Impact of Starch Content and Digestibility in Dairy Cattle Diets

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Introduction

Compared with other nutrients, starch was the most under evaluated research topic in dairy nutrition for many years. Consequently, starch requirements for dairy cows were never established by the NRC (2001). Recently, improvements in the use of starch by lactating dairy cows garnered much interest by dairy farmers and their nutritionists, particularly over the past decade with the two-fold rise in corn prices. Consequently, starch utilization by lactating dairy cows became an important research topic. Thus, the objective of the present article is to present and discuss potential strategies to optimize starch utilization by lactating dairy cows.

Dietary Starch Content

High-producing dairy cows require high-energy diets to fulfill their genetic potential. Corn is the predominant energy source in the dairy industry with approximately 75% of the energy value in corn grain being contributed by starch. Therefore, the substantial increase in corn prices resulted in renewed interest in the potential for feeding reduced-starch diets. The Dairy NRC (2001) established energy but not starch requirements for dairy cows. Thus, other fermentable carbohydrates (i.e. fiber and sugars) may be fed to fulfill the established energy requirements of lactating dairy cows. Reduced-starch diets could be formulated by partially replacing corn grain with high-fiber, low-starch byproduct feedstuffs (e.g. soy hulls, citrus pulp, whole cottonseed, beet pulp, cottonseed hulls, and wheat middlings), high starch forages (i.e. whole-plant corn silage) or high-sugar ingredients (i.e. molasses, whey, and sucrose). Although these varied carbohydrate sources can be used for energy, their ruminal fermentation by microorganisms yields different fermentation end-products, which in turn alter metabolism and performance by dairy cows.

Starch is rapidly fermented by ruminal microorganisms into propionate. Propionate is absorbed into the bloodstream and transported to the liver, and later it is used as a precursor for glucose. If not digested in the rumen, starch reaches the small intestine and is digested by pancreatic amylase directly into glucose. Thus, despite starch not having established requirements, its supplementation directly affects glucose supply and thereby, lactation performance of dairy cows.

According to Shaver (2010), results from short-term (10 to 21 d) switchback feeding trials in the literature suggest that reduced-starch diets formulated by partially replacing corn grain with high-fiber, low-starch byproduct feedstuffs (e.g. soy hulls, citrus pulp, and whole cottonseed) may be feasible. However, few long-term (10 to 12 wk) feeding

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trials can be found in the literature, and the effects of these feedstuffs on lactation performance should be verified in long-term continuous lactation trials. A summary of four continuous-lactation trials conducted at the University of Wisconsin – Madison was presented previously in this conference (Shaver, 2013). Across these four trials, feeding less dietary starch reduced actual-milk feed efficiency by 2 to 12% and solids-corrected milk feed efficiency by 1 to 11%. These results were related to either decreased milk production or increased DMI while maintaining similar milk production when starch was replaced with high-fiber, low-starch byproduct feedstuffs.

A recent review used a meta-analysis approach to evaluate the effect of dietary starch on lactation performance by dairy cows (Ferraretto et al., 2013). The authors considered only dietary starch values and not the specific type of carbohydrate used to replace starch. Starch concentration in the diet did not affect intake and this was thought to be related to two opposing effects: rumen fill limitation (Mertens, 1987) and increased ruminal propionate concentrations with corresponding decreased meal size (Allen et al., 2009) when corn grain was partially replaced by forage and non-forage fiber sources, respectively. Although milk yield increased 0.08 kg/d per %-unit increase in dietary starch content, feed conversion was unaffected by dietary starch. In addition, increased dietary starch concentration enhanced milk protein content. Reduced milk protein content for cows fed reduced-starch diets are related to lower starch intake reducing ruminal microbial protein production (Oba and Allen, 2003). Alternatively, less starch reaches the small intestine mediating milk protein content through alterations in arterial insulin concentrations (Rius et al., 2010). Conversely, milk fat content decreased as dietary starch content increased. Milk fat depression in high-starch diets is likely related to greater starch and lower NDF intakes (Jenkins and McGuire, 2006). The milk urea nitrogen concentration was also reduced by increasing dietary starch concentrations. Overall these data suggest better ruminal nitrogen utilization (NRC, 2001) as starch in the diet increases.

