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A revised CNCPS feed carbohydrate fractionation scheme for formulating rations for ruminants

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Abstract

Balancing ruminant diets for appropriate levels and types of dietary carbohydrates (CHO) is necessary to maximize production while assuring the health of the animals. Several feed fractions (*i.e.*, volatile fatty acids (VFA), lactate, sugars, starch) are now being measured in some commercial feed laboratories and this information may assist in better formulating diets. A CHO fractionation scheme based on ruminal degradation characteristics needed for nutritional models is described and its impact on predictions with the Cornell Net Carbohydrate and Protein System (CNCPS) is assessed. Dietary CHO are divided into eight fractions: the CA1 is volatile fatty acids (VFA), CA2 is lactic acid, CA3 is other organic acids, CA4 is sugars, CB1 is starch, CB2 is soluble fiber, CB3 is available neutral detergent fiber (NDF), and CC is unavailable NDF. A Monte Carlo analysis was conducted with an example lactating dairy cow ration to compare the original CNCPS CHO scheme (CA = sugars and organic acids, CB1 = starch and soluble fiber, CB2 = available NDF, CC = unavailable NDF) with the developed CHO scheme. A database was used to obtain distributions and correlations of the feed inputs used in the schemes for the ingredients of the ration (corn and grass silages, high moisture

Abbreviations: AA, amino acids; aNDR, NDF assayed with amylase and without sodium sulfite; CHO, carbohydrates; CNCPS, Cornell Net Carbohydrate and Protein System; CPM, Cornell–Penn–Miner Net Carbohydrate and Protein System; DM, dry matter; EE, ether extract; FC, fiber carbohydrates; HMCG, high moisture corn grain; ME, metabolizable energy; MP, metabolizable protein; ND, neutral detergent; NDF, neutral detergent fiber; NDICP, neutral detergent insoluble CP; NFC, non-fiber carbohydrates; R.M.S.E., root mean standard error; VFA, volatile fatty acids; Y_g, maximum rumen microbial growth yield

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corn, soybean meal, and distillers' grains). The CHO fractions varied in a decreasing order as VFAs, soluble fiber, lactic acid, sugar, NDF, starch, and total non-fiber carbohydrates (NFC). Use of the expanded scheme in the CNCPS decreased the microbial CP production, which was sensitive (standard regression coefficient in parenthesis) to corn silage starch (0.55), grass silage NDF rate (0.46), high moisture corn grain starch rate (0.44), and corn silage NDF rate (0.33). Predicted ruminal NFC digestibility remained similar. The expanded CHO scheme provides a more appropriate feed description to account for variation in changes in silage quality and diet NFC composition. However, to fully account for differences in feed CHO utilization, further improvements in the methodology used to estimate the fractions and their corresponding degradation rates, inclusion of dietary factors in dry matter intake predictions, and prediction of ruminal VFA production and pH are necessary.

Keywords: Carbohydrates; Nutritional models; Rumen; Simulation

1. Introduction

Carbohydrates (CHO) are the largest component of rations for lactating dairy cows, and can be partitioned into fiber (FC) and non-fiber carbohydrates (NFC). Fiber CHO (*i.e.*, hemicelluloses and celluloses) is the slowly digestible fraction of feeds that occupies space in the gastrointestinal tract and fiber CHO associated with lignin resists digestion and therefore does not contribute energy to the animal (Mertens, 1997). Carbohydrates soluble in neutral detergent (ND) solution include organic acids, monosaccharides, oligosaccharides, fructans, pectic substances, β-glucans and starch (Hall, 2003). Balancing for an appropriate level and type of NFC is a major challenge in ruminant ration formulation. Feeds vary widely in their amount and composition of NFC, and CHO fractions in NFC differ in rate and extent of fermentation, products of fermentation, and contribution to microbial CP production (Hall and Herejk, 2001; Nocek and Tamminga, 1991), and therefore to animal performance. For example, lactating dairy cows fed diets with by-product feeds high in soluble fiber and sugars had decreased milk protein and increased milk fat yields (Leiva et al., 2000; Mansfield et al., 1994) and lower N efficiency for milk production (Broderick and Radloff, 2004) than those fed high starch diets. Ruminants fed high starch diets that have increased metabolizable energy (ME) tend to have increased microbial amino acid (AA) supply (Oba and Allen, 2003), but are more predisposed to suffer from ruminal acidosis.

The Cornell Net Carbohydrate and Protein System (CNCPS) (Fox et al., 2004) accounts for effects of variation in feed CHO fractions in predicted feed ME supply, rumen N, and AA balances when developing diets to meet cattle nutrient requirements. Its current feed CHO fractionation scheme divides NFC into two aggregated fractions; an A fraction, which includes organic acids and sugars and a B1 fraction, which includes soluble fiber and starch (Sniffen et al., 1992). Several limitations of this scheme have become apparent because these fractions are not precisely defined or analyzed (Alderman, 2001; Offner and Sauvant, 2004; Pitt et al., 1996). It does not account for all the variability observed in NFC digestibility when various processing treatments are applied (Offner and Sauvant, 2004). In addition, the description and ruminal digestibility of the fraction containing starch and soluble fiber

were highlighted as an area that needed further improvement to accurately predict ruminal VFA production and pH (Pitt et al., 1996).

Our objectives are to describe a feed CHO fractionation scheme that classifies CHO based on ruminal degradation characteristics and available analytical methods, to evaluate its impact on CNCPS model behavior and sensitivity, and to discuss its application in ruminant ration formulation.

2. Material and methods

2.1. Feed carbohydrate fractionation schemes

2.1.1. Original CHO fractionation scheme

In the original CNCPS CHO fractionation scheme (Sniffen et al., 1992), total carbohydrate content in the *j*th feedstuff is estimated by difference:

$$\mathrm{CHO}_j\,(\mathrm{g/kg\ DM}) = 1000 - \mathrm{CP}_j - \mathrm{EE}_j - \mathrm{Ash}_j \tag{1}$$

where Ash_j is the mineral content of the *j*th feed (g/kg DM), CP_j the crude protein content of the *j*th feed (g/kg DM), and EE_j is the ether extract content of the *j*th feed (g/kg DM).

Carbohydrates are divided into FC and NFC, with FC defined as NDF. Within FC, the indigestible fiber fraction (CC) is computed as

$$\mathrm{CC}_j\,(\mathrm{g/kg\ DM}) = \frac{\mathrm{NDF}_j \times \mathrm{Lignin}_j \times 2.4}{1000} \tag{2}$$

where Lignin_j is the lignin(sa) content of the *j*th feed (g/kg NDF) and NDF_j is the NDF assayed with amylase and without sodium sulfite (aNDR) content of the *j*th feed (g/kg DM).

The available FC (CB2) is computed as

$$\mathrm{CB2}_j\,(\mathrm{g/kg\ \ DM}) = \frac{\mathrm{NDF}_j - (\mathrm{NDICP}_j \times \mathrm{CP}_j)}{1000} - \mathrm{CC}_j \tag{3}$$

where CC_j is the indigestible carbohydrate content of the *j*th feed (g/kg DM), CP_j the CP content of the *j*th feed (g/kg DM), NDF_j the aNDR content of the *j*th feed (g/kg DM) and NDICP_j is the ND insoluble CP content of the *j*th feed (g/kg CP).

