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In situ dry matter, crude protein, and starch degradabilities of selected grains and by-product feeds

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Abstract

In situ degradabilities were determined for some commonly used grains and by-product feeds in dairy cattle rations. Ingredients evaluated were barley, shelled corn, soybean meal, brewers dried grains, corn gluten feed, distillers dried grains, soybean hulls, and wheat middlings. In situ studies were conducted in three rumen-fistulated Holstein cows. Cows were fed a total mixed rations containing 55% alfalfa silage and 45% shelled corn-based concentrate (dry matter basis). Dacron bags containing 6 g (as fed basis) of each feed were immersed in duplicate at each time point in the ventral rumen of each cow for 2, 4, 6, 12, 24, 48, and 72 h. Ruminal availabilities of dry matter, crude protein, and starch calculated as a percentage of nutrient were ranked from high to low: dry matter: barley (67.3%), soybean meal (63.9%), distillers dried grains (58.3%), corn gluten feed (56.9%), wheat middlings (54.6%), shelled corn (51.1%), soybean hulls (48.8%), and brewers dried grains (38.3%); crude protein: wheat middlings (71.9%), corn gluten feed (70.3%), soybean meal (62.9%), barley (60.0%), soybean hulls (58.2%), brewers dried grains (48.9%), shelled corn (40.0%), and distillers dried grains (39.6%); starch: wheat middlings (88%), distillers dried grains (85.5%), soybean meal (81.8%), barley (80.5%), brewers dried grains (76.0%), corn gluten feed (70.6%), soybean hulls (66.4%), and shelled corn (56.5%). Grains and by-product feeds vary widely in their ruminal availability. This study provides estimates of kinetics of ruminal degradation of feeds for use in dynamic models of protein and carbohydrate digestion. © 1998 Elsevier Science B.V.

Keywords: In situ; By-products; Grains; Protein; Starch

Abbreviations: BAR: barley; BDG: brewers dried grains; COR: dried shelled corn; CGF: corn gluten feed; DDG: distillers dried grains; SBM: soybean meal; SBH: soybean hulls; WMD: wheat middlings

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1. Introduction

By-product feeds have been used extensively in dairy cattle rations in many parts of the world when economical as substitutes for corn and soybean meal. There is increasing interest in the nutritive value of by-product feeds as nutritionists seek to manipulate undegraded intake protein and nonfiber carbohydrate concentrations of dairy cattle rations. Corn gluten feed (CGF), wheat middlings (WMD), and soybean hulls (SBH) are typically used as grain replacers. Brewers dried grains (BDG) and distillers dried grains (DDG) are generally sought for their higher content of undegraded intake protein (National Research Council, 1989) relative to soybean meal (SBM). However, to optimize the feeding value of these by-product feeds, knowledge of their ruminal degradation properties is needed for proper inclusion in the diet through formulation programs. For example, by-product feeds with very rapid ruminal rates of starch degradation may result in low ruminal pH and lactic acidosis (Nocek and Russell, 1988; Nocek, 1995) if this degradation characteristic is not accounted for in ration formulation. On the other hand, by-product feeds that are low in rumen-available carbohydrate may reduce microbial protein output (Stokes et al., 1991a,b). Dynamic models of carbohydrate and protein digestion rely on estimates of kinetics of ruminal degradation of feeds (Russell et al., 1992), but literature values are limited particularly for starch (Nocek and Russell, 1988). The objective of this study was to evaluate some commonly used grains and by-product feeds in dairy cattle rations for their ruminal in situ degradabilities of dry matter, crude protein and starch.

2. Materials and methods

Measurements of in situ degradabilities were in three multiparous Holstein cows (200 ± 18 days in milk, 629 ± 43 kg BW) fitted with rumen cannulae. Cows were fed a total mixed rations containing 55% alfalfa silage (65% DM, 18.5% CP) and 45% concentrate (DM basis) two weeks before and during the study. The concentrate consisted of (DM basis) dried shelled corn (90.5%), corn gluten meal (3.3%), soybean meal (2.1%), meat and bone meal (2.1%), and mineral and vitamin mix (2%). Diets were formulated to contain 16.5% CP and fed twice daily at 0900 and 1800 h. Test feeds (grains and by-products) were obtained from the University of Wisconsin Arlington Feed Mill and ground to pass a 1-mm Wiley mill screen. Test grains were corn (COR) and barley (BAR). Test by-products were BDG, CGF, DDG, SBH, SBM and WMD. Test feeds were analyzed for DM, CP, NDF, starch and EE.

