle, dry corn grain usually is coarsely rolled or cracked yielding 4 to 10 particles per kernel of corn. And with mature corn silage, some whole corn may be found unless the corn forage is adequately "kernel processed" during harvest to damage the kernels and increase starch digestibility. Because starch digestibility generally is lower for ruminants than non-ruminants, this review will emphasize grain processing for ruminants.

Grain processing for feeding ruminants has been reviewed extensively (Nocek and Tamminga, 1991; Huntington, 1997; Theurer et al., 1999a; Rowe et al., 1999; Firkins et al., 2001; Harmon and McLeod, 2001, 2005; Owens and Zinn, 2005). For comments about the impact of site of digestion on energetic efficiency and differences among hybrids and corn types on digestibility, readers should examine other sources (Owens and Zinn, 2005; Harmon and McLeod, 2005). This review will concentrate on results of trials with lactating dairy cows typically fed diets with 40 to 60% roughage and feedlot cattle fed diets with less than 20% roughage. All digestion values cited represent the reported disappearance within a specific location of the digestive tract without adjustment for microbial constituents.

Grain for livestock is processed to enhance its nutritional value. The feeding value of any feed is a function of three factors: nutrient content, intake, and digestibility. Physical and chemical characteristics of a grain can alter its digestibility, its dustiness and acceptability (palatability), and its associative effects (interactions of roughage with concentrate) within the digestive tract. Processing methods are selected to economically enhance digestibility and acceptability without detrimentally affecting ruminal pH and causing digestive dysfunction.

Typical grain processing methods involve particle size reduction with or without addition of water or steam. Grinding or rolling to form dry rolled or dry ground grain with or without addition of moisture is the most common method of grain processing. For more extensive processing, grain can be rolled or ground and fermented if adequate moisture (typically 24 to 35%) is present. Moisture may either be inherent in the grain due to early harvest forming high moisture grain or added to dry grain to form reconstituted grain. To form steam rolled or "flaked" grain, dry whole grain is moistened with steam and crushed between corrugated rolls. Compared with steam flaked grain, steam rolled grain is steamed for a shorter time, crushed flakes are thicker, and starch is less gelatinized (damaged). Gelatinized starch is very rapidly and completely fermented. Effects of processing on site and extent of digestion can vary with processing conditions (grain moisture, screen size or roll gap; fermentation moisture and time; steaming time) as discussed by Zinn et al. (2002). For less extensively processed corn, feeding value can vary with the hybrid or variety of the grain and agronomic conditions. Finally, chewing and rumination as well as bunk management can alter site and extent of digestion and passage rate through the digestive tract; these vary with animal age and background, diet composition, feeding frequency, and dietary forage or fiber (NDF) level.

This paper 1) reviews site and extent of digestion by cattle fed corn grain processed by various commercial methods and 2) considers specific physical and chemical factors that can limit the rate and extent of digestion of corn grain components.

SITE AND EXTENT OF STARCH DIGESTION BY CATTLE

Results were assembled from 44 published trials and two unpublished trials from 1990 to 2005 that have measured site of starch digestion for 180 diets fed to feedlot cattle (steers and heifers) and 34 diets fed to lactating cows. The total number of diet-animal measurements was 153 for lactating cows and 815 for feedlot steers plus heifers. Data sources are included in the literature listing. To evaluate site and extent of starch digestion, the factors of primary concern were: 1) percentage of dietary starch apparently digested in the rumen, 2) percentage of starch flowing out of the rumen that was digested in the intestines, 3) total tract starch digestion, and 4) site of starch digestion (fraction of total tract starch digested that disappeared in the rumen). For statistical analysis, diet means were weighted by the number of cattle measurements in each mean. Because data were limited, results from trials with lactating cows fed steam flaked and steam rolled grain were merged; least squares means for corn processing methods were generated and effects of diet composition (N, starch, NDF) and other management and ruminal factors (intake as a fraction of body weight; ruminal dilution rate for concentrate) on site and extent of starch digestion were tested. Because responses sometimes differed between lactating cow and feedlot cattle, means for each animal class and processing method are presented in Table 1.

First, total tract digestion of starch from grain ranged from 90 to 96% for lactating cows and from 87 to 99% for feedlot cattle. With grain being approximately 70% starch, feeding value differences due to processing from starch alone should be about 4% for lactating cows and 9% for feedlot cattle. These must be balanced against the expenses of handling and processing grain. Additional benefits from processing can accrue from increased digestion of other grain or diet components, from a more efficient site of digestion (energy lost with fermentation in the rumen and large intestine), and an altered site of digestion. If starch is fermented in the rumen, ruminal microbes use the energy to synthesize protein for the animal to digest and deposit or secrete. However, if starch digested in the small intestine, energy loss during ruminal fermentation as methane and heat of metabolism is avoided. This makes site of digestion (rumen versus intestines) of interest.

Extent of ruminal fermentation of starch from corn grain is lower for cows than for feedlot cattle (Table 1). But post-ruminally, starch disappearance was quite similar for cows and feedlot cattle indicating that similar factors probably limited post-ruminal starch digestion. Starch digestion from high moisture corn was consistently quite high due to extensive starch disappearance both in the rumen and the intestines. As a fraction of total tract starch digestion, the proportion of the total digestion that occurred post-ruminally from processed grains (flaked, high moisture) was much greater for lactating cows than for feedlot cattle. As compared with dry rolled grain, steam flaking of corn for feedlot cattle increased both ruminal and total tract starch disappearance but shifted the site of starch digestion toward the rumen. In contrast, for lactating cows the increase in digestibility obtained from flaking was due primarily to increased post-ruminal digestion of starch.

Table 1. Site and extent of starch digestion from corn-based diets by lactating cows and feedlot steers with corn processed by various methods

Animal class:	**Lactating cows**			
Processing method:	**Dry rolled**	**High moisture**	**Steam flaked**	**Steam rolled**
Trials/diets measured	22	4	5	3
Total cattle	102	20	18	13
Total tract dig., % diet	89.9	96.0	93.9	94.2
Ruminal dis., % diet	49.2[b]	76.3[a]	51.8[b]	55.7[b]
Post-ruminal dis., % flow	77.7	82.9	88.4	88.3
Small intest. dis., % flow	48.4	57.8	71.2	-
Fraction dis. in rumen, %	55.5[b]	79.4[a]	54.8[b]	58.8[ab]

[a,b] Means within a row not sharing a superscript differ (P < .05).