Non-fiber carbohydrates are calculated by difference:

$$\mathrm{NFC}_j\,(\mathrm{g/kg\ \ DM}) = \mathrm{CHO}_j - \mathrm{CB2}_j - \mathrm{CC}_j \tag{4}$$

The NFC is divided into fractions CB1 and CA. The CB1 fraction represents soluble fiber and starch, with its degradation rates ranging from 0.05 to 0.50 h^{-1}. Tabular values were provided for the soluble fiber (Sniffen et al., 1992). The CA fraction represents the rapidly fermented (1–3 h^{-1}) water soluble CHO fraction, and is calculated by difference:

$$\mathrm{CB1}_j\,(\mathrm{g/kg\ \ DM}) = \mathrm{CB1NFC}_j \times \mathrm{NFC}_j \times 1000 \tag{5}$$

$$\mathrm{CA}_j\,(\mathrm{g/kg\ \ DM}) = \mathrm{NFC}_j - \mathrm{CB1}_j \tag{6}$$

Table 1
List of the equations for the expanded carbohydrate fractions (g/kg DM)

Fraction	Description	Equation
CHO	Total carbohydrates	$1000 - CP_j - EE_j - Ash_j$
CC	Indigestible fiber	$NDF_j \times Lignin_j \times 2.4/1000$
CB3	Digestible fiber	$NDF_j - (NDICP_j \times CP_j)/1000 - CC_j$
NFC	Non-fiber carbohydrates	$CHO_j - CB3_j - CC_j$
CA1	Volatile fatty acids	$Acetic_j + Propionic_j + Butyric_j + Isobutyric_j$
CA2	Lactic acid	$Lactic_j$
CA3	Organic acids	$Organics_j$
CA4	Sugars	$Sugar_j$
CB1	Starch	$Starch_j$
CB2	Soluble fiber	$NFC_j - CA1_j - CA2_j - CA3_j - CA4_j - CB1_j$

where CA_j is the sugar content the *j*th feed (g/kg DM), $CB1_j$ the starch and soluble fiber content of the *j*th feed (g/kg DM), $CB1NFC_j$ the starch and soluble fiber content of the *j*th feed (g/kg NFC), and NFC_j is the non-fiber carbohydrate content of the *j*th feed (g/kg DM).

The Cornell–Penn–Miner (CPM) dairy implementation of the CNCPS model (Boston et al., 2000) divided the NFC CA and CB1 fractions. The CA fraction was separated into a silage acids fraction (CPM CA1, containing VFA and lactic acid) with degradation rates of $0\,h^{-1}$ and a sugar fraction (CPM CA2) with degradation rates of $1–3\,h^{-1}$. The CB1 fraction was divided into starch (CPM CB1) and soluble fiber fractions (CPM CB2, containing soluble fiber and organic acids). The CPM CB1 and CPM CB2 have identical degradation rates ($0.05–0.50\,h^{-1}$).

2.1.2. New expanded CHO fractionation scheme

Based on ruminal degradation characteristics and available analytical methods, a new scheme, which further disaggregates the original CNCPS and CPM schemes, was developed. Table 1 lists the equations of the new expanded carbohydrate scheme. In the expanded CHO fractionation scheme, CHO and CC fractions are calculated as described in Eqs. (1) and (2). The available FC (CB2, Eq. (3)) was renamed from CB2 to CB3, since the CB1 (Eq. (5)) is divided into starch (CB1) and soluble fiber (CB2). Similar to Eqs. (3) and (4), available NDF and NFC are computed as

$$CB3_j\,(g/kg\ DM) = \frac{NDF_j - (NDICP_j \times CP_j)}{1000} - CC_j \tag{7}$$

$$NFC_j\,(g/kg\ DM) = CHO_j - CB3_j - CC_j \tag{8}$$

The CA (Eq. (6)) is divided into four fractions: volatile fatty acids (VFA) (CA1), lactic acid (CA2), other organic acids (CA3), and sugars (CA4). Although organic acids (CA1, CA2, and CA3) are not carbohydrates, they are included in the carbohydrate fractions because they are judged to be more closely related to carbohydrates than to fat or protein.

Fraction CA1 represents VFA:

$$CA1_j\,(g/kg\ DM) = Acetic_j + Propionic_j + Butyric_j + Isobutyric_j \tag{9}$$

where Acetic_j is the acetic acid content of the jth feed (g/kg DM), Propionic_j the propionic content of the jth feed (g/kg DM), Butyric_j the butyric acid content of the jth feed (g/kg DM) and Isobutyric_j is the isobutyric acid content of the jth feed (g/kg DM).

The VFA can represent up to 60 g/kg of DM of the silages (McDonald et al., 1991). Volatile fatty acids, which are end products of fermentation are not sources of energy for rumen microorganisms. Therefore, their ruminal degradation rates and maximum rumen microbial growth yield (Y_g) are 0.

The fraction CA2 represents lactic acid:

$$\text{CA2}_j\,(\text{g/kg DM}) = \text{Lactic}_j \tag{10}$$

In fermented feeds, lactic acid is the predominant organic acid, which can be present at 50–150 g/kg DM (McDonald et al., 1991). In addition to ensiled feeds, lactic acid may be also present in molasses (Table 2) from degradation of invert sugar, but also includes malic, citric, fumaric and oxalic acids (Amin, 1980). Lactic acid is mainly converted to acetate and propionate in the rumen, with no direct contribution to glucose flux in the animal (Gill et al., 1986). Based on gas production measurements, the ruminal degradation rate of lactic acid was measured to be 0.07 h^{-1} (Molina, 2002). The CNCPS uses a theoretical Y_g of 50 g of microbial cells for 100 g of CHO fermented, or 0.55 mole of hexose fermented (Isaacson et al., 1975), which assumes approximately 3.63 moles of ATP per mole of hexose, and an ATP yield of 25 g of cells per mole. However, lactic acid supplies less ATP per mole than CHO. For lactic acid, the Y_g was set to 10.8 g cells for 100 g of lactic acid because it was assumed that, on average, 0.65 mole/mole of lactic acid is fermented via the acrylate pathway, which provides 0.33 mole of ATP per mole of lactate and the remaining is fermented mainly through the succinate–propionate pathway, which yields 0.5 mole of ATP per mole of lactate (Counotte et al., 1981). The Y_g is then decreased by 20% to account for protozoa predation (Russell et al., 1992).

The fraction CA3 represents organic acids other than lactic acid:

$$\text{CA3}_j\,(\text{g/kg DM}) = \text{Other Organics}_j \tag{11}$$

Organic acids other than lactic and VFA are almost undetectable in silages (McDonald et al., 1991), but in fresh forages, citric, malic, and aconitic acids can comprise more than 100 g/kg of the forage DM (Dijkshoorn, 1973). Acetate is the primary fermentation product from organic acids (Russell and Van Soest, 1984). Based on gas production measurements, the ruminal degradation rate for organic acids was set to 0.05 h^{-1} (Molina, 2002), less ATP per mole than CHO and lactic acid. For the CA3 fraction, the Y_g was set to 3.5 g cells for 100 g of organic acids based on the average yields for malic acid (Dimroth and Schink, 1998) and citric acid (Gottschalk, 1986).

The fraction CA4 includes monosaccharides, disaccharides, and oligosaccharides:

$$\text{CA4}_j\,(\text{g/kg DM}) = \text{Sugars}_j \tag{12}$$

The predominant sugars in feeds are glucose, fructose and sucrose (Knudsen, 1997; Van Soest, 1994). Sucrose is the most common sugar, is the principal means of transport in plants and can be stored as a reserve in feeds such as sugar beets (Van Soest, 1994). In legume seeds, raffinose and stachyose represent an important proportion of sugars (Knudsen, 1997). Sugars

Table 2
Carbohydrate fractions measured from the expanded scheme in selected feeds and their corresponding degradation rates