In situ bags were made of dacron cloth (19×9.5 cm, 52 μ pore size; 100% dacron polyester, R102 Marvelaire White, N. Erlanger, Blumgardt, 1450 Broadway, NY, USA). Bags were prepared as described by Shaver et al. (1986). Bags containing 6 g of respective test feeds were immersed in duplicate at each time point in each cow in reverse order at 2, 4, 6, 12, 24, 48, and 72 h. In situ bags were placed inside a mesh nylon laundry bag that was tied to a weighted chain and located in the ventral rumen. Duplicate blank bags were also placed in the laundry bag to estimate influx of DM into the bag. To avoid overloading the rumen with in situ bags, test feeds were incubated in two batches. The second batch of test feeds was incubated two weeks after the first

batch. Dried shelled corn and SBM were incubated in both batches as standards. Six measurements were made for each test feed at each time point (3 cows $\times$ 2 replicates) except for corn and soybean meal, which were incubated in both batches (12 observations per time point). After the incubation, all bags were removed at the same time and hand washed until rinsings were clear. Zero hour bags were soaked in tepid tap water for 30 min prior to hand washing to estimate the rapidly disappearing or A fraction. Bags were dried for 72 h at 60°C in a forced-air oven. Residual DM of each bag was corrected for DM entry into their corresponding blank bags. Dried residues from duplicate bags for each cow at each time point were composited for further analysis. In situ estimates have been reported to be underestimated by the inclusion of microbial starch (McAllen and Smith, 1974) and nitrogen (Nocek and Grant, 1987), which attaches to the residues but correction for microbial starch and nitrogen were not carried out in this study. Six hours after AM feeding, ruminal fluid was obtained from the ventral rumen, and pH was measured on each cow during each set of incubations.

Residues from each time point were analyzed for DM, CP (Association of Official Analytical Chemists, 1990), and starch (Herrera-Saldana et al., 1990a). Because of the small amount of sample remaining after CP and starch analysis degradability of NDF was measured as percentage disappearing at 24 h only. For starch analysis, duplicate samples of residue (50 mg) were weighed into 35-ml Pyrex tubes fitted with Teflon-lined screw caps. Then, 25 ml of acetate buffer (0.1 M; pH 5.0) and 100 μl of α-thermoamylase (Taka-Therm L-170, Miles, Elkhart, IN, USA; contained 170 enzyme units/ml) were added. Duplicate blank tubes were also incubated to correct for color from enzymes and reagents. Tubes were placed in a boiling water bath (90 to 95°C) for 30 min. Caps were tightened after several minutes of heating, and tubes were agitated three times during incubation. Tubes were then removed and cooled to 60°C and 100 μl of glucoamylase (Diazyme L-200, Miles, Elkhart, IN, USA; solution contained 200 enzyme units/ml) were added. Tubes were then recapped, incubated for 14 h in a 60°C waterbath, and centrifuged for 10 min ($500 \times g$). Aliquots (1 ml) of supernatants were then diluted (1:10) with distilled water. From this dilution, 200-μl aliquots were mixed with 2 ml of a glucose oxidase solution (Glucose-Trinder, Sigma Chemical, St. Louis, MO, USA) and let stand at room temperature for 18 min. The absorbance was read at 490 nm in an EIA auto reader (EL 310, Bio-Teck Instruments, Burlington, VA, USA). A purified corn starch sample was used as a reference standard to adjust for starch recovery that ranged 96 to 99.5%. Starch content of the sample was calculated using a regression equation from a calibration curve obtained from varying dilutions (0, 1.25, 2.5, 5, 10, 20 and 25 μg/ml) of a standard glucose solution (Sigma Chemical, St. Louis, MO, USA) incubated with glucose oxidase.