Animal class:	**Feedlot cattle**			
Processing method:	**Dry rolled**	**High moisture**	**Steam flaked**	**Whole**
Trials/diets measured	42	8	94	6
Total cattle	231	82	451	51
Total tract dig., % diet	91.0[b]	99.2[a]	99.1[a]	87.1[c]
Ruminal dis., % diet	63.8[b]	86.5[a]	84.1[a]	68.3[b]
Post-ruminal dis., % flow	72.2[b]	93.1[a]	94.3[a]	53.0[b]
Small intest. dis., % flow	58.8[b]	94.9[a]	92.5[a]	64.6[b]
Fraction dis. in rumen, %	70.1[c]	87.2[a]	84.7[a]	79.2[b]

[a,b,c] Means within a row not sharing a superscript differ (P < .05).

Is there a ceiling to the amount of starch that can be digested in the rumen or small intestine? To address this question, the amount of starch digested at various segments of the digestive tract was plotted against starch supply (Figure 1). The regression slope (forced through zero) provides an index of true digestibility. Values for lactating cows in each plot are circled; values for feedlot cattle are not circled. Based on all experiments with both cows and feedlot cattle, total tract digestibility of starch from high moisture, steam rolled (or flaked), dry rolled, and whole corn averaged 98, 97, 90, and 84% of starch intake. Only one major deviation from these regression lines was observed; this was very low starch digestion for a high bushel weight steam rolled corn grain diet fed to lactating cows.

Extent of dietary starch that disappeared in the rumen at various starch intakes is shown in Figure 2. Averaged across trials, extent of ruminal disappearance of dietary starch for high moisture, steam rolled (or flaked), dry rolled, and whole corn was 85, 77, 55, and 77%, respectively. The values for lactating cows consistently fell below the regression lines for all cattle for flaked and rolled corn; this confirms the idea that ruminal starch digestion is lower for cows as noted in Table 1. This can be attributable to a faster particle passage rate from the rumen associated with high feed intake or a greatly (500%) enlarged size of the opening of the reticulo-omasal orifice (Welch, 1982; 1986) that will allow larger less digested but dense corn particles to flow from the rumen.

Post-ruminal starch disappearance as a fraction of starch entering the small intestine is presented in Figure 3. Several past reviews have suggested that intestinal starch digestibility DECREASES as starch flow to the intestines increases. However, when calculated WITHIN a processing method, post-ruminal digestion did not decline as passage of starch to the small intestine (abomasal supply) increased. Post-ruminal disappearance of abomasal starch for high moisture, steam rolled (or flaked), dry rolled, and whole corn grain averaged 84, 82, 80, and 29%. Abomasal flow of starch as high as 6000 g daily caused no decrease in the fraction of starch digested post-ruminally. However, very low post-ruminal digestion of starch from whole corn (29%) indicates that very large particles are poorly digested in the intestines. With whole dry corn, starch that is not chewed but escapes ruminal digestion has virtually no value for ruminants.

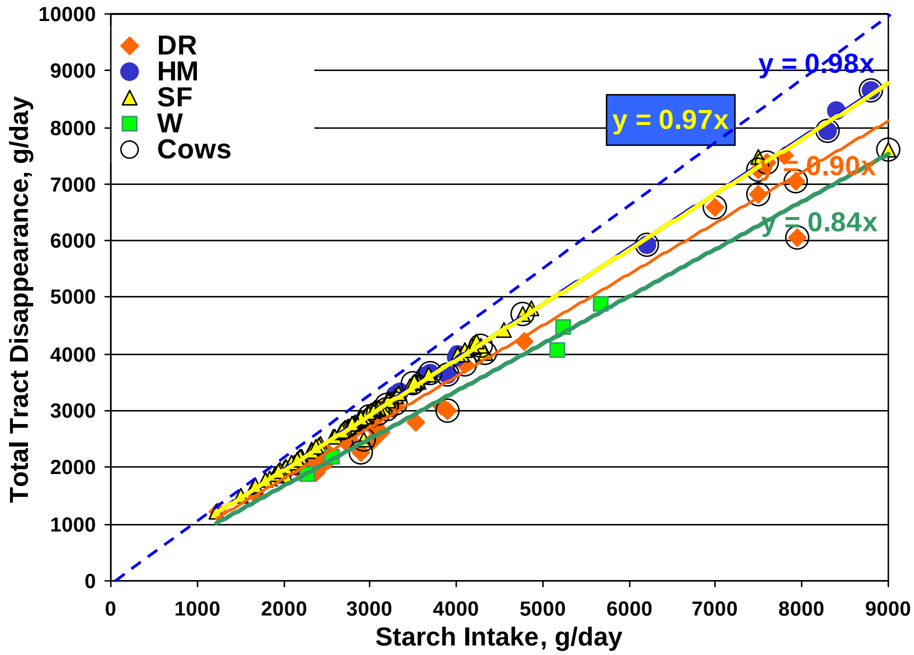

Figure 1. Total tract digestion of starch from corn grain processed in different manners and fed to lactating cows and feedlot cattle. Processing methods included dry rolled or ground (DR), high moisture (HM), steam flaked or steam rolled (SF) and whole (W). The dashed line represents the points where 100% of starch would have been digested. Values from lactating cows are circled.

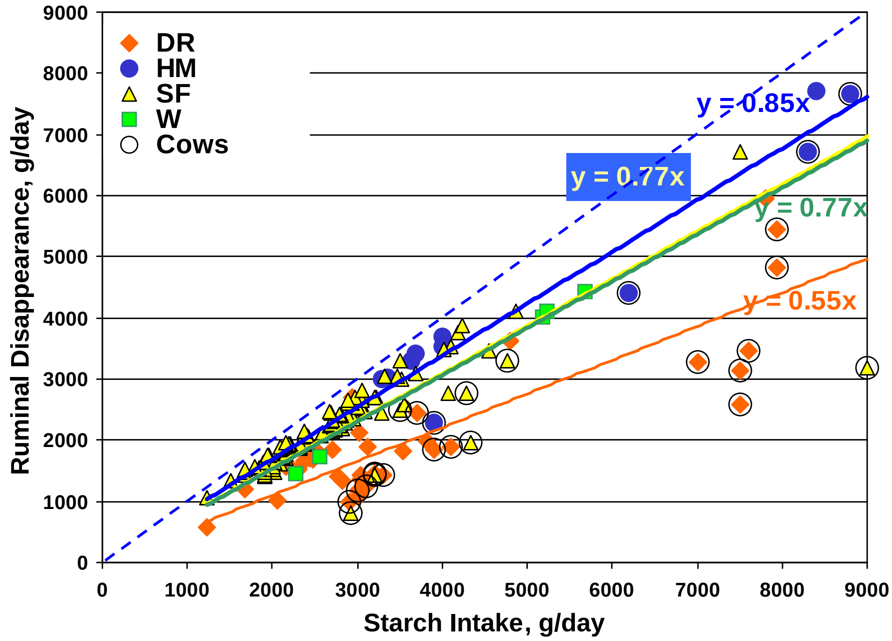

Figure 2. Ruminal disappearance of starch from corn grain processed in different manners and fed to lactating cows and feedlot cattle. For definitions, see Figure 1.