	Fractions[a] (g/kg DM)								Degradation rates (h^{-1})			
	CA1[b]	CA2[c]	CA3[d]	CA4	CB1	CB2	CB3	CC	CA4	CB1	CB2	CB3
Energy rich feeds												
Barley grain, steam-rolled	0	0	0	24	523	61	186	58	0.40	0.35	0.30	0.05
Barley grain, ground	0	0	0	24	523	61	186	58	0.40	0.30	0.30	0.05
Beet pulp, dry	0	0	0	133	30	267	259	91	0.40	0.20	0.40	0.08
Citrus pulp, dry	0	0	0	269	12	344	188	56	0.40	0.30	0.30	0.09
Corn grain, cracked	0	0	0	15	748	8	79	5	0.40	0.10	0.20	0.03
Corn grain, ground fine	0	0	0	15	748	8	79	5	0.40	0.15	0.20	0.06
Corn grain, flaked	0	0	0	16	756	8	76	4	0.40	0.25	0.20	0.06
High moisture corn grain, ground	6	17	0	17	714	14	80	5	0.20	0.30	0.20	0.06
Molasses, beet	0	40	55	700	0	0	0	0	0.40	0.30	0.30	0.05
Sorghum grain, ground coarse	0	0	0	24	564	24	205	34	0.40	0.05	0.20	0.03
Soy hulls	0	0	0	7	10	156	616	32	0.40	0.30	0.08	0.08
Cottonseed, whole	0	0	0	23	2	25	350	310	0.40	0.30	0.30	0.06
Forages												
Alfalfa hay	0	0	30	105	18	200	275	151	0.40	0.30	0.35	0.08
Alfalfa silage	16	48	0	31	15	197	303	206	0.20	0.30	0.35	0.06
Corn silage (processed, 250 g/kg DM)	30	54	0	4	309	4	390	108	0.20	0.40	0.30	0.04
Corn silage (unprocessed, 250 g/kg DM)	30	54	0	4	281	32	395	97	0.20	0.40	0.30	0.04
Corn silage (processed, 350 g/kg DM)	26	46	0	8	309	12	395	97	0.20	0.32	0.30	0.04
Corn silage (unprocessed, 350 g/kg DM)	26	46	0	8	309	12	395	97	0.20	0.25	0.30	0.04
Grass pasture	0	0	40	77	4	82	483	92	0.40	0.30	0.30	0.05
Grass silage	22	46	0	48	23	88	466	106	0.20	0.30	0.30	0.06
Legume pasture	0	0	80	156	6	82	213	97	0.40	0.30	0.35	0.08
Protein-rich feeds												
Distillers'grains	0	0	0	34	122	103	187	111	0.40	0.17	0.30	0.07
Soybean meal, solvent	0	0	0	109	22	141	80	6	0.40	0.25	0.30	0.06

[a] CA1 = acetic, propionic and butyric acids; CA2 = lactic acid; CA3 = other organic acids; CA4 = sugars; CB1 = starch; CB2 = soluble fiber; CB3 = available neutral detergent fiber (NDF); CC = unavailable NDF (lignin(sa) × 2.4).
[b] Degradation rate for CA1 is 0 h^{-1}.
[c] Degradation rate for CA2 is 0.07 h^{-1}.
[d] Degradation rate for CA3 is 0.05 h^{-1}.

produce similar propionate and higher butyrate than starch and, at low pH, produce more lactate than starch (Strobel and Russell, 1986). Using gas production measurements, Molina (2002) reported fermentation rates of 0.40 h^{-1} for glucose and 0.16 h^{-1} for arabinose when fermented with a fiber source. As five carbon sugars support less microbial growth than hexoses (Strobel and Russell, 1986), and based on the composition of the sugar fraction in feeds and their ability to support microbial growth, degradation rates for feeds containing mainly sucrose were set at 0.40 h^{-1} for the sugar fraction (Molina, 2002), but for milk derived products the assigned degradation rate for sugars is 0.30 h^{-1} as lactose supports less microbial growth than sucrose (Bond et al., 1998; McCormick et al., 2001). For silages, with the exception of immature corn silages, the sugar fraction does not contain unfermented sugars, in favor of arabinose and other simple sugars derived from the hydrolysis of the side chains of pectin and hemicelluloses (Dewar et al., 1963; Jones et al., 1992). Thus, a rate of 0.20 h^{-1}, closer to the arabinose fermentation rate was assigned to the sugar fraction of silages.

The fraction CB1 represents starch:

$$\mathrm{CB1}_j\,(\mathrm{g/kg\ DM}) = \mathrm{Starch}_j \tag{13}$$

Starch degradability varies depending on the particle size, grain type, processing effect and preservation method (Offner et al., 2003). Ruminal degradation rates of starch are feed specific, with values that range from 0.03 h^{-1} for bird resistant sorghum to 0.40 h^{-1} for wheat (Table 2).

Soluble fiber (CB2) is calculated by difference as

$$\mathrm{CB2}_j\,(\mathrm{g/kg\ DM}) = \mathrm{NFC}_j - \mathrm{CA1}_j - \mathrm{CA2}_j - \mathrm{CA3}_j - \mathrm{CA4}_j - \mathrm{CB1}_j \tag{14}$$

The CB2 fraction includes β-glucans and pectic substances and are defined as dietary fiber because they are not digested by mammalian enzymes. Fermentation of soluble fiber is depressed at low pH and the main VFA produced from its fermentation is acetic acid (Strobel and Russell, 1986). Pectic substances occur in high concentration in by-product feeds such as citrus pulp, beet pulp and soybean hulls, as well as in the cell walls of legume forages (Van Soest, 1994). They ferment quickly, with ruminal degradation rates that range from 0.20 to 0.40 h^{-1} with the exception of soybean hulls (0.08 h^{-1}) (Hall et al., 1998; Hatfield and Weimer, 1995). β-Glucans are present in barley and oat grains at 40–120 g/kg DM and are degraded at similar rates to starch (Engstrom et al., 1992).

2.2. *Variability of feed CHO fractions and sensitivity analysis*

The expanded CHO fraction scheme was evaluated by completing a sensitivity analysis of the expected variation in feed composition and degradation rates. The sensitivity analysis was conducted using a sample lactating cow diet and expected variation in carbohydrates and their digestion rates. The simulated animal was a lactating dairy cow (650 kg BW and 43 kg milk/day) daily fed 7.5 kg DM high moisture corn grain (HMCG), 7 kg grass silage, 6 kg corn silage, 3 kg soybean meal, 1 kg distillers grains, 1.1 kg whole cottonseed and a mineral–vitamin mixture. The ration provide 330 g aNDF/kg DM, 410 g NFC/kg DM, 173 g CP/kg DM, and 11.09 MJ/kg DM.

Monte Carlo techniques were used in the sensitivity analysis. In a Monte Carlo analysis, model inputs are described as probability density functions from which samples are drawn to drive the model and derive probabilities of possible model solutions (Law and Kelton, 2000). The Monte Carlo analysis was done with @Risk version 4.5 (Palisade Corp., Newfield, NY, USA) in a spreadsheet version of the CNCPS (Fox et al., 2004). In order to describe feed composition as distributions, a database provided by a commercial laboratory (Dairy One, Ithaca, NY, USA) was used. All feeds were analyzed by 'wet' chemistry. For starch analysis, a pre-extraction for sugar was completed and a glucose oxidase–peroxidase assay combined with a peroxide-detecting probe (YSI Incorporated, Yellow Springs, OH, USA) was used. For sugars, a water extraction method was used. Feed composition data were fit to a normal distribution. When feed inputs were not statistically normal, the distribution with the best fit to the data was assigned (Table 3). Goodness of fit was assessed with several statistics (Chi-squared, Kolmogorov–Smirnov and Anderson–Darling statistical tests) and graphical methods (distribution function differences plots and probability plots) (Law and Kelton, 2000). Minimum and maximum values in the database were used to truncate distributions and a correlation matrix was incorporated to account for correlation among inputs within feeds when sampling (Table 4). For degradation rates, a normal distribution with a S.D. proportional to their mean was used to account for variability in the rates estimates increases as the mean value increases (Weiss, 1994).

Several sampling techniques that are suitable for Monte Carlo simulation are available (McKay et al., 1979). The sampling technique chosen for drawing samples from the distribution was the Latin Hypercube, in which the probability density function is divided into intervals of equal probability and from each interval a sample is randomly taken (McKay et al., 1979). Sampling is forced to represent values at each interval. Ten thousand samples for simulation were completed. For each sampling, the same random numbers were used to simulate the model with the original and expanded CHO schemes.