In situ digestion kinetics were estimated using the nonlinear procedure of SAS® User's Guide: Statistics (SAS Inst., 1985; Cary, NC, USA) as described by Sievert and Shaver (1993). Ruminal availabilities of DM, CP, and starch were calculated with the formula: $[A + B * k_d/(k_d + k_p)]$, where A is the rapidly disappearing fraction, B is the slowly degraded fraction, k_d is the degradation rate of fraction B, and k_p is the passage rate assumed at 0.07/h (Batajoo and Shaver, 1994). Fraction A and B were defined mathematically, not chemically. Differences between feeds were determined using the least significant difference method after a significant F test ($P < 0.05$).

3. Results and discussion

Nutrient composition of test feeds are presented in Table 1. Shelled corn tested lower starch (71.9 vs. 75%) and higher in NDF (16.4 vs. 9.0%) than typical analyses (National Research Council, 1989; Tamminga et al., 1990). The higher NDF value could be due to incomplete extraction of starch from the residue during NDF analysis or partial inclusion of cob in the corn. There was some cob visible in the corn, but no attempt was made to quantitate the amount. The higher CP (19.2 vs. 12%) and lower NDF (53.4 vs. 67%) found in SBH relative to National Research Council (1989) suggests the inclusion of some meal with the hulls. This may partially explain the measurement of 9.4% starch and free glucose in SBH. Others (Belyea et al., 1989) have not found starch and free glucose in SBH. Content of CP in SBM was lower than the National Research Council (1989) value (45.4 vs. 50.0%). Similar concentrations of NDF (53 to 54.0%) were found in BDG, SBH and WMD.

Starch in WMD was similar to the report of Cerneau and Michalet-Doreau (1991; 24.9%). All by-product feeds had higher percentages of EE than COR, BAR or SBM (3 to 6.9 vs. 0.6 to 2.9%). Test feeds varied in starch content; BAR and COR were highest (59 and 72%), CGF and WMD intermediate (23 to 24%), and BDG, DDG, SBM, and SBH were lowest (less than 15%).

Ruminal pH measured 6 h post-feeding averaged 5.98 ± 0.18 and did not differ across in situ runs. Degradability estimates for SBM and COR were similar across in situ runs (percent DM disappearing at 24 h of 74.4 ± 0.7 for COR and 79.3 ± 0.6 for SBM, respectively) indicating minimal differences between runs.

The A and B fractions, k_d of the B fraction are presented in Table 2. Degradation curves are presented in Figs. 1–3. Dry matter A fraction was highest ($P < 0.05$) for DDG (40.2%; Fig. 1) and lowest for COR and BDG (14.5%). Dry matter A fraction for corn was similar to previous reports of Nocek (1987; 16.6%) and Herrera-Saldana et al. (1990a); 18.6%). Dry matter A fraction for BAR was lower than reported by Herrera-Saldana et al. (1990a); 19.2 vs. 47%). Corn gluten feed had the highest ($P < 0.05$) crude protein A fraction (54.2%; Fig. 2) while SBM, SBH and WMD were intermediate (26 to 32%). These values were lower than those reported by Belyea et al. (1989) for CGF

Table 1
Nutrient composition of selected grains and by-product feeds[a]

	Percentage of DM							
	BAR	COR	SBM	BDG	CGF	DDG	SBH	WMD
OM[b]	97.8 ± 0.1	97.9 ± 0.1	92.9 ± 0.1	95.6 ± 0.1	93.2 ± 0.1	92.5 ± 0.2	94.1 ± 0.1	97.6 ± 0.2
CP	14.8 ± 0.2	11.5 ± 0.1	45.4 ± 0.9	28.1 ± 0.2	22.8 ± 0.3	25.9 ± 0.4	19.2 ± 0.3	19.3 ± 0.6
NDF	27.1 ± 1.4	16.4 ± 0.6	18.5 ± 0.5	54.0 ± 0.2	36.4 ± 0.2	32.5 ± 0.1	53.4 ± 0.2	53.7 ± 0.2
Starch[c]	59.2 ± 0.2	71.9 ± 0.3	12.8 ± 0.8	13.1 ± 0.8	24.3 ± 1.5	14.5 ± 0.2	9.4 ± 0.7	23.4 ± 0.9
EE	1.4 ± 0.1	2.9 ± 0.2	0.6 ± 0.1	6.9 ± 0.5	4.0 ± 0.6	6.5 ± 0.4	3.0 ± 0.1	4.1 ± 0.3

[a]Abbreviation: BAR: barley; BDG: brewers dried grains; COR: dried shelled corn; CGF: corn gluten feed; DDG: distillers dried grains; SBM: soybean meal; SBH: soybean hulls; WMD: wheat middlings.
[b]Standard deviation within feeds, $n = 6$; except for COR and SBM, $n = 12$.
[c]Starch and free glucose (Herrera-Saldana et al., 1990a,b).