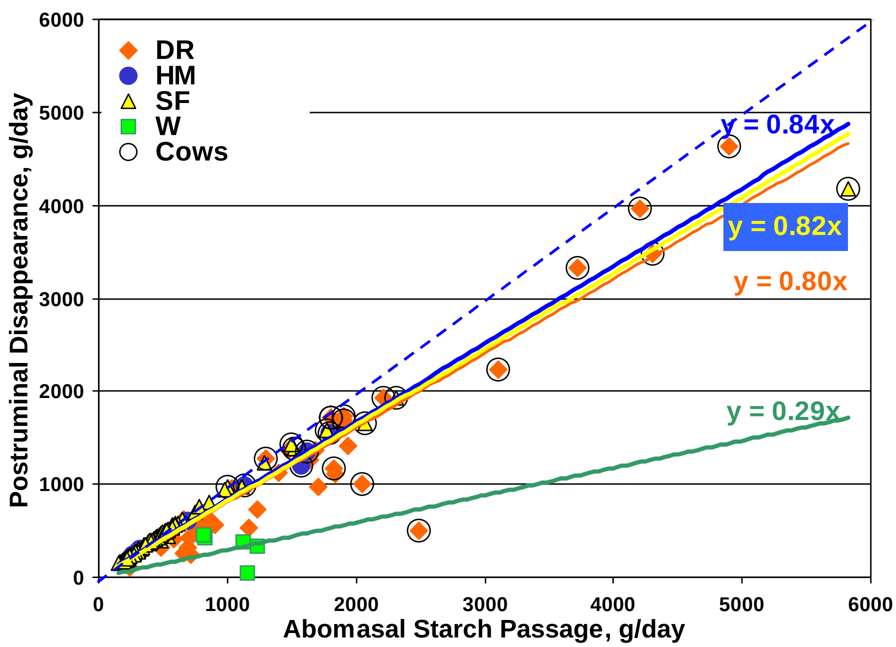

Figure 3. Postruminal disappearance of abomasal starch from corn grain processed in different manners and fed to lactating cows and feedlot cattle. For definitions, see Figure 1.

Of the starch disappearing postruminally, how much is digested in the small intestine and how much is fermented in the large intestine? Starch digestion in the small and large intestine has been separated in only 4 trials in this large data set and results have been quite variable. In one trial with lactating cows fed dry rolled corn, the amount of starch leaving the small intestine EXCEEDED the quantity of starch entering the small intestine. For feedlot cattle fed dry rolled corn, an average of 49.8% of duodenal starch was digested in the small intestine. Hence, with lactating cows, from 38 to 131% (sic) of starch from dry rolled corn that was digested post-ruminally was digested in the large intestine, not the small intestine. In contrast, with high moisture corn fed to lactating cows, 57.8% of the abomasal starch was digested in the small intestine. For feedlot cattle fed steam flaked corn, this value was 88.4%. Averaged across cows and steers, for high moisture and steam flaked corn an average of 71 and 96% of post-ruminal starch disappearance apparently was digested in the small intestine. For small energetic efficiency to be improved by shifting site of digestion toward the small intestine, digestion of starch supplied to the small intestine would need to exceed about 70%.

Diet composition, intake level, and ruminal passage rate can alter the site and extent of digestion. To examine these factors within animal class but across corn processing methods, the difference between predicted and observed starch digestion was regressed individually 1) against diet composition (percentage of N, starch, NDF), 2) against intake (dry matter intake as a fraction of body weight) and 3) against concentrate dilution rate (calculated from intake and diet NDF as proposed by Seo et al. (2004). Interactions with animal class also were tested averaged across processing methods. Results are presented in Table 2.

First, increasing the quantity of protein in the diet decreased ruminal starch disappearance, particularly for lactating cows, shifting site of starch digestion away from the rumen toward the small intestine. In contrast, having more starch in the diet (and less fiber) increased ruminal starch disappearance, shifting site of starch digestion toward the rumen. A higher amount of fiber (NDF) in the diet decreased total tract starch digestion, particularly for lactating cows, by decreasing starch disappearance both in the rumen and postruminally. Increasing dietary NDF shifted site of starch digestion toward the intestines. Intake level (dry matter as a percentage of body weight) within animal class had no significant effect on ruminal, postruminal, or total tract starch disappearance, but higher feed intake across both animal types shifted site of starch digestion toward the intestines. Finally, a high ruminal dilution rate, driven primarily by greater feed intake and dietary NDF, decreased ruminal starch disappearance and, surprisingly, tended to increase postruminal starch disappearance, shifting site of digestion toward the intestines.

Based on these measurements, for maximum total tract digestion of starch, diets rich in protein but low in NDF are desired. For maximum ruminal fermentation, diets low in NDF and low intakes are preferred; these changes should slow passage of concentrate particles from the rumen. So for maximum post-ruminal disappearance of abomasal starch, a diet rich in protein and low in NDF is preferred. To shift site of digestion toward the rumen, a diet low in protein and NDF and a slower concentrate passage rate is desired. But to shift site of digestion toward the intestines, a diet rich in protein and NDF resulting in a high concentrate passage rate would be preferred. In addition to the diet and animal characteristics noted above, specific characteristics of cereal grains can alter site and extent of digestion.

Table 2. Impact of dietary and management factors on site and extent of starch disappearance averaged across processing methods.