The sensitivity analyses are in Table 6. Model predictions for metabolizable protein (MP) from bacteria, and ruminal NFC digestibility were assessed using the original and expanded CHO fractionation schemes. To assess the impact of feed variability on the model outputs with the two schemes, Bonferroni confidence intervals were computed for the mean and S.D. of the simulated outputs (Banks et al., 2004). In addition, a stepwise regression analysis was used to assess the strength of the relationship between specific inputs and outputs. Standard regression coefficients (SRC) were used to rank the inputs and provide a measure of importance based on the effect of moving each variable away from its expected value by a fixed fraction of its S.D. while retaining all other variables at their expected values (Helton and Davis, 2002).

3. Results and discussion

3.1. Feed carbohydrate fractionation schemes and analytical methods

Table 2 lists average CHO fractions for common feedstuffs. Volatile fatty acids and lactic acid for silages are currently available from fermentation profiles offered by commercial laboratories. Dry matter content of the silages was a poor predictor of total VFA

Table 3
Means, coefficients of variation (CV), minimum, maximum and distribution of the feed composition (g/kg DM) for the feeds used in the sensitivity analysis

	N	Mean	CV	Minimum	Maximum	Distribution[a]
Corn silage						
Ash	6292	44	25.8	12	196	Normal (44, 11)
CP	8908	85	12.4	43	192	Loglogistic (21, 62, 11.3)
NDICP	6018	14	23.9	5	58	Loglogistic (3, 11, 6.1)
EE	6189	33	12.4	13	53	Normal (33, 4)
aNDF	9678	441	13.4	281	743	Normal (441, 59)
Lignin(sa)	6257	35	18.4	9	97	Loglogistic (3, 32, 9.3)
Starch	6353	308	25.4	3	499	Weibull (8.9, 613)
Sugar	6045	41	46.3	1	191	PearsonV (13.6, 747)
Acetic acid	440	23	63.1	0	78	Beta general (1.7, 5.2)
Propionic acid	440	4	130.0	0	31	Beta general (0.4, 4.4)
Butyric acid	440	1	254.7	0	19	Exponential (0.7)
Isobutyric acid	440	6	111.0	1	7	Lognormal (0.6, 0.6)
Lactic acid	440	50	41.3	0	101	Normal (50, 21)
Grass silage						
Ash	895	96	27.7	36	226	Loglogistic (14, 77, 5.7)
CP	1385	144	26.7	24	292	Beta general (7.7, 11.7)
NDICP	680	33	27.0	12	78	Lognormal (35, 9)
EE	726	37	25.7	9	103	Normal (37, 10)
aNDF	1384	584	11.9	397	818	Normal (584, 69)
Lignin(sa)	728	69	24.5	19	174	Logistic (68, 9)
Starch	681	24	62.9	1	104	Weibull (1.6, 28)
Sugar	689	28	39.4	8	192	Lognormal (105, 28)
Acetic acid	34	22	74.9	0	63	Loglogistic (−5, 22, 2.6)
Propionic acid	34	2	128.5	0	8	Exponential (2)
Butyric acid	34	4	132.1	0	19	Exponential (4)
Isobutyric acid	34	1	122.0	0	5	Exponential (1)
Lactic acid	34	47	56.8	1	111	Loglogistic (−131, 176, 11.6)
High moisture corn grain						
Ash	1613	17	12.9	11	32	Loglogistic (5, 11, 9.8)
CP	2166	97	10.7	67	149	PearsonV (53.5, 3874)
NDICP	1575	8	23.4	2	19	Logistic (8, 1)
EE	1618	44	15.2	21	105	Loglogistic (13, 31, 8.7)
aNDF	2153	101	20.6	51	272	PearsonV (17.3, 1157)
Lignin(sa)	1576	10	23.9	2	25	Logistic (10, 1)
Starch	1602	706	4.3	543	774	Logistic (708, 15)
Sugar	45	22	65.0			Normal (22, 14)
Acetic acid	94	3	113.0			Exponential (3)
Propionic acid	94	0.4	200.0			Exponential (0.4)
Butyric acid	94	0.1	278.0			Exponential (0.1)
Isobutyric acid	94	0.1	300.0			Exponential (0.1)
Lactic acid	94	11	84.0			Normal (11, 9)
Distillers' grains						
Ash	83	63	17.9	32	96	Normal (63, 11)
CP	354	314	7.6	236	406	Normal (314, 24)
NDICP	1427	310	30.6			Normal (310, 95)
EE	286	135	18.0	36	190	Weibull (9.7, 209)

Table 3 (*Continued*)

	N	Mean	CV	Minimum	Maximum	Distribution[a]
aNDF	284	338	9.5	245	424	Loglogistic (−387, 723, 36.9)
Lignin(sa)	370	57	38.6			Normal (57, 22)
Starch	188	45	51.7	4	229	Loglogistic (−12, 54, 5.7)
Sugar	162	53	41.6	4	138	Loglogistic (−25, 75, 7.1)
Soybean meal						
Ash	298	73	30.1			Normal (73, 22)
CP	681	510	6.2	372	569	Logistic (510, 17)
NDICP	124	54	62.4			Normal (54, 34)
EE	322	36	104.4	3	220	PearsonV (1.9, 33)
aNDF	306	123	30.4	70	333	Loglogistic (15, 100, 6.3)
Lignin(sa)	253	14	64.3			Normal (14, 9)
Starch	186	19	60.0			Normal (19, 11)
Sugar	158	135	19.2			Normal (135, 26)
Whole cottonseed						
Ash	99	43	11.9	32	60	Normal (43, 5)
CP	320	241	18.1	114	375	Loglogistic (−163, 401, 16.4)
NDICP	63	24	25.3	17	58	Loglogistic (14, 9, 3.6)
EE	184	225	22.5	122	361	Loglogistic (92, 124, 4.5)
aNDF	311	508	19.8	247	803	Logistic (508, 57)
Lignin(sa)	95	154	24.0	52	250	Normal (154, 37)
Starch	36	11	52.7	1	23	Loglogistic (−1, 11, 2.7)
Sugar	39	59	29.0	34	105	Normal (59, 17)

[a] The parameters necessary to characterize the distribution are indicated between brackets: a α parameter indicates shape of the distribution, a β parameter indicates scale (p.e. σ for the normal distribution), a γ parameter indicates location (p.e. μ for the normal distribution). The distributions are beta general (α_1, α_2), exponential (β), logistic (α, β), loglogistic (γ, α, β), lognormal (μ, σ), normal (μ, σ), PearsonV (α, β), and Weibull (α, β). When maximum and minimum values are not indicated, the original database was not available to fit the distributions. A normal or exponential (for volatile fatty acids) distribution was assumed.

content (Fig. 1). The amount of DM in silage was negatively, and exponentially, related with the amount of fermentation end products during ensiling (Fig. 1). Lactic acid content was positively, and linearly, related to the amount of EE of grass silages (Lactic (g/kg DM) = 18.9 EE (g/kg DM) − 66.1, $R^2 = 0.58$, R.M.S.E. = 18.2) and legume silages (Lactic (g/kg DM) = 28.1 EE (g/kg DM) − 30.2, $R^2 = 0.46$, R.M.S.E. = 20.2). As the EE content of silages may increase with the increase in microbial mass, both EE and lactic acid increase with extent of fermentation. For corn silages, both VFAs and lactic acid were poorly related with other feed fractions (Table 4) and DM (Fig. 1).

Overall, the correlation among feed inputs were low or moderate (*i.e.*, $r < 0.70$) (Table 4), and prevents use of more common feed analysis, such as NDF assays, as predictors of fractions that are less commonly assayed, such as sugar contents. The components with the highest correlation were the starch and aNDF content of corn silage, which were strongly linearly related (Starch (g/kg DM) = 845.4 − 12.1 NDF (g/kg DM), $R^2 = 0.84$, R.M.S.E. = 31.1) due to the increase in grain content with plant maturity.

