

RUMINAL AND POSTRUMINAL STARCH DIGESTION BY CATTLE

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ABSTRACT

Grains are fed to livestock primarily to supply energy, and most of the digestible energy in cereal grains comes from starch. To maximize starch digestion by livestock, corn and sorghum grain must be processed. For non-ruminants, starch from finely ground grain is fully digested, but for ruminants fed high concentrate diets, finely ground grain often causes metabolic diseases. Hence, rather than finely grinding corn, processes including steam rolling, steam flaking and fermentation (high moisture storage) are used to increase extent of starch digestion from grains fed to ruminants. These processing methods usually increase starch digestion in the rumen, in the intestines (of starch reaching the small intestine), or at both locations. The lower the density (bushel weight) of flaked corn, 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 grain particles spend less time for digestion in the rumen of lactating cows than of feedlot cattle. This shorter ruminal retention time can explain why ruminal and total tract starch digestibility generally is lower for lactating cows than for finishing cattle. Ruminal escape of starch is greater with dry rolled and whole corn grain than with steam flaked and high moisture corn, but starch from dry rolled and whole corn grain is poorly digested in the small intestine. Averaged across processing methods, starch digestibility in the small intestine decreases as the quantity of starch entering the small intestine increased, but when grain processing methods are considered individually, disappearance of starch in the small intestine remains roughly proportional to starch entry rate. Due to reduced loss of energy as methane and heat, available energy supply for the ruminant is greater when starch is digested in the small intestine than when starch is fermented in either the rumen or large intestine. But if starch digestion in the small intestine is below about 70%, no energetic benefit from increasing ruminal output of starch will be achieved.

Characteristics that make a grain or a hybrid ideal for livestock differ with processing method. For whole and dry rolled corn, the combination of very fine grinding of grain with a floury endosperm, a thin or loose pericarp, and a low amylose:amylopectin ratio will maximize starch digestion. For fermented corn grain with adequate moisture content as well as adequately processed steam flaked corn, starch digestion usually exceeds 97% so any remaining differences in digestibility among corn samples (1 to 3%) are due to 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, altering the starch content (more starch and less NDF and protein) is the simplest way to increase its content of digestible energy.

Key Words: Starch, Rumen, Small intestine, Processing, Grains

INTRODUCTION

The value of any livestock feed is the multiple of three factors: nutrient or energy content, feed intake, and digestibility. Nutrient and energy content of grain at harvest is influenced by genetic (hybrid and grain type) and environmental (soil fertility, growth conditions, maturity) factors and the interaction between genetics and environment. Blending or dilution with grain of lower nutritive value further alters the composition of commodity grains. The influence of corn genetics on composition and feeding value as well as the interrelationships among nutrients present in corn grain have been outlined elsewhere (Owens 2005a; Soderlund and Owens - elsewhere in these proceedings, 2007) and will not be discussed

further here. The second factor, dry matter or feed intake, usually is reduced by extensive grain processing primarily because energy availability of the grain has been increased. With high-concentrate feedlot diets, except for very low roughage diets, high moisture grains, and possibly with barley, metabolizable energy intake by cattle is not altered by grain processing (Buchanan-Smith –Elsewhere in these proceedings, 2007). The third factor, digestibility, is the point where livestock producers can increase the value of a feed through altering site and extent of digestion through grain processing.

Selection of a processing method must consider not only the animal performance response but also the

cost of grain handling and processing (Peters – Elsewhere in these proceedings, 2007). Ideally, optimal processing economically increases digestibility; processing also may alter the site of digestion but must not detrimentally affect ruminal pH and cause digestive dysfunction. In essence, grains are processed to enhance their nutritional value. However, the extent of processing often is slightly limited in an attempt to reduce the incidence of metabolic disorders. A higher grain price helps to justify more extensive and expensive grain processing methods.

Processing methods and responses in site and extent of digestion have 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; Owens 2005a, 2005b; Huntington et al., 2006). This review will highlight the results of digestion trials with lactating dairy cows typically fed diets with 40 to 60% roughage and with feedlot cattle fed diets with less than 20% roughage. Because most grain processing trials have been conducted with yellow dent corn grain, information from that commodity will be emphasized. Compared to dent corn grain, flint corn grain and sorghum grain should respond more extensively to processing whereas cereal grains with less vitreous starch (oats, barley, wheat) will exhibit much less response. Because starch comprises over 70% of the dry matter of most cereal grains, starch will be the primary focus of attention.

