INTRODUCTION

The optimum starch content of diets for lactating dairy cows is not well defined, but 25% starch (DM basis) has been suggested based on a review of published feeding trials (Staples, 2007). Shaver (2010) reported on surveys of high-producing commercial dairy herds performed in Wisconsin and Michigan with dietary starch concentrations averaging 27% and ranging from 25% to 30% (DM basis). Increased corn prices (Figure 1), however, have created great interest in the potential for feeding reduced-starch diets.

Results from short-term switchback dairy cattle feeding trials in the literature suggest that reduced-starch diets formulated by partially replacing corn grain with high-fiber, low-starch byproduct feedstuffs may be feasible (Shaver, 2010). Partial replacement of corn grain with forage, i.e. corn silage, to reduce purchased feed costs is also of much interest and results in reduced-starch diets. Depending upon market prices for high-sugar ingredients, the partial replacement of corn starch with sugar may be another alternative for reducing feed costs also resulting in reduced-starch diets.

Longer-term continuous lactation feeding trials are more appropriate than short-term switchback trials for evaluating the effect of reducing dietary starch content on feed efficiency, BW change and income over feed cost (IOFC), and several trials of this type that evaluated the aforementioned feedstuffs will be reviewed herein. Coincident with the interest in reduced-starch diets is a renewed focus on increasing the digestibility of starch by dairy cows. Another objective of this paper is to provide an update on some aspects of the starch digestibility topic.
REDUCED-STARCH DIETS

Lactation performance responses to reduced-starch diets from four recent continuous lactation experiments are summarized in Table 1. Three trials were from UW-Madison (UW; Gencoglu et al., 2010; Ferrarett et al., 2011a,b) and evaluated high-fiber, low starch byproduct feeds as partial corn grain replacers, while a trial from the Ohio Agricultural Research and Development Center (OARDC; Weiss et al., 2011) evaluated the partial replacement of corn grain with corn silage. The NDF from forage concentrations were 20%-21% across all diets with 5% to 10%-units less starch for reduced-starch (RS) than normal-starch (NS) diets in the UW trials. For the OARDC trial, NDF from forage concentrations were 23% and 26% for the NS and RS diets, respectively, with 5%-units less starch for RS than NS diets. Across the four trials, the earliest and latest DIM at trial initiation were 51 and 114 d, respectively, and treatment length ranged from 10 to 14 wk. Milk yield for cows fed the NS diet ranged from 38 kg to 52 kg/cow/d across the four trials.

Dry matter intake was greater for RS than NS in the UW trials, but lower for RS than NS in the OARDC trial. Greater DMI for RS than NS in the UW trials may be related to reduced ruminal propionate concentration (Allen, 1997; Beckman and Weiss, 2005) leading to increased meal size and consequently greater DMI (Allen et al., 2009). Firkins (1997) suggested that increased digestibility and passage rate of by-product NDF can allow for increased NDF intake relative to forage NDF, which could explain the difference in DMI response for RS between the UW trials and the OARDC trial. In other words rumen fill likely limited DMI in the OARDC trial (23% to 26% NDF from forage), but not in the UW trials (20% to 21% NDF from forage), where metabolic control of DMI appears to have been more likely (Allen et al., 2009).