Organic acids are generally analyzed by gas or high-pressure liquid chromatography (Amin, 1980; Russell and Van Soest, 1984) or can be estimated indirectly as NFC minus

Table 4
Correlation matrix (Spearman correlations) of the feed fractions for the feeds used in the sensitivity analysis (P<0.05) [Blanks indicate no significant (*i.e.*, P>0.05) correlations]

	Ash	CP	NDICP	EE	aNDF	Lignin(sa)	Starch	Sugar	Acetic	Propionic	Butyric	Isobutyric	Lactic
Corn silage													
Ash	1	0.38	0.38	−0.21	0.50	0.47	−0.61	0.14	0.29		0.24		0.24
CP		1	0.45		0.22	0.21	−0.40	0.16					0.21
NDICP			1		0.47	0.49	−0.49	0.24				0.27	−0.18
EE				1	−0.36	−0.22	0.31	−0.38	0.30	0.27			
aNDF					1	0.64	−0.92	0.15	0.17				0.12
Lignin(sa)						1	−0.66	0.16					
Starch							1	−0.27	−0.24				−0.25
Sugar								1	−0.39	−0.28			
Acetic									1	0.65			0.10
Propionic										1			−0.21
Butyric											1		
Isobutyric												1	−0.28
Lactic													1
Grass silage													
Ash	1	0.59	0.25	0.36	−0.37	−0.28	−0.55	−0.27	0.49		0.49	0.42	0.45
CP		1	0.41	0.75	−0.80	−0.44	−0.19						0.48
NDICP			1		−0.21	0.15							
EE				1	−0.67	−0.58	−0.10		0.48				0.79
aNDF					1	0.44	−0.20	−0.32					
Lignin(sa)						1		−0.32					−0.58
Starch							1	0.43	−0.68				−0.59
Sugar								1	−0.49				−0.52
Acetic									1	0.60			
Propionic										1			
Butyric											1	0.74	
Isobutyric												1	
Lactic													1

Table 4 (*Continued*)

	Ash	CP	NDICP	EE	aNDF	Lignin(sa)	Starch	Sugar
High moisture corn grain								
Ash	1	0.35	0.24	0.31	0.27	−0.10	−0.57	
CP		1	0.24	0.52	0.10	−0.21	−0.32	
NDICP			1	0.27	0.30	0.33	−0.13	
EE				1	0.16	−0.29	−0.44	
aNDF					1	0.21	−0.46	
Lignin(sa)						1		
Starch							1	
Sugar								1
Distillers' grains								
Ash	1	0.30			0.23			
CP		1		0.26			−0.43	−0.16
NDICP			1					
EE				1	0.13		−0.14	
aNDF					1		−0.14	
Lignin(sa)						1		
Starch							1	
Sugar								1
Soybean meal								
Ash	1							
CP		1		0.53	0.52			
NDICP			1					
EE				1	0.44			
aNDF					1			
Lignin(sa)						1		
Starch							1	
Sugar								1
Whole cottonseed								
Ash	1	0.52		0.68	0.58		−0.39	0.62
CP		1		0.57	0.61	−0.29		0.45
NDICP			1					
EE				1	0.69	−0.51	−0.44	0.65
aNDF					1	0.41		−0.66
Lignin(sa)						1		−0.55
Starch							1	
Sugar								1

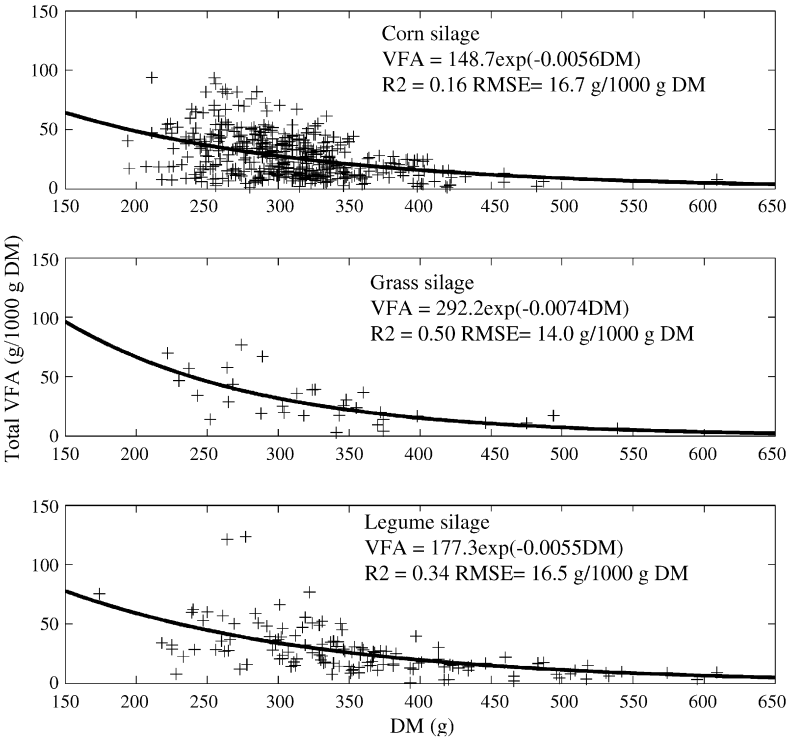

Fig. 1. Relationship between total volatile fatty acids and dry matter of corn silage ($N = 440$), grass silage ($N = 34$), and legume silage ($N = 131$).

ethanol insoluble residue (adjusted for CP) and sugar content (Hall et al., 1999). Because of difficulties in measuring organic acids as a group, the CA3 fraction may rely more on feed library values compared to other fractions. In the CPM dairy, non-silage acids were included within the soluble fiber fraction (CPM CB2), while we included the other organic acids as a separate fraction to account for their fermentation characteristics. Although they provide some fermentable energy, it is considerably less than the other components that were included in the CPM soluble fiber fraction. Dicarboxylic acids (*i.e.*, aspartate, fumarate, and malate) stimulate lactate utilization by the predominant ruminal bacteria, *Selenomonas ruminantium* (Evans and Martin, 1997; Martin and Streeter, 1995). In the feed library, the highest organic acid concentrations were allocated in pastures and fresh forages (Table 2) (Callaway et al., 1997; Martin, 1970; Mayland et al., 2000). In forages, organic acids decline with maturity and age (Martin, 1970). In silages, other organic acids were assumed to be degraded during fermentation during ensiling (McDonald et al., 1991), and therefore were assigned a value of 0 (Table 2).

The sugar fraction represents a heterogeneous fraction and most sugar measurements in commercial laboratories are based on ethanol/water extractions (Hall, 2003), which may extract different components depending on the proportion of ethanol (Hall et al., 1999; Smith

and Grotelueschen, 1966), the standard used (*e.g.*, glucose, fructose or sucrose) and type of feedstuff matrix. Some of the differences in the sugar composition have been accounted for by using different ruminal degradation rates (Table 2). The proportion of ethanol used in the extraction may affect partition of components between sugar and soluble fiber. For example, in temperate cool season grasses, variable amounts of fructans are extracted depending on the ethanol concentration (Smith and Grotelueschen, 1966). Fructans are classified as dietary fiber since they are not digested by mammalian enzymes (Nilsson et al., 1988). Even so, the VFA profile of fructans is similar to sugars because sucrose is the precursor for fructan synthesis (Marounek et al., 1988; Pollock, 1986) and their release from the plant cells is similar to that of free sugars (Boudon et al., 2002). Therefore, in predicting nutrient availability for ruminants, it may be more appropriate to associate fructans with sugars rather than soluble fiber.