Response:	Main effect		Interaction	
Measurement and factor:	**Slope**	**P<**	**Class**	**Response**
Ruminal disappearance, % of diet				
Diet N, %	-0.45	0.05	0.04	Cow>Steer
Diet starch, %	0.72	0.01	0.67	
Diet NDF, %	-2.18	0.01	0.29	
DMI, % of BW	-3.45	0.07	0.30	
Concentrate k_p	-6.00	0.03	0.55	
Postruminal disappearance, % of abomasal supply				
Diet N, %	4.36	0.53	0.15	
Diet starch, %	-0.03	0.09	0.12	
Diet NDF, %	-2.02	0.01	0.01	Cow>Steer
DMI, % of BW	3.26	0.27	0.62	
Concentrate k_p	1.97	0.07	0.16	
Total tract disappearance, % of diet				
Diet N, %	1.63	0.71	0.61	
Diet starch, %	0.07	0.89	0.22	
Diet NDF, %	-1.06	0.01	0.05	Cow>Steer
DMI, % of BW	0.41	0.3	0.41	
Concentrate k_p	-0.07	0.07	0.07	
Fraction disappearing in rumen, % of total disappearance				
Diet N, %	-2.17	0.03	0.01	Cow>Steer
Diet starch, %	0.71	0.01	0.88	
Diet NDF, %	-1.59	0.01	0.57	
DMI, % of BW	-3.95	0.01	0.13	
Concentrate k_p	-6.25	0.01	0.16	

ASSOCIATIVE EFFECTS

Fiber digestion by ruminants also can be altered by grain processing (Table 3). Total tract digestion of NDF was lower for high moisture than for dry rolled, flaked, or whole corn with both lactating cows and feedlot cattle. This depression was primarily a result of reduced ruminal digestion. Flaking corn grain depressed ruminal NDF digestion more for lactating cows than for feedlot cattle. Rate of ruminal digestion of NDF can be reduced by a low ruminal pH, a condition more prevalent with feedlot cattle than lactating cows due to level of grain in the diet and NDF intake. In addition, NDF digestion may be depressed by presence of digestible or soluble starch as may occur with high moisture corn.

Table 3. Site and extent of NDF digestion from corn-based diets by lactating cows and feedlot cattle with corn processed by various methods.

Animal class:	**Lactating cows**			
Processing method:	**Dry rolled**	**High moisture**	**Steam flaked**	**Steam rolled**
Ruminal dis., % diet	42.6[a]	17.9[b]	51.5[a]	45.9[a]
Total tract dig., % diet	56.5[a]	38.5[b]	62.0[ab]	53.0[ab]

Animal class:	**Feedlot cattle**			
Processing method:	**Dry rolled**	**High moisture**	**Steam flaked**	**Whole**
Ruminal dis., % diet	48.1[a]	18.5[c]	27.7[b]	33.4[b]
Total tract dig., % diet	50.8[a]	34.3[c]	44.4[b]	38.1[bc]

OPTIMIZING PROCESSING CONDITIONS

Dry rolled corn and whole corn. As noted in classic studies from Beltsville (Moe and Tyrrell, 1976), dry corn grain must be ground finely to obtain the maximum total tract digestion. Certainly, particles that are large and resist uptake of water will resist attack by microbes in the rumen and enzymes in the intestines. Though fine grinding can enhance extent of starch digestion slightly, primarily due to enhanced starch disappearance in the rumen, starch from rolled corn leaving the rumen was poorly digested in the small intestine of lactating cows; instead much of the starch was fermented in the large intestine. With lactating cows fed coarsely rolled (1725 micron geometric mean diameter-GMD) corn, Knowlton et al. (1998) indicated that none of the starch that entered the small intestine was digested there. Even with ground corn (618 micron GMD), small intestinal disappearance was only 13% of abomasal flow; these contrast with small intestinal disappearance of 59% and 64% of starch from ground and rolled high moisture corn for these same lactating cows. Hutjens (2002) described the use of sieves to appraise the particle size of ground grain; his recommended particle distribution among sieves calculates to an optimal GMD of 1150 to 1250 microns. By comparison, for maximum digestion, corn for pigs usually is ground to a GMD between 400 and 600 microns. When sufficient roughage is present in the diet to prevent acidosis and cattle are frequently fed a totally mixed ration, grinding to a fine particle size is unlikely to cause acidosis while improving starch digestibility and feed efficiency. Grain can be either rolled or ground to reduce mean particle size. Compared to rolled grain, ground grain typically has a much larger range in particle size because more fine particles are generated during grinding than rolling. Hence, GMD alone, though useful, is incomplete as an index of processing. Baker and Herrman (2002) describe additional components (particle surface area; particles per gram) that can be calculated through sieving of processed grain. Presence of fines and GMD also will vary with moisture content and hybrid of the grain being processed; wetter and more vitreous grains generate fewer fines and particles will have a larger GMD. With whole corn grain, less than one-third of starch entering the abomasum disappeared postruminally! This matches field observations that a diet composed of whole shelled corn should be fed to feedlot cattle only with a very low roughage diet that permits grain to be retained in the rumen to be ruminated and fermented; with such a diet, feed efficiency sometimes is better whole corn than rolled corn. Though adding roughage to the diet usually shortens the time that particles are retained in the rumen for fermentation, extent of ruminal separation of roughage particles from whole grain also is important; separated grain that settles in the rumen will not be ruminated and intact whole corn grain is not digested at any site. Indeed, ruminal outflow rates for starch greater than 20% per hour have been reported for high producing lactating cows (Ying and Allen, 2005). Such outflow, being as fast as for ruminal liquid, indicates that consumed starch must be rapidly flushed from the rumen, possibly being sluiced through the rumen, instead of being fully mixed with ruminal contents and held there for digestion. Such rapid passage should be more prevalent with very dense grain particles when the rumen is stuffed with fiber, feed intakes are high, and grain is fed or consumed separately from forage.

