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Digestion kinetics of dried cereal grains

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Abstract

Grain fermentability largely determines the feed value of grains for ruminants. Our objective was to evaluate the variation in kinetics of gas production of cereal grains and the relationship among gas production, chemical composition and feed value. Eighteen barley, 99 corn, 23 sorghum, and 57 wheat samples were fermented *in vitro* for 48 h. Gas production was measured with a computerized system and an exponential model was fitted to the data. The impact of the variation in composition and kinetics on the feed value of grains in feedlot rations was assessed with the Cornell Net Carbohydrate and Protein System (CNCPS). Fractional gas rates were significantly different between grains ($P<0.001$), with a mean and S.D. of 0.24 (0.029) h^{-1} for barley ($n=20$), 0.15 (0.026) h^{-1} for corn ($n=98$), 0.06 (0.016) h^{-1} for sorghum ($n=23$) and 0.26 (0.039) h^{-1} for wheat ($n=57$). Fermentation rates were more variable than the chemical components. Fractional rates were poorly correlated with chemical composition within grain with the highest correlations for acid detergent insoluble crude protein (ADICP) ($r=-0.31$, $P<0.01$) and ADF ($r=-0.27$, $P<0.01$) for corn and neutral detergent insoluble crude protein (NDICP) ($r=0.35$, $P<0.05$) for wheat. The impact of the variation in composition and kinetics on the feed value of grains in feedlot rations was assessed. The CNCPS predicted a maximal variation of <2.1 MJ/day and <60 g/day in metabolizable energy (ME) and metabolizable protein (MP) supply from grains, respectively. For sorghum, the fermentation rate was predicted to be a

Abbreviations: ADICP, acid detergent insoluble crude protein; CNCPS, Cornell Net Carbohydrate and Protein System; EE, ether extract; ME, metabolizable protein; MP, metabolizable protein; NDICP, neutral detergent insoluble crude protein; SOL CP, soluble crude protein; TDN, total digestible nutrients; VFA, volatile fatty acid

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major determinant of the site of starch fermentation. A detailed evaluation of feed values for grains needs to include information on rates of fermentation.

Keywords: Fermentation rates; Cereal grains; Gas production; Feed variation; CNCPS

1. Introduction

Grain fermentability largely determines the feed value of grains for ruminants. It affects the site of starch digestion and microbial protein supply (Herrera-Saldana et al., 1990), has an important effect on the rumen environment since it is related to changes in ruminal pH, volatile fatty acid (VFA) production, and cellulolytic activity (Sauvant, 1997), and ultimately affects milk yield and dry matter intake (Herrera-Saldana et al., 1990). Variety, location, cultivar, and environment, among other factors, interact to affect the rate and extent of ruminal cereal grain digestion (Van Barneveld, 1999).

In vitro gas production has been previously used to estimate digestion kinetics for starchy feeds (Chai et al., 2004; Chen et al., 1999; Opatpatanakit et al., 1994). Gas production techniques are based on the principle that anaerobic microbial digestion of carbohydrates releases gas (primarily CO_2 and CH_4) and VFAs. They permit the study of digestion kinetics of neutral detergent soluble fractions (Hall et al., 1998; Schofield and Pell, 1995a). In addition, rates of fermentation are conveniently estimated by the automated technique (Cone et al., 1996; Pell and Schofield, 1993). Rates of gas production have been applied in diet evaluation programs that use digestion rates as feed inputs (Fox et al., 2004; NRC, 2000).

Our objectives were: (1) to assess the variability in gas production kinetics for dried ground grains, (2) to determine relationships between chemical analysis and gas kinetics, and (3) to evaluate the impact of the variation in composition and kinetics on the feed value of the grains in feedlot diets as predicted by the Cornell Carbohydrate and Protein System (CNCPS).

2. Material and methods

2.1. Samples

We used 98 corn, 57 wheat, 23 sorghum, and 20 barley unprocessed grain samples in the study. Since one of our goals was to assess variability in feed composition and gas production rates, samples were collected from a wide range of locations around the world to analyze samples that differ genetically and in environmental growing conditions. The set included samples from different locations from 22 countries (Argentina, Brazil, Canada, China, Colombia, France, Honduras, Hungary, India, Indonesia, Italy, Korea, Mexico, Nicaragua, Peru, Philippines, Spain, Sri Lanka, Thailand, Turkey, USA, and Venezuela). Samples were selected by feed company representatives to represent the variability in chemical composition found within each country. Differences in endosperm texture for corn, sorghum and wheat, tannin content for sorghum, and hull presence for barley were

identified. The samples were ground to pass a 4 mm screen (Wiley mill, model 3, Arthur H. Thomas Co., Philadelphia, PA) for the *in vitro* gas procedure. Preliminary results showed that a 4 mm particle size was the best compromise between analytical repeatability and discrimination among samples (Lanzas, unpublished data).