In the expanded scheme, the soluble fiber fraction is calculated by difference. Thus, it contains errors from other component assays. Knudsen (1997) measured β-glucans, and other soluble polysaccharides, for selected energy and protein-rich concentrate feeds. For cereal grains, values for soluble fiber calculated by difference were similar to measured soluble fiber as the sum of β-glucans and other soluble polysaccharides. For example, calculated and measured values for corn grain, barley grain and wheat middlings were 8 g/kg DM *versus* 10 g/kg DM, 73 g/kg DM *versus* 98 g/kg DM, and 98 g/kg DM *versus* 97 g/kg DM, respectively. For protein-rich feeds, calculated values were not consistently related to measured values (*e.g.*, soybean meal, 63 g/kg DM *versus* 141 g/kg DM; cottonseed meal, 24 g/kg DM *versus* 18 g/kg DM; linseed meal, 521 g/kg DM *versus* 138 g/kg DM; white lupins, 131 g/kg DM *versus* 134 g/kg DM, respectively). Several factors may contribute to underprediction of the soluble fiber fraction (Eq. (14)) for some feeds. While VFAs (CA1) are expressed on a DM basis, they are typically measured in 'wet' feeds because they are partly volatilized during oven drying. For acetic acid, drying losses can be as high as 53% for grass silages, and 83% for corn silages (Sorensen, 2004). This may especially contribute to the underprediction of CB2 in legume silages because both CA1 and CB2 fractions can be a substantial proportion of the CHO. Based on the assumption that protein contains 16% N, the conversion factor of 6.25 is used as an average to convert N into CP for all the feeds. However, when non-protein compounds and variations in their AA composition are considered, the conversion factor for most common feeds are consistently lower than 6.25 (*e.g.*, soybean meal, 5.49; barley, 5.17; fish meal, 4.75) (Boisen et al., 1987). Ash contamination may result in insoluble ash being recovered in aNDF, overpredicting available FC. In contrast, over-estimation may result from correcting NDF assayed with sodium sulfite in the ND for NDICP assayed without sodium sulfite in the ND. The NDF method approved by the Association of Official Analytical Chemists International (Mertens, 2002) uses sodium sulfite, which removes most N the insoluble fiber. For most feeds, the difference in NDICP with and without sodium sulfite are less than 10 g/kg DM, but, for protein-rich feeds, the difference can be as high as 90 g/kg DM (Hintz et al., 1996). The CB2 pool size was very sensitive to NDICP adjustment for canola and sunflower meals, distillers' grains and whole soybean (results not shown). Correcting aNDF for NDICP and ash is the most accurate way to estimate FC and NFC. However, because of the inconsistency of method used to measure NDF among feed analysis laboratories, we assumed that the NDICP fraction is in the NDF fraction.

3.2. Ruminal degradation rates and microbial yield

Although *in vitro* gravimetric and gas measurements have been extensively used to measure degradation rates, no *in vitro* method has been proven to be appropriate to measure rates in all CHO fractions. The rates used are a mix of rates from fermentation and hydrolysis. Rates for the CA2, CA3, and CA4 fractions have been updated from data available using a gas production system (Doane et al., 1998; Molina, 2002). Gas production systems determine rates of ruminal fermentation. Sugars are the most rapidly degraded CHO, with rates of hydrolysis as high as $10\,h^{-1}$ (Weisbjerg et al., 1998). Despite their high rates of hydrolysis, fermentation rates for sugars are several magnitudes lower (Van Kessel and Russell, 1997). Part of the discrepancy between hydrolysis and fermentation rates is because sugars can be partially stored as microbial glycogen and used later for endogenous metabolism (Van Kessel and Russell, 1997). Thus the rates for these fractions are lower than the values for the A fraction in the original CNCPS scheme (Sniffen et al., 1992), which overpredicted fluctuations in ruminal pH (Pitt and Pell, 1997) and microbial yield for the A fraction (Alderman, 2001).

Some of the starch degradation rates for the new scheme have also been updated based on *in vivo* and *in vitro* data (Lanzas, 2003; Monteils et al., 2002; Remond et al., 2004; Richards et al., 1995; Tothi et al., 2003; Yang et al., 2000). In contrast, *in situ* rates have not been used for the starch fraction because the *in situ* method divides starch into a soluble fraction which is considered to be degraded instantaneously and completely, and an insoluble fraction which is degraded exponentially. As *in situ* results measure the digestion rate for the slowly degradable pool, while starch in our fractionation scheme is treated as single fraction with a rate for the entire degradable pool, values for the starch degradation rates (Table 2) are generally higher than those derived from *in situ* (Offner et al., 2003). Because of variability in starch degradation rates in feeds due to processing and starch sources, starch degradation rates are feed specific and a method to estimate them routinely is needed.

3.3. Variability of feed CHO fractions

Table 3 lists the expected variation and probability density functions used to describe the feeds used in the simulations. They represent variability within the population of the feedstuff since they were derived from an extensive database, and distributions for a large proportion of the feeds were not normal (Table 3).

In silages, sugars and VFA were the fractions that varied the most as indicated by their high coefficients of variations (Table 3). Distributions for corn silage sugars and grass and corn silage VFA were not symmetrical in that some VFA had an exponential distribution, in which the probability of a given value decreased as values depart from 0, with a negative rate (Evans et al., 2000). Ensiling adds variability to the forage composition because it adds a wide range of factors, including forage quality, silo type, particle size, packing and covering (McDonald et al., 1991). In addition, pre-harvest and weather conditions can affect forage quality. Although corn silage starch and aNDF had symmetrical distributions (Table 3), both components had heavy tails and a subpopulation of corn silages had low starch (<150 g/kg) and high fiber (>580 g/kg) contents. Drought conditions, or high plant densities, decreases grain content to less than 270 g/kg of DM (Woody, 1978). High moisture corn grain had

Table 5
Variation of carbohydrate (CHO) fractions (g/kg ration DM) when all the feed inputs were varied

CHO fraction	Mean	S.D.	Minimum	Maximum
NDF[a]	307	23.4	234	388
NFC[b]	403	27.4	303	403
Lactic acid[c]	28	8.1	4	60
Starch[d]	284	19.8	192	339
Sugar[e]	57	9.8	30	99
Soluble fiber[f]	40	13.9	4	114
VFAs[g]	14	5.3	2	40

[a] The inputs that had the most influence (regression coefficient in brackets) were grass silage aNDF (0.77) and corn silage aNDF (0.58).

[b] The inputs that had the most influence (regression coefficient in brackets) were grass silage aNDF (−0.64) and corn silage aNDF (−0.5).

[c] The inputs that had the most influence (regression coefficient in brackets) were grass silage acetic (0.67) and corn silage acetic (0.64).

[d] The inputs that had the most influence (regression coefficient in brackets) were corn silage starch (0.89) and HMCG starch (0.37).

[e] The inputs that had the most influence (regression coefficient in brackets) were grass silage sugar (0.75) and corn silage sugar (0.41).

[f] The inputs that had the most influence (regression coefficient in brackets) were grass silage aNDF (−0.70) and grass silage CP (−0.43).

[g] The inputs that had the most influence (regression coefficient in brackets) were grass silage lactic (0.78) and corn silage lactic (0.55).

the lowest nutrient variation of all the feeds. In by-product feeds and soybean meal, the inputs with the largest variability are the nutrients influenced by processing. For soybean meal, EE had the largest variation because of differences in oil extraction (Table 3). For distillers' grains, lignin(sa), sugar and NDICP were the fractions with the largest variation due to differences in heat damage and content of solubles among samples (Table 3).

When variability in feed inputs was considered in the simulated diet, the CHO fractions varied in a decreasing order as: VFAs, soluble fiber, lactic acid, sugar, aNDF, starch, and total NFC (Table 5). Volatile fatty acids, soluble fiber and lactic acids are small proportions of the total CHO. Variation in calculated NFC, CA and CB1 fractions causes variation in the soluble fiber fraction. Feeds in the simulated diet were generally low in soluble fiber, and it was sensitive to aNDF and CP content of grass silage, since grass silage provided the greatest amount of CB2 of all the feeds in the simulated diet. Variability in the sugar fraction was due mainly to variation in sugar content of the silages (Table 5) and it may be a highly variable fraction among dairy cattle diets. In fresh forages, the sugar fraction is a highly labile pool, which accumulates and depletes throughout the day (Pollock, 1986). In silages, sugar fractions vary with the ensiling process (Table 6). Analytical variability may occur due to differences in extraction conditions and methods used to analyze sugars (Hall, 2003). Although NFC is calculated by difference (Eq. (8)), variation in the inputs used to calculate NFC offset each other to some extent, thereby decreasing the uncertainty range of the NFC fraction. The moderate correlations among the grass silage aNDF, the most influencing input (Table 5) and other inputs used to calculate NFC (*i.e.*, grass silage CP and EE), may contribute to decreasing the NFC variation (Table 4).