GRAIN PROCESSING METHODS

Unprocessed grains can be fed to livestock. Kaiser (1999) and Loerch and Gorocica-Buenfil – Elsewhere in these proceedings (2007) have outlined the economic advantages and limitations of feeding cereal grains whole (without mechanical processing). With less vitreous grains (oats, barley, triticale, rice, wheat), with sheep and with young animals that chew their feed thoroughly, and with very low levels of dietary roughage or forage, extent of starch digestion usually is quite high for unprocessed grains. However, for corn and sorghum grains, particle size reduction, either by the animal or by mechanical processing of the grain prior to feeding, generally increases starch digestibility slightly. Adverse associative effects (interactions of grain with roughage) where added roughage depresses starch

digestion are most evident with whole or rolled grains. Presumably, higher intakes and higher roughage diets flush large corn particles through the rumen before the starch is fully digested (Wylie et al., 1990). To expose more surface area for digestion and to fracture the pericarp, most cereal grains are rolled or ground prior to feeding to cattle. For more mature feedlot cattle, dry corn grain usually is coarsely rolled or cracked yielding 4 to 10 particles per kernel of corn, but for lactating dairy cows, much finer grinding is used. Surprisingly, in some trials with feedlot cattle, starch digestibility and net energy value are greater for whole than for rolled grains (Owens et al., 1997). This may be attributed to longer ruminal retention time for whole than rolled corn. With mature corn silage, as well, some whole corn kernels will be found in feces unless feedstuffs have been adequately “kernel processed” during harvest to damage the kernels or the corn particles are adequately softened during fermentation to increase starch digestibility.

Grain processing typically involves kernel damage and a reduction in particle size either with or without addition of water or steam. Grinding or rolling to form dry rolled or dry ground grain, occasionally with addition of moisture to reduce fine particles and dust, is the most common method of grain processing. Fracturing kernels by high speed milling generally results in a very wide range in particle sizes; the crushing action involved with rolling the grain results in a much narrower range in particle sizes. However, moisture content can alter both the mean particle size and distribution of particles generated by either dry processing method. To increase digestion further, grains (whole, rolled or ground) can be fermented if adequate moisture (typically 24 to 35%) is present. The fermentation process appears similar whether the moisture is inherent to the grain due to early harvest to form high moisture grain or added to dry grain prior to fermentation to form reconstituted grain (Benton et al., 2005). To form steam rolled or steam 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 period, crushed flakes are thicker, and a smaller proportion of the starch will be gelatinized (fracturing of starch granules). Starch that is gelatinized is very rapidly and completely fermented within the rumen. However, amylose starch in flaked grain can retrograde (harden to form digestion-

resistant starch) if the grain is cooled slowly (Ward and Galyean, 1999).

Effects of processing on the site and extent of starch digestion will vary with processing conditions (grain moisture, screen size or roll gap; fermentation moisture and time; steaming time) as discussed by Zinn et al. (2002). The primary factor limiting the extent of digestion either in the rumen or the intestines is the extent to which surface area is exposed for microbial or enzymatic attack (e.g., primarily particle size). In addition, with more vitreous grain, encapsulation or imbedding of starch granules within a matrix of either protein or fiber delays or retards digestion. However, restrictions associated with vitreousness are removed readily by either fermentation or by heat processing. Consequently, for less extensively processed corn, feeding value will vary with vitreousness of the hybrid or variety, its maturity, and certain agronomic conditions for grain production (Philippeau and Michalet-Doreau, 1997; Philippeau et al., 1999; Shaver and Majee, 2002). In contrast, by markedly increasing the extent of starch digestion, fermentation (Szasz et al., 2007) and flaking (Corona et al., 2006) minimizes or completely obliterates differences among grain hybrids and grain types associated with vitreousness. Finally, chewing and rumination as well as bunk management can alter site and extent of digestion and rate of passage through the digestive tract; these in turn vary with animal age and background, diet composition, feeding frequency, and dietary forage or fiber (NDF) level.

IMPACT OF PROCESSING ON SITE AND EXTENT OF STARCH DIGESTION

A summary of trials published since 1990 where site of starch digestibility was measured either with lactating dairy cows or with feedlot steers or heifers initially compiled by Owens (2005b) has been updated in Tables 1 and 2. Many more trials have measured site and extent of starch digestion by feedlot cattle than by lactating cows. Lack of a strong research emphasis on grain processing for lactating cows seems surprising considering the huge opportunity to increase ruminal and total tract starch digestion by lactating dairy cows. Note that this literature summary includes information from all research trials regardless of the degree or extent of processing of the grain. For example, results from trials with rolled and ground grain were combined even though the mean particle sizes can differ greatly; all trials with steam

flaked and steam rolled grains were included regardless of flake density that alters site and extent of digestion; all grain called “high moisture corn” was included in the summary despite the marked effect that moisture content has on energy value of this product. How such factors can alter digestibility and feeding value within these processing methods have been discussed elsewhere (Zinn et al., 2002; Owens 2005b; Owens and Zinn 2005).

Within both feedlot and dairy cattle, ruminal and total tract starch digestion was greater for fermented than for dry rolled grain. Whenever the ruminal digestion of starch increases, the supply of postruminal starch decreases. However, postruminal digestion of starch leaving the abomasum was numerically greater for high moisture than for dry rolled corn grain. Steam processing of corn led to a marked increase in ruminal digestion by feedlot cattle, but surprisingly steam rolling or flaking did not significantly increase ruminal starch digestion by lactating dairy cows. Because ruminal digestion of flaked corn depends on flake thickness and bulk density, perhaps the extent of flaking was less in trials with lactating cows than with feedlot cattle. Compared with whole or dry rolled or ground corn, processed corn generally had greater digestibility in the total digestive tract indicating that its net energy value had been increased.

Grinding grain to a very fine particle size will increase starch digestibility. However, benefits in starch digestion from fine grinding are considerably less than those obtained from fermentation or heat processing (Firkins et al., 2001). Nevertheless, fine rolling or grinding has increased the feeding value of more vitreous grains for steers (Brethour, 1990) and lactating cows (Bush et al., 1972).