2.2. Chemical analysis

Starch content was determined by enzymatic hydrolysis with amyloglucosidase (Boehringer Mannheim, Germany) (McCleary et al., 1994). Neutral detergent fiber (aNDF) (analyzed with a heat stable amylase (Termamyl, Novozymes, Baysvaerd, Denmark) and sodium sulfite and included residual ash), ADF, and lignin(sa) were analyzed using the methods as described by Van Soest et al. (1991). Lignin(sa) (analyzed by solubilization with sulfuric acid) was analyzed as described by Robertson and Van Soest (1981). Neutral detergent insoluble crude protein (NDICP), ADICP, and soluble crude protein (SOL CP) were determined (Licitra et al., 1996). Fat content was determined using ether extraction in the Tecator Soxtec system (AOAC, 1999-ID 954.02). Ash was determined as the sample left after ignition at 600 °C (AOAC, 1999-ID 942.05). Crude protein was determined by a combustion method (AOAC, 1999-ID 990.03).

2.3. In vitro gas production procedure

Ruminal fluid was collected from a mature, nonlactating Holstein cow cared for according to the rules of the Institutional Animal Care and Use Committee. The donor cow was fed mixed medium quality mostly grass hay and corn meal. The ruminal fluid, collected 4 h after feeding, was filtered through two layers of cheesecloth and glass wool and transferred into a 100 mL serum bottle flushed with oxygen-free CO_2.

Eighty milligrams of sample were fermented in a 50 mL serum bottle with 2 mL of ruminal fluid and 8 mL of anaerobic medium (Goering and Van Soest, 1970). The sodium sulfide of the anaerobic medium was replaced with an equal amount of cysteine hydrochloride. The gas production technique was used as described by Pell and Schofield (1993) and Schofield and Pell (1995b). The gas measurements were recorded every 20 min for 48 h using the Atlantis© program for Windows (Lakeshore Technologies, Chicago, IL). After the fermentation, the bottles were vented prior to removal of the sensors and the pH was measured. The gas volumes were corrected for atmospheric pressure and expressed as the volume of gas produced for 100 mg of sample DM. Each sample was fermented on 2 days using inocula from separate ruminal fluid collections.

2.4. Data analysis and curve fitting

A one-pool exponential equation with lag was fitted to the data (Schofield et al., 1994);

$$V_t = V_f(1 - e^{-k(t-L)}) \quad (1)$$

where V_t = volume of gas at time t (mL), V_f = final asymptotic gas volume (mL), k is rate constant (h^{-1}), and L is a discrete lag term (h), when it is assumed that digestion does not

occur using the NLIN procedure of SAS (1999). The *f*-values and *t*-values of the parameters were checked to assure the goodness of fit of the model.

Samples were fermented on two separate days. Samples were treated as replicates and kinetic parameters were averaged. For all fermentation runs, a standard sample was incubated and used as a quality control check. If the digestion kinetic parameters for the check sample differed greatly from the average (>2 S.D.), the run was repeated. Differences in gas kinetics among grains were analyzed using one-way analysis of variance, and comparisons among grains were done using Turkey's studentized range test using PROC GLM (SAS, 1999). Differences due to country within grain were evaluated using one-way analysis of variance with country as a fixed variable using PROC GLM (SAS, 1999). The Spearman correlations between chemical components and exponential fractional rates were determined using the PROC CORR (SAS, 1999). When fractional digestion rates were plotted against chemical components, the relationships between the variables were nonlinear, leading us to use Spearman correlations, rather than Pearson correlations to assess the nature of the relationships.

2.5. Simulations

To evaluate the impact of variability in chemical composition and digestion kinetics on the feed value of the grains for growing feedlot animals, evaluations using the CNCPS model (Version 5) (Fox et al., 2004) were carried out. The fermentation rate measured in these studies was entered for the starch-containing fraction (CHO B1), since it is the predominant fermentable carbohydrate in grains. The impact of the variation in feed composition on the predicted CHO B1 pool, ruminally digested CHO B1 pool, apparent total digestible nutrients (TDN), metabolizable energy (ME) and metabolizable protein (MP) supply from the grain meal were evaluated. Four standard feedlot rations with barley, corn, sorghum or wheat as the primary grain in the concentrate were used (Table 1). The same animal and environment descriptions were used for all diets (Table 2).