Table 6
Impact of varying the inputs used to calculate carbohydrate fractions with the original and expanded scheme and their corresponding rates on metabolizable protein (MP) from bacteria, and ruminal non-fiber carbohydrates (NFC) digestibility

	Original CHO scheme		Expanded CHO scheme	
	Mean	S.D.	Mean	S.D.
MP from bacteria (g/day)				
Calculated CHO[a]	1633 a	36.4 a	1574 a	28.1 a
FC *vs.* NFC[b]	1632 a	27.4 b	1587 b	30.1 b
NFC fractions[c]	1629 b	29.4 c	1581 c	50.1 c
NFC rates[d]	1619 c	46.2 d	1543 d	42.5 d
FC rate[e]	1617 c	54.3 f	1540 d	53.4 e
All inputs[f]	1613 d	88.3 g	1570 a	91.5 f
Rumen NFC digestibility (g/g)				
Calculated CHO[a]	0.82 a	0.007 a	0.81 a	0.020 a
FC *vs.* NFC[b]	0.82 ab	0.010 b	0.82 b	0.032 b
NFC fractions[c]	0.82 b	0.010 b	0.81 c	0.030 b
NFC rates[d]	0.81 c	0.017 c	0.79 d	0.015 c
FC rate[e]	0.82 d	0.000 d	0.79 d	0.000 d
All inputs[f]	0.81 e	0.021 e	0.81 c	0.035 e

Means or standard deviation (S.D.) with different letters within a column (for each scheme).

[a] The inputs need to compute CHO (CP, EE, and ash, Eq. (1)) were varied.

[b] The inputs needed to partition FC and NFC were varied (Eqs. (2)–(4) for the original scheme, and Eqs. (2), (7) and (8) for the expanded scheme).

[c] The inputs needed to fractionate NFC were varied (Eqs. (5) and (6) for the original scheme, and Eqs. (9)–(14) for the expanded scheme).

[d] The rates for the NFC fractions were varied (A, and B1 for the original scheme, and A2, A3, A4, B1, and B2 rates for the expanded scheme).

[e] The rates for the FC fraction were varied.

[f] All the inputs were varied (Eqs. (1)–(6) and corresponding rates for the original scheme, and Eqs. (1) and (2), (7)–(14) and corresponding rates for the expanded scheme).

3.4. Model behavior and sensitivity analysis

Model predictions for MP from bacteria and ruminal NFC digestibility were assessed with the original and expanded schemes (Table 6). The expanded CHO scheme decreases mean predicted microbial CP with 43 g difference in MP between the schemes. Assuming an efficiency of MP utilization of 0.65 for milk production and 30 g true protein per kg of milk, the difference would represent approximately 1 kg in predicted MP allowable milk (MP milk = $43 \times 0.65/30$) (Table 6). The decrease in MP from bacteria is due mainly to a decrease in the microbial yield supported by the CA fraction; the rates for the A fractions have been reduced compared to the rates for the original scheme. In the original scheme, the CA rate for the entire pool in silages was set at an intermediate rate (*e.g.*, $0.10\,h^{-1}$) to account indirectly for the presence of organic acids. The expanded scheme may not always result in lower rumen microbial growth than the original scheme for a silage-based diet. For immature corn silages with high water soluble CHO and low VFA content, the expanded scheme predicts greater MP from bacteria than the original scheme (results not shown).

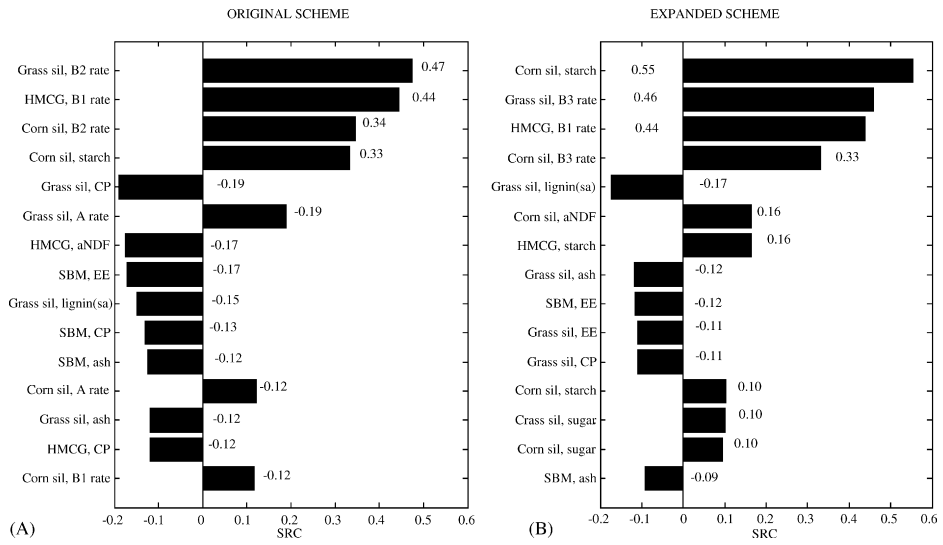

Fig. 2. Standard regression coefficients (SRC) for the inputs ranked as the most influential in predicting microbial growth with the original carbohydrate scheme (panel A) and expanded scheme (panel B) (CP = crude protein; EE = ether extract; HMCG = high moisture corn grain; NDF = neutral detergent fiber; SBM = soybean meal).

Predicted ruminal NFC digestibility is similar between the two schemes (Table 6). The prediction of site of digestion is less sensitive to CHO degradation rates than microbial CP production. With the first-order approach used to predict site of digestion, the model is sensitive to degradation rates that are closer to its ruminal passage rate.

The expanded fractionation scheme also repartitions impact of the different inputs on model predictions (Table 6). Predictions with the original scheme are more sensitive to NFC rates and inputs used to calculate CHO than predictions with the expanded scheme, which were more sensitive to NFC fractions and their corresponding rates (Table 6). For MP from bacteria, for both schemes, the fractional degradation rates for fiber had the biggest effect (Table 6).

The use of the expanded CHO scheme increases the number of inputs, as listed in Table 6, and thus the risk of use of the model may increase if the inputs to the model are sensitive and have not been measured. The S.D. for model predictions when all inputs were varied was greater for the expanded scheme (Table 6). Despite this, the individual feed inputs that contributed most to variability in MP from bacteria were similar for both schemes (Fig. 2). The same four variables had the highest regression coefficients in both schemes (*i.e.*, corn silage starch, grass silage NDF rate, high moisture corn grain starch rate, and corn silage NDF rate). The only important change in the regression coefficient was a much higher value for variation in the corn silage starch pool in the expanded CHO scheme. This is likely due to removing soluble fiber from this pool. The grass and corn silage CA rates ($0.10\,h^{-1}$) were sensitive in the original scheme but none of the CA fraction rates were sensitive in the expanded scheme. In the expanded scheme, the CA1, CA2, and CA3 provide 0 or very low microbial CP yield or large microbial CP yield (CA4), making them nearly all escape from

the rumen or degrade in it, which makes the model more sensitive to their pool size, rather than their degradation rates. Although the sugar fraction was highly variable (Table 5), the sensitivity of the model to sugar content of silages was moderate (Fig. 2). When taken into account feed composition uncertainty in a feed analysis program, the uncertainty of concern in relation to predictions of the nutritional model used for formulating rations may be important. Feed inputs that vary the most within a feed may not necessarily be the ones that the model is most sensitive to. Therefore the feed inputs that have moderate or large variability and the model is sensitive to are the ones that should be subject to more frequent analysis. Within feed composition uncertainty, both accuracy and precision of the analysis should be considered. Low accuracy occurs when values reported from a laboratory differ from known reference values and may result in systematic bias in the model predictions. Low precision results from random variation and can be overcome by increasing analysis frequency.