High moisture corn. Two factors are critical for maximum feed efficiency and ruminal starch digestion from high moisture corn grain -- adequate moisture content (preferably above 26% moisture) and a sufficient duration of fermentation. For some unknown reason(s), when ensiled between 20 and 24% moisture, high moisture corn consistently results in poorer feed efficiency than either drier (rolled) grain or wetter grain. Moisture level and storage time responses have been reviewed previously (Owens et al., 1986) and demonstrated both in vivo (Jaeger et al., 2004) and in situ (Benton et al., 2004). Results from the latter trial indicate that in situ disappearance of starch in the rumen from high moisture corn increased rapidly during the first month of storage, but starch availability continued to during the full study that lasted nine months! This increase in starch disappearance parallels the increase in N solubility usually seen as high moisture corn grain is held for a longer time before feeding. Applying this principle, wetter high moisture corn, typically harvested first, should be fed first whereas drier high moisture corn, harvested last, should have water added and allowed to ferment for a longer time period. This is precisely the opposite the first-in last-out system used in most upright or bunker silos! Furthermore, an increase in the rate and extent of ruminal fermentation of high moisture grain stored for many months can place cattle fed grain stored longer at greater risk of acidosis even if the diet composition is not changed. Because corn grain that had been reconstituted (water added and allowed to ferment) has resulted in similar in situ starch disappearance and feed efficiency as corn grain harvested at a similar moisture content, the greater digestibility of starch from fermented than unfermented grain appears to be due to the fermentation process, not to kernel characteristic of corn grain that is harvested before it dries in the field. The increase in starch digestibility with longer storage appears correlated with solubilization of corn proteins that encase or link starch granules. Hence, the types and activity of bacteria inherently present on the crop or added to harvested grain as an inoculum are likely to influence starch digestibility.

Steam flaked corn. As reviewed by Zinn et al. (2002), the degree of damage of starch and extent of denaturation of protein in flaked grain varies with processing conditions. Flake thickness and density (flake bushel weight) are used as quality control indices at the flaker whereas starch availability (glucose release during exposure to amylolytic enzymes) often is measured in a laboratory long after the grain is fed. The relationship of bushel weight of corn grain (from dry rolled grain through to grain that has been steam flaked at various densities) to ruminal starch disappearance is illustrated in Figure 4. Except for one of these 17 trials in which corn flaked to different bushel weights were fed, steam flaking or steam rolling to a lighter test weight increased starch disappearance. But even in these trials, ruminal starch disappearance tended to be less with lactating cows than feedlot cattle. Compared with feedlot cattle, cows respond readily to very low flake weights, perhaps due to short ruminal residence time for concentrate particles or increased starch flushing to the small intestine where a large particle size limits starch digestion.

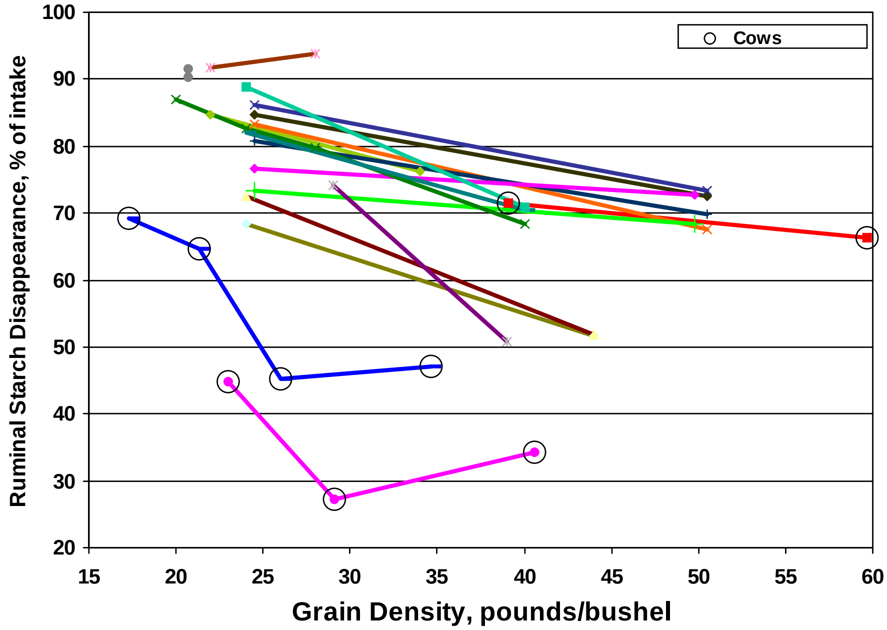

Figure 4. Impact of density of processed grain on ruminal starch disappearance. Each line represents values from a single experiment and lines connect individual diets within the experiment. Circled values are from lactating dairy cows.

Effects of density of processed grain on postruminal starch disappearance as a fraction of starch leaving the abomasum are shown in Figure 5. Again, corn grain that was steam rolled or steam flaked to a lower density had greater postruminal disappearance than grain processed to a higher bulk density. Similar responses were evident for lactating cows (circled values) as for feedlot cattle.

Total tract starch digestibility responses to density of processed grain are shown in Figure 6. Total tract starch digestion by feedlot cattle exceeded 95% when flake density was below about 38 pounds per bushel; for cows, a lower flake bushel weight, under 24 pounds, was needed to reach this point due primarily to less ruminal disappearance of starch by cows fed grain with a higher test weights. As corn flaked to a very light test weight often depresses feed intake by feedlot cattle, possibly due to greater gelatinization and elevated ruminal acid concentrations, processing for maximum starch digestibility through gelatinizing more than 50% of the starch often depresses energy intake and rate of gain of feedlot cattle. If abomasal starch from flaked grain can be digested in the small intestine, and if absorbed glucose is used more efficiently than absorbed volatile fatty acids, the optimum energetic efficiency may be reached at a slightly higher flake weight than needed to obtain a total tract starch digestibility of 100%. Zinn (1990b) demonstrated that within a processing system, total tract starch digestion increased as flake density decreased; net energy value of steam-flaked corn was greatest when total tract starch digestion was approximately 99%. For a given mill (flaking system), he suggested that flake density should be adjusted to achieve 99% starch digestion (typically less than 4% fecal starch when addition starch is not provided by other diet components like corn silage).