Table 2
In situ degradability estimates of grains and by-product feeds[g]

	BAR	COR	SBM	BDG	CGF	DDG	SBH	WMD	SE
Rapidly disappearing fraction, A (%)									
DM	19.2^{d}	14.4^{e}	35.4^{b}	14.5^{e}	34.7^{b}	40.2^{a}	21.8^{cd}	26.6^{c}	1.8
CP	9.4^{d}	9.6^{d}	27.0^{b}	16.7^{c}	54.2^{a}	16.6^{c}	26.4^{b}	31.9^{b}	2.4
Starch	26.7^{de}	19.8^{e}	60.6^{b}	59.1^{b}	35.9^{dc}	77.7^{a}	43.0^{c}	68.1^{ab}	4.6
Slowly disappearing fraction, B (%)									
DM	69.9^{c}	81.6^{a}	63.6^{d}	57.2^{e}	54.9^{e}	44.0^{f}	75.9^{b}	46.0^{f}	0.93
CP	87.1^{a}	87.7^{a}	72.4^{b}	64.3^{c}	37.4^{e}	56.1^{d}	67.3^{c}	56.5^{d}	1.57
Starch	68.5^{b}	79.2^{a}	36.1^{e}	23.4^{f}	58.8^{c}	16.7^{g}	52.2^{d}	26.8^{f}	1.81
Rate of degradation of B fraction, k_d, (/h)									
DM	0.156^{a}	0.059^{c}	0.058^{cd}	0.049^{cd}	0.048^{cd}	0.049^{cd}	0.039^{d}	0.109^{b}	0.46
CP	0.097^{b}	0.041^{c}	0.069^{c}	0.072^{c}	0.053^{cde}	0.049^{de}	0.063^{cd}	0.171^{a}	0.63
Starch	0.266^{a}	0.057^{c}	0.085^{c}	0.212^{ab}	0.101^{c}	0.136^{bc}	0.072^{c}	0.235^{ab}	3.9
Ruminal availabilities[1] (%)									
DM	67.3^{a}	51.1^{e}	63.9^{b}	38.3^{f}	56.9^{cd}	58.3^{c}	48.8^{e}	54.6^{d}	0.66
CP	60.0^{bc}	40.0^{e}	62.9^{b}	48.9^{d}	70.3^{a}	39.6^{e}	58.2^{c}	71.9^{a}	1.11
Starch	80.5^{b}	56.5^{d}	81.8^{b}	76.0^{b}	70.6^{c}	85.5^{a}	66.4^{c}	88.4^{a}	1.81

[a,b,c,d,e,f]Means in the same row with different superscripts differ ($P < 0.05$).
[g]Ruminal availabilities calculated as percentage of feed nutrient = $A + B * k_d/(k_d + k_p)$, where k_d = rate of degradation and k_p = rate of passage assumed at 0.07/h.

(54.0 vs. 61.0), DDG (16.6 vs. 51.0), and SBH (26.4 vs. 37.0%), respectively. Tamminga et al. (1990) reported higher crude protein *A* fraction values for corn and barley than we found (15 vs. 9.6% and 25 vs. 9.4%, respectively). Crude protein A

