# Effects of grain variability and processing on starch utilization by lactating dairy cattle[1]

**J. L. Firkins[2], M. L. Eastridge, N. R. St-Pierre, and S. M. Noftsger**

Department of Animal Sciences, The Ohio State University, Columbus, OH 43210

**ABSTRACT:** Variation in site of digestion and lactation performance among lactating dairy cows fed different grain sources was evaluated and reviewed. The enzymatic assay for starch contributes to variation among and possibly even within experiments. Genetic differences within grain source affect digestibility, but effects of grain processing are considerable. When quantifying response criteria among numerous experiments with varying experimental procedures, the variation among experiments is very high and should be considered in regressions used to evaluate treatment responses. Some of the variation among experiments could be explained by variable DMI (positive relationship with milk production and microbial N flow to the duodenum but negative relationship with milk fat percentage and ruminal digestibility of starch) and other chemical measurements of dietary composition (especially forage and NDF percentages of the diet). Other sources of variation that could not be quantified among experiments were accounted for in regression models as experiment effects. After these adjustments, least squares means were calculated as the average of all effects remaining in the models. Our results documented that processing procedures to enhance the ruminal degradability of starch generally decreased NDF digestibility by a lesser degree, partially negating responses in true ruminal OM digestibility. However, lactating cows fed diets with low ruminal degradability of starch had higher, nearly complete compensatory digestion of starch in the hindgut, thereby resulting in relatively minor improvements in total tract OM digestibility or lactation performance for the more highly available starch sources, assuming similar DMI. These results highlight the importance of maximization of DMI compared with grain-processing method and the need for more production experiments comparing grain sources at similar intakes of ruminally digestible starch (i.e., lower percentages in the diet for more highly degradable starch sources) for better evaluation of overall efficacy. In particular, the long-term responses and potential for residual responses over time (i.e., treatment × time interactions) are needed. Until better mechanistic prediction of lactation response is available, the least squares means of ruminal and total tract digestibilities of nutrients should be useful for empirical formulation and evaluation of dairy rations.

Key Words: Dairy Cattle, Feed Grains, Starch Digestion

 J. Anim. Sci. 79(E. Suppl.):E218–E238

## Introduction

High-producing dairy cows require high intakes of $NE_l$ without causing metabolic disturbances that result from ruminal acidosis and related disorders from high amounts of concentrate (Nocek, 1997; Owens et al., 1998; Garrett et al., 1999). Therefore, negative and positive aspects of cereal grain digestibility need to be balanced for optimal $NE_l$ intake.

The differences in structure (Kotarski et al., 1992; Mills et al., 1999a), degradability (Kotarski et al., 1992; Forsberg et al., 1997), and genotype (Dado, 1999) of grains have been reviewed extensively. Previous reviewers (Huntington, 1997; Reynolds et al., 1997; Mills et al., 1999a) have documented the variable ruminal degradable starch (**RDS**) from various cereal grains, ranging from below 30% (Joy et al., 1997; Crocker et al., 1998) to virtually 100% (Van Vurren et al., 1999). Some of the variation can be a result of the different grain types (Huntington, 1997; Mills et al., 1999a). Processing is needed for all cereals to break the seed coat (Beauchemin et al., 1994b), especially for corn and grain sorghum (Theurer et al., 1999). Despite these advances, extensive variation within grain source and processing method remains unexplained, thereby reducing the accuracy of models for research and ration formulation. For instance, the variation in site of starch digestion,

[1]Salaries and research support were provided by state and federal funds appropriated to the Ohio Agricultural Research and Development Center, The Ohio State Univ. Manuscript no. 2-01AS.

[2]Correspondence: 223 Animal Science Building, 2029 Fyffe Road (phone: 614-688-3089; fax: 614-292-2929; E-mail: firkins.1@osu.edu).

Received July 26, 2000.

Accepted June 4, 2001.

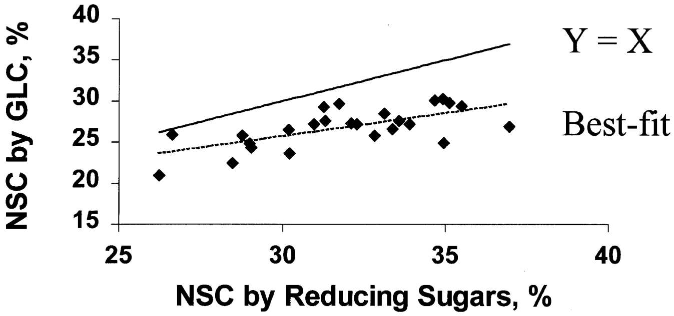


**Figure 1.** The relationships between nonstructural carbohydrates (NSC, enzymatic hydrolysis followed by a reducing sugar assay) and starch (enzymatic assay followed by sugar analysis using GLC in individual diets (Callison et al., [2001]). The best-fit line represents the equation 8.86 (± 4.21) + 0.563 (± 0.132) × NSC; $r^2 = 0.44$.

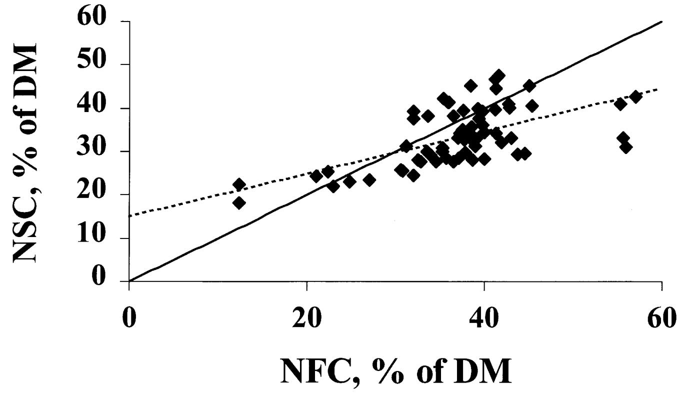


**Figure 2.** The relationship of nonfiber carbohydrates (NFC, by difference method) to nonstructural carbohydrates (NSC, enzymatic assay using colorimetric quantification of sugars) in 73 diets reported in Oldick et al. (1999). The best-fit line represents the equation NSC = 15.0 (± 3.0) + 0.492 (± 0.08) × NFC; $r^2 = 0.35$.

including the degree of compensatory digestion in the intestines, greatly influences metabolism (Huntington, 1997; Reynolds et al., 1997; Mills et al., 1999b; Allen, 2000) and, therefore, $NE_l$ concentration.

Our first objective was to review grain-processing methods and their effects on digestibility and lactation performance after accounting for variation among experiments and other dietary factors. Second, sources of variation that still need further delineation will be discussed.

## Methods of Assessing Variability Among Grains

Reynolds et al. (1997) and Petterson et al. (1999) noted that problems in the analysis of starch using enzymatic release of glucose introduce considerable variation, recommending improvements or at least standardization in methodology to further progress in evaluation of site of starch digestion. This variation can be a result of sample preparation, the source of enzymes, and assay conditions (Reynolds et al.,1997; Hall et al., 2000). For instance, samples should be processed to be fine enough for complete starch extraction. Enzymes need to be periodically checked for full enzymatic activity and lack (or minimization) of artifact activities and for background sugars. We recommend thoroughly checking a starch assay for local laboratory conditions by extending incubation periods in a slope-response fashion, serially increasing enzyme addition, and performing recovery analyses on all types of samples. We noted that alterations were needed in the colorimetric procedures for fecal samples in one study (Harmison et al., 1997) and noted some interference with colorimetric quantification of released sugars in ileal and fecal samples, leading to highly negative concentrations of sugars (unpublished data) in another study (Callison et al., 2001). When sugars (glucose and small amounts of mannose) from enzymatic breakdown of diets were recovered and quantified by GLC or quantified using a standard colorimetric procedure, the latter consistently had higher concentrations (Figure 1). Although starch hydrolysis releases glucose by adding one water molecule per each glucose linkage, our laboratory routinely corrects recovery to a purified cornstarch control rather than to a correction factor of 0.9 × glucose (as is often done). Chen et al. (1994) reported a nonlinear standard curve, which could be occurring more frequently without being described in publications.

Variation in starch procedures among laboratories seems to be large. Hall et al. (2000) sent purified cornstarch samples to six laboratories and noted an average recovery of 93.6% (SE = 17.9%). Some assays are not specific to glucose but, rather, react with many sugars. Because addition of glucose, fructose, or cellobiose to cornstarch also introduced considerable variation, authors should consider reporting free sugars separately from starch or at least designating their data as nonstructural carbohydrates (**NSC**) rather than as starch. Also, ethanol extraction prior to enzymatic digestion of starch could reduce the sample interference described previously for ileal and fecal samples. Although generally not reported, digestibility of nonfiber carbohydrates (**NFC**; calculated by differences of OM − CP − fat − NDF + NDFCP; NDFCP is CP contamination of NDF) can give different treatment responses than digestibility of starch by enzymatic procedures (Harmison et al., 1997). The NFC procedure usually results in higher concentrations in feeds than NSC (Figure 2) because of neutral detergent-soluble fiber, especially pectins in legumes (Hall et al., 1997).

Sampling or sample processing procedures can add variation to studies. For instance, some studies have reported concentrations of starch in corn that, when multiplied by the percentage of corn in a total mixed ration (**TMR**), were slightly greater than the measured starch concentration of the entire TMR. Sampling of a TMR could result in preferential selection for forage particles because the denser grains settle. Segregation during processing of samples or during storage also could introduce error. Much larger variation was detected in ruminal starch digestibility than in ruminal NDF or OM digestibilities in some studies (Joy et al., 1997; Garcia et al., 2000). Variation in starch recovery among laboratories likely contributes significantly to trial effects for starch digestibility (see later discussion).

Similar quandaries occur for processing of grains prior to in situ or in vitro analyses. Lack of grinding assumes no particle size reduction during eating or rumination, which is not accurate (Beauchemin et al., 1994b). However, when ground, the actual processing effects can be minimized (Yang et al., 1997a; Shabi et al., 1999). Also, oven drying (even at ≤ 60°C) significantly reduced OM and starch degradabilities in situ for corn grain at early incubation times (Matthé et al., 1999).

## Site of Starch Digestion

Various chemical processes have been evaluated to increase or decrease starch degradability in the rumen. Although starch digestibility in the small intestine is theoretically more efficient metabolically than gluconeogenesis from propionate that has been produced during microbial fermentation, actual benefits from starch breakdown in the rumen or small intestine seem to be equivocal; recent articles (Reynolds et al., 1997; Mills et al., 1999b) have concluded that no appreciable limit in starch digestibility will be reached for dairy cows adapted to high starch intakes. Readers are referred to recent reviews (Huntington, 1997; Reynolds et al., 1997; Mills et al., 1999a,b; Allen, 2000). The focus of the current review will be on ruminal and total tract starch digestibility and their relationships to dairy production.

## Alternative Methods of Altering Ruminal Degradability of Starch

Sodium hydroxide, ammonia, and aldehydes have been used to alter starch degradability in the rumen (Nocek and Tamminga, 1991; Mills et al., 1999a). Although sodium hydroxide treatment of grain can increase ruminal pH (Mills et al., 1999a), this treatment generally has not been beneficial (Nocek and Tamminga, 1991; McNiven et al., 1995; MIron et al., 1997). Similarly, ammonia treatment of barley has not offered any real advantage (Robinson and Kennelly, 1989). Aldehydes, especially formaldehyde, reduced starch degradability in situ but did not affect starch flow to the duodenum (Ortega-Cerrilla et al., 1999) or feedlot steer performance (Oke and Loerch, 1991). Therefore, the potential to shift site of starch breakdown to the small intestine by using formaldehyde does not seem likely to be effective for dairy cows. Roasting (McNiven et al., 1994; Robinson and McNiven, 1994) and expansion and extrusion (Arieli et al., 1995; Shabi et al., 1999) have been evaluated, also, with limited benefit. In the latter study (Shabi et al., 1999), feeding frequency interacted with corn-processing method and needs further evaluation. In addition, dent varieties are more accessible to enzymatic breakdown than flint types (Philippeau et al., 1999, 2000; Martin et al., 1999).

## Conventional Methods of Grain Processing

Ladely et al. (1995) concluded that method of processing had a greater effect on feedlot cattle performance than did hybrid of corn. Theurer et al. (1999) reviewed conventional methods of grain processing for lactating dairy cows. They found that ruminal starch digestibility was highly correlated (r = 0.82) with total tract starch digestibility and with milk protein percentage (r = 0.73). Postruminal digestibility (calculated as a percentage of duodenal starch flow) was highly correlated with total tract starch digestibility (r = 0.95), milk production (r = 0.88), and milk fat percentage (r = −0.89). Theurer et al. (1999) summarized the direct comparisons of processing of corn and sorghum (Table 1). Steam-flaking of corn or sorghum increased milk production, marginally increased milk-protein percentage, decreased milk-fat percentage, tended to increase microbial protein in the flow to the duodenum, and improved ruminal and total tract starch digestibilities. The authors warned against comparisons among trials because of unequal replication of grain sources across trials. Our statistical procedures (St-Pierre, 2001) have taken trial effects into consideration (see next section) and should provide safer conclusions among treatments that were not compared within trial (hereafter termed *experiment*).