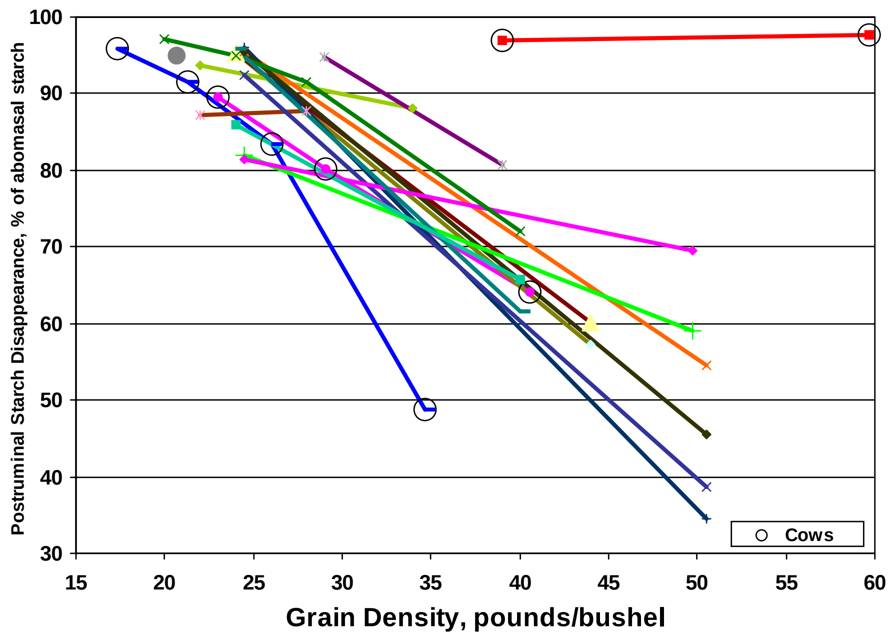

Figure 5. Impact of density of processed grain on postruminal starch disappearance. Lines connect individual diets and values from lactating cows are circled.

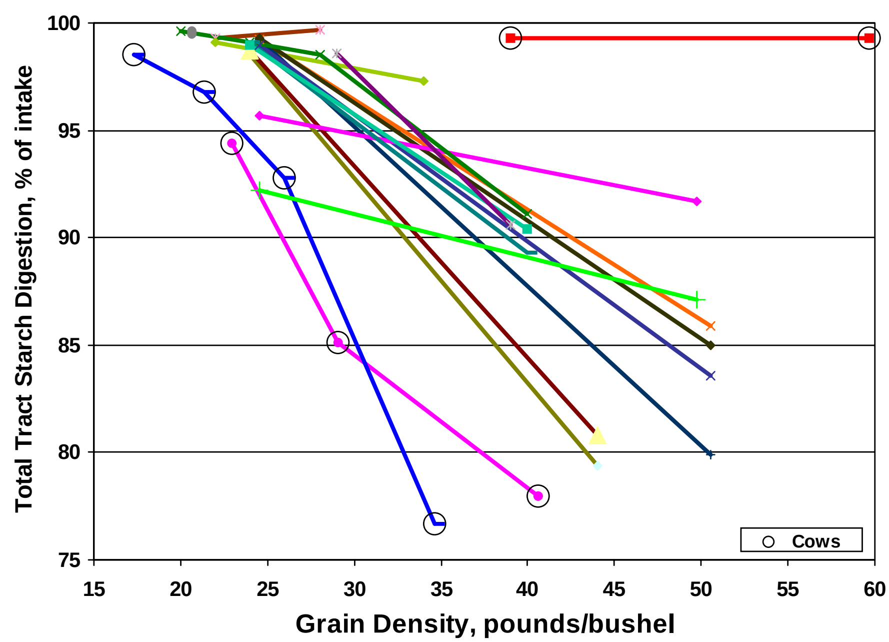

Figure 6. Influence of density of processed grain on total tract starch digestion. Each line presents values from a single experiment and lines connect individual diets within the experiment. Circled values are from lactating dairy cows.

COMPONENTS OF CEREAL GRAINS LIMITING DIGESTION

Rowe et al. (1999) summarized the physical impacts of various grain processing techniques on seed components that can limit site and extent of digestion (Table 4). Note that processing methods can differ in their physical effects. How individual components limit grain digestion can explain why grains respond differently to different processing methods. Furthermore, digestion-limiting components can be modified either by genetics or environmental conditions that alter characteristics inherent to the grain.

Table 4. Impact of various processing techniques on grain and its digestion.

Grain treatment/ processing	Disrupts pericarp or exposes endosperm	Reduces particle size	Disrupts endosperm matrix	Disrupts starch granules	Increases fermentation rate	Increases intestinal digestion
Dry rolling	+++	+	-	-	++	+
Grinding	+++	+++	-	-	++	+
Steam flaking	+++	++	+	+	+++	++
Extrusion	+++	-	++	+	++	++
Pelleting	+++	-	+	?	+	++
Ensiling	+		++	-	++	+
Micronization	+	+	?	?	?	++
Popping	++	-	+	+++	?	+++
Protease	-	-	?	?	++	?

Seed coat. The coat or pericarp of cereal grain protects the seed from moisture, insects, and fungal infections that can hamper germination. In oats, the hull can be 25% of the grain dry matter, but with sorghum and corn, the hull makes up only 3 to 6% of the weight of the grain. Although it comprises only about 4.7% of the weight of the corn kernel, the pericarp contains nearly half of the NDF of the kernel (average for corn grain of about 10.0% NDF). As noted at the base of Figure 7, energy availability of a grain is roughly proportional to the amount of starch present, primarily because starch is more digestible than other components, especially NDF. The primary component that displaces starch in grain is NDF. For digestion of the starchy endosperm, the seed coat must be cracked to permit microbes and enzymes to enter. Even after being dry rolled, the pericarp of the corn kernel usually remains attached to vitreous starch and can shield the starch from localized microbial and enzyme attack. Tenacity of adherence of the pericarp to the endosperm can limit access of the endosperm for fermentation or digestion. With food-grade corn, processors desire a pericarp that is removed easily. For livestock fed coarse grains, any factor that introduces stress cracks into the pericarp (e.g., high temperature drying of grain; premature harvest) will increase starch exposure and rate and extent of starch digestion. Steam rolling or flaking and ensiling also can reduce the physical association of the pericarp with the endosperm, but even extensive processing cannot fully alleviate the negative effects of NDF on extent of digestion by ruminants and nonruminants.