Another result highlighted by the meta-analysis of Ferraretto et al. (2013) is the effect of dietary starch concentration on in vivo NDF digestibility (**Figure 1**). The digestibility of dietary NDF decreased 0.61%-units ruminally and 0.48%-units total-tract per %-unit increase in dietary starch content. Similar to milk fat depression, decreased fiber digestibility may be partially explained by a decrease in ruminal fluid pH as a consequence of greater amounts of starch being digested in the rumen as starch intake increases. Low ruminal fluid pH is known to affect microbial growth and bacterial adherence and thereby fiber digestion. Also, the inherently high fiber digestibility of non-forage fibrous by-products used to partially replace corn grain in reduced-starch diets may be partly responsible. An exercise presented by Weiss (unpublished) during the 28^{th} ADSA Discover Conference on Starch for Ruminants calculated the effects of a 0.5%-unit change in total tract NDF digestibility for each 1%-unit change in dietary starch content (slope of Figure 1) on dietary energy values. In the Weiss exercise, a 5%-unit increase in dietary starch content (e.g. 30% vs. 25%) would increase dietary NE_L content by 6.5% without accounting for adverse effects of dietary starch on total tract NDF digestibility. However, the reduction of 2.5-% units (46.5% to 44.0%) in total tract NDF digestibility alters this scenario to a 5.3% increase in dietary NE_L content. Further incorporation of these effects on models are warranted.

Fredin (2015) conducted a meta-analysis to identify feeding strategies that could mitigate potential negative effects of feeding reduced-starch diets to lactating dairy cows. Milk yield was decreased when starch was replaced by either non-forage fiber sources (0.16 kg/d per %-unit decrease in dietary starch) or forage (0.32 kg/d per %-unit decrease in dietary starch). Reduced intake and ruminal degradation of forage NDF compared to non-forage NDF (Allen, 1997) were thought to induce greater reduction in milk yield when dietary starch was replaced by forage in the study by Fredin (2015). However, Fredin (2015) highlighted that 24 out of 61 treatment means for milk yield were greater for reduced-starch compared to high-starch diets, suggesting that positive lactation performance can be achieved when feeding reduced-starch diets. Yields of milk components were also reduced when dietary starch was replaced.

Potential negative effects on either milk yield or feed efficiency underscores that monitoring income over feed costs is recommended rather than price per unit of dietary DM to fully assess economic benefits of reduced-starch diets. Based on the summary of four continuous lactation trials (Shaver, 2013) and the meta-analysis reviews of literature (Ferraretto et al., 2013; Fredin, 2015), reducing dietary starch for peak and mid-lactation dairy cows may not be feasible and each scenario must be carefully evaluated.

Starch Digestibility in Corn Grain and Silage

The energy value of corn silage and grain contributed by starch is approximately 50 and 75%, respectively (calculated from NRC, 2001). Thus, to optimize starch availability in combination with the use of reduced-starch diets may have the potential to improve ruminal and total tract starch digestion. An increase in starch digestion may lead to better nutrient utilization and decreased feed costs. Detailed descriptions about factors influencing starch utilization in corn silage and grain will be discussed in this section.

Starch digestibility of whole-plant corn silage (**WPCS**), high-moisture corn (**HMC**) and dry ground corn (**DGC**) may be affected by several factors. First, the starch endosperm is protected by the pericarp which, if intact, is highly resistant to microbial attachment (McAllister et al., 1994); thereby breakage of the seed coat is obligatory. Diets containing HMC with mean particle size (**MPS**) below 2 mm had greater total tract starch digestibility (**TTSD**) compared with HMC with MPS greater than 2 mm (95.2% to 89.5%; Ferraretto et al., 2013). Likewise, increased MPS reduced TTSD in DGC-based diets (77.7% to 93.3% for 4 mm and 1 mm respectively; Ferraretto et al., 2013). This is related to increased surface area for bacterial and enzymatic digestion of finer particles (Huntington, 1997). Greater starch digestibility and corresponding milk production by dairy cows is achieved when corn silage is harvested using a kernel processor with roll gap settings between 1 to 3 mm (Ferraretto and Shaver, 2012). However, other harvesting practices may impair the efficacy of kernel processors.

Kernel processing was effective when theoretical length of cut (**TLOC**) settings on choppers was set at 0.93 to 2.86 cm but not when set at shorter or longer settings (Ferraretto and Shaver, 2012). This could be possibly explained by greater kernel breakage by cutting knives at the lower TLOC (Johnson et al., 1999) or inhibition of kernel breakage during passage through the rollers by the stover portion at the longer TLOC. Furthermore, processing increased TTSD for diets containing WPCS with 32% to 40% DM at feed-out, but not when WPCS was above 40% DM (Ferraretto and Shaver, 2012). An increased proportion of vitreous endosperm in the kernel is associated with greater maturity (Phillipeau and Michalet-Doureau, 1997). Increased kernel vitreous endosperm increases kernel hardness which in turn may cause kernels in very dry corn silage to be less susceptible to breakage during kernel processing at harvest.