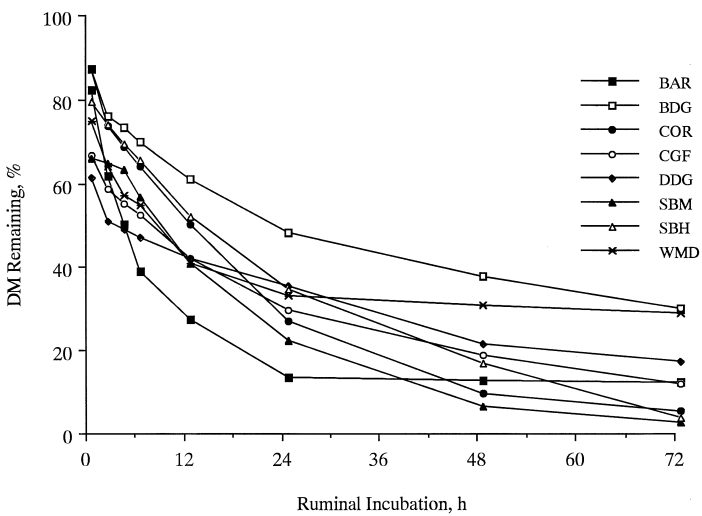

Fig. 1. In situ percent DM remaining at various ruminal incubation times. BAR: barley; BDG: brewers dried grains; COR: dried shelled corn; CGF: corn gluten feed; DDG: distillers dried grains; SBM: soybean meal; SBH: soybean hulls; WMD: wheat middlings.

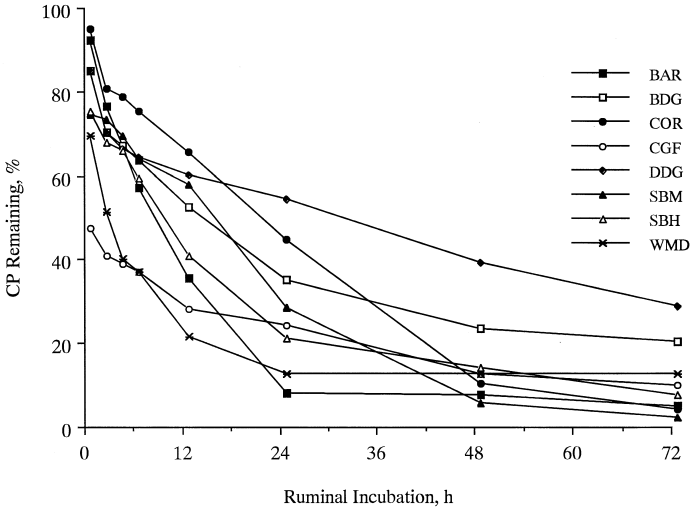

Fig. 2. In situ percent CP remaining at various ruminal incubation times.

fractions were similar for SBM and SBH (27%) and BDG and DDG (17%). Lower crude protein *A* fraction for SBM had been reported by others (Roe et al., 1991; 18%). Variation in this fraction between studies could be due to differences in feed particle size and processing methods (i.e., degree of heating) or differences in analytical techniques. In the present study, feeds were ground to 1 mm, which may have contributed to higher soluble fraction observed in some feeds. However, feed particle size did not affect rates of DM and N degradation in some studies (Weakley et al., 1983;

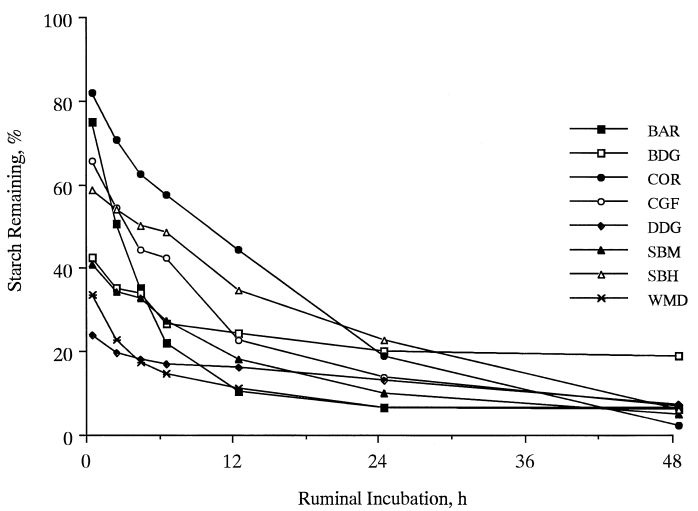

Fig. 3. In situ percent starch remaining at various ruminal incubation times.