## Regression Analyses of Grain-Processing Data

A data file was generated using means from 22 experiments with lactating Holstein cows in which total tract digestibility was reported for corn, sorghum, or barley processed in different ways (Herrera-Saldana and Huber, 1989; McCarthy, Jr. et al., 1989; Oliveira et al., 1993, 1995; Chen et al., 1994; Mitzner et al.,1994; Overton et al., 1995; Simas et al., 1995; Plascencia and Zinn, 1996; Knowlton et al., 1996, 1998; Joy et al., 1997; Lykos et al., 1997; Santos et al., 1997a, 1999; Wilkerson et al., 1997; Yang et al., 1997a,b, 2000; Crocker et al., 1998; Yu et al., 1998; Harvatine, 2000; Callison et al., 2001). Means from three experiments were excluded from some regressions because of incomplete digestibility data for starch (Wilkerson et al., 1997), NDF (Plascencia and Zinn, 1996), or OM and NDF (Mitzner et al., 1994). Although some data did not list forage NDF percentage, the following NDF values were assumed: alfalfa (42%), corn silage (45%), bromegrass (58%), barley silage (56%), and alfalfa-grass mix (50%) in our calculations. Because several studies had low forage NDF but high cottonseed NDF contributions to the diet, whole cottonseed and cottonseed hulls were assumed

**Table 1.** Summary of direct comparisons of processing of corn or sorghum[a]

| | Corn | | | Sorghum | | |
|---|---|---|---|---|---|---|
| | Steam-rolled | Steam-flaked | P[b] | Dry-rolled | Steam-flaked | P |
| Number of studies | 6 | 6 | — | 24 | 24 | — |
| DMI, kg/d | 26.5 | 26.5 | NS | 25.6 | 25.1 | NS |
| Milk, kg/d | 35.8 | 38.0 | 0.02 | 35.6 | 37.4 | 0.01 |
| Milk fat, % | 3.11 | 2.98 | 0.02 | 3.20 | 3.03 | 0.001 |
| Milk protein, % | 2.99 | 3.06 | 0.11 | 2.95 | 3.02 | 0.01 |
| Total tract starch digestibility, % | 87.4 | 95.7 | 0.05 | 83.7 | 97.1 | 0.01 |
| Number of studies | 3 | 3 | — | 6 | 6 | — |
| DMI, kg/d | 18.4 | 18.8 | NS | 22.1 | 22.4 | NS |
| Apparent starch digestibility | | | | | | |
| Ruminal, % intake | 35 | 52 | 0.03 | 54 | 76 | 0.01 |
| Postruminal, % intake | 42 | 44 | NS | 36 | 23 | 0.01 |
| Postruminal, % duodenal flow | 61 | 93 | 0.05 | 74 | 90 | 0.04 |
| Total tract, % intake | 77.5 | 96.6 | 0.01 | 88.7 | 97.9 | 0.01 |
| Microbial CP flow to duodenum, kg/d | 1.04 | 1.23 | 0.08 | 2.10 | 2.33 | 0.11 |

[a]From Theurer et al. (1999), who summarized direct trial comparisons from lactation studies and from studies with duodenally cannulated dairy cows.
[b]Probability of treatment response within grain source comparison. NS = $P > 0.15$.

to have 44 and 90% NDF, respectively (NRC, 1989); one unit of cottonseed NDF was assumed to equal 0.84 forage NDF (Harvatine, 2000). However (see later discussion), the combined effects of the variable, forage NDF plus effective cottonseed NDF, was eliminated from all models, perhaps because the effectiveness value varied among studies and because of our inclusion of average forage NDF for some studies that did not report it. Backward elimination of multiple regression was performed similarly to the algorithm reported by Oldick et al. (1999). St-Pierre (2001) explained the statistical rationale for adjusting literature-derived means for unequal variance among experiments and for the random effect of experiment. Dependent variables included apparent total tract digestibilities of starch, NDF, and OM; DMI; and milk yield. Independent continuous variables included the dietary percentages of grain, forage, CP, NDF, effective NDF (forage plus effective cottonseed), and starch. We recognize that different laboratories used different assays for starch, some of which would include free sugars. Differences among laboratories would contribute to experiment effects in the regressions.

Several experiments evaluated combinations of grain sources, and these combinations were not used. Steam-flaked sorghum data were only used if sorghum was optimally processed as concluded by Theurer et al. (1999). For steam-flaked corn, no effect of flaking density was detected in a preliminary multiple regression analysis; thus, all densities were recoded the same for data used in the final models. Similarly, one study evaluated rolling density for barley (Yang et al., 2000), and these data were all recoded the same because optimal rolling density has not been delineated. When calculated as a percentage of BW, DMI was removed during the backward elimination procedures for digestibility data, so the process was repeated with actual DMI (kg/d).

Because a full model with all continuous independent variables and their squared terms induced near-collinearity and was too unstable to be fit with the limited number of observations, only the linear effects of these variables (no squared terms or interactions) were included in the initial backward elimination multiple regressions performed using Proc Mixed (SAS Inst. Inc., Cary, NC). Grain source was set as a fixed-effect class variable, and experiment was a random-effect class variable. All dependent variables were weighted by the reciprocal of their squared standard error. In a few studies, the SE was exceptionally low; to prevent overweighting the data, these SE were set to one-half of the mean SE across experiments. In the elimination process, when all remaining continuous independent variables were $P < 0.10$, then all possible interactions of these continuous effects were added to the model, and backward elimination multiple regression was performed on the continuous variables. The potential interactions of these continuous variables with the fixed effect of grain source could not be evaluated because of incomplete replication of continuous variables across diets with various grain sources. The linear effect was forced to remain in the model if it was contained in any squared term. The best fit was chosen as the one with the lowest root mean square error, acceptable correlation among estimates of independent variables, and the highest Schwarz's Bayesian criterion.

A description of the data used in the analyses is provided in Table 2. Least squares means shown for grain source (Tables 3 and 4) were adjusted for the random effect of experiment and were recalculated at the means of all continuous independent variables remaining in final models. Table 2 shows means of all data, which

**Table 2.** Statistical description of variables used in the data file for prediction of total tract digestibility

| Variable[a] | n | Mean | SD | Minimum | Maximum |
|---|---|---|---|---|---|
| Grain, % of DM | 83 | 39.3 | 6.9 | 20.5 | 50.6 |
| Forage, % of DM | 83 | 40.2 | 7.5 | 21.3 | 53.0 |
| CP, % of DM | 83 | 17.4 | 1.9 | 14.3 | 21.7 |
| NDF, % of DM | 79 | 30.9 | 3.4 | 24.5 | 39.6 |
| FNDF, % of DM | 83 | 18.1 | 4.1 | 9.0 | 24.9 |
| ENDF, % of DM | 83 | 21.0 | 1.8 | 18.0 | 24.9 |
| Starch, % of DM | 75 | 30.9 | 5.8 | 13.7 | 45.2 |
| Starch digestibility, % | 79 | 90.6 | 7.4 | 69.8 | 99.8 |
| NDF digestibility, % | 75 | 48.0 | 10.9 | 25.7 | 69.3 |
| OM digestibility, % | 79 | 67.2 | 5.4 | 54.3 | 77.7 |
| Milk, kg/d | 83 | 32.2 | 5.3 | 22.6 | 45.6 |
| Milk protein, % | 83 | 3.08 | 0.19 | 2.63 | 3.69 |
| Milk fat, % | 83 | 3.46 | 0.39 | 2.72 | 4.46 |
| BW, kg | 39 | 586 | 52 | 501 | 660 |
| DMI, kg/d | 83 | 22.3 | 3.1 | 16.5 | 28.4 |
| DMI, % of BW | 57 | 3.72 | 0.35 | 2.72 | 4.30 |

[a]FNDF = forage NDF; ENDF = effective NDF. Starch was measured by enzymatic hydrolysis but included free sugars in some experiments. Starch and OM digestibilities were apparent.

would be close to the means of data remaining in the final models. The final models (Table 5) have regression and intercept coefficients for dry-rolled corn, and an example of the relationships between these figures is given as a footnote in Table 5. For other grains, the regression coefficients would remain the same, but the intercept would be adjusted according to the difference of the least squares means of other grains (Tables 3 and 4) minus that of dry-rolled corn within the respective regression. Dry-rolled corn was chosen as the basis to which improvement by processing could be evaluated because corn treatments had the highest number of observations, and this treatment had the lowest starch digestibility. We chose not to evaluate significance of differences among treatment means because the data were unbalanced and treatments were not preplanned.

### *Digestibility Differences Among Cereal Grains*

Apparent total tract digestibility of starch in corn-based diets was increased by grinding compared with rolling and by steam-flaking compared with steam-rolling (Table 3). Steam-rolling of corn seems not to be as effective as flaking because the corn kernel has not been exposed enough to enzymatic attack. Fine grinding offered a marginal improvement compared with coarser rolling, but increased dustiness needs to be considered (see later discussion). Based on a limited number of studies, further processing of high-moisture corn marginally improved starch digestibility. When all high-moisture corn data were combined (not separated by particle size) and regression procedures repeated, only minor differences in digestibilities were detected (data not shown).

Starch digestibility means were adjusted for effects of dietary NDF percentage (Table 5). Increasing starch digestibility was related to decreasing NDF percentage of the diet, possibly because of an inverse relationship of decreasing NDF with increasing percentage of starch in the diet. Starch percentage was eliminated from all models, perhaps because of its large variability among laboratories compared with lower variation in NDF. Increasing starch percentage of the diet could dilute endogenous (bacterial) starch in feces.

Total tract digestibilities of NDF and OM (Table 3) were similar for dry and steam-processed corn, demonstrating how compensatory digestion of starch in the hindgut from diets with low RDS or compensatory digestion of NDF from those with high RDS can equalize apparent total tract digestibilities of OM. The higher total tract OM digestibility of high-moisture corn could

**Table 3.** Least squares means of apparent total tract digestibilities from lactating cows fed different grain sources[a]

| | | Starch | | NDF | | OM | |
|---|---|---|---|---|---|---|---|
| Grain | n[b] | Mean | SE | Mean | SE | Mean | SE |
| Corn | | | | | | | |
| Dry, cracked, or rolled | 9 | 85.0 | 1.3 | 52.0 | 2.7 | 66.6 | 1.2 |
| Dry, ground | 12 | 90.7 | 1.1 | 49.0 | 2.3 | 67.8 | 1.1 |
| Dry, ground finely | 2 | 91.4 | 1.8 | 51.2 | 4.5 | 69.8 | 1.8 |
| Steam-rolled | 10 | 88.8 | 1.2 | 49.8 | 2.5 | 67.2 | 1.2 |
| Steam-flaked | 10 | 94.2 | 1.2 | 48.2 | 2.5 | 68.6 | 1.2 |
| High-moisture, rolled | 3 | 94.2 | 2.6 | 50.0 | 3.7 | 71.9 | 1.5 |
| High-moisture, ground | 2 | 98.8 | 5.7 | 50.4 | 4.2 | 73.9 | 1.6 |
| Sorghum | | | | | | | |
| Dry, rolled or ground | 6 | 83.5 | 1.5 | 45.2 | 3.7 | 64.6 | 1.5 |
| Steam-flaked | 7 | 94.9 | 1.4 | 52.3 | 3.0 | 67.7 | 1.6 |
| Barley | | | | | | | |
| Dry- or steam-rolled | 11 | 95.8 | 1.3 | 40.4 | 2.8 | 66.7 | 1.2 |
| Steam-rolled, hull-less | 3 | 82.0 | 1.6 | 47.0 | 3.4 | 60.4 | 1.5 |

[a]All least squares means are adjusted for the random effect of experiment and for the mean of all continuous variables remaining in the final models (see Table 5).
[b]Number of treatment means.

**Table 4.** Least squares means of lactation performance for Holstein cows fed different grains[a]

| Grain | n[b] | DMI, kg/d | | Milk, kg/d | | Protein, % | | Fat, % | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SE | Mean | SE | Mean | SE | Mean | SE |
| Corn | | | | | | | | | |
| Dry, cracked or rolled | 9 | 22.5 | 0.7 | 30.9 | 0.9 | 3.09 | 0.04 | 3.59 | 0.09 |
| Dry, ground | 13 | 23.1 | 0.8 | 31.5 | 0.9 | 3.18 | 0.04 | 3.53 | 0.09 |
| Dry, ground finely | 3 | 21.9 | 0.9 | 32.4 | 1.0 | 3.02 | 0.05 | 3.49 | 0.10 |
| Steam-rolled | 10 | 22.1 | 0.8 | 31.9 | 0.9 | 3.10 | 0.04 | 3.49 | 0.09 |
| Steam-flaked | 10 | 22.8 | 0.8 | 32.5 | 1.1 | 3.10 | 0.04 | 3.36 | 0.09 |
| High-moisture, rolled | 3 | 22.7 | 1.0 | 32.5 | 1.0 | 3.17 | 0.05 | 3.54 | 0.12 |
| High-moisture, ground | 2 | 23.1 | 1.2 | 33.9 | 1.2 | 3.17 | 0.06 | 3.37 | 0.14 |
| Sorghum | | | | | | | | | |
| Dry, rolled or ground | 8 | 23.4 | 0.9 | 31.5 | 1.0 | 2.99 | 0.04 | 3.50 | 0.09 |
| Steam-flaked | 7 | 23.0 | 1.1 | 32.7 | 1.1 | 3.11 | 0.05 | 3.41 | 0.10 |
| Barley | | | | | | | | | |
| Dry- or steam-rolled | 11 | 20.5 | 0.8 | 33.1 | 1.0 | 3.11 | 0.04 | 3.44 | 0.10 |
| Steam-rolled, hull-less | 3 | 20.9 | 1.0 | 31.9 | 1.1 | 3.05 | 0.05 | 3.53 | 0.10 |

[a]All least squares means were adjusted for the random effect of experiment and for the mean of all continuous variables remaining in the final model (See Table 5).

[b]Number of treatment means. For DMI and milk protein percentage, n was increased to 10 for dry-rolled corn and to 13 for steam-flaked corn.

be related to low numbers of treatment means, decreasing the ability of our regression procedure to standardize data for the average experiment effect. When other factors remained constant, increasing percentages of dietary forage and NDF were predicted to increase NDF digestibility, probably through increasing ruminal pH.

**Table 5.** Best-fit equations for multiple regression of responses to grain source standardized to dry-rolled corn for apparent total tract digestibility and lactation performance by lactating Holstein cows[a]

| Parameter | Intercept | SE | Variable[b] | Coefficient | SE | RMSE[c] |
|---|---|---|---|---|---|---|
| Starch digestibility, % | 103.2 | 5.5 | NDF | –0.585 | 0.168 | 2.02 |
| NDF digestibility, % | 31.5[d] | 24.6 | CP | –1.97 | 0.98 | 4.44 |
| | | | NDF | 1.36 | 0.37 | |
| | | | Forage | 0.337 | 0.150 | |
| OM digestibility, % | 89.0 | 8.0 | CP | –1.28 | 0.46 | 1.80 |
| DMI, kg/d[e] | 26.9 | 2.6 | Forage | –0.110[f] | 0.061 | 1.25 |
| Milk, kg/d | –70.5 | 13.5 | DMI | 6.28 | 1.02 | 1.14 |
| | | | $DMI^2$ | –0.116 | 0.025 | |
| | | | Forage | 1.40 | 0.43 | |
| | | | $Forage^2$ | –0.0157 | 0.0055 | |
| | | | Grain | –0.240 | 0.098 | |
| Milk protein, % | 1.96 | 0.26 | Grain | 0.0177 | 0.0045 | 0.058 |
| | | | Forage | 0.0109 | 0.0035 | |
| Milk fat, %[g] | 6.41 | 1.01 | DMI | –0.225 | 0.097 | 0.0116 |
| | | | $DMI^2$ | 0.00436[f] | 0.00232 | |

[a]All data are adjusted for the random effect of experiment and weighted for unequal variance. The equations are standardized relative to the mean of dry-rolled corn in Tables 3 and 4. For example, the mean NDF concentration (30.9%; Table 2) multiplied by the coefficient for NDF (–0.585) and added to the intercept (103.2) equals the least squares mean for starch digestibility for dry-rolled corn (85.0%; Table 3). The intercept in this table would be adjusted for the difference of each least squares mean minus that for dry-rolled corn (from Tables 3 and 4) for each respective regression. Unless shown differently, all estimates were $P < 0.05$ from zero.