Evaluations were based on Monte Carlo analysis. In a Monte Carlo analysis, model inputs (grain composition and rates) are described as probability density functions from which samples are drawn to feed the model and derive the probabilities of possible solutions for the model (Law and Kelton, 2000). Monte Carlo sampling techniques were accomplished through the use of @Risk Version 4.5 (Palisade Corp., Newfield, NY), a commercially available Microsoft Excel add-in, in a spreadsheet version of the CNCPS model (Version 5.0) as described by Fox et al. (2004). To describe grain composition as distribution functions, the feed composition and fractional gas rates data were fit to several distributions and the distribution with the best fit to the data was assigned. The goodness of fit was assessed with several statistics (χ^2, Kolmogorov–Smirnov and Anderson–Darling Statistics) and graphical methods (distribution function difference plots and probability plots) (Law and Kelton, 2000). Minimum and maximum values in the data base were used to truncate the distributions. A correlation matrix was incorporated to take into account the correlation among inputs within feed (Table 3). A sample was randomly taken from each input distribution and used as an input to the model. Ten thousand samplings for simulation were carried out and the response variables of interest were recorded.

Table 1
Composition of the diets used in the simulations

	Barley diet	Corn diet	Sorghum diet	Wheat diet
Ingredients (kg DM)				
Corn silage	1.7	1.0	2.3	1.2
Soybean meal	0.3	0.8	1.0	0.8
Orchard grass hay	0.6	1.5	0.6	1.8
Barley	7.5	–	–	–
Corn	–	6.3	–	3.0
Sorghum	–	–	6.3	–
Wheat	–	–	–	3.3
Urea	0.1	0.1	0.1	0.1
Vitamin–mineral concentrate	0.2	0.2	0.2	0.2
Composition				
Metabolizable energy (MJ/kg DM)	11.69	12.44	11.61	11.69
CP (g/kg DM)	141	147	151	161
NDF (g/kg DM)	224	188	192	229
NFC (g/kg DM)	590	610	610	570

CP = crude protein; NDF = neutral detergent fiber; NFC = nonfiber carbohydrates.

The relation between the response variables and the feed composition was assessed with stepwise regression and Spearman correlations (Law and Kelton, 2000).

3. Results and discussion

3.1. Gas production kinetics

The average curves of the cumulative gas production for each grain are presented in Fig. 1. Wheat and barley fermented faster than the other grains, reaching an asymptote at 15 h. Sorghum fermented slower than the other grains achieving values close to the final observed volume after 35 h of fermentation.

Table 2
Animal and environment descriptions used in the CNCPS model to evaluate starch digestion rates in grains

Description	Input	Units
Animal type	Growing/finishing	
Age	13.00	Months
Sex	Steer	
Current shrunk body weight (SBW)	503	Kg
Expected SBW at 28% body fat	544	Kg
Grading system	Low marbling 28% body fat	
Condition score	5	(1–9 scale)
Breeding system	Angus × Hereford	
Additive	implant + ionophore	
Current temperature	4	°C
Current relative humidity	75	%
Activity	Dry lot, 4.64–9.29	m^2/head

Table 3
Spearman correlations between gas production fractional rate (exponential model) and chemical composition for of barley ($n = 20$), corn ($n = 98$), sorghum ($n = 23$), and wheat ($n = 57$) grain samples

Item	CP	ADICP	NDICP	NDF	STARCH	EE	ADF	LIGNIN	SOL CP	ASH
Overall[a]	0.57***	−0.65***	0.43***	0.67***	−0.45***	−0.74***	−0.12	0.51***	0.46***	0.58***
Barley	−0.43	−0.03	0.21	−0.20	0.31	0.24	−0.19	0.07	0.04	0.26
Corn	−0.19	−0.31**	0.08	0.03	0.13	−0.23	−0.27**	0.05	−0.21	−0.02
Sorghum	−0.20	−0.14	0.01	−0.09	−0.14	0.44	0.02	−0.60	−0.08	−0.05
Wheat	−0.08	0.05	0.35*	0.18	−0.08	−0.20	0.00	−0.14	0.21	−0.13

*P<0.05, **P<0.01, *** P<0.001; ADICP = acid detergent insoluble crude protein; ADF = acid detergent fiber; CP = crude protein; EE = ether extract; aNDF = neutral detergent fiber; NDICP = neutral detergent insoluble crude protein; SOL CP = soluble crude protein.

[a] All the cereals together ($n = 198$).