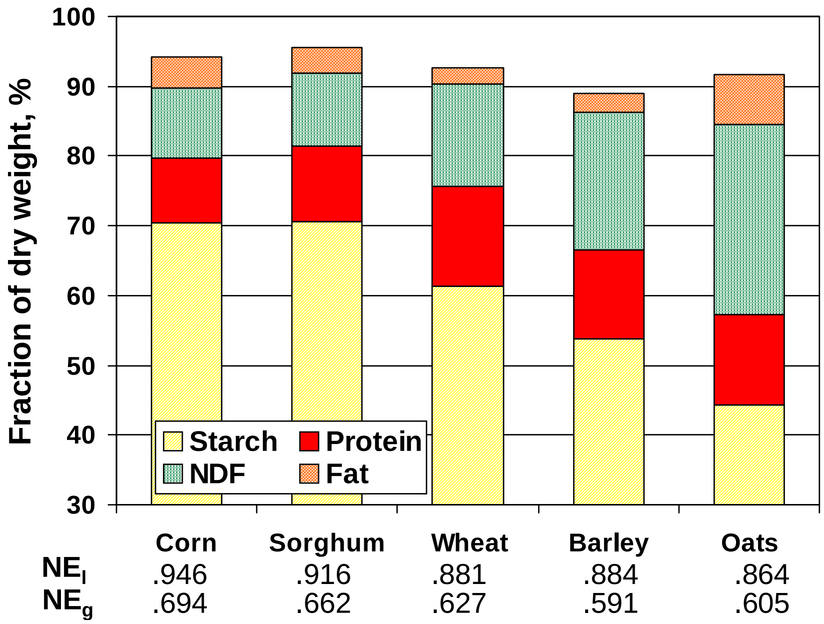

Figure 7. Nutrient composition of various cereal grains.

Damage during handling, processing, or chewing may explain why ruminal digestion of starch from whole corn grain may be equal to that for dry rolled grain in trials summarized in Table 2. Note, however, that postruminal disappearance of starch from whole grain remained very low indicating that accessibility of particles for enzyme digestion was limited. Kernel damage associated with chewing of whole grain during eating and rumination can be altered by numerous factors. These include species (sheep > cattle), cattle age (younger > older), cattle background (concentrate > roughage backgrounding), diet moisture (dry > wet), dietary roughage level and source (more rumination of grain particles if grain is widely dispersed within roughage inside the rumen), and ruminal retention time (ruminal retention is longer if passage rate is low due to low feed intake and low dietary NDF).

Cereal grains also differ in size of various component structures; the relative size of various components of the typical corn kernel and their composition are shown in Figure 8. Note that most of the oil and ash is located in the germ whereas the pericarp contains most of the NDF. Surface area of a sphere per unit of volume decreases by half as diameter doubles. Thus, a larger kernel will have less pericarp as a fraction of total weight. If NDF content of pericarp is constant, large kernels will have less NDF than small kernels. This relationship may explain why net energy value is greater for corn hybrids with the larger mean kernel weight according to a feeding trial comparing 7 commercial hybrids (Jaeger et al., 2004). What determines kernel weight? Grown in the same irrigated field in 2002, 10 commercial Pioneer corn hybrids had mean kernel weights that ranged from 320 to 401 mg; maximum kernel size is characteristic of a hybrid, but kernel weight can be reduced by water shortage or other environmental stresses. Kernel weight also increases with maturity; for certain hybrids, mean kernel weight appears to increase even after kernel moisture falls below 30% moisture, a point often used to initiate high moisture corn harvest. Selection of corn with large kernel size (and low NDF content) should increase net energy value of the grain. For grain that is not heat processed or ensiled, hybrids with thinner pericarp or less tenacious binding of the pericarp to the endosperm also should have an enhanced rate and extent of starch digestion.

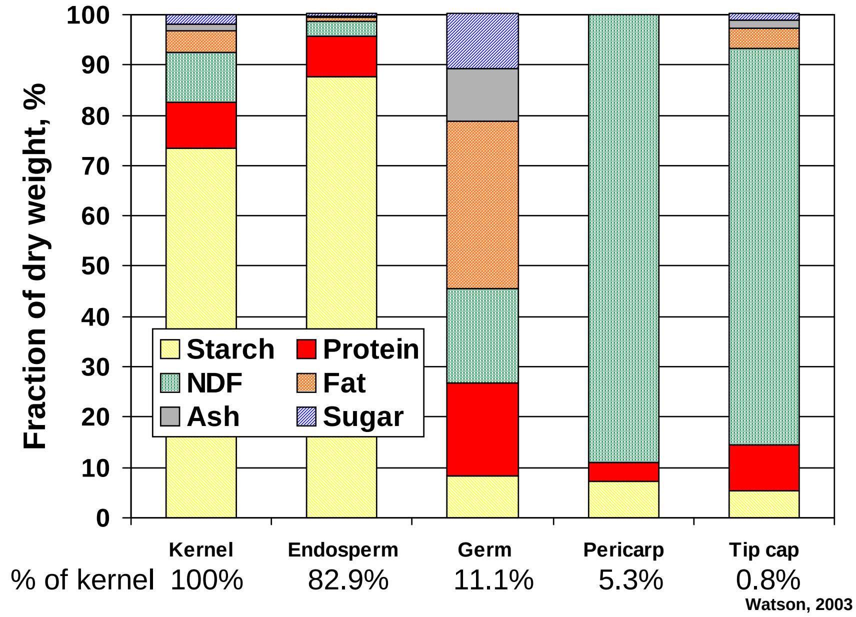

Figure 8. Nutrient content of various parts of the corn kernel.

Germ size. Although grain with a smaller germ will have less ash and NDF, the germ also carries most of the oil and a large proportion of the essential amino acids in corn grain. Simply reducing the size of the germ may not enhance net energy value of the grain because of reduced oil content. Relative size of the germ is greater for hybrids that have been selected for high oil content. Hybrids being marketed as being "nutrient dense" typically contain more oil than other hybrids. Because ruminal microbes do not ferment oil as a source of energy, microbial protein yield will be reduced as oil replaces starch in grain. The value of oil in corn grain depends on its cost relative to other sources of supplemental fat and oil.