Actual milk yield was similar for cows fed RS and NS in the UW trials with soy hulls (SH; Gencoglu et al., 2010; Ferrarett et al., 2011b), but tended (P < 0.07) to be 4% lower for RS than NS in the UW trial with whole cottonseed (WCS) and wheat middlings (WM; Ferrarett et al., 2011a). Because WCS and WM are moderate-protein ingredients, they partially replaced both corn grain and soybean meal (SBM) in the
RS diet. Greater ruminal protein degradation for these ingredients compared to SBM along with reduced rumen microbial protein production for RS may have decreased metabolizable protein flow, which could partially explain the decrease in milk yield (NRC, 2001). Actual milk yield was lower \((P < 0.05)\) for RS than NS in the OARDC trial and was consistent with the DMI response in that trial. Responses for milk yield corrected for concentrations of fat, protein and lactose (solids-corrected milk; SCM) were inconsistent for the UW trials with either greater \((P < 0.03; \) Gencoglu et al., 2010), trend for lower \((P < 0.08; \) Ferraretto et al., 2011b), or similar \((P > 0.10; \) Ferraretto et al., 2011a) SCM observed for RS compared to NS. The SCM yield was lower \((P < 0.05)\) for RS than NS in the OARDC trial and was consistent with the actual milk yield and DMI responses in that trial. Body weight gain was not different for cows fed RS compared to cows fed NS across the four trials.

Feed efficiencies, across the four trials, were reduced for RS compared to NS by 5% to 12% for Milk/DMI and by 4% to 11% for SCM/DMI. Reduced feed efficiency for dairy cows fed RS diets creates an economic concern for nutritionists desiring to use this formulation strategy to reduce diet cost per unit of DM. Midwest USA March-2011 market prices for feed ingredients and milk were applied to ration composition, DMI and milk production data from the four trials to estimate feed costs and IOFC. Feed costs per unit DM were reduced in all trials by 3% to 8% for RS. Feed costs per cow per day for RS, however, were increased for two trials by 3% to 5% and decreased for two trials by 5% to 10%. Estimates of IOFC were unaffected in one trial, increased in one trial by 4% for RS, and decreased in two trials by 6% to 7% for RS.

Feed efficiency and IOFC results indicate that for high producing cows in early to mid lactation, partially replacing corn grain with NDF from either high-fiber byproducts or corn silage to formulate RS diets was not beneficial. Reduced market prices for high-fiber byproducts relative to corn grain and soybean meal would improve the economics of feeding RS compared to NS diets. Use of higher quality corn silage with reduced NDF content and (or) greater NDF digestibility when partially replacing corn grain with corn silage in RS diets may improve responses compared to the trial reviewed herein, and further research is
warranted. Furthermore, RS diets formulated by partially replacing starch with fiber may offer more potential for beneficial responses when fed to lower producing, later lactation cows than evaluated in the trials reviewed herein; potentially less concerns about rumen fill limitations to DMI and milk yield when partially replacing starch with forage NDF or reduced feed efficiency when partially replacing starch with byproduct NDF (Allen, 2008).

Broderick and Radloff (2004) partially replaced starch from high-moisture shelled corn (HMC) with sugar from either dried (Trial 1) or liquid (Trial 2) molasses. Dietary starch and total sugar concentrations (DM basis) ranged from 31.5% to 23.2% and 2.6% to 7.2%, respectively, in Trial 1, and from 31.4% to 26.1% and 2.6% to 10.0% in Trial 2. Cows averaged 128 and 85 DIM at trial initiation for Trials 1 and 2, respectively, and were on treatment for 8 wk. The estimated overall optimum for total dietary sugar, based on yields of fat and FCM in Trial 1 and yields of milk and protein in Trial 2, was 5.0% (DM basis); feeding diets with more than 6% total sugar with the added sugar from molasses appeared to depress milk production. Broderick et al. (2008) partially replaced corn starch with sucrose. Dietary starch and total sugar concentrations (DM basis) ranged from 28.2% to 21.5% and 2.7% to 10.0%, respectively. Cows averaged 77 DIM at trial initiation, and were on treatment for 8 wk. Milk yield was unaffected by treatment, but milk fat yield was greatest for the diet containing 7.1% total sugar and 24.5% starch (DM basis). Alternatives for high-sugar ingredients include molasses, whey, whey permeate, liquid feed supplements, and sucrose. Evaluate prices of these ingredients (sugar) relative the price of corn (starch) to determine appropriate supplementation strategies.