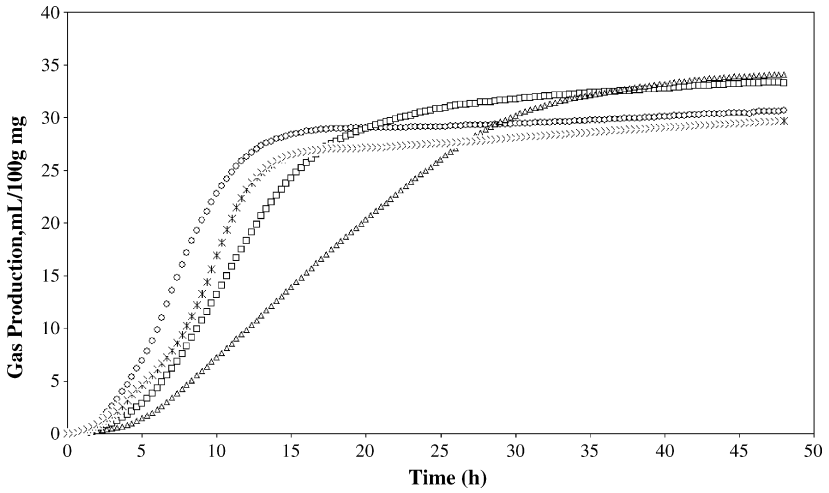

Fig. 1. Average cumulative gas production of: barley (*) ($n = 20$), corn (□) ($n = 99$), sorghum (△) ($n = 23$), and wheat (◯) grain ($n = 53$).

The digestion kinetics of the grains are summarized in Table 4. The one-pool exponential model fitted all the cumulative gas curves with R^2 higher than 0.99, and t-values higher than 14 for sorghum samples and higher than 20 for the other grains. Both the cumulative gas volume (mL) and gas production rate (h^{-1}) differed among grains (P<.001). The largest gas volume was for sorghum followed by corn, wheat and barley. Slowly fermented grains had greater lag times than did wheat and barley. Lag times of corn and sorghum did not differ.

The ranking of the grains in descending order of fractional rate of gas production was wheat, barley, corn and sorghum. The ranking of the cereals based on fractional rates of gas production was consistent with previous rankings based on enzymatic and *in situ* starch and dry matter degradation rates (Herrera-Saldana et al., 1990) and ruminal digestibility measured *in vivo* (Galloway et al., 1993). Gas evolves from fermentation of starch as well as non-starch components of grain. Fig. 2 displays the absolute rates ($mL\,h^{-1}$) for the average accumulative gas production. Only one distinct pool was evident in each of the four grains, indicating that the fermentation of the different carbohydrate fractions was occurring simultaneously rather than sequentially. Despite the different carbohydrate composition of barley and wheat (Table 5), the absolute rates for both grains peaked early in the fermentation and were narrowly distributed around the peak (Fig. 2), in agreement with their extensive ruminal digestion (Boss and Bowman, 1996). For starchy feeds, the relationship between gas production and starch degradation was linear (Chai et al., 2004), which indicates that the carbohydrate fractions were fermented simultaneously. Under these conditions, it would be expected that kinetic analysis of gas production from fermentation would rapidly provide information on the predominant carbohydrate fraction (for cereal grains, mainly starch). Chen et al. (1999) showed that the variation in gas production for dried corn grain can be attributed primarily to the neutral detergent soluble fraction and that the amount of fermentable material from the neutral detergent soluble fraction that was soluble in 80% aqueous ethanol (ash, ether extract, crude protein, and sugars) was small. This led them

Table 4
Kinetics of gas production from the *in vitro* fermentation of corn, sorghum, wheat and barley (exponential model)