Nocek, 1985) but others (Figroid et al., 1972) have observed large differences in disappearance of substrate with different particle size.

Starch *A* fraction was highest for DDG (77.7%; $P < 0.05$; Fig. 3) and intermediate for BDG, SBM and WMD (59 to 68%). Relative to our study, Tamminga et al. (1990) and Herrera-Saldana et al. (1990a) reported higher starch *A* fractions for BAR (64 to 66% vs. 26.7%). Corn had the lowest starch *A* fraction (19.8%), supporting the findings of others (Herrera-Saldana et al., 1990a, 21%; Tamminga et al., 1990, 27.6%; Cerneau and Michalet-Doreau, 1991, 26.5%). This fraction contains soluble sugars (glucose, fructose, sucrose, and fructans), as well as soluble nonstarch polysaccharides (arabinose, xylose, mannose, galactose, and uronic acids; Aman and Hesselman, 1984). Differences observed in this fraction among feeds could also be due to the variation in feed particle size. Small feed particles could be physically expelled from the bag during soaking prior to incubation and washing which would overestimate the amount leaving the bag due to solubilization. Also, soluble protein or particles exiting the bag do not necessarily reflect degradation. For example, bovine serum albumin, which is soluble in water, is not highly degradable when incubated in rumen fluid (Broderick, 1987; Broderick and Craig, 1989).

The dry matter *B* fraction for all feeds ranged from 44 to 76%. Dry matter *B* fraction for corn was similar to Nocek (1987); 81.6 vs. 80.6%). Dry matter *B* fraction in this study was higher than reported by Cerneau and Michalet-Doreau (1991) for barley (69.9 vs. 25.5%), corn (81.6 vs. 71.8%) and wheat middlings (46 vs. 33.6%). Barley and corn had highest ($P < 0.05$) crude protein *B* fraction (87%), SBM was intermediate (72.4%), and CGF was lowest (37%). Crude protein B fraction was similar for DDG and WMD (56%). Starch B fractions for BAR, COR, and WMD were 68.5, 79.2 and 26.8% and were higher than reported by Cerneau and Michalet-Doreau (1991); 18.0, 73.5, and 16.8%, respectively).

Degradation rate (k_d) of DM was fastest ($P < 0.05$) for BAR (0.156/h) followed by WMD (0.109/h; Fig. 1). Soybean hulls DM was digested most slowly (0.039/h; $P < 0.05$). Similar DM degradation rates were observed for COR and SBM (0.059/h) and BDG, CGF and DDG (0.049/h). Rate of DM degradation for BAR was higher than reported by Herrera-Saldana et al. (1990a); 0.085/h). Dry matter degradation rate for COR was slower than reported by Nocek (1987; 0.091/h) but closer to the values reported by Herrera-Saldana et al. (1990a); 0.047/h).

Wheat middlings had the fastest CP degradation rate (0.171/h; $P < 0.05$) followed by BAR (0.097/h; Fig. 2). Rate of CP degradation was similar for SBM, SBH and BDG (0.06 to 0.07/h) and COR, CGF and DDG (0.04 to 0.05/h). Grings et al. (1992) reported a similar degradation rate of CP for corn (0.049 vs. 0.041/h) but Nocek (1987) reported a slightly faster k_d (0.068/h). Rate of CP degradation for DDG averaged 0.049/h and was faster than reported by Grings et al. (1992); 0.026/h). Degradation rate observed for SBM was slower than reported by Erdman et al. (1987); 0.078/h) but faster than reported by Susmel et al. (1993; 0.049/h).