[b]NDF and CP = percentages of dietary DM, DMI (kg/d) is of the entire diet, grain = the dietary percentage of the respective cereal grain, and forage = the percentage of forage in the entire diet.

[c]RMSE = root mean square error after adjusting for the random effect of experiment.

[d]Not significant ($P > 0.10$).

[e]The effect of grain source was $P = 0.07$.

[f]$P < 0.08$.

[g]The effect of grain source was $P = 0.13$.

Least squares means for NDF digestibility (Table 3) must be interpreted with reference to adjustments made by other dietary factors remaining in the model (Table 5), which varied both among and within experiments. For example, forage percentage changed among trials; within trials, if barley replaced corn, the dietary NDF typically also increased. When other factors remained constant, CP percentage was negatively related to NDF digestibility, probably reflecting a deficiency of ruminally degradable protein for fibrolytic microbes (Firkins, 1996), or as a result of the low range and lack of a deficiency of CP in diets (Table 2).

Starch and OM digestibilities (Table 3) were lower for diets with dry-rolled than for those with steam-flaked sorghum. The digestibility of OM for dry-rolled sorghum seemed to be lower than that for corn diets.

For barley, dry- and steam-rolling seemed to be equally effective (similar high total tract starch digestibility, and data were combined). However, for rolled barley, NDF digestibility was low, causing OM digestibility to be similar to that of corn or sorghum diets with lower RDS. Hull-less barley had low starch and OM digestibilities, but the grain source needs further evaluation at lower density (see later discussion).

*Lactation Performance for Cows Fed Different Grains*

For corn, grinding vs rolling seemed to marginally increase milk production without affecting DMI (Table 4), supporting trends in OM digestibility (Table 3). Fine grinding of corn had numerically lower DMI, higher milk production, and lower percentages of milk fat and milk protein compared with dry-rolling (Table 4). Processed high-moisture corn seemed to support the highest level of milk production. Milk components did not seem to be consistently related to RDS of corn. The relatively small differences in lactation performance are due, in part, to the adjustments made by other independent variables. For this data file, DMI was decreased by increasing percentage of dietary forage (Table 5), probably through increased bulk fill or other factors (Allen, 2000). For milk production, increasing DMI and forage percentages had diminishing positive relationships with milk production. Although DMI was related negatively to forage percentage, there was a surprisingly low correlation (r = –0.07) of forage percentage with DMI in the current model for milk production (data not shown). Thus, the effect of forage seems to be independent of DMI. When DMI is held constant, increasing forage could improve metabolic efficiency in some way, although conclusions are not clear. When DMI and forage are constant, grain percentage had a negative relationship. This is probably a reflection of the much larger effect of forage than of grain in this model (i.e., coefficients for forage have much larger impact). Similarly, milk protein was positively related to increasing grain and forage percentages in this data file. Feed grain sources that were high in RDS (i.e., steam-flaked corn and high-moisture corn) decreased milk fat percentage only marginally (Table 4). If factors associated with milk fat depression also decreased DMI, then the predicted effect of RDS probably was lessened. Increasing milk fat percentages were associated with decreasing DMI below 25.8 kg/d, possibly because of a negative relationship of DMI with forage percentages or increased lipolysis of adipose tissue with decreasing DMI. When milk fat data (Figure 3a) were adjusted for the random effect of experiment and the effect of grain source, the effect of DMI on milk fat percentage can be illustrated in Figure 3b. The basis and procedures used

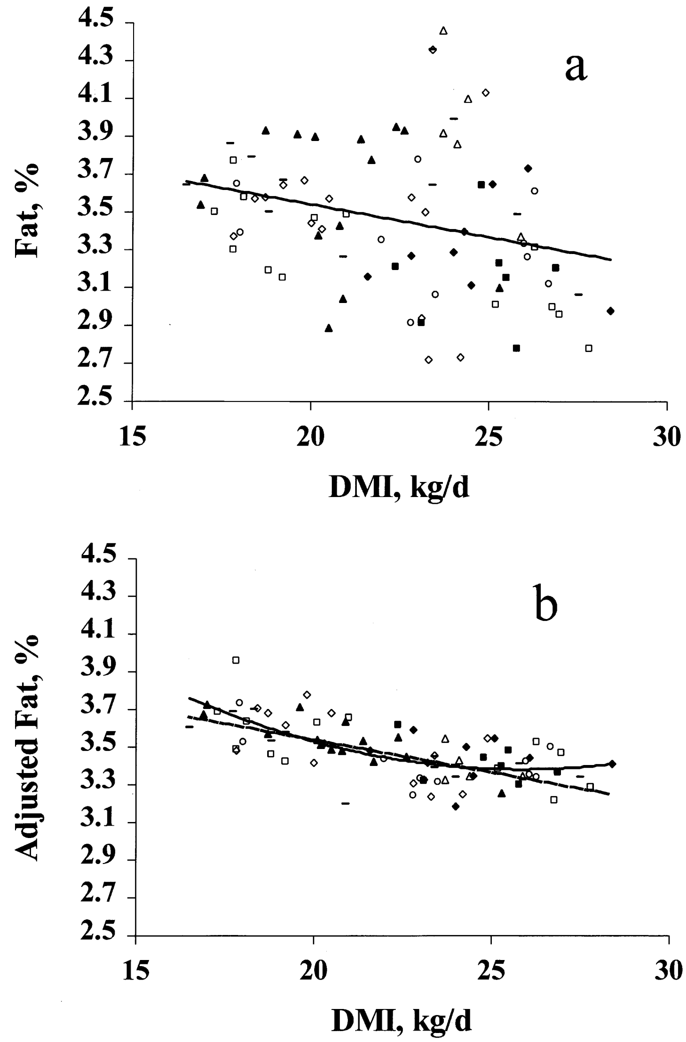


**Figure 3.** The relationship of DMI with milk fat percentage from Holstein cows fed different grain sources. Unweighted observed data (Panel a) and observed data that were weighted for unequal variance and adjusted for the random effect of experiment (Panel b) are shown. For Panels a and b, the best-fit linear line = 4.23 (± 0.30) – 0.0345 (± 0.0132) DMI; $r^2$ = 0.08. The quadratic regression (Panel b) = 5.78 (± 0.67) – 0.178 (± 0.061) DMI + 0.00330 (± 0.00137) $DMI^2$; $r^2$ = 0.46. Data are for dry-rolled corn (—), dry-ground corn (◇), steam-rolled corn (*O*), steam-flaked corn (□), high-moisture corn (△), dry-rolled sorghum (♦), steam-flaked sorghum (■), and barley (▲).

for data adjustment were discussed recently by St-Pierre (2001).

Steam-flaking of sorghum increased milk protein percentage, tended to increase milk production, and tended to decrease milk fat percentage (Table 4).

Despite low DMI, rolled barley supported high milk production (Table 4). However, much of this apparent benefit for barley is a result of the adjustments of least squares means (Table 5; see next section) to the average DMI. Milk fat percentage was similar for barley, corn, and sorghum (Table 4), again partly explained by the means being adjusted upward because of decreased DMI (Table 5; Figure 3b).

### *Weighting of Means for Grain Sources*

Our regression analyses were weighted for unequal variance among experiments and were adjusted for the random effect of experiment and other dietary attributes, thereby equalizing some of the production responses for corn and sorghum noted by Theurer et al. (1999). Experiment effects could include differences in starch assays, stage of lactation, forage source, and other sources of variation among experiments. Interpretation of actual coefficient values and interpolation beyond the data range should be done with caution. For instance, higher NDF percentage of the diet could be more empirically related to starch digestibility than would a lower grain inclusion level (which increases NDF). In contrast, DMI would be expected to have a large causal relationship with milk production.

Figure 3 illustrates how accounting for among-experiment effects (e.g., differences in days in milk, grain processing, grain source, or proportion of grain in the diet) greatly tightens the relationship of milk fat percentage with DMI. At 24 kg/d, uncorrected milk fat percentage (Panel a) ranged from about 2.70 to 4.50% and had a poor relationship with DMI. In contrast, when milk fat percentages were adjusted for differences among experiments (Panel b), a quadratic relationship was noted, and the range was about one-fourth of that at 24 kg/d of DMI for the unadjusted data. Performing regressions with data that are extracted from different experiments without accounting for large among-experiment effects has a high likelihood of hiding true relationships.

An example comparing dry-rolled corn to dry-rolled barley can be used to illustrate the importance of comparing milk production by cows fed different grain sources at equal DMI. For dry-rolled corn, least squares means for DMI, milk production, and milk fat were 22.5 kg/d, 30.9 kg/d, and 3.59%; for dry- or steam-rolled barley these values were 20.5 kg/d, 33.1 kg/d, and 3.44% (Table 4). These least squares means show a large advantage for barley in milk efficiency. However, the means for milk and milk fat were adjusted for the average DMI effect (i.e., as predicted for a DMI of 22.3; Table 2). If the means for milk production were adjusted for the actual DMI using the coefficients in Table 5, predicted milk by cows fed barley would be decreased by 2.4 kg/d (by decreasing DMI from the data file average of 22.3 kg/d to the data file average for barley, 20.5 kg/d), but milk production would be increased by 0.3 kg/d (by increasing DMI from 22.3 to 22.5) for dry-rolled corn. Therefore, the net benefit for milk production from barley is more than counteracted by the decreased DMI in these studies. The difference of 0.15 percentage units in milk fat would be decreased to a 0.11-unit difference. Therefore, the similar OM digestibilities for dry-rolled corn and barley seem to accurately reflect no net benefit for feeding barley vs dry-rolled corn.

## Literature Comparisons of Total Tract Digestibility and Milk Production Within Trials

### *Starch Digestibility*

*Wheat.* Wheat starch is readily accessible to enzymatic attack following physical disruption of the seed coat (see earlier discussion). Huntington (1997) documented high ruminal starch availability of ground wheat. Therefore, it follows that steam processing had minor effects (Espindola et al., 1997). Fat-corrected milk production was greater for high-moisture wheat than for high-moisture corn, but DMI was not measured (Petit and Santos, 1996). In the study of Harmison et al. (1997), total tract starch digestibility was not statistically increased when dry ground wheat replaced half of the dry ground corn, probably because of compensatory hindgut digestion of cornstarch.

*Barley.* Compared with dry-rolled sorghum, dry-rolled barley increased starch digestibility in the rumen (Herrera-Saldana et al., 1990) and total tract (Herrera-Saldana and Huber, 1989; Herrera-Saldana et al., 1990). Similarly, steam-rolling of barley compared with ground corn increased ruminal starch digestibility greatly in the rumen and much less in the total tract (McCarthy et al., 1989; Overton et al., 1995). When different degrees of steam-rolling were assessed (31.7 to 57.2 g/L density), more extensive rolling increased ruminal and total tract starch digestibilities (Yang et al., 2000). Dry matter intake was affected quadratically, with the finest roll size depressing DMI. Ruminal pH data helped to verify that more highly processed barley was more potentially acidotic. Similarly, DMI was decreased by barley, apparently as a result of low ruminal pH, in the aforementioned studies (McCarthy et al., 1989; Overton et al., 1995). In contrast, barley did not depress ruminal pH or DMI and had ruminal starch digestibilities similar to those of ground corn (Garcia et al., 2000). The authors attributed these effects to a smaller particle size of ground corn than of ground barley. Yang et al. (2000) recommended a medium roll size to balance the benefit of increased starch availability against the increased risk of depressed ruminal pH or DMI. Barley with higher bushel weight prior to rolling had a higher rate of starch disappearance in situ and higher milk protein yield but did not increase DMI or milk yield (Grings et al., 1992). Unfortunately, details of particle size or density after rolling are not available, but rolling different varieties at the same settings could result in different particle sizes among varieties. In production situations, a lower amount of highly processed barley could be fed to prevent reduced DMI, but this concept has received little attention in research cited herein.

Hull-less barley has been evaluated because barley hulls are relatively poorly digestible. However, when hull-less barley was steam-rolled at settings used for hulled barley, starch digestibility in the total tract was depressed, apparently because hull-less barley needs finer rolling than hulled varieties (Yang et al., 1997a). Similarly, feeding hull-less barley depressed fat-corrected milk production, apparently because it was not processed finely enough (Beauchemin et al., 1997). The authors discussed the possibility that barley hulls increased rumination. However, our regression analyses did not support this suggestion (see later). More research comparing these types of barley at similar starch availabilities and effective fiber concentrations is needed.

*Corn.* Corn conventionally has been ground or cracked. Recently, researchers have called attention to the fineness of grind for lactating cows. Callison et al. (2001) reported that fine grinding greatly increased ruminal starch availability but only marginally improved total tract starch digestibility because of compensatory digestion post ruminally. Similarly, total tract digestibility of starch (Knowlton et al., 1996; Yu et al., 1998) or nonfiber carbohydrates (Wilkerson et al., 1997) was improved by fine grinding of dry corn. Grinding high-moisture corn did not improve nonfiber carbohydrate digestibility in one study (WIlkerson et al., 1997) and improved starch digestibility marginally in another (Knowlton et al., 1998). Grinding of rolled high-moisture ear corn slightly improved digestibility of starch in the total tract (Ekinci and Broderick, 1997). The higher starch digestibility of ground high-moisture corn than of cracked dry corn (Lykos et al., 1997) also supports the improvement in starch digestibility from fine grinding of dry corn rather than high-moisture corn for lactating cows. Unfortunately, not enough researchers reported particle size of their ground corn to distinguish a continuous response to corn particle size.