Even the exposed endosperm is not fully digested due to existence of a starch-protein matrix formed by the chemical bonds of zein proteins with starch granules (Kotarski et al., 1992; McAllister et al., 1993). Ruminal in vitro starch digestibility was greater when HMC was harvested at lower DM content (**Figure 3**; Ferraretto et al., 2014). Furthermore, reduced TTSD were detected in diets containing WPCS above 40% DM in the meta-analysis review by Ferraretto and Shaver (2012). This may be related to an increase in the proportion of vitreous endosperm in the kernel associated with greater maturity (Correa et al., 2002; Ngonyamo-Majee et al., 2009). Alternatively, a reduction in the extent of fermentation for drier WPCS (Der Bedrosian et al., 2012) may attenuate the breakdown of zein proteins during fermentation (Hoffman et al., 2011). Goodrich et al. (1975) harvested HMC with 67% DM and oven-dried corn to 73% and 79% DM to study the effects of moisture content on fermentation of HMC. They reported a decrease in acetate and lactate concentrations and a corresponding increase in pH as DM content of HMC increased. Lower lactate and acetate concentrations are likely related to a reduced bacterial growth due to limited water availability (Muck, 1988). Goodrich et al. (1975) also observed reduced ruminal in vitro gas production as DM content increased, suggesting reduced starch digestibility for HMC at greater DM contents. These results combined suggest that proper maturity at harvest is required to maximize starch digestibility in WPCS and HMC.

Research trials on the effects of ensiling time on ruminal in vitro starch digestibility (**ivSD**) of WPCS are summarized in **Table 1**. At 30 or 45 days of ensiling, starch digestibility was increased by 7 percentage units on average and is likely related to the fermentation phase which typically occurs in this time frame. Interestingly, all 7 trials had a gradual increase in ivSD after additional storage time suggesting that perhaps ivSD continuously increases during storage. Proteolytic activity, either from microbial or plant proteases, occurs more extensively during the anaerobic fermentation process (Baron et al., 1986). The anaerobic phase is characterized by a drastic decrease in pH (Muck, 2010) which favors the activity of plant proteases specific to the endosperm of cereal grains (Simpson, 2001), even though the activity of plant proteases is typically reduced under low pH (Muck, 1988). Junges et al. (2015) evaluated the contribution of proteolytic sources on protein solubilization in rehydrated corn ensiled for 90 d. These authors reported that bacterial proteases are responsible for 60% of the increase in soluble CP concentration, followed by kernel enzymes (30%), and fungi and fermentation end-products (5% each).

Although allowing an extended ensiling period may be beneficial for increasing starch digestibility in situations where coarser, drier, or more vitreous hybrids are harvested, research in this area is still limited. Two other studies (Ferraretto et al., 2015a,b) were conducted to evaluate the interaction between hybrid types and ensiling time on starch digestibility of WPCS. Our hypothesis was that prolonged storage would attenuate, or perhaps overcome, the difference in starch digestibility between hybrid types. In the first experiment (Ferraretto et al., 2015b), another industry-university collaborative study, 8 WPCS hybrids (4 bm_3 and 4 leafy) were ensiled for 0, 30, 120, and 240 d. Although ivSD was similar between hybrids throughout the storage period, the N fraction response to time of fermentation varied with hybrid type suggesting greater effects on the breakdown of zein proteins in leafy than bm_3 hybrids. The second experiment (Ferraretto et al., 2015a) compared 3 hybrids (bm_3, dual-purpose, and experimental floury-leafy) ensiled for 0, 30, 60, 120, and 240 d. Contrary to our hypothesis, however, extended ensiling time did not attenuate the negative effects of kernel vitreousness on ivSD. The results from these experiments emphasize the importance of further WPCS starch digestibility research with regard to potential interactions between hybrid, harvest maturity, kernel processing, and ensiling. Furthermore, results suggest that the best opportunity for benefit from altering kernel endosperm properties for greater starch digestibility may reside within the bm_3 type hybrids.