3.5. Applications of the expanded CHO scheme

The expanded CHO scheme increases the ability of the CNCPS model to account for variation in animal production due to differences in feed composition, including accounting for silage quality, assessing production responses to changes in diet NFC composition and sugar supplementation.

3.5.1. Supplementing silages

Extent of silage fermentation is highly variable (Table 3), and it can be stimulated by adding inoculants such as lactic acid bacteria, enzymes and added fermentable CHO, while wilting or formic acid addition reduces the extent of silage fermentation (Huhtanen, 1998). The expanded scheme accounts for more variation in silage fermentation and Table 6 summarizes CNCPS model predictions with the expanded CHO scheme for grass silages derived from the same crop, but with different fermentations (*i.e.*, inoculated *versus* restricted fermentation). When they are fed alone, the model predicts protein to be first limiting for both silages, with lower MP allowable milk for cows fed the inoculated silage. The model with the expanded CHO scheme predicted milk responses to increased MP supply for both silages with predicted responses for both fermentable CHO and CP supplementation larger for the inoculated silage (Table 7). Histidine was predicted to be the first limiting AA, in agreement with previous reports (Korhonen et al., 2000). The content of some AA (*i.e.*, histidine and leucine) in microbial CP is lower than in milk protein, which may attenuate the responses to sources of fermentable CHO to the diet when one of these AA is first limiting in the ration. The model with the original CHO scheme did not predict differences due to extent of silage fermentation (results not shown).

3.5.2. Balancing for NFC

While the NRC (2001) provides few guidelines for balancing total diet NFC, altering the proportions of the types of NFC can alter recommendations for total NFC, and other components, of the ration since interactions among NFC components and fiber and protein fractions have been described (Hall, 2002). Table 8 shows changes in CHO fractions and model predictions using the expanded scheme as a result of replacing HMCG, a high starch

Table 7
CNCPS predictions with the expanded carbohydrate scheme for un-treated grass silage or inoculated with lactic acid bacteria with supplements (formulated for a lactating dairy cow 650 kg BW, intake: 24.9 kg)

	MP allowable milk	ME allowable milk	First limiting AA
Untreated grass silage alone[a]	22.3	35.9	Histidine
Grass silage (500 g/kg diet DM) and cracked corn (500g/kg diet DM)	30.0	45.9	Isoleucine
Grass silage (840 g/kg diet DM) and extruded SBM (160 g/kg diet DM)	46.3	36.7	Leucine
Inoculated grass silage alone[b]	15.6	30.2	Histidine
Inoculated silage (500 g/kg diet DM) and cracked corn (500 g/kg diet DM)	26.6	43.3	Valine
Inoculated silage (840 g/kg diet DM) and extruded SBM (160 g/kg diet DM)	40.7	32.1	Leucine

[a] Grass silage composition (g/kg): sugar 160, lactic acid 35, volatile fatty acids 14.
[b] Grass silage inoculated with lactic acid bacteria composition (g/kg): sugar 61, lactic acid 132, volatile fatty acids 5.

concentrate, with the high soluble fiber by-product beet pulp in a ration. Replacing HMCG with beet pulp causes an increase in the content of sugar, soluble fiber and NDF of the ration and a decrease in the starch content. With increasing levels of beet pulp, the model predicts a reduction in both ME and MP allowable milk. The ME allowable milk decreases more

Table 8
Effect of replacing high moisture corn grain (HMCG) with beet pulp (BP) in dietary carbohydrate composition on CNCPS predictions with the expanded carbohydrate scheme

	100 HMCG: 0 BP[a,b]	75 HMCG: 25 BP[b]	50 HMCG: 50 BP[b]	25 HMCG: 75 BP[b]	0 HMCG: 100 BP[b]
Diet composition (g/kg)					
Sugar	38	49	59	70	80
Starch	333	273	213	153	93
Soluble fiber	71	95	119	143	167
NDF	237	264	290	317	344
CNCPS predictions					
Pred DMI (kg/day)[c]	23.2	23.2	23.2	23.2	23.2
Pred DMI (kg/day)[d]	25.5	25.5	25.5	25.5	25.5
ME allowable milk (kg/day)	44.7	42.4	40.1	37.9	35.6
MP allowable milk (kg/day)	44.6	44.1	43.3	42.0	40.7
Microbial MP (g/day)	1491	1492	1478	1441	1361
Fecal N (g/day)	244	253	261	267	273
Urinary N (g/day)	406	399	394	390	386

[a] Diet formulated for a lactating dairy cow 650 kg BW consuming 24.8 kg DM. Diet composition (g/kg): 360 HMCG, 200 corn silage, 200 alfalfa silage, 150 solvent soybean meal, 40 corn distillers' grains with solubles, 10 blood meal, and 40 mineral vitamin mixture.
[b] Beet pulp substituted for HMCG as 0, 25, 50, and 75 g/100 g of the HMCG of the ration. All diets were 188 g CP/kg DM.
[c] Fox et al. (2004).
[d] NRC (2001).

sharply than MP allowable milk because of the higher content of NDF of the beet pulp, which reduces the total digestible nutrients derived from the ration. Metabolizable protein allowable milk also decreases due mainly to a decrease in the microbial CP supply (Table 8). A small repartitioning of N excretion was also predicted. Beet pulp changed some of the N excretion from urine to feces. With beet pulp, indigestible DM intake increases, which in turn increases predicted metabolic fecal N. Vanvuuren et al. (1993) observed a similar trend in N partition when replacing a corn grain based diet with a beet pulp based diet. The model with the original scheme also predicted a decrease in ME allowable milk when beet pulp content was increased because this effect was caused by an increase in diet FC; however predicted microbial MP and MP allowable milk were rather insensitive to changes in the percentage inclusions of beet pulp (results not shown).

Some differences in animal responses when they are fed different sources of CHO are mediated through changes in DM intake. Voelker and Allen (2003) reported a decrease in DM intake when beet pulp constituted 240 g/kg of the ration DM, which they attributed to a physical fill effect. Changes in DM intake have also been observed when HMCG is replaced with dried molasses (Broderick and Radloff, 2004). Predictions of DM intake (NRC, 2001; Roseler et al., 1997) were insensitive to changes in the NFC composition of the ration (Table 8). Empirical equations used to predict DM intake account for body weight, fat-corrected milk, ambient temperature, mud depth and early lactation lag in intake (Fox et al., 2004; NRC, 2001), but dietary factors are not considered. Predicting changes in DM intake due to changes in dietary factors is an important addition to nutritional models needed to account for differences in CHO utilization.

Prediction of the amount and profile of VFA in the rumen due to variation in CHO fractions is important in relating feed composition to milk production and composition, as well as to changes in body composition (Dijkstra, 1994; Pitt et al., 1996). While total VFA production is acceptably predicted by many models, proportions of the VFA have been poorly predicted (Dijkstra et al., 1992; Pitt et al., 1996). Description of the nutrient profile of the diet and substrate availability affects the profile of VFA produced in the rumen. While the original CNCPS scheme divided CHO based on the rate of degradation, it combines CHO fractions that differ in their ruminal VFA profile (*e.g.*, pectin and starch). Therefore, the expanded scheme would be more suitable to provide dietary inputs for a VFA production pH rumen submodel (Fox et al., 2004).

4. Conclusions

The expanded CHO scheme for the CNCPS model that is outlined in this paper divides feed CHO in fractions that more accurately relate to ruminal fermentation characteristics. It is practical to use this scheme for quantifying CHO fractions in feeds because most of the fractions are now being provided by some commercial laboratories. Shortcomings in the current analytical methodology to measure some of the fractions (*e.g.*, sugars) and their corresponding ruminal degradation rates complicate full characterization of feed CHO. Nevertheless, the proposed fractionation provides a framework for applying this information, and may stimulate research to develop appropriate laboratory methods to measure them.

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