Steam-flaking of corn considerably improves starch digestibility compared with steam-rolling and especially dry rolling (Table 1). The actual ruminal starch digestibility data ranged from about 79% for lactating cows fed steam-flaked corn (Harvatine, 2000) to about 45% (Joy et al., 1997; Crocker et al., 1998). However, because the steam-flaked corn was of a low density for the latter two studies, the low RDS is surprising. Other authors have questioned sampling (Titgemeyer, 1997) or subsampling (Knowltonet al., 1998) of duodenal samples from cattle fed corn-based diets. A large amount of duodenal chyme from a relatively low number of samples was taken from these two studies (Stokes et al., 1991; Crocker et al., 1998), which could be responsible for the low apparent ruminal starch digestibility data for steam-flaked corn in Table 1. Differences in forage source, level of feed intake, or passage rates of corn from the rumen also could be responsible for differences among trials, although data are too limited to draw conclusions. Differences in processing conditions of steam-flaking can cause variation (Theurer et al., 1999), but air-drying of steam-flaked corn did not affect digestibility (Zinn and Barrajas, 1997). Because these studies (Joy et al., 1997; Crocker et al., 1998) with low RDS had corn treatments that were replicated across other studies with higher starch digestibility data, our regression approach generated adjusted means higher than the actual digestibility data.

*Sorghum Compared with Corn.* As with corn, steam-flaking considerably improves ruminal and total tract starch digestibilities of grain sorghum (Theurer et al., 1999). Direct comparisons of sorghum to corn are relatively few. Corn and sorghum processed similarly seem to be relatively equal, especially when steam-flaked (Theurer et al., 1999). However, steam-flaking improved total tract starch digestibility more for corn than for sorghum in one study (Santos et al., 1999), whereas dry-rolled sorghum had a lower starch digestibility than dry-rolled corn in another (Mitzner et al., 1994). No associative effects of combining steam-flaked and dry-rolled sorghum were apparent in one study (Oliveira et al., 1993), but a negative associative effect of combining these two grains seemed evident for apparent starch digestibility in the rumen in another study (Oliveira et al., 1995). Similarly, combining cracked and steam-rolled corn resulted in an apparent negative association for total tract starch digestibility (Callison et al., 2001). Clearly, when corn and sorghum are not highly processed (e.g., steam-flaked), considerable variation in RDS remains to be explained.

### *Production Responses to Grain Source and Processing*

*Barley.* Substitution of corn with barley in metabolism experiments decreased milk production largely as a result of decreased DMI (McCarthy et al., 1989; Overton et al., 1995; Casper et al., 1999). These studies showed evidence of ruminal acidosis from barley. Cows fed barley tended to have lower ruminal pH at early hours after feeding (Yang et al., 1997b) but this did not affect milk production. When the same diets were fed to noncannulated cows, barley decreased DMI and milk production for multiparous cows (Yang et al., 1997a). Other researchers have shown no effect of grain source (barley vs corn), but NDF was relatively high (Herrera-Saldana and Huber, 1989) and ruminal buffers were fed (Grings et al., 1992; Santos et al., 1997b). When adjusted for various effects (Table 5), milk production by cows fed barley tended to be higher than that by cows fed most other grain sources (Table 4). Therefore, the overall responses in DMI and milk production from rolled barley need to be considered with respect to the ratio of effective NDF to RDS. A medium roll of barley was optimal, as evidenced by quadratic responses of DMI and milk production (Yang et al., 2000). When corn- or barley-based concentrates were substituted with nonforage fiber sources, DMI increased for cows fed corn but only tended to increase for those fed barley (Beauchemin et al., 1997). Increasing NDF from 33 to 43% in the barley-based diet might have counteracted the benefit of decreasing the acidogenic properties of rolled barley by increasing ruminal fill. Allen (2000) noted that filling effects are more likely for forage fiber, although nonforage fiber also apparently can limit DMI (Younker et al., 1998).

*Corn and Sorghum.* Theurer et al. (1999) reported that steam-flaking of corn or sorghum increased milk production by about 2 kg/d (Table 1). There were small positive responses for milk protein percentage and small decreases in milk fat percentage. These responses were lower in our analyses (Table 4). Although Kalscheur et al. (1997) reported a role of *trans* $C_{18:1}$ for milk fat depression, steam flaking of corn depressed milk fat percentage without any effect on duodenal flow of *trans* $C_{18:1}$ (Harvatine, 2000), and the concentration of *trans* $C_{18:1}$ in milk fat was lower from cows fed barley than in milk fat from those fed sorghum flaked to different densities, without any difference in milk fat percentage (Santos et al., 1997b). Fine grinding of corn increased milk production in one of three Latin squares (Knowlton et al., 1996). Fine grinding of corn depressed DMI but not milk production in a lactation study when compared to coarsely cracked corn (Yu et al., 1998). However, because fine grinding also caused milk fat to protein inversion, a higher ratio of effective NDF to RDS might have allowed an improvement in milk production from fine grinding. The authors attributed the decreased DMI by cows fed finely ground corn to increased dustiness (no wet feeds were in the TMR). Although this possibility has not been adequately researched, cows fed steam-flaked corn of a low density had a higher DMI than those fed finely ground corn in that study. In another lactation study, fine-grinding of dry corn increased DMI and milk production, and ruminal pH was not affected in a companion study (Knowlton et al., 1998). The acetate to propionate ratio was similar among treatments. Higher propionate production could depress DMI (Allen, 2000). Steam-flaking of corn at 361 vs 309 g/L increased fat-corrected milk production, but the fat to protein ratio was similar. Processing to increase digestibility of sorghum starch decreased DMI (Santos et al., 1997a,b) and caused fat to protein inversion (Santos et al., 1997a). When a 50:50 mix of steam-flaked and dry-rolled sorghum was fed, a positive associative response in DMI seemed to occur (Oliveira et al., 1993); although milk production was not affected, these cows increased BW gain.

Production trials with high-producing cows fed similar amounts of RDS from different processing methods (i.e., varying starch percentage in the diet) for long enough periods to measure true lactation performance responses (including BW change) are needed. In support of this conclusion, fine-grinding of dry corn increased milk production in only one of three Latin squares (Knowlton et al., 1996), and fine grinding of corn had no effect on milk production in a Latin square design while increasing milk production in a companion production trial (Knowlton et al., 1998). Production trials allow evaluation of treatment × time responses, which could have residual effects on DMI or other factors as a result of grain processing. However, Dann et al. (1999) noted that in cows steam-flaked corn compared with cracked corn increased milk production whether or not it was fed prepartum or starting immediately postpartum.

### *Effects of Grain Processing on Ruminal Starch and Fiber Digestibilities*

Theurer et al. (1999) noted that steam-flaking of corn decreased fiber digestibility by 22% in the rumen and 16% in the total tract, but results were less consistent for sorghum. In contrast, when means were adjusted for unequal variance and experiment effects, differences in total tract NDF digestibility were lower (Table 3). Reynolds et al. (1997) noted that some studies might have had depressed ruminal fiber digestibility as a result of limitations in ruminally degradable protein rather than only as a result of starch availability as affected by grain processing. The decreased fiber digestibility in the total tract by steam-flaking of corn in some studies seems to be related to a ruminal effect and the potential for compensatory fiber digestion postruminally. Steam-flaking at 309 compared with 361 g/L (Yu et al., 1998) or 320 vs 390 g/L (Plascencia and Zinn, 1996) depressed total tract fiber digestibility by 28 and 15%, respectively. However, in the latter study, fiber digestibility in the rumen was depressed for steam-flaked corn compared with the dry-rolled corn control, negating a benefit on ruminal OM digestibility (Table 6). In contrast, compensatory digestion of fiber postruminally allowed an improvement in total tract OM digestibility for the average of the steam-flaked corn diets (Table 6). This study clearly shows how a large improvement in starch digestibility can be offset by reduced fiber digestibility and why corn probably should not be flaked too finely without potentially needing to increase the concentration of effective fiber in the diet. It also illustrates how large differences in ruminal digestibilities of starch and fiber can be equalized for total tract OM digestibility (Table 3). Steam-flaking depressed ruminal cellulose, but not hemicellulose, digestibility but had no effect on total tract fiber digestibility (Poore et al., 1993a). When high-moisture corn replaced dry corn (rolled or ground), total tract NDF digestibility was depressed from 31.7 to 26.0% (Knowlton et al., 1998). Because even the dry corn diets had low NDF digestibilities, apparently even postruminal compensatory digestion could not overcome the inhibition of fiber digestion in the rumen in that study.

**Table 6.** Site of digestibility in dairy cows fed corn steam-flaked to different densities[a]

| | | Steam-flaked corn density, kg/L | | |
|---|---|---|---|---|
| Apparent digestibility | Dry-rolled corn | 0.39 | 0.32 | 0.26 |
| Rumen, % intake | | | | |
| Starch[b] | 47.0 | 45.3 | 64.6 | 69.1 |
| ADF[bc] | 49.7 | 41.8 | 36.9 | 25.4 |
| OM | 46.0 | 41.6 | 49.8 | 47.2 |
| Total tract, % intake | | | | |
| Starch[cd] | 76.7 | 92.8 | 96.8 | 98.5 |
| ADF[bc] | 45.0 | 50.0 | 42.4 | 40.5 |
| OM[c] | 62.7 | 71.2 | 72.6 | 72.8 |

[a]From Plascencia and Zinn (1996).
[b]Linear effect of steam-flaking density ($P < 0.05$).
[c]Dry-rolled vs average of steam-flaked ($P < 0.01$).
[d]Linear effect of steam-flaking density ($P < 0.10$).
[e]Quadratic effect of steam-flaking density ($P < 0.05$).

Variable responses in fiber digestibility can be attributed, in part, to type and amount of effective fiber in the diet. Fine-grinding of corn shifted more digestion of NDF postruminally with no net effect on total tract fiber digestibility (Callison et al., 2001). Similarly, fine-grinding increased total tract digestibility of starch by 6.6 percentage units while depressing NDF digestibility by 2.9 percentage units (Knowlton et al., 1996). In many studies the lack of effect of grain processing on NDF digestibility (Poore et al., 1993a; Joy et al., 1997; Harvatine, 2000) could have been a result of alfalfa's high cation exchange capacity (Erdman, 1988; Van Soest et al., 1991). Also, when comparing barley to corn, depressed fiber digestibility could be due to lower ruminal pH (McCarthy et al., 1989; Overton et al., 1995); when pH remained higher than 6.0 for much of the feeding cycle, fiber digestibility was not affected (Yang et al., 1997b).

*Grain Processing and Ruminal Nitrogen Metabolism*

Reynolds et al. (1997) and Theurer et al. (1999) noted that increasing the ruminal degradability of starch through processing of grains typically increases microbial N flow to the duodenum, which was confirmed by our regression analysis (see later discussion; Table 8). Steam-flaking increased microbial N flow for diets based on corn (Crocker et al., 1998; Harvatine, 2000) or sorghum (Poore et al., 1993a). However, fine-grinding of corn did not increase microbial N flow, despite a large increase in ruminal starch digestibility (Callison et al., 2001). Ruminal NDF digestibility and pH tended to be depressed in the latter study. Overton et al. (1995) reported a quadratic effect of replacement of barley starch for cornstarch on microbial N flow, coinciding with decreased ruminal NDF digestibility and decreasing DMI. Increased availability of starch likely supports more microbial growth until depressions in ruminal fiber digestibility or DMI offset the increased amount of carbohydrate available for microbial protein synthesis. Also, when DMI decreases, the intake of RDS (g/d) increases to a lower degree than the improvement in percentage of RDS. Efficiency of microbial protein synthesis typically was not affected by starch availability in the rumen in studies cited herein.

Nonammonia-nonbacterial N flow, calculated as percentages of N intake or nonammonia N flow, is an estimate of dietary protein degradability. This needs to be considered concomitantly with effects of grain availability on microbial N flow. Grinding corn more finely (Callison et al., 2001), replacing barley for corn (McCarthy et al., 1989; Overton et al., 1995), or feeding dent vs flint corn (Philippeau et al., 1999) decreased nonammonia-nonbacterial N flow. Because denaturing the protein matrix surrounding starch probably increases starch availability (Kotarski et al., 1992; McAllister et al., 1993), it seems likely that the improvement in microbial N flow to the duodenum from grain processing should be partially offset by the decreased ruminal escape of protein from the grain. However, although steam-flaking of sorghum decreased flow of undegraded protein in one study (Poore et al., 1993a), no effect or numerical increases were noted for steam-flaked sorghum (Yu et al., 1998) or corn (Plascencia and Zinn, 1996; Joy et al., 1997; Crocker et al., 1998) compared to dry-rolled grains. The heat and pressure from steam-flaking compared with dry-rolling could alleviate a reduction in flow of grain protein resulting from more extensive processing. An important consideration should be the net duodenal flows of methionine and lysine. Increased ratio of microbial protein to undegraded grain protein reaching the duodenum should increase lysine flow even if the overall net effect on nonammonia N flow is not greatly affected (Clark et al., 1992).

More research relating ruminal availability of starch to ruminal N metabolism is needed. Huntington (1997) noted that ruminal degradability of starch and supply of ruminally degradable protein were often confounded with differences in DMI. Also, many studies comparing barley to corn or sorghum concomitantly altered the total NDF concentration of the diet, and barley fiber might be at least partly effective at simulating chewing (Beauchemin et al., 1997). Finally, if microbial DM flow to the duodenum increases, the increased flow of microbial starch could reduce the perceived treatment response on apparent ruminal starch digestibility or on efficiency of microbial protein synthesis. Mills et al. (1999a) noted that harvested bacteria have 17 to 25% starch. Harvatine (2000) noted that efficiency of microbial protein synthesis was not affected by replacement of forage NDF with cottonseed NDF when microbial N flow was expressed per unit of OM truly digested but was decreased by 25% when expressed per unit of carbohydrate (starch and NDF) truly digested in the rumen.