Fastest rate of starch degradation was observed in BAR, WMD and BDG (0.21 to 0.27/h; $P < 0.05$, Fig. 3). Rate of starch degradation was intermediate for CGF and DDG (0.10 to 0.14/h; $P < 0.05$) and slowest for COR, SBM and SBH (0.06 to 0.08/h; $P < 0.05$). Rate of starch degradation for BAR (0.27/h) was higher than reported by

Herrera-Saldana et al. (1990a); 0.147/h) and Cerneau and Michalet-Doreau (1991); 0.057/h) but similar to Tamminga et al. (1990); 0.242/h). As expected (Orskov, 1986), starch in corn was slowly degraded. This could be related to association of the protein matrix with starch granules and type and proportion of protein bodies found in the endosperm (Rooney and Pflugfelder, 1986; McAllister et al., 1993). Except for corn, most of the starch in test feeds was completely degraded by 24 h. Rapid degradation rate of starch in the rumen can reduce ruminal pH and cause lactic acidosis and reduce fiber digestion and feed intake (Nocek and Russell, 1988). Degradation rate of starch varies greatly among feeds and rate is influenced by type of feed (Herrera-Saldana et al., 1990a; Tamminga et al., 1990), processing method (Theurer, 1986), and preservation method (dry vs. high moisture grain; Nocek, 1987). Matching ruminal starch and protein degradability of feeds is a strategy that has been used to maximize the ruminal microbial protein production (Herrera-Saldana et al., 1990b; Stokes et al., 1991a,b).

Ruminal availabilities of DM, CP, and starch calculated as a percent of feed nutrient are also presented in Table 2. Rate of passage was assumed at 0.07/h for calculation of ruminal availabilities (Batajoo and Shaver, 1994). Barley and BDG had the highest (67.3%; $P < 0.05$) and lowest (38.3%) ruminally available DM respectively. Cerneau and Michalet-Doreau (1991) reported higher ruminally available DM for BAR (82.8 vs. 67.3%), COR (58.0 vs. 51.1%), and WMD (77.2% vs. 54.6%) than reported here. Corn gluten feed and DDG were similar in ruminally available DM (57 to 58%).

Ruminal availability of CP was highest in CGF and WMD (70.3 and 71.9%; $P < 0.05$). Crude protein from COR and DDG was least ruminally available (40%), indicating that over half of the protein would pass to the small intestine. Other researchers have reported higher ruminal protein availability for corn (Herrera-Saldana et al. (1990a), 70%; Grings et al. (1992), 56%). Soybean meal ruminal available CP was similar to the value reported by Broderick et al. (1988); 63 vs. 62.9%), but Susmel et al. (1993) reported a lower value (52%). Ruminally available CP in barley was similar to the value reported by Susmel et al. (1993); 62.6 vs. 60%). Relative to National Research Council (1989), percentage of CP escaping ruminal degradation were: barley (27 vs. 40), corn (52 vs. 60), soybean meal (35 vs. 37), brewer's dried grains (49 vs. 51), corn gluten feed (25 vs. 30), distillers dried grains (54 vs. 60), and wheat middlings (42 vs. 28). Our values for COR, SBM, BDG, CGF, and DDG were in close agreement with National Research Council (1989). Undegraded CP value was not listed for soyhulls in National Research Council (1989) but averaged 58.2% in our study.

Wheat middlings and DDG were highest in ruminally available starch (88.4 and 85.5%; $P < 0.05$) followed by BAR, SBM and BDG (76 to 82%). As expected (Orskov, 1986; Owens et al., 1986), corn starch was least ruminally available (56.5%). Lower starch degradability for corn could be related to the presence of a protein matrix surrounding the endosperm starch which limits access to enzymatic digestion (Rooney and Pflugfelder, 1986). Similar ruminal availabilities of starch in corn have been reported by Cerneau and Michalet-Doreau (1991); 57.8%) and Herrera-Saldana et al. (1990a); 61.9%). Cerneau and Michalet-Doreau (1991) reported higher ruminal starch availabilities than our values for barley (98.3 vs. 80.5%) and wheat middlings (96.4 vs. 88.4%). Feeds with similar ruminal availabilities of CP and starch could be used in synchronizing nutrient supply for maximum microbial protein production in ruminants

(Herrera-Saldana et al., 1990b; Stokes et al., 1991a). In our study, WMD and BAR had high starch and CP availabilities; whereas, low starch and CP availabilities were observed in COR and SBH.