For lactating cows, less than 60% of the starch digested in the total tract was digested in the rumen with all corn processing methods except high moisture corn. This leaves a substantial supply of starch available for digestion in the small intestine or fermentation in the large intestine. The importance of postruminal starch digestion automatically increases when the extent of ruminal digestion is low and more of the dietary starch is flushed to the intestines. Due to reduced methane and heat losses, starch digested in the intestine has considerably greater energy value than starch fermented in the large intestine

(Huntington et al., 2006). However, as they ably illustrated, the impact that site of digestion has on energetic efficiency of the animal relies heavily on the degree to which starch is digested in the small intestine. Starch from high moisture and steam flaked corn was quite well digested in the small intestine of feedlot cattle, but despite large numerical differences, no significant effect of processing method on small intestinal starch disappearance by lactating cows was detected. Whether the lower digestion of starch in the small intestine of lactating cows than of feedlot cattle is due to larger size of grain particles (associated with less extensive processing or less efficient or thorough chewing or rumination of grain by cows), to less activity of starch-digesting enzymes by cows fed diets with more NDF associated with the roughage, e.g., amylase inhibitors in alfalfa products, or to some additional unidentified factors is not certain. A shorter retention time in the small intestine is unlikely to be responsible considering that Wylie et al. (1990) noted that increasing the NDF content of the diet failed to decrease retention time in the small intestine of cattle.

The quantity of starch digested in the small intestine is the multiple of starch flow and its digestibility. As a fraction of dietary starch, more starch was digested in the intestines of cattle fed whole, dry rolled, and steam rolled corn than for cattle fed high moisture corn. For feedlot cattle, two processing methods, high moisture preservation and steam flaking, shifted the fractional site of starch digestion away from the intestines but toward the rumen. But in addition, these two processing methods increased small intestinal digestibility of starch reaching the intestines. This supports the concept advanced by Rowe et al. (1999) that processing corn grain to enhance ruminal digestion also enhances the post-ruminal digestibility of the starch flowing to the intestines. This also supports the concept that similar factors (particle size and protein shielding) limit the extent of starch digestion at both sites.

Greater ruminal and intestinal disappearance of starch from high moisture and for steam flaked corn than for dry rolled or whole corn can be attributed to the reduction in particle size and alteration of the protein matrix by processing. Just as these factors limit starch access by ruminal microbes, as indicated by McAllister et al. –Elsewhere in these proceedings (2007), they presumably limit starch access by

intestinal enzymes. But in contrast with the suggestion that starch that resists attack by ruminal microbes also should resist digestion by intestinal enzymes, starch disappearance in the small intestine as a fraction (percentage) of that entering the small intestine consistently exceeded the percentage of starch digested in the rumen for some processing methods. Such was not the case for rolled or ground corn. Visual inspection of duodenal contents from steers fed rolled corn reveals both vitreous grain fragments and grain particles shielded by the pericarp. But because particle size reduction post-ruminally appears minimal, renewed starch digestion must be due to chemical changes. Indeed, exposure to acid, pepsin, and other proteases in the abomasum and to lipases of the intestine must increase the accessibility of starch in particles for enzymatic attack in the small intestine.

In contrast to the effects of grain processing on starch digestion in the small intestine, starch digestion in the large intestine, either as a fraction of the starch supply or as a percentage of starch intake, was decreased by grain processing. Although compensatory starch digestion in the large intestine serves to recover energy from grain, fermentation of starch in the large intestine is energetically less desirable (yielding undigested microbes, VFA, and heat) than either fermentation in the rumen (yielding VFA, potentially digested ruminal microbes, methane, and heat) or digestion in the small intestine (presumably yielding glucose). Quite extensive digestion of starch from less processed grain in the large intestine further indicates that some physical or chemical barriers to starch fermentation must be altered by physical or enzymatic actions in the abomasum or small intestine or that the large intestinal microflora has additional starch fermenting capability as could evolve with a consistent supply of resistant starch.

Table 1. Influence of corn grain processing on site and extent of starch and NDF digestion by lactating dairy cows

Processing method	Dry rolled	High moisture	Steam flaked	Steam rolled	SEm*
Starch digestion in the rumen, % of intake	49.20 ^b	76.34 ^a	51.79 ^b	55.70 ^b	9.89
Postruminal starch disappearance, % of supply	77.67	82.93	88.43	88.32	12.96
Fraction of starch digestion in the rumen, % of total	55.50 ^b	79.37 ^a	54.83 ^b	58.81 ^{ab}	10.78
Total tract starch digestion, % of intake	89.95	95.99	93.94	94.23	5.60
Starch digestion in the small intestine, % of supply	48.40	57.75		71.20	39.97
Starch digestion in the small intestine, % of intake	26.62	9.84		36.90	23.95
Starch digestion in the rumen plus small intestine, % of intake	79.82	93.87		89.10	14.53
Starch digestion in the large intestine, % of supply	42.00	51.58		62.00	31.86
Starch digestion in the large intestine, % of intake	8.55	3.03		8.17	8.00
NDF digestion in the rumen, % of intake	42.59 ^a	17.90 ^b	51.50 ^a	45.90 ^a	10.63
NDF digestion in the total tract, % of intake	56.47 ^a	38.48 ^b	61.99 ^a	52.95 ^{ab}	9.92
NDF digestion past the rumen, % of supply	17.41 ^a	24.05 ^a	13.89 ^{ab}	-0.36 ^b	9.05

*Standard error of the mean.