**DIGESTIBILITY OF CORN GRAIN STARCH**

The impact of the digestibility of corn grain starch on lactation performance by dairy cows was reviewed by Firkins et al. (2001). Greater starch digestibility increased milk and protein yields. Research is limited, however, with regard to the impact of increasing starch digestibility in RS diets on lactation performance by dairy cows.
Three experiments evaluated the addition of exogenous amylase to RS diets (Gencoglu et al., 2010; Ferraretto et al., 2011b; Weiss et al., 2011). Gencoglu et al. (2010) reported that fat-corrected milk (FCM), SCM and energy-corrected milk (ECM) feed efficiencies (kg/kg DMI) were 12% to 13% greater for cows fed the RS diet with amylase than for cows fed the RS diet without added amylase. Amylase addition to RS diets tended ($P < 0.09$) to increase the actual milk feed efficiency by 6% in the Ferraretto et al. (2011b) trial, but was ineffective in the OARDC trial. Across these three trials with RS diets and in the trial of Klingerman et al. (2009) with NS diets, dietary addition of exogenous amylase more consistently increased NDF digestibility than starch digestibility. More research on exogenous amylase addition to both NS and RS diets is warranted.

Total tract digestibility of starch by dairy cows ranges between 70% and 100% (Firkins et al., 2001) with a host of factors that influence starch digestibility. These factors include particle size (fine ground vs. coarse rolled), grain processing (steam flaked vs. dry rolled), storage method (dry vs. HMC), moisture content and duration of silo fermentation for HMC, and type of corn endosperm (Firkins et al., 2001; Hoffman et al., 2011; Nocek and Tamminga, 1991).

Kernel vitreousness, the ratio of vitreous to floury endosperm, has been used to assess type of corn endosperm (Ngonyamo-Majee et al., 2008a, b). Increased kernel vitreousness was related to reduced ruminal in situ corn starch degradation (Correa et al., 2002; Ngonyamo-Majee et al., 2008b). Kernel vitreousness was lower and ruminal in situ starch degradation was greater for dry corn with floury or opaque endosperm compared to normal dent endosperm (Ngonyamo-Majee et al., 2008a, b). Taylor and Allen (2005) reported greater ruminal and total tract starch digestibilities in ruminally and duodenally cannulated lactating dairy cows for floury (3% vitreousness) than normal dent (67% vitreousness) endosperm dry corn.

Highly vitreous corn types contain greater concentrations of prolamin proteins than floury or opaque corn types (Larson and Hoffman, 2008). Starch granules in the corn endosperm are surrounded by hydrophobic prolamin proteins which are slowly degraded (McAllister et al., 1993). Lopes et al. (2009) conducted an experiment to evaluate the
effect of type of corn endosperm on nutrient digestibility in lactating dairy cows using near-isogenic variants of a normal dent endosperm hybrid carrying floury-2 or opaque-2 alleles. The percentage vitreous endosperm was zero for floury and opaque endosperm corns and 64% for the vitreous corn. Prolamin protein content of floury and opaque endosperm corns was 30% of the content found in vitreous corn. Starch disappearance after 8-hr ruminal in situ incubation was 32%-units on average greater, respectively, for floury and opaque endosperm corns than vitreous corn. Total-tract starch digestibility was 6.3%-units, on average, greater for cows fed diets containing floury and opaque endosperm corns than vitreous corn.

Hoffman and Shaver (2009) developed a corn grain evaluation system (UWFGES) for dairy cows where total-tract starch digestibility, energy value, and relative grain quality index are predicted from equations that include starch content, mean particle size, prolamin protein content, and whether or not the corn is dry or HMC (> 22.5% moisture). This system as originally proposed, however, does not account for effects of varying corn maturities, moisture contents or extents of silo fermentation. Hoffman et al. (2011) reported that ensiling HMC for 240 d reduced zein protein subunits that cross-link starch granules, and suggested that the starch-protein matrix was degraded by proteolytic activity over an extended ensiling period. This could explain reports of greater ruminal in situ starch degradability for HMC with greater moisture contents and duration of silo fermentation (Benton et al., 2005). The Larson and Hoffman (2008) turbidity assay determination of total zein protein content did not detect a reduction in zein protein subunits over the ensiling period for HMC as measured by high-performance liquid chromatography (HPLC; Hoffman et al., 2011). Ammonia nitrogen content increased, however, as HPLC zein protein subunits in HMC decreased (Hoffman et al., 2011), and ammonia nitrogen analysis could offer an improvement to the UWFGES for modeling effects of corn maturity, moisture content and length of silo fermentation time on starch digestibility and energy value of HMC at feed out.