## Regression Analysis of Ruminal Digestibility for Different Grains

Although numerous studies have evaluated lactation performance and nutrient digestibilities in the total

**Table 7.** Statistical description of variables used in the data file for prediction of ruminal digestibility[a]

| Variable | n | Mean | SD | Minimum | Maximum |
|---|---|---|---|---|---|
| Forage, % of DM | 139 | 47.2 | 10.8 | 0 | 74.3 |
| CP, % of DM | 139 | 16.9 | 1.6 | 11.3 | 19.9 |
| NDF, % of DM | 137 | 32.9 | 5.0 | 17.6 | 45.8 |
| Starch, % of DM | 100 | 31.4 | 7.2 | 13.7 | 47.6 |
| Starch digestibility, % intake | 8 | 57.6 | 15.6 | 24.8 | 87.4 |
| NDF digestibility, % intake | 121 | 43.5 | 11.3 | 11.4 | 71.2 |
| OM digestibility, % intake | 121 | 36.5 | 9.4 | 15.5 | 55.3 |
| Microbial N, g/d[b] | 139 | 270 | 71 | 126 | 492 |
| DMI, kg/d | 139 | 20.3 | 2.6 | 14.1 | 26.8 |
| DMI, % of BW | 112 | 3.41 | 0.48 | 2.17 | 4.97 |

[a]Starch was measured by enzymatic hydrolysis but included free sugars in some experiments. Starch digestibilities were apparent, but OM digestibilities were on a true basis (corrected for bacterial OM).
[b]Duodenal flow of microbial N.

tract for different grain types, fewer data like that in Table 6 evaluating site of nutrient digestion are available for grain sources and processing methods. A data file was established containing studies with objectives generally not related to grain processing, and grain source was evaluated as in the previous regression analysis. All lactating cows in the data file generated by Oldick et al. (1999) were used, and treatment means and SE of the means from eight additional studies with lactating cows were added (Plascencia and Zinn, 1996; Joy et al., 1997; Yang et al., 1997b, 2000; Crocker et al., 1998; Beauchemin et al., 1999; Harvatine, 2000; Callison et al., 2001). All cows were Holsteins, but there was a large range in DMI calculated as a percentage of BW (Table 7). A study (Espindola et al., 1997) evaluating ruminal digestibilities of wheat could not be used because it was the only experiment with lactating cows fed wheat, and the experiment effect could not be separated from the effect of grain source.

The same regression procedures were used as described previously. Briefly, experiment was a random effect class variable, and grain source was a fixed-effect class variable. Continuous dependent variables were apparent starch (enzymatic procedure) digestibility, NDF digestibility, true (corrected for duodenal flow of bacterial OM) OM digestibility in the rumen, and duodenal flow of microbial N. Continuous independent variables were dietary concentrations of NDF, CP, forage, and starch; another continuous independent variable was DMI both as a percentage of BW and kilograms per day (Table 7). In all regressions, DMI (percentage of BW) and starch were eliminated, so the procedure was redone with DMI (kg/d) and without starch. When final independent variables were $P < 0.05$, all possible squared terms were added, and the process was repeated until all linear and squared terms for independent variables were $P < 0.10$ (actually, all were $P < 0.05$ for all data shown). The least squares means for grain source are presented in Table 8, and the other parameter estimates remaining in the final regression models are shown in Table 9 standardized to dry-rolled corn. As explained previously, dry-rolled corn was chosen as the initial reference to which processing improved starch digestibility. If a different standard would have been used, only the intercept would have been changed by the magnitude that the least squares means of the alternative standard would differ from the least squares mean for dry-rolled corn.

The range in the dependent and independent continuous variables (Table 7) is similar to that for the previous analysis (Table 2). However, because many of the experiments did not overlap and because the final models were different, use of results for ruminal digestibility should be compared with caution to results for total tract digestibility. One study in the current data file had all forage replaced with sources of nonforage fiber. Because only cannulated cows were used, the DMI averaged about 2 kg/d lower in the current data file than in the previous one.

### *Ruminal Starch Digestibility*

As expected, grinding increased apparent ruminal digestibility of starch compared with rolling. Steam-flaked corn had a low RDS compared with high-moisture corn (Table 8). The low apparent digestibilities of starch for steam-flaked corn sources in two recent trials (Joy et al., 1997; Crocker et al., 1998) probably had a large impact on the least squares means, and the random effect of experiment might not have totally equalized these data compared with much higher starch digestibility in other experiments with other grain sources. However, the means for both dry-rolled and steam-flaked corn were adjusted to be higher than those shown in Table 1, even though many of the same data were used. Also, even corn sources that were steam-flaked suboptimally to result in higher densities were used in the regressions. Because the apparent ruminal starch digestibility means for dry-rolled corn are similar in this data file to that in Table 6, the starch digestibilities for steam-flaked corn shown in that particular study seem to be more realistic, and steam-flaked corn should probably have an apparent RDS of about 65%. The high apparent ruminal digestibility of starch for

**Table 8.** Least squares means of ruminal digestibilities (% of intake) and duodenal flow of microbial N (g/d) from lactating cows fed different grain sources[a]

| | Starch, apparent | | | NDF | | | OM, true | | | Microbial N | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Grain | n[b] | Mean | SE | n | Mean | SE | n | Mean | SE | n | Mean | SE |
| Corn | | | | | | | | | | | | |
| Dry, cracked or rolled | 6 | 44.6 | 4.6 | 6 | 48.1 | 3.3 | 9 | 52.3 | 2.5 | 10 | 276 | 14 |
| Dry, ground | 77 | 52.3 | 2.1 | 52 | 44.9 | 2.2 | 69 | 48.6 | 1.6 | 73 | 257 | 10 |
| Steam-flaked | 9 | 56.9 | 4.4 | 9 | 41.9 | 3.1 | 6 | 52.8 | 2.7 | 4 | 296 | 14 |
| High-moisture | 12 | 86.8 | 8.6 | 2 | 47.1 | 6.2 | 12 | 60.1 | 4.5 | 12 | 236 | 26 |
| Sorghum | | | | | | | | | | | | |
| Dry, rolled or ground | 4 | 48.1 | 6.8 | 4 | 49.6 | 7.1 | 4 | 49.2 | 5.0 | 4 | 278 | 38 |
| Steam-flaked | 7 | 74.0 | 5.9 | 7 | 43.9 | 7.3 | 3 | 56.3 | 4.7 | 6 | 357 | 34 |
| Barley | | | | | | | | | | | | |
| Dry- or steam-rolled | 15 | 71.2 | 2.8 | 15 | 37.6 | 3.1 | 15 | 56.2 | 2.3 | 11 | 299 | 13 |
| Steam-rolled, hull-less | 3 | 67.9 | 5.2 | 3 | 36.8 | 3.6 | 3 | 56.4 | 2.9 | 3 | 274 | 17 |

[a]All least squares means were adjusted for the random effect of experiment and for the mean of all continuous variables remaining in the final model (See Table 9).
[b]Number of treatment means.

high-moisture corn (Table 8) could be a result of low number of treatment means (many studies with this source of corn did not measure starch digestibility) and the high SE of the least squares mean; because correction for microbial starch would result in nearly complete starch digestion in the rumen, more research is needed to evaluate the RDS of high-moisture corn. However, this high RDS coincides with its high total tract starch digestibility (Table 3).

As discussed previously, the apparent ruminal digestibility of starch was higher for steam-flaked sorghum than for its dry-rolled form, and apparent starch digestibility in the rumen was high for barley (Table 8).

The least squares means for the apparent ruminal digestibility of starch (Table 8) are influenced by other dependent variables remaining in the final models (Table 9). Each increase in 1 kg/d of DMI would be predicted to decrease the RDS by 1.2 percentage units, and each increase of one percentage unit of forage would decrease RDS by 0.5 percentage unit. The latter effect could be an indirect result of the inverse relationship with forage and grain percentage in the diet. Higher intake of grain starch could dilute endogenous sources or other dietary sources of starch that are lower in digestibility.

The effect of DMI on apparent ruminal starch digestibility is shown in Figure 4a. Apparent ruminal starch digestibility data were adjusted for the effect of forage percentage (mean of 45.5%) from the experiments remaining in the final model. The mean for forage percentage deviated slightly from that from all experiments (47.7%; Table 7) because some experiments did not report NSC digestibility. To adjust for the effect of grain

**Table 9.** Best-fit equations for multiple regression of responses to grain source standardized to dry-rolled corn for ruminal digestibility and duodenal flow of microbial N by lactating dairy cows[a]

| Parameter | Intercept | SE | Variable[b] | Coefficient | SE | RMSE[c] |
|---|---|---|---|---|---|---|
| Apparent starch digestibility, % of intake | 91.6 | 12.6 | DMI | –1.21 | 0.59 | 5.3 |
| | | | Forage | –0.474 | 0.134 | |
| NDF digestibility, % of intake | –57.0 | 26.7 | NDF | 3.17 | 0.82 | 3.2 |
| | | | Forage | 1.92 | 0.56 | |
| | | | Forage$^2$ | –0.00617 | 0.00294 | |
| | | | NDF × forage | –0.0483 | 0.0165 | |
| True OM digestibility, % | 59.5 | 3.9 | Forage | –0.153 | 0.065 | 3.3 |
| Microbial N, g/d | –15.2[d] | 38.6 | DMI | 14.4 | 1.9 | 19 |

[a]All data are adjusted for the random effect of experiment and weighted for unequal variance. The equations are standardized relative to the mean of dry-rolled corn in Table 8. The intercept in this table would be adjusted for each least squares mean minus that for dry-rolled corn (Table 8) for each respective regression. Unless shown otherwise, all estimates were $P < 0.05$ from zero.
[b]NDF = percentages of dietary DM, DMI (kg/d) is of the entire diet, and forage = percentage of forage in the diet.
[c]RMSE = Root mean square error after adjusting for the random effect of experiment.
[d]Not significant ($P > 0.10$).

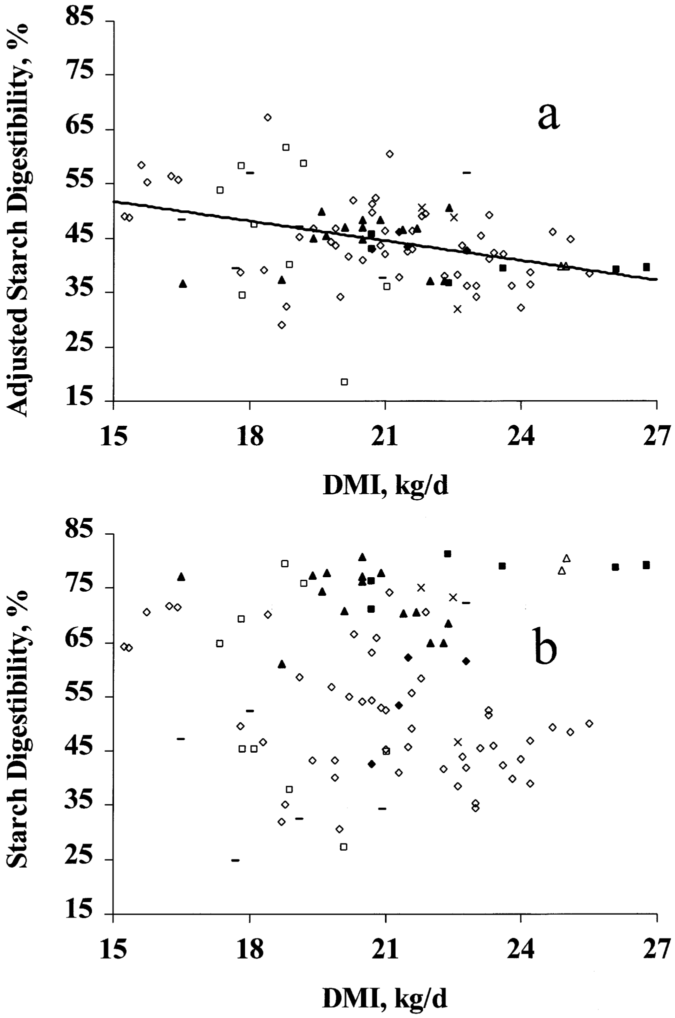


**Figure 4.** The relationship between apparent starch digestibility in the rumen (of intake) and DMI. Data were weighted for the unequal variance among experiments, adjusted for the random effect of experiment, adjusted to the mean forage level of 45.5%, and adjusted for the effect of grain source by being standardized relative to dry-rolled corn in Panel a, but unweighted, observed data are shown in Panel b. In Panel a, the line represents the regression coefficient for DMI (Table 9; slope of –1.21; SE of 0.59). Data are for dry-rolled corn (—), dry-ground corn (◇), steam-flaked corn (□), high-moisture corn (△), dry-rolled sorghum (♦), steam-flaked sorghum (■), barley (▲), and hull-less barley (X).

source, all data were adjusted to the dry-rolled corn reference; that is, data were adjusted as if the grain source were always dry-rolled corn (St-Pierre, 2001). The line represents the slope of a 1.2-percentage-unit decrease per 1-kg increase in DMI (Table 9). At the mean DMI of 20.9, the predicted RDS would be 44.6%, which is the least squares mean for apparent ruminal starch digestibility of dry-rolled corn reported in Table 8. A 1-kg increase is about a 5% change in DMI from the mean of 20.9 kg/d; therefore, the associated change in RDS (1.2% per 1-kg change in DMI) is relatively minor. This could be because increasing DMI could increase ruminal volume along with increasing passage rate. Because BW measurements were not reported in some studies, DMI was not scaled to BW in order to better represent effects of passage rate on RDS. Clearly, the adjustment procedures accounted for considerable variation (Figure 4a vs Figure 4b). However, when compared to the large impact of adjustment of experiment and dietary effects on milk fat percentage (Figure 3a vs 3b), a large amount of variation remained unaccounted for in the RDS data. In addition to the lack of BW data, analytical methods for starch analysis and errors in duodenal flow measurements seem to be likely sources of error. Despite this variation, the effect of grain processing on ruminal or total tract starch digestibility would seem to have a smaller impact on total $NE_L$ intake than would the effect of grain processing on DMI.

## *Ruminal NDF and OM Digestibility*

Except for high-moisture corn, increasing the digestibility of the grain by grinding or steam-flaking decreased ruminal NDF digestiblity (Table 8). The depressed NDF digestibility partially negated the overall response in true OM digestibility in the rumen. The least squares means for ruminal digestibilities of NDF and OM were related to NDF and(or) forage percentages of the diet (Table 9). When forage percentage of the diet is held constant, NDF digestibility is predicted to decrease at a diminishing rate by decreased dietary percentage of NDF; when NDF percentage is held constant, NDF digestibility is predicted to increase at a diminishing rate as forage percentage decreases. With changing forage NDF concentrations in the diet, these two factors would tend to cancel each other, but with replacement of forage with nonforage NDF, NDF digestibility should increase. Many sources of nonforage fiber have a relatively high potential digestibility of NDF (Firkins, 1997). Also, decreasing NDF percentage would likely increase the percentage of dietary starch, increasing negative associative effects. Decreasing percentage of forage in the diet would be predicted to increase true OM digestibility and NDF digestibility at a relatively similar rate within the range of forage percentages used in these experiments.