^{a,b}Means with different superscripts within a row are different ($P < 0.05$).**Table 2.** Influence of corn grain processing on site and extent of starch and neutral detergent fiber (NDF) digestion by feedlot cattle

Processing method	Dry rolled	High moisture	Steam flaked	Whole	SEm*
Starch digestion in the rumen, % of intake	63.80 ^b	86.55 ^a	84.05 ^a	68.34 ^b	3.38
Postruminal starch disappearance, % of supply	72.16 ^b	93.10 ^a	94.33 ^a	52.99 ^c	4.07
Fraction of starch digestion in the rumen, % of total	70.15 ^c	87.24 ^a	84.74 ^{ab}	79.20 ^b	3.64
Total tract starch digestion, % of intake	91.03 ^b	99.25 ^a	99.09 ^a	87.08 ^c	1.12
Starch digestion in the small intestine, % of supply	58.83 ^b	94.86 ^a	92.48 ^a	64.64 ^b	22.38
Starch digestion in the small intestine, % of intake	20.08	17.18	16.39	24.50	7.62
Starch digestion in the rumen plus small intestine, % of intake	83.67 ^b	99.07 ^a	98.48 ^a	86.60 ^{ab}	12.01
Starch digestion in the large intestine, % of supply	56.32 ^a	24.80 ^b	20.47 ^b	32.09 ^{ab}	22.25
Starch digestion in the large intestine, % of intake	11.66 ^a	0.23 ^b	0.42 ^b	4.30 ^b	5.42
NDF digestion in the rumen, % of intake	48.07 ^a	18.48 ^d	27.71 ^c	33.43 ^{bc}	8.18
NDF digestion in the total tract, % of intake	50.83 ^a	34.27 ^d	44.39 ^{bc}	38.10 ^{cd}	7.02
NDF digestion past the rumen, % of supply	9.95	15.50	19.89	2.43	15.06

*Standard error of the mean.

^{a,b,c}Means with different superscripts within a row are different ($P < 0.05$).

Table 3. Influence of animal class on site and extent of starch and neutral detergent fiber (NDF) digestion

Animal class	Lactating cows	Feedlot cattle	SEM*	<i>P</i> <
Starch digestion in the rumen, % of intake	58.48	75.34	2.37	0.01
Postruminal starch disappearance, % of supply	80.90	79.71	2.89	0.66
Fraction of starch digestion in the rumen, % of total	63.43	79.56	2.54	0.01
Total tract starch digestion, % of intake	92.45	94.55	0.96	0.02
Starch digestion in the small intestine, % of supply	63.26	78.77	12.26	0.07
Starch digestion in the small intestine, % of intake	25.75	21.85	5.46	0.31
Starch digestion in the rumen plus small intestine, % of intake	88.06	92.17	1.95	0.31
Starch digestion in the large intestine, % of supply	35.40	41.25	13.24	0.53
Starch digestion in the large intestine, % of intake	3.58	5.47	3.16	0.40
NDF digestion in the rumen, % of intake	33.70	34.84	4.85	0.74
NDF digestion in the total tract, % of intake	49.55	42.63	4.03	0.02
NDF digestion past the rumen, % of supply	14.36	8.39	7.00	0.25

*Standard error of the mean.

Starch digestion by cows and feedlot cattle has not been compared directly in any research trials. However, effects of cattle class can be examined when differences associated with processing methods are removed statistically (Table 3). Compared with feedlot cattle, lactating cows had considerably less dietary starch digestion in the rumen, the small intestine (as a percentage of abomasal starch), and the total digestive tract. This indicates that site of digestion differed with cattle class. As a fraction of dietary starch, almost twice as much starch (averages of 37% vs 20%) disappeared postruminally with lactating cows than with feedlot cattle. A faster solids dilution rate and reduced time for ruminal digestion associated with higher feed intakes and higher NDF content of the diet may explain why ruminal starch digestion was lower for lactating cows. Similarly, time for compensatory digestion of starch in the large intestine probably is lower with higher intakes of NDF leading to slightly lower large intestinal starch digestion by lactating cows.

One sidelight of altering site of starch digestion by grain processing is its impact on site and extent of NDF digestion. Combined with diets richer in forage and a higher ruminal pH, one would anticipate that extent of dietary NDF digestion in the rumen should be greater for lactating cows than for feedlot steers. Such was not the case. The greater NDF digestion in the total tract for lactating cows was due surprisingly not to increased ruminal but to increased postruminal digestion of NDF. Certainly, the source of NDF will

differ with cattle type and can markedly influence NDF digestibility; lactating cows typically are fed more digestible forages. However, in feedlot diets, much of the NDF is derived from grains and protein supplement; ruminal digestibility of NDF from fine particle forages, e.g., soybean hulls, is quite high.