On-Farm Assessment of Starch Digestibility

Fredin et al. (2014) reported a strong relationship between fecal starch measurements and TTSD. These results suggest that additional measurements to fecal starch, such as starch content of the diet or indigestible marker concentrations (iNDF or lignin) in the feces or diet are unnecessary. Furthermore, Fredin et al. (2014) reported high accuracy of near infrared reflectance spectroscopy (**NIRS**) to predict fecal starch, which allows for more rapid and inexpensive analysis. Although benefits of greater starch digestibility on milk production is well known, it is very difficult to reliably estimate its economic impact. The exercise presented and discussed in this article is an attempt to provide some numbers to dairy producers and their nutritionists as a starting point.

To accomplish our goal, a hypothetical scenario was created and five values of fecal starch were arbitrarily chosen and used to predict TTSD using the equation of Fredin et al. (2014; **Table 2**). Subsequently, the amount of corn that would need to be supplemented in order to obtain the same amount of digestible starch as if TTSD was 100% was estimated using the following assumptions: dietary starch was 25% of DM and consumption of DM was 55 lbs/d. Consequently, it was assumed that cows were eating 13.75 lbs of starch per day. Based on TTSD, values of starch loss in the manure was calculated and ranged from 0 to 3.5 lbs. If one consider that corn grain has 70% starch and 70% ruminal in vitro starch digestibility, for each lb of corn supplemented only 0.49 lbs of digestible starch is provided. Thus, by dividing starch loss by 0.49 we reached the amount of corn necessary to fulfill for undigested starch. Last, US$130.40/ton (approximately US$0.065/lb) was used to calculate corn grain costs. Values used in the present exercise is not representative of the entire American dairy industry, but it is a good indication of potential economic loss related to low starch digestibility. Thus, it is recommended that dairy farmers and their nutritionists perform similar calculations based on their own scenarios and goals.

Summary

Fecal starch does not indicate digestibility of specific feedstuffs but of total diets, and it can be used as a valuable tool to monitor specific groups of cows over time by collecting samples from at least 10% of animals in the group. If fecal starch levels are above 3%, specific starchy feedstuffs should be evaluated to elucidate the problem. In addition, re-evaluation of fecal starch values are recommended after 2 or 3 weeks of dietary or management adjustments.

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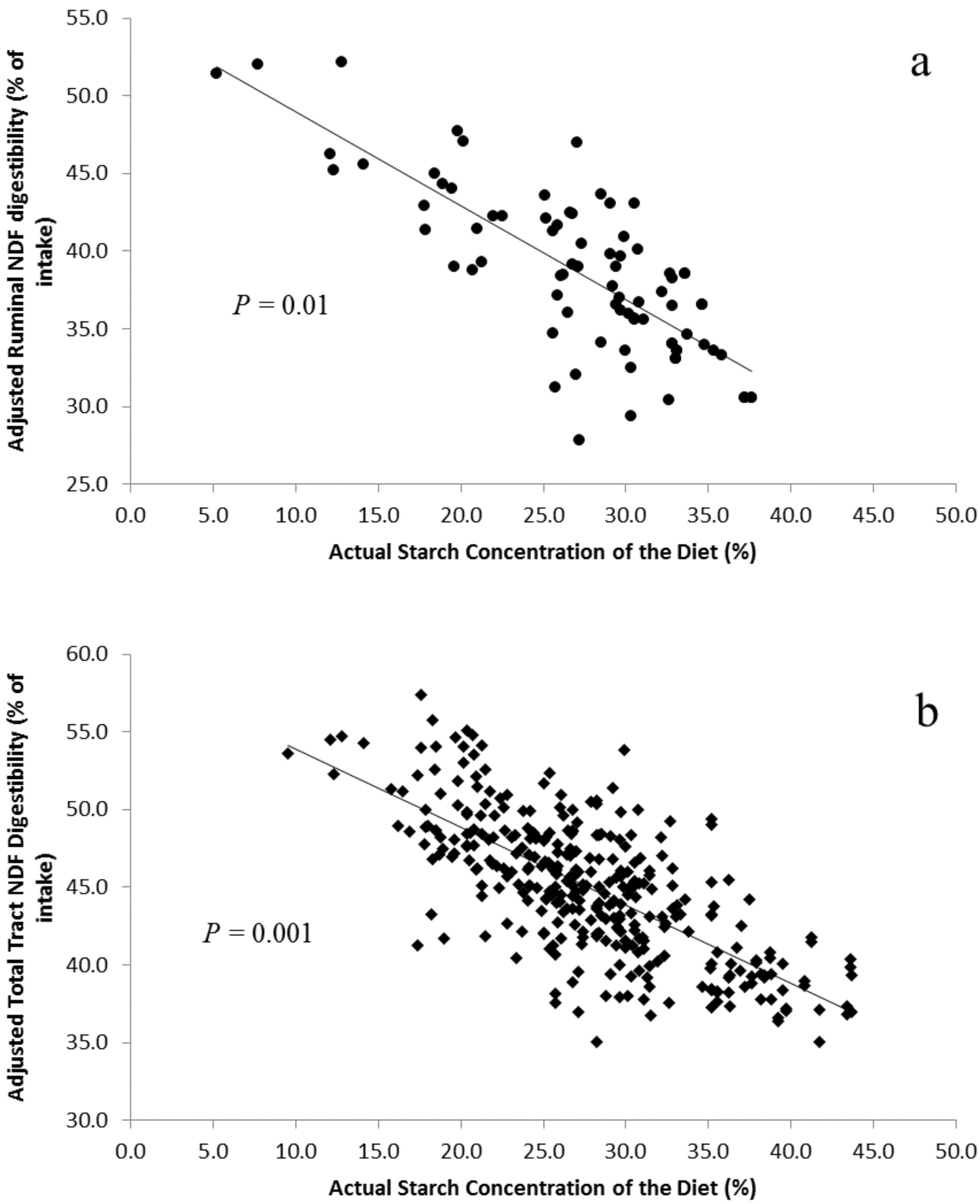