Microbial contamination of the feed residues can contribute to the source of variation in degradability estimates. Also, microbial population inside the bag is restricted to numbers fewer than that of the surrounding digesta (Meyer and Mackie, 1986), thus in situ protein degradation rates could be lower than actual in vivo rates (Broderick et al., 1988). Microbial attachment with the feed particles had been shown to underestimate CP degradability in fibrous feeds (Nocek and Grant, 1987). We did not correct for bacterial N contamination of the bag residue, and thus may account for some of the differences between studies in CP degradation. However, Nocek (1985) did not find significant differences between N disappearance rate constants determined (for SBM) with or without correction for bacterial N contamination. Bacterial carbohydrates are reported to be formed in the rumen (McAllen and Smith, 1974), which underestimates the starch degradation values, but correction for bacterial carbohydrate contamination was not attempted in this study. Several researchers have attempted to correct for microbial contamination of in situ residues. Mehrez and Orskov (1977) using diaminopimelic acid as a marker concluded that microbial N contamination of barley residue was negligible. Mathers and Aitchinson (1981) using ^{35}S as a marker showed substantial microbial contamination of alfalfa and fishmeal residues. Varvikko and Lindberg (1985) applying ^{15}N and diaminopimelic acid as markers, found large contamination and concluded that microbial colonization is an important source of error when estimating in situ degradability of protein in forages and starchy feeds. Contamination of bacterial cells (as a percentage of residual DM) averaged 10% in corn grain, 17.5% in corn husks and 22% in alfalfa hay showing that the degree of attachment varied with the nature of feeds (Wanderley et al., 1993).

The indigestible nutrient fraction was estimated as the percent nutrient remaining after 72 h ruminal incubation (Figs. 1–3). Brewer's dried grains and WMD had highest proportion of rumen indigestible DM residue (27 to 28%) where as corn, soybean meal and soybean hulls had the least residual DM (1 to 4%). Barley and WMD had nearly complete digestion of DM and CP by 24 h of ruminal incubation (Figs. 1 and 2). High indigestible DM and CP fractions observed in BDG (28.4 and 18.9%) and DDG (15.8 and 27.3%) could be due to the formation of Maillard reaction products during processing. Maillard reaction products have been found to be resistant to digestion in vivo (Adrian, 1974; Van Soest and Mason, 1991). This might also explain the higher indigestible starch fraction in BDG (17.5%) relative to 4.8% for SBH.

Percent NDF which disappeared after 24 h of ruminal incubation were: CGF (32.6%), BDG (33.3%), DDG (43.6%), SBH (44.9%), WMD (45.0%), COR (48.7%), SBM (54.6%), and BAR (59.2%). Soyhulls and BDG were similar in NDF (54%; Table 1), but SBH was 12% units lower in NDF remaining (55.1 vs. 66.7%). NDF in soyhulls is highly degradable (MacGregor and Owen, 1976; Nakamura and Owen, 1989) and SBH have been reported to be equal to corn as an energy source for dairy cows (Wagner et al., 1965; Edionwe and Owen, 1989; Cunningham et al., 1993). This likely results from the replacement of nonfiber carbohydrate from corn in the diet with highly digestible NDF from SBH.

In situ degradability estimates are affected by factors such as feed particle size (Figroid et al., 1972; Nocek, 1985; Cerneau and Michalet-Doreau, 1991), bag surface area ratio (Uden et al., 1974; Mehrez and Orskov, 1977), sample size, origin of grains, and bag material and pore size (Weakley et al., 1983; Nocek, 1985), test animal diet (Ganev et al., 1979; Weakley et al., 1983), washing procedures (Cherney et al., 1990), and sampling schedules (Nocek, 1985; Fadel, 1992). These factors may partially explain differences in kinetic measurements between our study and others in the literature.

4. Conclusions

Grain and by-product feeds varied widely in their ruminal DM, CP and starch degradation. Variation in ruminal starch degradation can be used in two ways, either to maximize substrate available for microbial growth and protein synthesis, or to enhance the intestinal starch supply (and hopefully glucose absorption from the small intestine). Our estimates of the kinetics of ruminal degradation of feeds provide values for use in dynamic models of carbohydrate and protein digestion. However, variation between our estimates and others in the literature was considerable for these feeds. This could be due to inherent differences between feeds tested (i.e., source of ingredient, processing method, particle size), or differences in analytical procedures between laboratories. Routine in situ procedures should emphasize on standardization with regard to fineness of grinding, pore size of the bag material, and washing procedure, etc.

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