Grain processing also altered site and extent of NDF digestion, but these responses tended to differ with animal class (Tables 1 and 2). With both cows and feedlot cattle, NDF digestion in the rumen and total tract was lower with high moisture than dry rolled corn, possibly due to inhibition of NDF digestion by a low ruminal pH. Conversely, compensatory NDF digestion past the rumen was lowest when starch digestion in the large intestine was greatest. This again may reflect pH reduction of digesta; starch digestion in the large intestine would reduce pH and inhibit fiber digestion therein. Consequently, although processing grain may reduce ruminal pH and inhibit ruminal fermentation of NDF, processing also reduced the supply of starch for fermentation in the large intestine; this allowed greater compensatory fermentation of NDF. This supports the concept that a low fecal pH reflects not only incomplete pre-cecal starch digestion, but also a reduction in compensatory fermentation of NDF in the large intestine. A fecal pH near neutrality should reflect both efficient pre-cecal starch digestion and greater NDF fermentation in the large intestine. Because many additional factors including level of feed intake and dietary buffers will influence fecal pH,

direct measurement of fecal starch would seem preferable to measuring fecal pH as an index of starch digestibility.

Because digestion of starch can be expressed as a fraction of available or of dietary starch, simple comprehension of the effects of grain processing on

site of digestion can prove confusing. To illustrate differences site of digestion of dietary starch with various processing methods, mean values for site of digestion from the published literature subdivided by animal class and grain processing methods are presented in Figure 1.

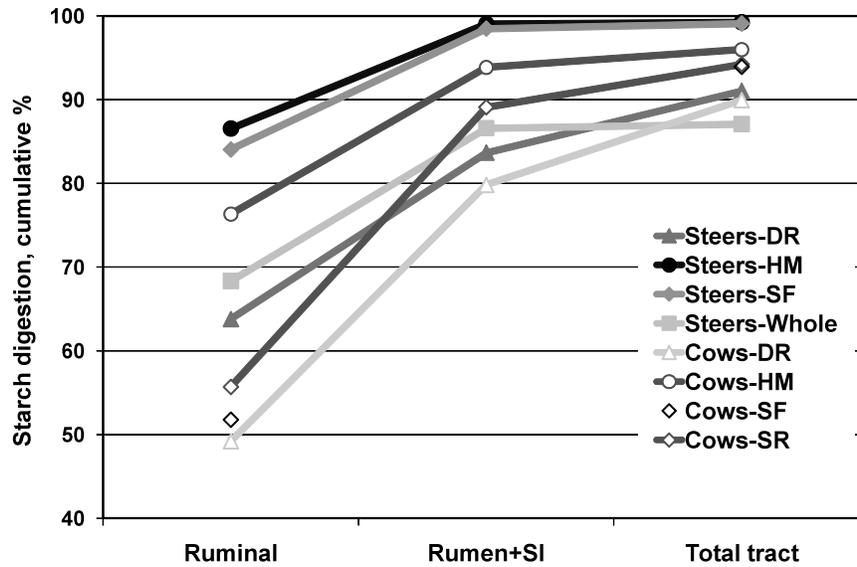


Figure 1. Site of digestion of dietary starch by feedlot cattle or lactating dairy cows fed corn grain processed by various methods. Open symbols are means for cows whereas closed symbols are for feedlot cattle. Triangles are for dry rolled corn, circles are for high moisture, and diamonds are for steam flaked corn grain.

Initial points on the left represent the extent of ruminal starch digestion. Relative slopes from ruminal to ruminal plus small intestinal points represent the quantities of dietary starch disappearing from the small intestine. Despite having a lower fractional digestion rate in the small intestine, rolled or whole grains provided quantitatively more starch to be digested in the small intestine. However, compensatory disappearance of dietary starch in the large intestine was greatest for dry rolled and steamrolled grain with very little additional starch disappearance from either high moisture or steam flaked grains (due to its extensive disappearance

before this point). Large intestinal disappearance of starch also was low for whole corn grain, presumably due to large particle size of the grain.

Values from literature summaries that have reported site and extent of digestion of starch for steers and for lactating cows are presented in Figures 2 and 3. Because these summaries probably were derived from a similar base of research data, high similarity in estimates of site and extent of starch digestion among trials both for total tract (Figure 2) and ruminal (Figure 3) disappearance should come as no surprise.

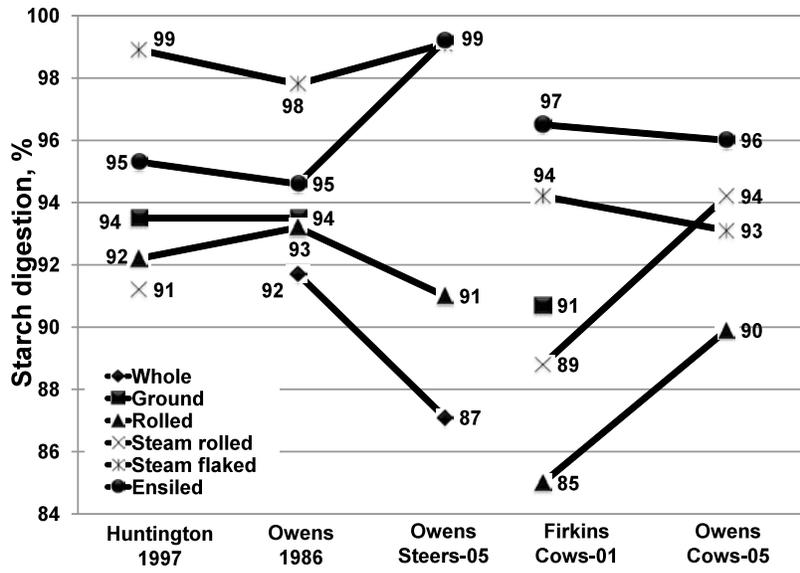


Figure 2. Total tract starch digestion from processed corn grain based on literature summaries for feedlot cattle and lactating cows.