Item	*N*	Final volume, mL/100 mg DM	Fractional rate (h^{-1})	Lag time (h)
Barley				
Total	20	28 (1.4)	0.24 (0.029)	2 (0.4)
Canada	6	28 (1.3)	0.22 (0.023)	2 (0.6)
Colombia	1	26	0.22	2
France	3	28 (0.7)	0.27 (0.031)	3 (0.9)
Hungary	5	28 (1.5)	0.22 (0.028)	3 (0.9)
Italy	1	27	0.29	2
Turkey	4	28 (1.0)	0.24 (0.023)	3 (0.9)
Corn				
Total	98	33 (1.9)	0.15 (0.026)	6 (0.9)
Argentina	2	31 (3.7)	0.12 (0.017)	6 (0.7)
Brazil	11	33 (1.7)	0.14 (0.012)	6 (1.0)
Canada	10	33 (1.8)	0.15 (0.019)	5 (0.8)
France	2	34 (3.7)	0.14 (0.009)	4 (0.8)
Hungary	2	32 (2.5)	0.15 (0.001)	5 (1.0)
Indonesia	4	32 (2.6)	0.14 (0.002)	6 (0.6)
Italy	3	31 (2.3)	0.14 (0.012)	5 (0.8)
Korea	5	34 (0.9)	0.17 (0.016)	6 (0.4)
Peru	5	35 (1.7)	0.12 (0.022)	5 (1.1)
Philippines	5	32 (1.2)	0.15 (0.022)	6 (0.7)
Spain	1	33	0.17	5
Sri Lanka	1	33	0.09	7
Thailand	1	34	0.12	6
Turkey	3	32 (2.6)	0.16 (0.008)	6 (0.7)
USA	40	33 (1.7)	0.16 (0.027)	6 (0.7)
Venezuela	3	35 (2.0)	0.12 (0.011)	6 (1.0)
Sorghum				
Total	23	39 (3.8)	0.06 (0.016)	6 (0.9)
Colombia	2	34 (0.5)	0.08 (0.014)	6 (0.1)
Honduras	1	40.5	0.06	7
Mexico	4	36 (3.5)	0.07 (0.015)	5 (1.1)
Nicaragua	4	43 (1.6)	0.05 (0.006)	5 (0.9)
USA	12	40 (3.4)	0.06 (0.016)	6 (1.3)
Wheat				
Total	57	30 (1.3)	0.26 (0.039)	4 (1.5)
Brazil	9	31 (1.0)	0.23 (0.037)	5 (0.8)
Canada	4	30 (1.0)	0.25 (0.052)	5 (0.9)
China	1	31	0.31	1
Hungary	5	31 (0.7)	0.24 (0.023)	5 (1.0)
India	6	30 (1.3)	0.26 (0.027)	3 (1.9)
Italy	5	30 (1.0)	0.26 (0.039)	3 (1.9)
Korea	2	31 (0.6)	0.25 (0.003)	4 (3.3)
Mexico	5	31 (2.3)	0.26 (0.037)	3 (1.8)
Philliphines	2	32 (2.3)	0.21 (0.016)	4 (0.4)
Spain	1	31	0.27	5
Turkey	4	29 (1.0)	0.25 (0.030)	5 (0.8)
USA	13	30 (1.2)	0.28 (0.040)	4 (1.5)

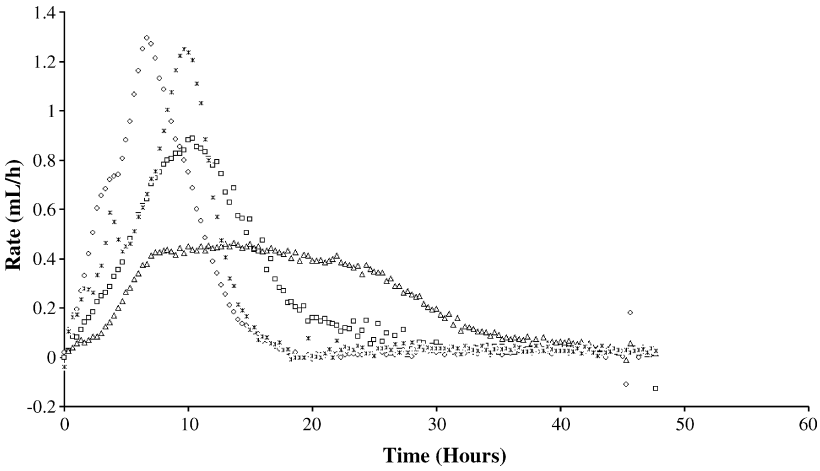

Fig. 2. Absolute rate plots calculated by subtracting the average accumulative gas volume at each 20 min time point from the volume at the next time point for barley (*), corn (□), sorghum (△), and wheat (◯).

to conclude that most of the variation in the shape of the gas curves could be attributed to starch fermentation.

Overall, information regarding *in vitro* digestion and gas production rates for cereal grains is scarce. Richards et al. (1995) reported fractional digestion rates of starch from *in vitro* rumen fluid fermentations (1 mm particle size) from 0.06 to 0.102 h^{-1} for sorghum and 0.151 h^{-1} for corn, which are similar to our gas production rates (Table 4). However, other authors have reported values lower than our gas production rates. Surber and Bowman (1998) reported *in vitro* starch disappearance rates of 0.07 h^{-1} for corn and 0.11 h^{-1} for barley (2 mm particle size). The discrepancies among studies may be attributed to methodological differences such as dissimilarities in the proportion of inoculum and buffer, type of buffer solution, processing effects and mathematical models used to evaluate the gas production data.