Effects of wide differences in corn grain vitreousness or prolamin, i.e. flinty or vitreous corn versus floury or opaque corn, on starch digestibility have been demonstrated (Correa et al., 2002;
Ngonyamo-Majee et al., 2008a, b; Lopes et al., 2009; Taylor and Allen, 2005). However, incorporation of these corn endosperm properties into corn breeding or hybrid selection programs for dairy cattle feed has been, and continues to be, slow to evolve. Until the recent extended period of high corn prices there had not been much interest in increasing starch digestibility by exploiting corn’s genetic traits. Recent interest in feeding RS diets, however, has spawned a much greater interest in this area. Furthermore, the potential for reduced vitreousness or prolamin corn to reduce the cost and management of corn processing methods and quality control and HMC maturity, moisture content and duration of fermentation is of interest to some in the industry; more research is needed, however, to better evaluate these potential interactions.

While interest has increased along with on-going research, practical challenges to pursuing reduced vitreousness or prolamin corn remain. The relative importance of kernel vitreousness or prolamin appears to be as follows: dry corn > HMC > corn silage. The normal co-mingling of dry corn that occurs through grain elevators and feed industry channels makes it very difficult to alter these parameters at the feed manufacturer or farm level, and HMC and corn silage comprise more of a niche market for the seed corn industry. Incorporation of these parameters into routine corn hybrid selection programs requires NIRS calibrations, which are not available on an industry-wide basis at this point. The potential for pollen drift (Thomison, 2002) to compromise small replicated field plot hybrid evaluations for endosperm properties warrants more scrutiny. Nitrogen fertility can influence the prolamin content of corn grain (Masoero et. al, 2011; Tsai et al., 1978), which could confound comparisons of field plot evaluations for this parameter across locations or companies. Important agronomic traits, such as yield and starch content, will also need to be evaluated relative to hybrid differences for vitreousness or prolamin. Much translational research is still needed for progress to be made in this area.

REFERENCES


http://www.ers.usda.gov/Data/FeedGrains/Table.asp?t=12
Figure 1. Average #2 yellow corn cash price in Minneapolis, MN at 5 year intervals from Sept. 1975 - Aug. 1976 through Sept. 2010 - Feb. 2011 (USDA ERS, 2011).
Table 1. Lactation performance responses to reduced-starch diets.

<table>
<thead>
<tr>
<th>Diet DM basis</th>
<th>Gencoglu et al., 2010</th>
<th>Ferraretto et al., 2011b</th>
<th>Ferraretto et al., 2011a</th>
<th>Weiss et al., 2011</th>
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<tr>
<td>Soy Hulls</td>
<td>WCS, WM</td>
<td>Soy Hulls</td>
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<td>Starch</td>
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<td>27% vs. 22%</td>
<td>30% vs. 20%</td>
<td>31% vs. 26%</td>
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<tr>
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<td>12</td>
<td>14</td>
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</table>

1 WCS = Whole Cottonseed; WM = Wheat Middlings.
2 Normal-starch diet.
3 RS/NS = Data for reduced-starch diet / data for normal-starch diet.
4 SCM = Solids-Corrected Milk = Milk yield × [(0.1224 × Fat %) + (0.071 × True Protein %) + (0.0625 × Lactose %) - 0.0345].