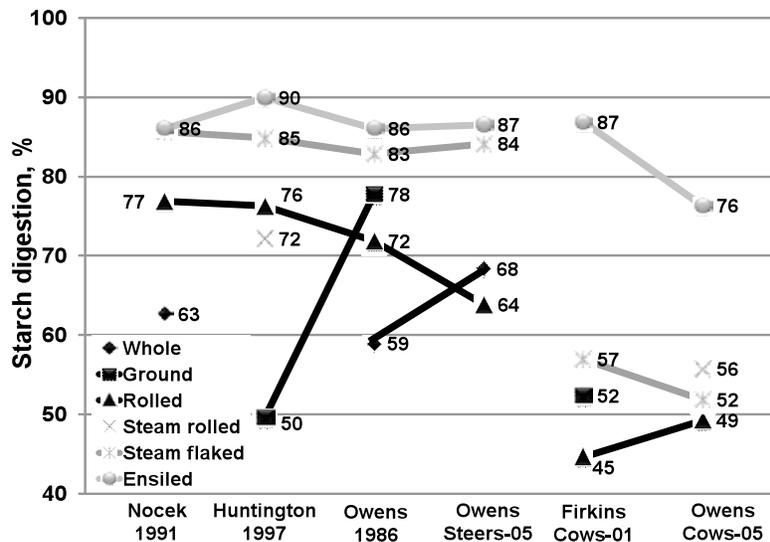


Figure 3. Digestion of dietary starch in the rumen of cattle from corn grain processed by various methods.

Such literature summaries of digestibility generally present the average of means from individual trials. An alternative approach to calculate starch digestibility is to regress disappearance (g) of starch against starch intake or starch entering a specific segment of the digestive tract. The regression line (disappearance/input) serves as an index of digestibility. Because starch output should be zero

when starch input is zero, this regression usually is forced through zero. In contrast with individual measurements of digestibility, this regression approach places greater emphasis on trials where input of starch is greater and the precision and reliability of the estimate should be greater. When plotted as in Figure 4, effects on digestion at different starch inputs can be visualized.

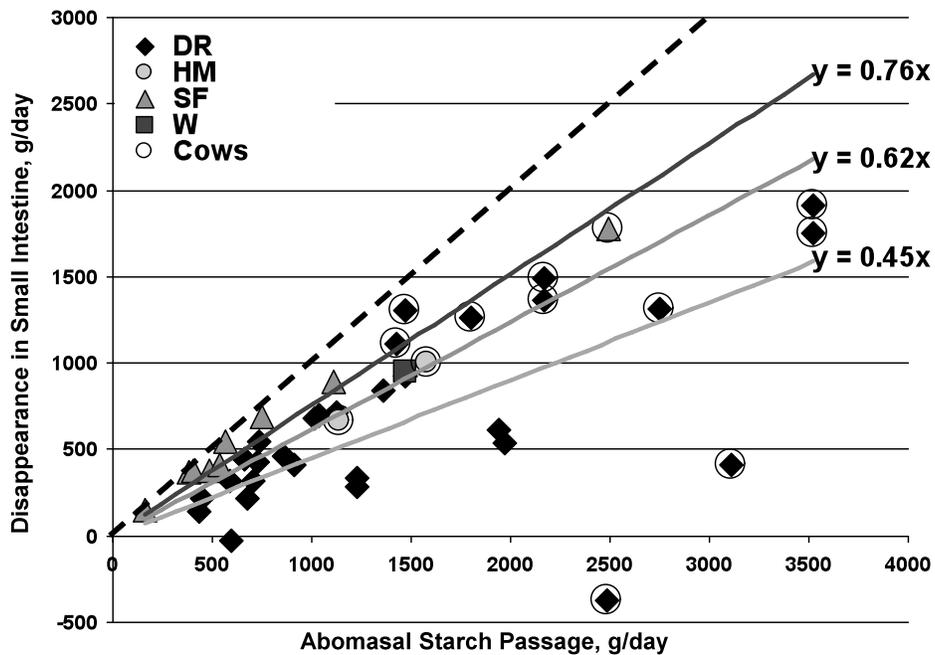


Figure 4. Disappearance of abomasal starch in the small intestine. The dotted line represents unity, where digestion would be complete (100%).