Figure 1. Effect of starch concentration of the diet on ruminal and total-tract digestibility of diet NDF adjusted for the random effect of trial. Ruminal digestibility data (Panel a) predicted from equation: y = 54.9746 + (-0.605*starch concentration) + (0.063 $\pm$ 3.524); n = 70, RMSE = 3.55. Total-tract digestibility diet (Panel b) predicted from equation: y = 58.2843 + (-0.4817*starch concentration) + (0.059 $\pm$ 3.191); n = 320, RMSE = 3.20. Source: Ferraretto et al., 2013.

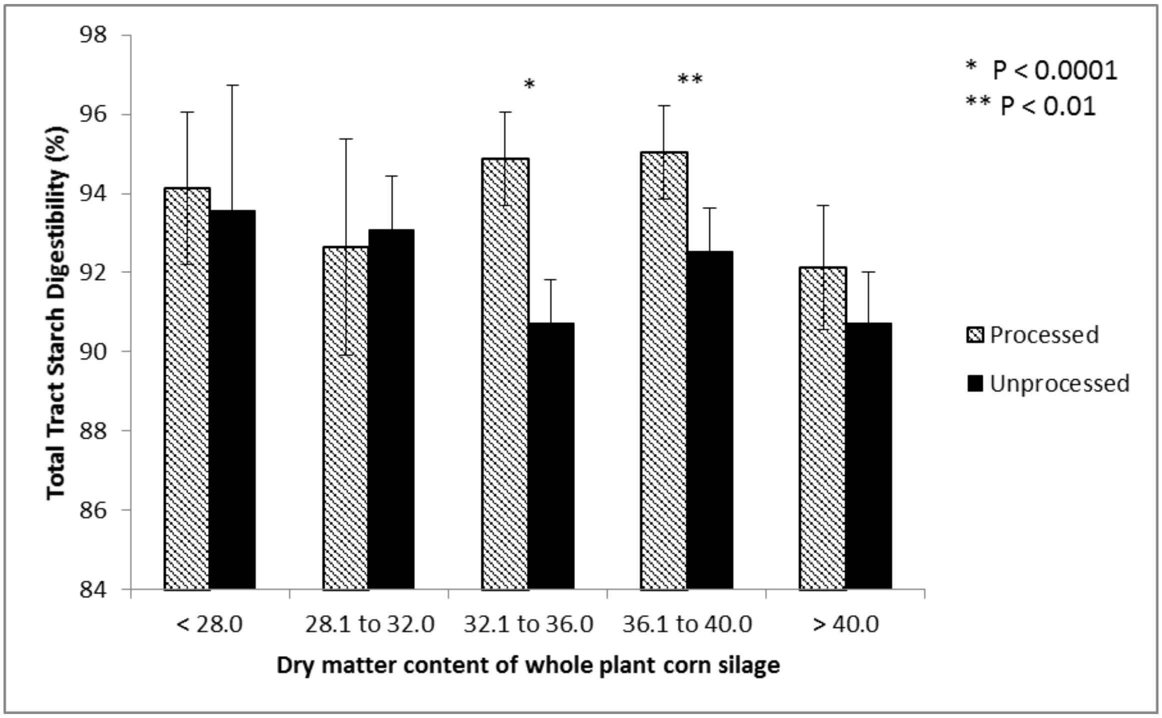

Figure 2. Effect of kernel processing and dry matter content of whole plant corn silage on total tract digestibility of dietary starch. Source: Ferraretto and Shaver (2012).