## *Microbial N Flow to the Duodenum*

Microbial N flow to the duodenum was highest for steam-flaked sorghum, barley, and steam-flaked corn but lowest for high-moisture corn (Table 8). Therefore, increasing RDS would be predicted to improve microbial N flow so long as DMI is not affected. Although a moderately high SE for high-moisture corn reduced the precision and perhaps accuracy of this least squares mean, a high ruminal starch digestibility would likely reduce ruminal pH, which could decrease efficiency of microbial protein synthesis (Firkins, 1996). However, this conclusion seems to contradict the ruminal pH and chewing responses by cows fed high-moisture corn in a different regression (see later discussion; Table 11). Therefore, another possibility is that high-moisture corn has a slow passage rate from the rumen and stimulates rumination because of its large size and hydration. A slower passage rate also could decrease efficiency of microbial protein synthesis (Firkins, 1996). More work is needed to evaluate differences in passage rate among grain sources and their effect on digestibility and microbial N flow.

If high RDS decreased DMI, then the amount of microbial N flowing to the duodenum should also decrease because DMI was positively related to microbial N flow (Table 9). In a previous regression analysis (Oldick et al., 1999), grain source was not included as a fixed effect in the model; NDF percentage was inversely related to microbial N flow, but DMI was positively related. In the present regression, NDF concentration was not related to microbial N flow, probably because grain source explained the variation better than did NDF concentration.

### Effective Fiber and Ruminal Available Starch

As forage NDF (**FNDF**) is replaced by nonforage NDF, total tract NDF digestibility seems to decrease as a result of increasing negative associative effects (Firkins, 1997). Similarly, as the ratio of forage NDF to RDS decreased below 1:1, Poore et al. (1993b) suggested that ruminal function was compromised by excessive acidity in the rumen. With lactating dairy cows fed 18% forage NDF, the following regression equation was developed (Beauchemin et al., 1997): Milk, kg/d = –5.6 + 23.4 (kg/d of RDS) – 4.31 × RDS$^2$. The maximum milk production can be predicted to occur at 2.7 kg/d RDS or a forage NDF to RDS ratio of 1.25:1 (18.6 kg/d DMI × 18% forage NDF ÷ 2.7 kg/d RDS). When FNDF was replaced with cottonseed fiber, RDS (ground vs steam-flaked corn) did not interact for digestibility or chewing response (Harvatine, 2000).

Dietary (e.g., FNDF) and animal response indices have been suggested as measures of effective fiber in diets (Allen, 1997; Mertens, 1997). Minimum FNDF percentages for dairy rations have been recommended based on the dietary NFC concentration (NRC, 2001). Poore et al. (1993b) suggested an optimum ratio of FNDF to RDS; however, values for RDS are not easily determined for routine use in ration evaluation without some potential error. Other complicating factors in evaluating the effects of concentration of dietary NSC on animal response are the lack of uniformity in laboratory analyses and varying rates of fermentation for different NSC sources. Therefore, it would be helpful for field application to have animal response indices that could be used to assess and trouble-shoot dairy rations on farms. The indices evaluated in published studies include both those difficult to measure under field conditions (e.g., ruminal pH, ruminal acetate to propionate, and chewing) and those easily assessed under field conditions (e.g., milk fat percentage and milk fat to protein ratio). We chose to perform regression analyses to relate FNDF to various response criteria related to ruminal function with the aim of developing relationships that could be used in field applications.

### Regression Analyses of Forage NDF Effects

Data from 31 studies (Sarwar et al., 1992; Aldrich et al., 1993; Clark and Armentano, 1993, 1997; Croomer et al., 1993; Cunningham et al., 1993; Wagner et al., 1993; Batajoo and Shaver, 1994; Beauchemin et al., 1994a, 1997; Swain and Armentano, 1994; Weidner and Grant, 1994; Depies and Armentano, 1995; Elliott et al., 1995; Ruiz et al., 1995; Weiss, 1995; Beauchemin and Rode, 1997; Harmison et al., 1997; West et al., 1997, 1998, 1999; Zhu et al., 1997; Younker et al., 1998; Kennelly et al., 1999; Mowrey et al., 1999; Pereira et al., 1999; Schingoethe et al., 1999; Allen and Grant, 2000; Harvatine, 2000; Oba and Allen, 2000; Slater et al., 2000) were compiled to investigate the interaction of dietary concentrations of effective fiber, as defined as FNDF, and NSC on animal responses. A description of the data is shown in Table 10. The data ranges for the animal response and dietary variables were similar to the data ranges used for analyses of total tract digestibility (Table 2). Some differences occurred because several of the studies were selected based on treatments with nonforage fiber sources for partial replacement of FNDF. All the studies were with lactating cows fed various forages, including alfalfa, bermudagrass, corn silage, barley silage, barley and triticale silage, elephant grass, orchardgrass, and sorghum. Backward elimination of multiple regression was performed similarly to the algorithm reported by Oldick et al. (1999). Grain source and dietary concentrations of CP, NDF, and FNDF were used to assess the variation in DMI, milk yield, milk fat percentage, and milk protein percentage. With fewer data available, grain source, CP, NDF, FDNF, NSC, and the ratio of FNDF to NSC were used to assess chewing, ruminal pH, ruminal acetate to propionate, and milk fat percentage. Data were analyzed using Proc Mixed (SAS Inst., Inc.) and the procedures discussed previously in this paper.

Dietary grain source and concentrations of effective fiber and NSC contributed to the variation in ruminal pH and ruminal acetate to propionate (Table 11). The shelled corn resulted in lower rumen pH compared to the dry ear corn, probably because the shelled corn was more finely ground and the fiber from the cob was not being accounted for as FNDF. The high-moisture shelled corn resulted in lower ruminal acetate to propionate because of high fermentability of the NSC (Table 8) and absence of the fiber from the cob. Dietary NSC did not affect chewing (minutes per day); however, a combination of corn and wheat in the diet vs high-moisture shelled corn decreased chewing. Yet, high-mois-

**Table 10.** Statistical description of variables used in the data file for investigating the interaction of dietary effective fiber and starch

| Variable[a] | n | Mean | SD | Minimum | Maximum |
|---|---|---|---|---|---|
| Animal response | | | | | |
| DMI, kg/d | 185 | 21.3 | 2.6 | 14.4 | 27.6 |
| Milk, kg/d | 185 | 28.5 | 5.4 | 19.5 | 40.4 |
| Milk fat, % | 184 | 3.45 | 0.51 | 2.35 | 5.01 |
| Milk protein, % | 183 | 3.28 | 0.25 | 2.84 | 4.04 |
| Ruminal pH | 57 | 6.16 | 0.40 | 5.62 | 7.34 |
| Ruminal acetate to propionate | 106 | 2.76 | 0.56 | 1.31 | 3.98 |
| Chewing, min/d | 72 | 657 | 119 | 469 | 962 |
| Chewing, min/kg NDF intake | 39 | 102 | 21 | 58 | 157 |
| Dietary composition, % | | | | | |
| CP | 185 | 17.8 | 1.6 | 13.0 | 22.1 |
| NDF | 185 | 33.7 | 6.3 | 19.5 | 49.5 |
| FNDF | 181 | 20.7 | 6.1 | 9.4 | 39.9 |
| NSC | 69 | 31.8 | 6.9 | 17.5 | 50.2 |

[a]FNDF = forage NDF, NSC = nonstructural carbohydrates (enzymatic assay).

ture shelled corn resulted in more chewing per day than diets with dry shelled corn.

In each of the dependent variables examined, FNDF was important in the models (Table 12). It was the only significant variable in the model for milk yield and milk fat percentage (Model 1). Milk yield decreased linearly with increasing FNDF, probably because of its effects on DMI. Although effective NDF did not enter the model, increasing the proportion of forage in the diet decreased DMI in the data file used for analysis of total tract digestibilities (Table 5). Milk fat percentage responded in a quadratic fashion to FNDF percentage of the diet (Table 12). The negative effects of NDF and FNDF on DMI were probably a result of bulk fill in some diets and FNDF not accounting for effective fiber from whole cottonseeds or other sources of nonforage fiber. Both FNDF and NSC concentrations were the variables that contributed significantly to the variation in milk fat percentage (Model 2), ruminal pH, ruminal acetate to propionate, and chewing (minutes per kilogram of NDF). When holding FNDF constant, increasing NSC decreases ruminal pH and acetate to propionate. The FNDF was much more influential than total NDF in explaining the variation in ruminal measurements and chewing because the diets in the data set contained a variety of nonforage fiber sources that contributed fiber that is less effective than that from forages.

In an attempt to use a single variable to account for the concentrations of dietary FNDF and NSC, the FNDF/NSC was examined. It was important in the regression for milk fat percentage (Model 2). At first

**Table 11.** Least squares means for dependent variables for which grain source contributed significantly to the regression model

| Item | n | Mean | SE | Other variables in model[a] |
|---|---|---|---|---|
| Ruminal pH | 27 | | | FNDF, NSC |
| Dry ear corn | | 6.27[x] | 0.11 | |
| High-moisture shelled corn | | 6.23[y] | 0.12 | |
| Shelled corn[b] | | 6.01[y] | 0.05 | |
| Ruminal acetate to propionate | 41 | | | FDNF, NSC |
| Corn and wheat | | 2.84[y] | 0.20 | |
| Dry ear corn | | 3.22[x] | 0.36 | |
| High-moisture shelled corn | | 2.65[y] | 0.36 | |
| Shelled corn[b] | | 2.80[xy] | 0.13 | |
| Chewing, min/d | 72 | | | CP, NDF, FNDF |
| Barley[c] | | 671[y] | 22 | |
| Corn and wheat | | 546[x] | 76 | |
| High-moisture shelled corn | | 760[y] | 51 | |
| Shelled corn[b] | | 649[x] | 15 | |

[a]FNDF = forage NDF; NSC = nonstructural carbohydrates (enzymatic assay). See Table 12 for regression coefficients.

[b]Shelled corn consisted of diets with dry shelled corn processed to various particle sizes, steam-rolled corn, or a combination of dry and high-moisture shelled corn.

[c]Barley consisted of diets with barley processed dry or steam-rolled, and with or without hulls.

[x,y]Means within item with different superscripts differ ($P < 0.05$).

**Table 12.** Best-fit equations for multiple regression of animal responses to grain source standardized to dry-shelled corn[a]

| Parameter | n | Intercept | SE | Variable[b] | Coefficient | SE | RMSE[c] |
|---|---|---|---|---|---|---|---|
| DMI, kg/d | 181 | 25.8 | 1.0 | NDF | −0.0728 | 0.0336 | 1.6 |
| | | | | FNDF | −0.0882 | 0.0366 | |
| Milk, kg/d | 181 | 32.7 | 1.4 | FNDF | −0.179 | 0.053 | 2.9 |
| Milk fat, %[d] | | | | | | | |
| Model 1 | 180 | 2.41 | 0.28 | FNDF | 0.0778 | 0.0235 | 0.25 |
| | | | | $FNDF^2$ | −0.00120 | 0.00048 | |
| Model 2 | 65 | 3.73 | 0.29 | FNDF | 0.0592 | 0.0126 | 0.15 |
| | | | | NSC | −0.0280 | 0.0075 | |
| | | | | FNDF/NSC | −0.887 | 0.298 | |
| Milk protein, % | 179 | 4.16 | 0.35 | CP | −0.0397 | 0.0183 | 0.16 |
| | | | | FNDF | −0.00920 | 0.00271 | |
| Ruminal pH[e] | 27 | 5.81 | 0.14 | FNDF | 0.0226 | 0.0061 | 0.04 |
| | | | | NSC | −0.00721 | 0.00238 | |
| Ruminal A:P[e,f] | 41 | 2.06 | 0.24 | FNDF | 0.0676 | 0.0084 | 0.13 |
| | | | | NSC | −0.0150 | 0.0037 | |
| Chewing, min/d[e] | 72 | −179 | 154 | CP | 30.07 | 7.4 | 28 |
| | | | | NDF | 5.014 | 1.588 | |
| | | | | FNDF | 6.779 | 1.092 | |
| Chewing, min/kg NDF intake | 23 | 62.2 | 25.2 | FNDF | 0.694 | 0.316 | 5.9 |
| | | | | NSC | 0.897 | 0.593 | |

[a]All data were adjusted for the random effect of experiment and weighted for unequal variance. The intercept is for dry-shelled corn in Table 11 when grain source was significant.
[b]FNDF = forage NDF; NSC = nonstructural carbohydrates (enzymatic assay).
[c]Root mean square error after adjustments for the random effect of experiment.
[d]Two models are shown because including NSC in the model limited the use of all data from the available trials.
[e]Grain source contributed ($P < 0.05$) to the model, and least squares means by grain source are provided in Table 11.
[f]A:P = acetate to propionate.

glance, the large coefficient for NSC would seem to cause a greater reduction in milk fat percentage than actually occurred. An increase in NSC concentration typically would decrease FNDF to NSC, which also has a negative relationship with milk fat percentage. Therefore, the net effect of NSC concentration for the prediction of milk fat percentage based on Model 2 was not as pronounced as the single coefficient for NSC would indicate. The FNDF/NSC was significantly correlated ($P < 0.01$) with ruminal pH, ruminal acetate to propionate, and chewing (minutes per day), but considerable collinearity among variables was noted (Table 13). Therefore, any single variable for assessment of rumen function should be used with caution.