When regressed across cattle types, apparent intestinal digestibility of starch from steam processed, high moisture, and dry rolled grain averaged 76, 62, and 45%, respectively (Figure 4). These digestibility estimates differ slightly from the mean values from individual trials with feedlot cattle and lactating cows of 92 and 71% for steam processed corn, 95 and 56% for high moisture, and 58 and 48% for dry rolled grains; this illustrates how regression values are driven more strongly by trials with higher starch inputs. For steam processed and high moisture corn grain, no curvilinearity is apparent indicating that digestibility remained constant across all intake levels. However, digestion estimates from individual trials are scattered widely for dry rolled corn grain. In two trials, starch disappearance from dry rolled corn in the small intestine was negative, perhaps reflecting the difficulty in obtaining a representative digesta sample from the ileum when the digesta contains larger grain particles. Insufficient data are available to calculate

separate regression lines for feedlot cattle versus lactating cows.

In Figure 5, grams of starch disappearing in the rumen plus small intestine are plotted against grams of starch digested in the total digestive tract. Except for some deviant points from one trial with lactating cows, grams of starch in the rumen plus small intestine seems roughly proportional to grams of starch digested in the total digestive tract. This indicates that the differences in digestibility of starch in the large intestine associated with different processing methods quantitatively are small when compared with the total quantity of starch digested. The fact that processing methods that alter site of starch digestion do not deviate markedly from each other indicates that relative to total tract starch digestibility, site of digestion (rumen versus small intestine) may have only minor effects on energetic efficiency. Nevertheless, effects of site of digestion on energetic efficiency have been the subject of a considerable amount of discussion and research.

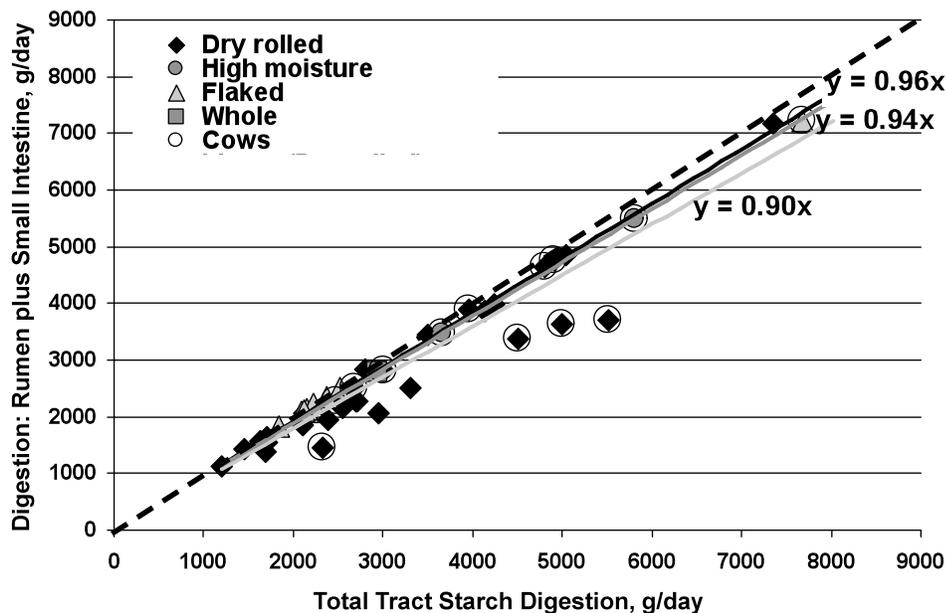


Figure 5. Digestion in the rumen plus small intestine versus total tract starch digestion by cows and feedlot cattle. Dotted line represents line for 100% digestion.

EFFECTS OF SITE OF DIGESTION ON ENERGETIC EFFICIENCY

Energetic efficiency is greater when glucose is infused into the abomasum or small intestine than when glucose is infused into the rumen (Harmon and McLeod, 2001; Huntington et al., 2006). Precisely where carbon and energy from glucose disappearing from the small intestine goes and whether it provides useful energy for the ruminant has been debated extensively because glucose recovery in the portal blood stream never is complete. Several studies have indicated that fat synthesis is increased when glucose is infused postruminally (Armstrong et al., 1968; Rust, 1992; McLeod and Harmon, - Elsewhere in this publication 2007). Armstrong et al. (1968) observed that 54% of ruminally infused energy was converted to fat whereas 71% of glucose abomasally infused was stored as fat. Similarly, 68 to 71% of the calories from sucrose or glucose provided to pigs and dogs was stored as fat. With ruminants, fat deposition in the omentum has increased when glucose has been infused either into the abomasum of sheep (Rust, 1992) or the small intestine of cattle (McLeod and Harmon, - Elsewhere in these proceedings 2007). Added glucose failed to increase lean mass or carcass weight but instead added to the intestinal mass.

Lipogenesis directly by the intestine or omentum also could explain why glucose disappearing from the intestine is not recovered in blood draining the intestines (the portal drained viscera). Increased omental fat and a lower dressing percentage matches observations at harvest of Holstein steers. This fits with the concept above if Holstein steers are similar to lactating cows (typically Holsteins) where ruminal starch outflow is large. If postruminal glucose merely increases fat deposition in and around the intestine, postruminal starch digestion would not prove useful for growth or lactation even though it avoids methane and heat losses associated with fermentation in the rumen. An increase in visceral fat would provide padding for protection of internal organs. All other things being equal, an increase in omental or small intestinal fat should decrease dressing percentage as these tissues are removed before hot carcass weight is measured.