Most of the kinetic data for grains are from *in situ* studies. However, starch and dry matter digestion parameters derived from *in situ* studies may not be directly compared with gas production rates. *In situ* methods assume two degradable pools; a soluble fraction that is considered to be degraded instantaneously and completely, and an insoluble fraction that is degraded exponentially (Tamminga et al., 1990). *In situ* studies measure digestion rate for the slowly degradable pool, while gas production rates are derived from the entire degradable pool. Offner et al. (2003) summarized published *in situ* studies on starch degradation; They reported averaged rates of degradation for sorghum (0.042 h^{-1}), barley (0.35 h^{-1}) and wheat (0.33 h^{-1}), which are within the range of our measured rates of gas production. However, the *in situ* rates for corn were consistently lower (0.06 h^{-1}) than those derived from gas production (0.148 h^{-1}) even for samples with a small particle size (1 mm) (Cerneau and Michalet-Doreau, 1991, Nocek and Tamminga, 1991, and Offner et al., 2003). When the effective degradability (at a passage rate of 0.06 h^{-1}) was compared with *in situ* based effective degradability as reported by Offner et al. (2003), values for corn were greater for

Table 5
Chemical composition of barley ($n = 20$), corn ($n = 98$), sorghum ($n = 23$), and wheat ($n = 57$) grain samples from 22 countries (mean (S.D.), g/1000 g DM)

Item	CP	ADICP	NDICP	aNDF	Starch	EE	ADF	Lignin	SOL CP[a]	Ash
Overall[b]	105 (22.5)	5 (6.0)	10 (3.9)	102 (31.4)	678 (53.7)	30 (12.4)	34 (16.6)	5 (4.6)	206 (138.0)	17 (5.4)
Barley	121 (15.8)	4 (1.9)	13 (1.3)	187 (21.9)	587 (43.8)	18 (2.5)	72 (12.6)	9 (3.2)	161 (133.0)	27 (4.4)
Corn	89 (8.1)	3 (1.9)	7 (2.6)	90 (10.8)	706 (38.1)	39 (8.1)	26 (5.2)	1 (1.9)	147 (58.1)	13 (1.9)
Sorghum	96 (15.4)	19 (5.0)	13 (5.1)	78 (7.1)	696 (30.4)	30 (1.5)	50 (13.5)	15 (6.3)	128 (113.4)	17 (3.5)
Wheat	130 (17.3)	1 (0.5)	12 (2.3)	105 (90)	654 (42.4)	17 (2.2)	27 (3.8)	8 (2.6)	323 (140.9)	17 (1.8)

ADICP = acid detergent insoluble crude protein; ADF = acid detergent fiber; CP = crude protein; EE = ether extract; aNDF = neutral detergent fiber; NDICP = neutral detergent insoluble crude protein.

[a] SOL CP expressed as g/1000 g CP.

[b] All the cereals together ($n = 198$).

gas rates (0.72 versus 0.60), and lower for sorghum (0.50 versus 0.60), barley (0.80 versus 0.91), and wheat (0.81 versus 0.94). *In situ* techniques over predicted effective degradability for barley and wheat while under predicted degradability for slowly fermented grains (Offner and Sauvant, 2004). Some feed evaluation systems use *in situ* starch measurements (Tamminga et al., 1994). In other nutritional models (e.g. CNCPS, NRC Beef level 2), starch and soluble fiber are included in the same pool with a single digestion rate (named CHO B1 pool) (Fox et al., 2004). Therefore, for these models, *in vitro* methods may be more suitable than *in situ* methods for obtaining digestion rate data. The CNCPS Version 5.0 library values for cracked corn grains were very similar to our gas production rates (Fox et al., 2003). The library feed values for dried sorghum ($0.08\,h^{-1}$) are higher than our gas production rates, but the library values were within the range we observed in this study. The CNCPS feed library values for wheat grain ($0.40\,h^{-1}$) and barley grain (finely ground and whole) ($0.30\,h^{-1}$) were higher than the range found in this study.

Differences due to country of origin were found only for corn grain ($P<0.001$) (Table 4). The ability to detect differences only for corn may be the result of having a larger and more representative dataset for corn than for the other grains. For barley, the range in fractional rates was 0.20–$0.29\,h^{-1}$. For corn, a wider range was found between the highest ($0.19\,h^{-1}$, Canada) and the lowest gas production rate ($0.09\,h^{-1}$, Sri Lanka). For sorghum and wheat, the ranges were 0.03–0.09 and 0.18–$0.35\,h^{-1}$, respectively. For slowly fermenting grains, distribution of zein protein across the endosperm for corn (Philippeau et al., 1999) and differences in vitreous endosperm between hybrids in sorghums (Streeter et al., 1990) have been related to differences in ruminal starch degradability. Philippeau et al. (2000) also reported wide ranges in the *in situ* degradation rates for dent and flint corn: the rates for dent corn varied from 0.05 to $0.11\,h^{-1}$ and from 0.03 to $0.05\,h^{-1}$ for flint corn.