## Net Energy Values of Processed Grains

### *Current Perspective*

Theurer et al. (1999) provided evidence that the $NE_l$ of steam-flaked corn and sorghum should be 2.17 and 2.15 Mcal/kg of DM, respectively, but the calculated response in $NE_l$ of steam-flaked corn and sorghum varied somewhat among studies cited therein. More studies need to report sieved fractions of grains that have generally been referred to as ground, cracked, or rolled. The comparison of $NE_l$ of a processed grain to a control (i.e., cracked) depends on the fineness of grind for the actual response but also to the control grain treatment in the by-difference calculations. The uncertainty and accuracy in response to the control are therefore compounded when they are compared to a more disruptive processing method. Also, as shown previously, the degree of processing seems to be related to NDF digestibility, partially negating the response in OM digestibility in many studies. Therefore, improving the $NE_l$ concentration of a grain source can be at the expense of the actual $NE_l$ concentration of other ingredients that contribute potentially digestible fiber. Because of these complicated interactions, calculating total dietary $NE_l$ concentration based on the weighted average of individual reference values for $NE_l$ concentration for individual feeds would likely cause significant error. Although microbial N flow calculations (NRC, 2001) ignore site of digestion, some of the error (microbial N flow should be based on ruminal, not total tract, OM digestibility) would be canceled out by the discounting procedure used by the NRC (2001).

### *Future Perspective*

More studies are needed to evaluate continuous response curves of effective NDF to RDS within studies rather than simple discrete differences among grains.

**Table 13.** Correlation coefficients for variables used in the analyses for investigating the interaction of dietary effective fiber and starch[a]

| Item | pH | A:P | Milk fat | Fat/protein | Chewing, min/d | Chewing, min/kg NDF | NDF | FNDF | NSC | FNDF/NSC |
|---|---|---|---|---|---|---|---|---|---|---|
| Ruminal pH | 1.00 | | | | | | | | | |
| Ruminal A:P | 0.56** | | | | | | | | | |
| Milk fat, % | 0.54** | 0.24** | | | | | | | | |
| Milk fat/milk protein | 0.51** | 0.29** | 0.83** | | | | | | | |
| Chewing, min/d | 0.61* | 0.34* | 0.41** | 0.41** | | | | | | |
| Chewing, min/kg NDF intake | 0.34 | 0.02 | −0.01 | −0.02 | 0.56** | | | | | |
| NDF, % of DM | 0.55** | 0.28** | 0.43** | 0.56** | 0.66** | −0.19 | | | | |
| FNDF, % of DM | 0.52** | 0.50** | 0.31** | 0.49** | 0.63** | 0.15 | 0.68** | | | |
| NSC, % of DM | −0.31 | −0.33* | 0.10 | −0.04 | −0.47** | −0.30 | −0.53** | −0.16 | | |
| FNDF/NSC | 0.66** | 0.70** | 0.01 | 0.25* | 0.68** | 0.28 | 0.68** | 0.84** | −0.61** | 1.00 |

[a]FNDF = forage NDF, NSC = nonstructural carbohydrates, and A:P = ruminal acetate to propionate.
**$P < 0.01$.
*$P < 0.05$.

Mills et al. (1999a) highlighted the need to look at responses rather than at requirements. Reynolds et al. (1997) also cautioned that the basal diet needs to be considered when comparing results within and among studies. Our method of adjusting the data to the average effect of trial is an important improvement in regression analysis (Oldick et al., 1999; St-Pierre, 2001), but too many sources of variation still remain unaccounted. A processing index (Yang et al., 2000) and other continuous assessors rather than discrete descriptions should help future compilations of variation among grain sources. Until then, improved prediction of ruminal and total tract digestibilities resulting from feeding processed grains can be used to set restraints in ration evaluation programs to help improve the flexibility and efficiency of dairy production.

## Implications

Methodologies to measure starch can be improved or at least standardized so that better comparisons of data across laboratories can be made. Regression procedures were used to account for the random effect of experiment and for other dietary variables to increase the accuracy of prediction of ruminal and total tract digestibilities of starch and NDF and of lactation performance for dairy cows fed various grain sources. Processing of grains to improve total tract starch digestibility also increased ruminal starch digestibility and increased microbial N synthesis but tended to decrease NDF digestibility. This information can help to formulate rations to reduce the risk of ruminal acidosis-related disorders and to evaluate the cost to benefit ratio of different grains or processing methods. Regression approaches such as these can improve predictability of responses, especially with better description by researchers of continuous variables (e.g., density and particle size) of processed grains.

## Literature Cited


Aldrich, J. M., L. D. Muller, G. A. Varga, and L. C. Griel. 1993. Nonstructural carbohydrate and protein effects on rumen fermentation, nutrient flow, and performance of dairy cows. J. Dairy Sci. 76:1091–1105.

Allen, D. M., and R. J. Grant. 2000. Interactions between forage and wet corn gluten feed as sources of fiber in diets for lactating dairy cows. J. Dairy Sci. 83:322–331.

Allen, M. S. 1997. Relationship between fermentation acid production in the rumen and the requirement for physically effective fiber. J. Dairy Sci. 80:1447–1462.

Allen, M. S. 2000. Effects of diet on short-term regulation of feed intake by lactating dairy cattle. J. Dairy Sci. 83:1598–1624.

Arieli, A., I. Bruckental, O. Kedar, and D. Sklan. 1995. In sacco disappearance of starch nitrogen and fat in processed grains. Anim. Feed Sci. Technol. 51:287–295.

Batajoo, K. K., and R. D. Shaver. 1994. Impact of nonfiber carbohydrate on intake, digestion and milk production by dairy cows. J. Dairy Sci. 77:1580–1588.

Beauchemin, K. A., B. I. Farr, L. M. Rode, and G. B. Schaalje. 1994a. Optimal neutral detergent fiber concentration of barley-based diets for lactating dairy cows. J. Dairy Sci. 77:1013–1029.

Beauchemin, K. A., T. A. McAllister, Y. Dong, B. I. Farr, and K.-J. Cheng. 1994b. Effects of mastication on digestion of whole cereal grains by cattle. J. Anim. Sci. 72:236–246.

Beauchemin, K. A., and L. M. Rode. 1997. Minimum versus optimum concentrations of fiber in dairy cow diets based on barley silage and concentrates of barley or corn. J. Dairy Sci. 80:1629–1639.

Beauchemin, K. A., L. M. Rode, and W. Z. Yang. 1997. Effects of nonstructural carbohydrates and source of cereal grain in high concentrate diets of dairy cows. J. Dairy Sci. 80:1640–1650.

Beauchemin, K. A., W. Z. Yang, and L. M. Rode. 1999. Effects of grain source and enzyme additive on site and extent of nutrient digestion in dairy cows. J. Dairy Sci. 82:378–390.

Callison, S. L., J. L. Firkins, M. L. Eastridge, and B. L. Hull. 2001. Site of nutrient digestion by dairy cows fed corn of different particle sizes or steam-rolled. J. Dairy Sci. 81:1458–1467.

Casper, D. P., H. A. Maiga, M. J. Brouk, and D. J. Schingoethe. 1999. Synchronization of carbohydrate and protein sources on fermentation and passage rates in dairy cows. J. Dairy Sci. 82:1779–1790.

Chen, K. H., J. T. Huber, C. B. Theurer, R. S. Swingle, J. Simas, S. C. Chan, Z. Wu, and J. L. Sullivan. 1994. Effect of steam flaking of corn and sorghum grains on performance of lactating cows. J. Dairy Sci. 77:1038–1043.

Clark, J. H., T. H. Klusmeyer, and M. R. Cameron. 1992. Microbial protein synthesis and flows of nitrogen fractions to the duodenum of dairy cows. J. Dairy Sci. 75:2304–2323.

Clark, P. W., and L. E. Armentano. 1993. Effectiveness of neutral detergent fiber in whole cottonseed and dried distillers grains compared with alfalfa haylage. J. Dairy Sci. 76:2644–2650.

Clark, P. W., and L. E. Armentano. 1997. Replacement of alfalfa neutral detergent fiber with a combination of nonforage fiber sources. J. Dairy Sci. 80:675–680.

Crocker, L. M., E. J. DePeters, J. G. Fadel, H. Perez-Monti, S. J. Taylor, J. A. Wyckoff, and R. A. Zinn. 1998. Influence of processed corn grain in diets of dairy cows on digestion of nutrients and milk composition. J. Dairy Sci. 81:2394–2407.

Croomer, J. C., M. J. Cecava, and T. R. Johnson. 1993. Response of early lactation cows to fat supplementation in diets with different nonstructural carbohydrate concentrations. J. Dairy Sci. 76:3747–3754.

Cunningham, K. D., M. J. Cecava, and T. R. Johnson. 1993. Nutrient digestion, nitrogen, and amino acid flows in lactating cows fed soybean hulls in place of forage or concentrate. J. Dairy Sci. 76:3523–3535.

Dado, R. G. 1999. Nutritional benefits of specialty corn grain hybrids in dairy diets. J. Anim. Sci. 77(Suppl. 2):197–207.

Dann, H. M., G. A. Varga, and D. E. Putnam. 1999. Improving energy supply to late gestation and early postpartum dairy cows. J. Dairy Sci. 82:1765–1778.

Depies, K. K., and L. E. Armentano. 1995. Partial replacement of alfalfa fiber with fiber from ground corn cobs or wheat middlings. J. Dairy Sci. 78:1328–1335.

Ekinci, C., and G. A. Broderick. 1997. Effect of processing high moisture ear corn on ruminal fermentation and milk yield. J. Dairy Sci. 80:3298–3307.

Elliott, J. P., J. K. Drackley, G. C. Fahey, and R. D. Shanks. 1995. Utilization of supplemental fat by dairy cows fed diets varying in content of nonstructural carbohydrates. J. Dairy Sci. 78:1512–1525.

Erdman, R. A. 1988. Dietary buffering requirements of the lactating dairy cow: A review. J. Dairy Sci. 71:3246–3266.

Espindola, M. S., E. J. DePeters, J. G. Fadel, R. A. Zinn, and H. Perez-Monti. 1997. Effects on nutrient digestion of wheat processing and method of tallow addition to the diets of lactating dairy cows. J. Dairy Sci. 80:1160–1171.

Firkins, J. L. 1996. Maximizing microbial protein synthesis in the rumen. J. Nutr. 126:1347–1354S.

Firkins, J. L. 1997. Effects of feeding nonforage fiber sources on site of fiber digestion. J. Dairy Sci. 80:1426–1437.

Forsberg, C. W., K.-J. Cheng, and B. A. White. 1997. Polysaccharide degradation in the rumen and large intestine. In: R. I. Mackie, B. A. White, and R. E. Isaacson (Ed.) Gastrointestinal Microbiology. vol. 2. Gastrointestinal Microbes and Host Interactions. pp 319–379. Chapman Hall, New York.

Garcia, S. C., F. J. Santini, and J. C. Elizalde. 2000. Sites of digestion and bacterial protein synthesis in dairy heifers fed fresh oats with or without corn or barley grain. J. Dairy Sci. 83:746–755.

Garrett, E. F., M. N. Pereira, K. V. Nordlund, L. E. Armentano, W. J. Goodger, and G. R. Oetzel. 1999. Diagnostic methods for the detection of subacute ruminal acidosis in dairy cows. J. Dairy Sci. 82:1170–1178.

Grings, E. E., R. E. Roffler, and D. P. Deitelhoff. 1992. Evaluation of corn and barley as energy sources for cows in early lactation fed alfalfa-based diets. J. Dairy Sci. 75:193–200.

Hall, M. B., J. P. Jennings, B. A. Lewis, and J. B. Robertson. 2000. Evaluation of starch analysis methods for feed samples. J. Sci. Food Agric. 81:17–21.

Hall, M. B., B. A. Lewis, P. J. Van Soest, and L. E. Chase. 1997. A simple method for estimation of neutral detergent-soluble fiber. J. Sci. Food Agric. 74:441–449.

Harmison, B., M. L. Eastridge, and J. L. Firkins. 1997. Effect of percentage of dietary forage neutral detergent fiber and source of starch on performance of lactating Jersey cows. J. Dairy Sci. 80:905–911.

Harvatine, D. I. 2000. Effectiveness of whole linted cottonseed as a forage substitute when fed with ground or steam-flaked corn. M.S. dissertation. The Ohio State Univ., Columbus.

Herrera-Saldana, R., R. A. Gomez-Alarcon, M. Torabi, and J. T. Huber. 1990. Influence of synchronizing protein and starch degradation in the rumen on nutrient utilization and microbial protein synthesis. J. Dairy Sci. 73:142–148.

Herrera-Saldana, R., and J. T. Huber. 1989. Influence of varying protein and starch degradabilities on performance of lactating cows. J. Dairy Sci. 72:1477–1483.

Huntington, G. B. 1997. Starch utilization by ruminants: From basics to the bunk. J. Anim. Sci. 75:852–867.

Joy, M. T., E. J. DePeters, J. G. Fadel, and R. A. Zinn. 1997. Effects of corn processing on the site and extent of digestion in lactating cows. J. Dairy Sci. 80:2087–2097.

Kalscheur, K. F., B. B. Teter, L. S. Piperova, and R. A. Erdman. 1997. Effect of dietary forage concentration and buffer addition on duodenal flow of *trans*-$C_{18:1}$ fatty acids and milk fat production in dairy cows. J. Dairy Sci. 80:2104–2114.

Kennelly, J. J., B. Robinson, and G. R. Khorasani. 1999. Influence of carbohydrate source and buffer on rumen fermentation characteristics, milk yield, and milk composition in early-lactation Holstein cows. J. Dairy Sci. 82:2486–2496.

Knowlton, K. F., M. S. Allen, and P. S. Erickson. 1996. Lasalocid and particle size of corn grain for dairy cows in early lactation. 1. Effect on performance, serum metabolites, and nutrient digestibility. J. Dairy Sci. 79:557–564.

Knowlton, K. F., B. P. Glenn, and R. A. Erdman. 1998. Performance, ruminal fermentation, and site of starch digestion in early lactation cows fed corn grain harvested and processed differently. J. Dairy Sci. 81:1972–1984.

Kotarski, S. F., R. D. Waniska, and K. K. Thurn. 1992. Starch hydrolysis by the ruminal microflora. J. Nutr. 122:178–190.

Ladely, S. R., R. A. Stock, F. K. Goedeken, and R. P. Huffman. 1995. Effect of corn hybrid and grain processing method on rate of starch disappearance and performance of finishing cattle. J. Anim. Sci. 73:360–364.

Lykos, T., G. A. Varga, and D. Casper. 1997. Varying degradation rates of total nonstructural carbohydrates: Effects on ruminal fermentation, blood metabolites, and milk production and composition in high producing Holstein cows. J. Dairy Sci. 80:3341–3355.