What is the appropriate control to evaluate an increase in supply of energy from postruminally administered glucose? An increased intestinal supply of energy from protein, volatile fatty acids, or lipid might cause similar increases in omental fat deposition by ruminants of a similar magnitude.

Indeed, pigs and dogs given supplemental sucrose or glucose exhibit increased fat deposition (Armstrong et al., 1968). Intestinal tissue would provide an additional location for synthesis of fatty acids when the capacity for lipogenesis by other tissues is limited if the lipid synthesized at this site can be transported to other depot sites or to the mammary gland for secretion.

Further research studies concerning the impact of site of starch digestion on energetic efficiency of milk and meat production are warranted. But besides energetics, site of digestion can be important nutritionally. An increase in ruminal starch escape would reduce the amount of energy available for synthesis of microbial protein that is needed for young, growing animals and for cows at high levels of lactation. If fermented in the large intestine, fecal loss of nitrogen as well as energy would be expected. However, shifting the site of starch digestion from the rumen to the small intestine for digestion should reduce methane loss to the environment as well as the ruminal acid load; reducing the acid load should help to maintain a ruminal pH that is higher and more optimal for fiber digestion.

PREDICTING STARCH DIGESTIBILITY

Several laboratory methods for appraising or predicting starch digestion have been advanced in addition to the enzymatic starch availability measure used at commercial laboratories to evaluate flaked grain. These include gas production measures during incubation with yeast (as compared with corn flakes), microscopically appraised gelatinization (measuring prevalence of maltose crosses), the Degree of Starch Access (DSA) reported by Basel et al. (2006) that is being used with both silages and grains, and particle size measurements with grains and silages that are

based on the concept that starch found in particles larger than $\frac{1}{4}$ kernel (> 4.25 mm) from in corn silage are less extensively digested in vitro than smaller particles (Ferreira and Mertens, 2005). Ultimately, direct analysis of the starch content of feces should provide a direct measurement of indigestible starch as noted below.

STARCH DIGESTIBILITY BY PRODUCING RUMINANTS UNDER FIELD CONDITIONS

If feed starch input and fecal starch output are known, starch digestibility can be calculated. By employing either an inherent or an added marker, starch digestibility can be calculated for cattle under field conditions using a method recently described by Zinn et al. (2007). In turn, net energy values of grains can be predicted from starch digestibility. This would imply that fecal starch output, representing an energy loss, must be proportional to energy availability from starch in the rumen plus small intestine. To quantify this relationship, daily starch digestion in grams in the rumen plus small intestine for feedlot cattle and lactating cows was plotted against fecal starch divided by the mean indigestibility of starch in the large intestine ($100 - 47.8 = 52.2\%$) across all processing methods as shown in Figure 6.

Sampling variability among animals and days need further study, but fecal starch concentrations above 5% of fecal dry matter presumably reflect inadequate flaking of grains for maximum starch digestion or the presence of fecal starch from other sources (e.g., corn silage). Direct measurement of starch digestibility under field conditions should prove useful in the field to assess the veracity of laboratory indices of starch availability as well as the efficacy of grain processing methods being employed by livestock producers.

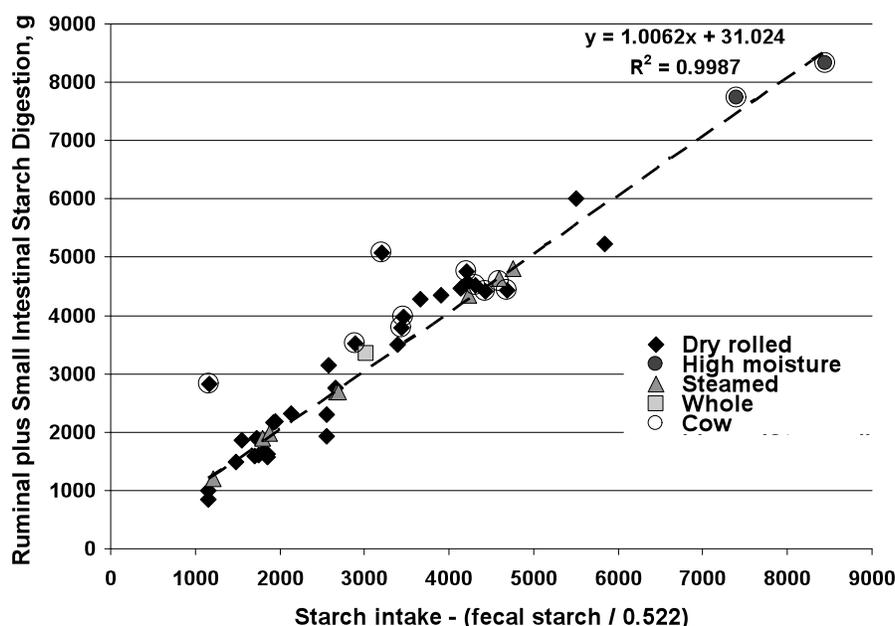


Figure 6. Relationship of digestion of starch in the rumen plus small intestine to starch intake minus fecal starch excretion divided by mean starch indigestibility.

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