3.2. Relationship between chemical constituents and gas production kinetics

The chemical composition data are summarized in Table 5. Variation in the parameters in the kinetics of gas production was higher than the variation in most of the chemical components. The coefficient of variation for starch content was lower than 7% for all the grains. The chemical components that had the greatest variability were the protein fractions, ADICP and NDICP, both between and within grain species. For all grains, significant correlations with digestion rates were found for all the constituents except for ADF (Table 3). Fractional rates were positively correlated with CP, NDICP, NDF, lignin, SOL CP, and ash, and negatively correlated with ADICP, starch, and EE. Getachew et al. (2004) found poor correlations between rate of gas production and chemical composition. Our higher correlations may be due to the wide range in grain types and sources in our data base. The overall correlations reflected the difference in chemical composition between fast and slowly fermented grains. Wheat and barley (fast fermenting) had higher NDF and CP and lower starch contents, thus NDF and CP were positively correlated with gas fractional rate and starch was negatively correlated with the fractional rate. However, chemical parameters were poorly correlated with rates of gas production within grains. The only parameters that were well correlated with digestion rate for corn grain were ADICP ($r=-0.31$, $P<0.01$) and ADF ($r=-0.27$, $P<0.01$). This may be due to the recovery of the zein proteins in the ADICP fraction. Zein proteins are prolamins, which are soluble in alkali (Wilson, 1987)

and they have been correlated negatively with ruminal starch degradability (Philippeau et al., 2000). Neutral detergent insoluble crude protein content was positively correlated with gas production rate in wheat ($r = 0.35$, $P<0.05$). The low correlation between chemical components and digestion parameters may be due to the narrow range of the chemical parameters and, more importantly, because grain digestibility is primarily affected by the physical structure of the kernel rather than by chemical composition components. The low correlations between chemical constituents and rates made development of prediction equations for fractional rates from chemical composition infeasible.

3.3. Impact of variation in digestion rate on feed value of the grains

Table 1 presents the diets used in the simulations with the CNCPS. For the wheat diet, wheat constituted only half of the concentrate because rations with higher proportions may increase the incidence of digestive upsets. For all the diets, grain provided approximately 4 kg of starch. The gas fractional rates measured in this study were used for the CHO B1 digestion rates, based on the assumption that most of the variability in gas production rates are derived from the neutral detergent soluble fraction (Chen et al., 1999). The exponential model used for fitting the gas data had a discrete lag time to reflect the time when digestion was slow or nonexistent (Eq. (1)). The CNCPS does not include a lag in predictions of ruminal digestion (Fox et al., 2004). The inclusion of the *in vitro* lag in predicting starch digestion would have decreased the amount of ruminally digested starch compared to model predictions (Table 6). Although *in vivo* digestion lag may exist, due to processes such as microbial attachment or particle hydration, its equivalence to an *in vitro* digestion lag is, at best, uncertain. *In vitro* digestion lag depends on factors associated with the *in vitro* technique and the fitting techniques as well as on any delays normally observed in the rumen. Inoculated microbial species, amount of inoculum added and initial anaerobiosis affect lag time (Pell and Schofield, 1993). In addition, when using nonlinear methods for curve fitting, discrete lag increases along with the fractional digestion rate since both parameters are positively correlated ($r = 0.70$ for our data set, data not shown).

The S.D. reported in Table 6 reflect the maximal impact that variation in grain composition has on the predicted variables. Because the dataset contained samples from different locations around the world and thus reflects the likely ranges of chemical components of

Table 6
Impact of feed variation on the predictions of nutrient supply from the grains (mean ± S.D.)

Item	Intake CHO B1 (g/day)	Ruminal digested CHO B1 (g/day)	Apparent TDN content (g/kg DM)	ME supply (MJ/day)	MP supply (g/day)
Barley diet	4411 (211)	3843 (189)	810 (80)	92.2 (1.01)	841 (30)
Corn diet	4450 (236)	3638 (221)	890 (90)	85.1 (0.88)	734 (41)
Sorghum diet	4371 (178)	2727 (277)	800 (200)	75.8 (2.05)	482 (57)
Wheat diet[a]	2157 (135)	1885 (122)	850 (60)	42.3 (0.29)	415 (19)

[a] For the wheat diet, the amount of nutrients supply for wheat is reported. Total CHO B1 intake, ruminal digested CHO B1, metabolizable energy (ME), and metabolizable protein (MP) supply for the corn and wheat were 4276 g/day, 3609 g/day, 82.5 MJ/day, and 775 g/day, respectively.