Martin, C., C. Philippeau, and B. Michalet-Doreau. 1999. Effect of wheat and corn variety on fiber digestion in beef steers fed high-grain diets. J. Anim. Sci. 77:2269–2278.

Matth, A., P. Lebzien, and G. Flachowsky. 1999. Influence of maize grain drying process on its in situ degradability in dairy cows. J. Anim. Feed Sci. 8:379–386.

McAllister, T. A., R. C. Phillippe, L. M. Rode, and K.-J. Cheng. 1993. Effect of the protein matrix on the digestion of cereal grains by ruminal microorganisms. J. Anim. Sci. 71:205–212.

McCarthy, R. D., Jr., T. H. Klusmeyer, J. L. Vicini, J. H. Clark, and D. R. Nelson. 1989. Effects of source of protein and carbohydrate on ruminal fermentation and passage of nutrients to the small intestine of lactating cows. J. Dairy Sci. 72:2002–2016.

McNiven, M. A., R. M. G. Hamilton, P. H. Robinson, and J. W. deLeeuw. 1994. Effect of flame roasting on the nutritional quality of common cereal grains for non-ruminants and ruminants. Anim. Feed Sci. Technol. 47:31–40.

McNiven, M. A., M. R. Weisbjerg, and T. Hvelplund. 1995. Influence of roasting or sodium hydroxide treatment of barley on digestion in lactating cows. J. Dairy Sci. 78:1106–1115.

Mertens, D. R. 1997. Creating a system for meeting the fiber requirements of dairy cows. J. Dairy Sci. 80:1463–1481.

Mills, J. A. N., J. France, and J. Dijkstra. 1999a. A review of starch digestion in the lactating dairy cow and proposals for a mechanistic model: 1. Dietary starch characterisation and ruminal starch digestion. J. Anim. Feed Sci. 8:291–339.

Mills, J. A. N., J. France, and J. Dijkstra. 1999b. A review of starch digestion in the lactating dairy cow and proposals for a mechanis-

tic model: 2. Postruminal starch digestion and small intestinal glucose absorption. J. Anim. Feed Sci. 8:451–481.
Miron, J., D. Ben-Ghedalia, and R. Solomon. 1997. Digestibility by dairy cows of monosaccharide components in diets containing either ground sorghum or sorghum grain treated with sodium hydroxide. J. Dairy Sci. 80:144–151.
Mitzner, K. C., F. G. Owen, and R. J. Grant. 1994. Comparison of sorghum and corn grains in early and midlactation diets for dairy cows. J. Dairy Sci. 77:1044–1051.
Mowrey, A., M. R. Ellersieck, and J. N. Spain. 1999. Effect of fibrous by-products on production and ruminal fermentation in lactating dairy cows. J. Dairy Sci. 82:2709–2715.
NRC. 1989. Nutrient Requirements of Dairy Cattle. National Academy Press, Washington, DC.
NRC. 2001. Nutrient Requirements of Dairy Cattle. National Academy Press, Washington, DC.
Nocek, J. E. 1997. Bovine acidosis: Implications on laminitis. J. Dairy Sci. 80:1005–1028.
Nocek, J. E., and S. Tamminga. 1991. Site of digestion of starch in the gastrointestinal tract of dairy cows and its effect on milk yield and composition. J. Dairy Sci. 74:3598–3629.
Oba, M., and M. S. Allen. 2000. Effects of brown midrib 3 mutation in corn silage on productivity of dairy cows fed two concentrations of dietary neutral detergent fiber: 1. Feeding behavior and nutrient utilization. J. Dairy Sci. 83:1333–1341.
Oke, B. O., and S. C. Loerch. 1991. Effects of chemical treatments of cereal grains on in vitro dry matter disappearance and steer feedlot performance. Anim. Feed Sci. Technol. 34:163–173.
Oldick, B. S., J. L. Firkins, and N. R. St-Pierre. 1999. Estimation of microbial nitrogen flow to the duodenum of cattle based on dry matter intake and diet composition. J. Dairy Sci. 82:1497–1511.
Oliveira, J. S., J. T. Huber, D. Ben-Ghedalia, R. S. Swingle, C. B. Theurer, and M. Pessarakli. 1993. Influence of sorghum grain processing on performance of lactating dairy cows. J. Dairy Sci. 76:575–581.
Oliveira, J. S., J. T. Huber, J. M. Simas, C. B. Theurer, and R. S. Swingle. 1995. Effect of sorghum grain processing on site and extent of digestion of starch in lactating dairy cows. J. Dairy Sci. 78:1318–1327.
Ortega-Cerrilla, M. E., H. J. Finlayson, and D. G. Armstrong. 1999. The effect of chemical treatment of barley on starch digestion in ruminants. Anim. Feed Sci. Technol. 77:73–81.
Overton, T. R., M. R. Cameron, J. P. Elliott, J. H. Clark, and D. R. Nelson. 1995. Ruminal fermentation and passage of nutrients to the duodenum of lactating cows fed mixtures of corn and barley. J. Dairy Sci. 78:1981–1998.
Owens, F. N., D. S. Secrist, W. J. Hill, and D. R. Gill. 1998. Acidosis in cattle: A review. J. Anim. Sci. 76:275–286.
Pereira, M. N., E. F. Garrett, G. R. Oetzel, and L. E. Armentano. 1999. Partial replacement of forage with nonforage fiber sources in lactating cow diets. I. Performance and health. J. Dairy Sci. 82:2716–2730.
Petit, H. V., and G. T. D. Santos. 1996. Milk yield and composition of dairy cows fed concentrate based on high moisture wheat or high moisture corn. J. Dairy Sci. 79:2292–2296.
Petterson, D. S., D. J. Harris, C. J. Rayner, A. B. Blakeney, and M. Choct. 1999. Methods for the analysis of premium livestock grains. Aust. J. Agric. Res. 50:775–787.
Philippeau, C., J. Landry, and B. Michalet-Doreau. 2000. Influence of the protein distribution of maize endosperm on ruminal starch degradability. J. Sci. Food Agric. 80:404–408.
Philippeau, C., C. Martin, and B. Michalet-Doreau. 1999. Influence of grain source on ruminal characteristics and rate, site, and extent of digestion in beef steers. J. Anim. Sci. 77:1587–1596.
Plascencia, A., and R. A. Zinn. 1996. Influence of flake density on the feeding value of steam-processed corn in diets for lactating cows. J. Anim. Sci. 74:310–316.
Poore, M. H., J. A. Moore, T. P. Eck, R. S. Swingle, and C. B. Theurer. 1993a. Effect of fiber source and ruminal starch degradability on site and extent of digestion in dairy cows. J. Dairy Sci. 76:2244–2253.
Poore, M. H., J. A. Moore, R. S. Swingle, T. P. Eck, and W. H. Brown. 1993b. Response of lactating Holstein cows to diets varying in fiber source and ruminal starch degradability. J. Dairy Sci. 76:2235–2243.
Reynolds, C. K., J. D. Sutton, and D. E. Beever. 1997. Effects of feeding starch to dairy cattle on nutrient availability and production. In: P. C. Garnsworthy and J. Wiseman (ed.) Recent Advances in Animal Nutrition. pp 105–134. Nottingham Univ. Press, Nottingham,U.K.
Robinson, P. H., and J. J. Kennelly. 1989. Influence of ammoniation of high-moisture barley on digestibility, kinetics of rumen ingesta turnover, and milk production in dairy cows. Can. J. Anim. Sci. 69:195–203.
Robinson, P. H., and M. A. McNiven. 1994. Influence of flame roasting and feeding frequency of barley on performance of dairy cows. J. Dairy Sci. 77:3631–3643.
Ruiz, T. M., E. Bernal, C. R. Staples, L. E. Sollenberger, and R. N. Gallaher. 1995. Effect of dietary neutral detergent fiber concentration and forage source on performance of lactating cows. J. Dairy Sci. 78:305–319.
Santos, F. A. P., J. T. Huber, C. B. Theurer, R. S. Swingle, and J. M. Simas. 1997a. Response of lactating dairy cows to various densities of sorghum grain. J. Dairy Sci. 75:1681–1685.
Santos, F. A. P., J. T. Huber, C. B. Theurer, R. S. Swingle, Z. Wu, J. M. Simas, K. H. Chen, S. C. Chan, J. Santos, and E. J. DePeters. 1997b. Comparison of barley and sorghum grain processed at different densities for lactating dairy cows. J. Dairy Sci. 80:2098–2103.
Santos, J. E. P., J. T. Huber, C. B. Theurer, L. G. Nussio, M. Tarazon, and F. A. P. Santos. 1999. Response of lactating dairy cows to steam-flaked sorghum, steam-flaked corn, or steam-rolled corn and protein sources of differing degradability. J. Dairy Sci. 82:728–737.
Sarwar, M., J. L. Firkins, and M. L. Eastridge. 1992. Effects of varying forage and concentrate carbohydrates on nutrient digestibilities and milk production by dairy cows. J. Dairy Sci. 75:1533–1542.
Schingoethe, D. J., M. J. Brouk, and C. P. Birkelo. 1999. Milk production and composition from cows fed wet corn distillers grains. J. Dairy Sci. 83:574–580.
Shabi, Z., I. Bruckental, S. Zamwell, H. Tagari, and A. Arieli. 1999. Effects of extrusion of grain and feeding frequency on rumen fermentation, nutrient digestibility, and milk yield and composition in dairy cows. J. Dairy Sci. 82:1252–1260.
Simas, J. M., J. T. Huber, Z. Wu, K. H. Chen, S. C. Chan, C. B. Theurer, and R. S. Swingle. 1995. Influence of steam-flaked sorghum grain and supplemental fat on performance of dairy cows in early lactation. J. Dairy Sci. 78:1526–1533.
Slater, A. L., M. L. Eastridge, J. L. Firkins, and L. J. Bidinger. 2000. Effects of starch source and level of forage neutral detergent fiber on performance by dairy cows. J. Dairy Sci. 83:313–321.
St-Pierre, N. R. 2001. Integrating quantitative findings from multiple studies using mixed model methodology. J. Dairy Sci. 84:741–755.
Stokes, S. R., W. H. Hoover, T. K. Miller, and R. Blauwiekel. 1991. Ruminal digestion and microbial utilization of diets varying in type of carbohydrate and protein. J. Dairy Sci. 74:871–881.
Swain, S. M., and L. E. Armentano. 1994. Quantitaive evaluation of fiber from nonforage sources used to replace alfalfa silage. J. Dairy Sci. 77:2318–2331.
Theurer, C. B., J. T. Huber, A. Delgado-Elorduy, and R. Wanderley. 1999. Invited review: Summary of steam-flaking corn or sorghum grain for lactating dairy cows. J. Dairy Sci. 82:1950–1959.
Titgemeyer, E. C. 1997. Design and interpretation of nutrient digestion studies. J. Anim. Sci. 75:2235–2247.
Van Soest, P. J., J. B. Robertson, and B. A. Lewis. 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. J. Dairy Sci. 74:3583–3597.
Van Vuuren, A. M., A. Klop, C. J. Van Der Koelen, and H. De Visser. 1999. Starch and stage of maturity of grass silage: Site of diges-

tion and intestinal nutrient supply in dairy cows. J. Dairy Sci. 82:143–152.

Wagner, K. M., J. L. Firkins, M. L. Eastridge, and B. L. Hull. 1993. Replacement of corn silage with wheat middlings and calcium chloride or sodium bicarbonate for lactating dairy cows. J. Dairy Sci. 76:564–574.

Weidner, S. J., and R. J. Grant. 1994. Soyhulls as a replacement for forage fiber in diets for lactating dairy cows. J. Dairy Sci. 77:513–521.

Weiss, W. P. 1995. Full lactation response of cows fed diets with different sources and amounts of fiber and ruminal degradable protein. J. Dairy Sci. 78:1802–1814.

West, J. W., G. M. Hill, J. M. Fernandez, P. Mandebvu, and B. G. Mullinix. 1999. Effects of dietary fiber on intake, milk yield, and digestion by lactating dairy cows during cool or hot, humid weather. J. Dairy Sci. 82:2455–2465.

West, J. W., G. M. Hill, R. N. Gates, and B. G. Mullinix. 1997. Effects of dietary forage source and amount of forage addition on intake, milk yield, and digestion for lactating dairy cows. J. Dairy Sci. 80:1656–1665.

West, J. W., P. Mandebvu, G. M. Hill, and R. N. Gates. 1998. Intake, milk yield, and digestion by dairy cows fed diets with increasing fiber content from bermudagrass hay or silage. J. Dairy Sci. 81:1599–1607.

Wilkerson, V. A., B. P. Glenn, and K. R. McLeod. 1997. Energy and nitrogen balance in lactating cows fed diets containing dry or high moisture corn in either rolled or ground form. J. Dairy Sci. 80:2487–2496.

Yang, W. Z., K. A. Beauchemin, B. I. Farr, and L. M. Rode. 1997a. Comparison of barley, hull-less barley, and corn in the concentrate of dairy cows. J. Dairy Sci. 80:2885–2895.

Yang, W. Z., K. A. Beauchemin, K. M. Koenig, and L. M. Rode. 1997b. Comparison of hull-less barley, barley, or corn for lactating cows: Effects on extent of digestion and milk production. J. Dairy Sci. 80:2475–2486.

Yang, W. Z., K. A. Beauchemin, and L. M. Rode. 2000. Effects of barley grain processing on extent of digestion and milk production of lactating cows. J. Dairy Sci. 83:554–568.

Younker, R. S., S. D. Winland, J. L. Firkins, and B. L. Hull. 1998. Effects of replacing forage fiber or nonfiber carbohydrates with dried brewers grains. J. Dairy Sci. 81:2645–2656.

Yu, P., J. T. Huber, F. A. P. Santos, J. M. Simas, and C. B. Theurer. 1998. Effects of ground, steam-flaked, and steam-rolled corn grains on performance of lactating cows. J. Dairy Sci. 81:777–783.

Zhu, J. S., S. R. Stokes, and M. R. Murphy. 1997. Substitution of neutral detergent fiber from forage with neutral detergent fiber from by-products in the diets of lactating cows. J. Dairy Sci. 80:2901–2906.

Zinn, R. A., and R. Barrajas. 1997. Comparative ruminal and total tract digestion of a finishing diet containing fresh vs. air-dry steam-flaked corn. J. Anim. Sci. 75:1704–1707.