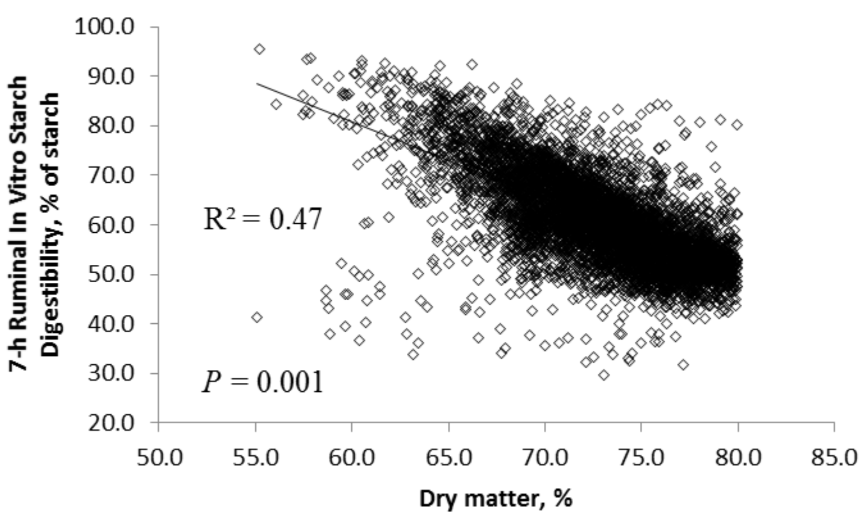

Figure 3. Relationship between DM content and 7-h ruminal in vitro starch digestibility in high moisture corn. Predictive equation: y = 174.30 ($\pm$ 1.57) - 1.56x ($\pm$ 0.02); n = 6,131, RMSE = 6.97, R^2 = 0.47, *P* = 0.001. Source: Ferraretto et al. (2014).

Table 1. Effects of ensiling time on ruminal in vitro starch digestibility in whole-plant corn silage[1]

Reference	Days ensiled											
	0	30	45	60	90	120	150	180	240	270	360	*P*-value
Whole-plant corn silage	- % of starch - - - - - - - - - - - - - - - - - -											
Der Bedrosian et al., 2012[1]	69	---	75	---	77	---	---	79	---	82	82	0.01
Windle et al., 2014[1]	54	---	59	---	63	---	68	---	---	---	---	0.01
Young et al., 2012[1]	66	---	76	---	---	---	79	---	---	---	---	0.01
Ferraretto et al., 2015a[2]	56	59	---	61	---	63	---	---	67	---	---	0.01
Ferraretto et al., 2015b[2]	62	72	---	---	---	79	---	---	84	---	---	0.01
Ferraretto et al., 2016 – exp. 1[2]	60.7	69.3	---	---	---	72.0	---	---	---	---	---	0.05
Ferraretto et al., 2016 – exp. 2[2]	54.0	61.7	---	---	---	66.7	---	---	---	---	---	0.04

[1,2] Ruminal in vitro starch digestibility at 7 h on samples ground through a 3-mm or 4-mm screen, respectively.

Table 2. Economic estimates of corn supplemented to fulfill undigested starch.

Measure	Fecal starch, % of DM				
	0	5	10	15	20
TTSD[1], % of starch	100	93.75	87.50	81.25	75.00
Starch intake[2], lbs/cow per day	13.75	13.75	13.75	13.75	13.75
Starch loss[3], lbs/cow day	0	0.89	1.72	2.58	3.44
Corn grain supplementation[4], lbs/cow per day	0	1.82	3.51	5.37	7.02
Corn grain cost[5], US$/cow per day	0.00	0.12	0.23	0.35	0.46

[1] Predicted from equation of Fredin et al. (2014); Total Tract Starch Digestibility (TTSD) = 100 – (1.25 x fecal starch).
[2] Starch intake = (55 lbs DMI x 25% starch) / 100.
[3] Starch loss = starch intake – ((starch intake x TTSD) / 100).
[4] Corn grain supplementation = starch loss / 0.49.
[5] Corn grain cost = corn grain supplementation x 0.0652. Corn grain cost obtained from values reported by FeedVal 2012 on November, 2016.

SESSION NOTES