Vitreous endosperm. Yellow dent corn grain as well as sorghum kernels have from 25 to 80% of the starch is present in the horny (hard or vitreous) endosperm where starch granules are densely packed within a protein matrix. The remaining starch as well as most starch present in other grains (barley, oats, wheat) is deposited as floury starch. Vitreousness or the horny to floury (H:F) ratio can be estimated through physical dissection of kernels, by measuring absolute density (not test weight) of the grain, or by grinding with a Stenvert mill. The H:F ratio varies genetically, being greater for corn grain classified as flint (versus dent) grain. This ratio often increases with grain maturation and nitrogen fertility (that also will increase crude protein content of corn grain). Starch granules isolated from barley, corn, and sorghum grain have digestion rates that are equal, presumably because they would be primarily from floury starch. In contrast, several workers have reported that when incubated in the rumen in Dacron bags (in situ), starch loss from ground corn grain is slower for hybrids that have a high H/F ratio (Phillippeau and Michalet-Doreau, 1997; Phillippeau et al, 1999; Shaver and Majee, 2002). Close examination of Dacron bag disappearance curves reveals that virtually all of the increased loss of starch from floury hybrids occurs before fermentation begins (wash loss). Certainly, floury hybrids generate more fines during grinding, and these fine particles readily sift through pores in Dacron bags even without being digested. The advantage of having more particles that are very fine is debatable. Increased total tract digestibility from finer particles should be beneficial, and if fine particles are flushed rapidly through the rumen with fluids, this would increase post-ruminal starch supply. However, fine particles of the floury endosperm are very rapidly fermented in the rumen; this can increase the risk of acidosis.

Greater in situ disappearance of floury hybrids has led to the suggestion that extent of digestion is greater for hybrids containing more floury and less vitreous endosperm when the grain is rolled (not extensively processed). This concept was supported in work by Jaeger et al. (2004); corn hybrids with a higher proportion of floury starch produced the best gain efficiency (r = 0.83) when dry rolled. Similarly Fanning et al. (2002) indicated that total tract digestion of starch from corn silage by lactating cows was greater for a hybrid with floury endosperm than a hybrid with a vitreous endosperm whether or not the silage had been kernel processed. However, no differences in milk production or components were detected between these two endosperm types (Longuski et al., 2002). The ideal H:F ratio also differs with the grain processing technique employed. Floury hybrids can complicate the steam flaking process. When flaked, floury hybrids yield more fine particles, quite fragile flakes, and they tend to flake slower than more vitreous hybrids. Fermentation also can influence vitreousness. When subjected to fermentation as part of corn silage, the proportion of vitreous starch in corn kernels declined (Johnson et al., 2002). When high moisture corn was prepared from a vitreous and a floury corn hybrid, ruminal and total tract starch digestibility of starch tended to be superior for the vitreous hybrid in a site of digestion study with steers (Josh Szasz, personal communication). Thus, extrapolation of hybrid differences from measurements on dry rolled grain to fermented grain or corn silage may prove erroneous.

Amylose content. Chemically, starch within a corn grain starch granule is present either as amylopectin (a multi-branched structure) or as amylose (a linear structure and that is less rapidly digested by enzymes). Amylose can comprise from below 2% (waxy corn) to a high of about 70% (high amylose) of total starch due to genetic differences in activity of the amylose-extending gene and enzyme. Environmental factors such as day length also may be involved; a circadian rhythm in amylose synthesis activity has been detected in some plants. Typical dent corn hybrids will range from 24 to 30% of starch present as amylose; floury starch typically is 4 to 9 units greater in amylose than vitreous starch. Compared to corn grain, wheat, rye, and normal amylose barley contain similar proportions of amylose (25 to 27.4%; Fredriksson et al, 1998). The amylose to amylopectin ratio increases with corn kernel maturity but can be decreased by high environmental temperatures. To increase starch flow to the large intestine for fermentation to reduce the incidence of colon cancer in humans, high amylose starch can be included in the diet; similarly, corn grain with a high amylose content was poorly digested in the small intestine of dogs even after the grain was extruded (Gajda et al., 2005). Susceptibility of flaked high amylose corn samples to ruminal digestion also is low. Fermentation of amylose appears to be restricted to a limited number of bacterial strains (Wang et al., 1999). Starch granules have been proposed to contain consecutive rings or spheres of amylose and amylopectin, and if amylose degradation is limited, granules may resist digestion. Linkage of reducing ends of starch within the starch granule to lipid or phosphorus also may reduce rate of digestion. Small intestinal digestion of starch (phosphorylated?) from potatoes by lactating cows was nil; in contrast, small intestinal digestion of starch was 70% and 65% for starch from wheat and corn in a study by van Vuuren et al. (2004). With total tract digestibility of starch usually exceeding 99% for flaked corn and sorghum grain (Table 1), disruption and gelatinization of starch by flaking corn grain must alter or solubilize amylose to the point that it is fermented or digested. In support of this concept, flaking removed the feed efficiency advantage of waxy hybrids (low amylose) over typical hybrids (normal amylose) noted in several steer performance trials. To date, analysis of the amylose: amylopectin ratio of abomasal, ileal, and fecal samples has not been reported; such information should help quantify the importance of amylose content on site and extent of starch digestion by cattle fed grain subjected to different processing methods.

Resistant starch. With exposure to heat and moisture, starch granules swell and form gels, a process called gelatinization. Swollen particles become enriched in amylopectin as amylose diffuses out of the swollen granules. Starch granules with high amylose content resist swelling. Upon cooling and storage of the gelatinized starch, the amylose gels and forms retrograde starch, one of three different types of "enzyme-resistant starch." Slow cooling of flaked corn grain decreases "starch availability," a commercial index of susceptibility of starch to a starch degrading enzymes (i.e., amyloglucosidase). Ward and Galyean (1999) measured in vitro dry matter disappearance of flaked corn samples that had been held warm; starch availability was decreased by one-third, presumably due to starch retrogradation. Yet, rate and extent of in vitro digestion was no lower for flaked corn that had decreased starch availability and presumably contained starch that had retrograded. This observation suggests that ruminal microbes from feedlot cattle fed flaked grain must have sufficient capacity to ferment retrograde starch or at least solubilize starch that resists hydrolysis by starch-degrading enzymes.

FUTURE PROSPECTS

Using rapid screening procedures based on Near Infrared Reflectance, corn hybrids currently are appraised for digestibility by pigs (Sauber et al., 2005); those having high digestibility are classed as "high available energy" hybrids. Work to develop similar prediction equations for ruminants is underway, but considering the many diverse processing methods used for ruminants and their more complex digestive system, classification of corn grain hybrids based on digestibility by ruminants is not yet available. Such information will need to be merged with current criteria to select hybrids or varieties to grow or purchase. Current selection items to enhance feeding value of dry matter from corn grain for ruminants should include high starch content and low fiber (low foreign matter; large kernel size), a vitreousness score designed for the specific processing method being used (floury for dry rolled or ground corn; vitreous and high test weight for flaked corn), absence of mycotoxins, and general characteristics desired for storage and handling (low moisture content; resistance to damage during handling).

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