Table 7
Impact of one S.D. variation in starch content[a] and CHO B1 rate[b] on the predicted ruminal digested CHO B1 pool (g/day)

Item	Starch content	CHO B1 rate[c]	Relative importance[d]
Barley diet	184	42	4.4:1
Corn diet	192	106	1.8:1
Sorghum diet	111	249	1:2.2
Wheat diet	118	32	3.7:1

[a] S.D. for starch content are presented in Table 5.
[b] S.D. for CHO B1 rate are presented in Table 4.
[c] Predicted concentrate passage rates (h^{-1}) were: barley, 0.035; corn, 0.033; sorghum, 0.035; and wheat; 0.036.
[d] Relative importance is the coefficient between the variation on predicted ruminal digested CHO B1 pool due to starch content and due to CHO B1 rate.

the grain but did not account for processing effects (all samples were dried), we expect that the variation at the farm level is lower than those reported here unless processing effects are present. The CNCPS uses competition between digestion and passage rates to predict the fermented mass in the rumen as described by Waldo et al. (1972). Higher variation in ruminally digested CHO B1 was observed compared to total CHO B1 intake (Table 6). The observed variation in ruminal digested CHO B1 pool may have a profound impact on rumen conditions. Changes in starch fermentation have been related to changes in protein synthesis, pH, total VFA production and acetate/propionate ratio (Sauvant, 1997). Table 7 shows the relative effects of variation in starch content and CHO B1 rate on the extent of ruminally digested CHO B1 pool. For the rapidly fermented grains, starch content had a greater effect than fermentation rate on the size of the ruminally digested CHO B1 pool. For sorghum, which had the slowest fermentation rate, the CHO B1 rate controlled the extent of digestion more than starch content.

The apparent TDN and energy calculation in the CNCPS model take into account the interactions of bacterial growth, and ruminally degraded carbohydrate and protein, degradation and passage rates, intestinal absorption, and fecal composition (Fox et al., 2004). Because the animal factors, which determine passage rates, are hold constant in the simulations, the variation in ME supply was narrow (less than 4.19 MJ/day) (Table 6). For the barley diet, the most influential inputs for predicting ME supply were barley NDF ($r = -0.62$), lignin ($r = -0.48$), and ash ($r = -0.47$). Lignin and ash do not provide energy, while increasing the NDF fraction decreases the calculated nonstructural carbohydrates, thus decreasing to TDN value. For the corn diet, ME predictions were sensitive to corn, ether extract ($r = 0.90$), dry matter ($r = 0.54$) and CHO B1 rate ($r = 0.28$). Corn had the highest ether extract content of all grains. Ether extract is strongly related to ME supply since it is assumed to provide 2.25 more TDN than protein or carbohydrates. For the sorghum diet, lignin ($r = -0.91$), CHO B1 rate ($r = 0.30$), and ADICP ($r = -0.15$) were the most influential variables. For corn and sorghum, the total digested carbohydrates were sensitive to CHO B1 rate. For the wheat diet, lignin ($r = -0.83$), NDF ($r = -0.64$), and EE content ($r = 0.30$) were the feed components that were most related to variation in ME prediction.

The variation in predicted MP averaged 37 g, and was higher for the sorghum diet (Table 6). The microbial protein represents more than 68% of the total metabolizable protein supply for all the rations so the metabolizable protein was very sensitive to the CHO-B1

pool size and digestion rate. Conversely, bacterial growth is dictated by the amount of carbohydrate degraded in the rumen. Increasing the starch content and the CHO-B1 rate results in a greater amount of degraded carbohydrate in the rumen, For each grain, variation in MP supply was linked to variation in SOL CP ($r = -0.65$), CP ($r = 0.50$), and CHO-B1 rate ($r = 0.32$) for barley, CHO-B1 rate ($r = 0.72$), ADICP ($r = -0.46$) and starch ($r = -0.39$) for corn, CHO-B1 rate ($r = 0.80$), CP ($r = 0.38$) and starch ($r = -0.31$) for sorghum, and SOL CP ($r = -0.70$), CHO-B1 rate ($r = 0.58$) and starch ($r = -0.43$) for wheat. Although concentrates constitute a greater proportion of feedlot diets than dairy rations, CHO-B1 rates for grains (especially for processed grains) also are important in predicting MP supply (Lanzas et al., 2007).

4. Conclusions

A detailed evaluation of feed values for grains needs to include information on rates of fermentation. Fermentation rates for grains can vary more than the chemical components, and this variation was not reflected by changes in chemical composition in this study. Grain processing can profoundly affect rate and site of digestion and should be considered in grain evaluations. The fermentation rates for slowly fermenting grains largely determine the site of starch digestion and MP supply.

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