Milk production, nitrogen balance, and fiber digestibility prediction of corn, whole plant grain sorghum, and forage sorghum silages in the dairy cow

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ABSTRACT

Total mixed rations containing corn (CS), whole plant grain sorghum (WPGS), or forage sorghum (FS) silages were fed to 6 primiparous Italian Friesian cows to determine the effects on lactation performance, nutrient digestibility, and N balance. Furthermore, the relationship between in vivo total-tract neutral detergent fiber (NDF) digestibility (ttNDFD) and the ttNDFD derived by the Cornell Net Carbohydrate and Protein System (CNCPS) model was assessed. Cows were assigned to 1 of 3 diets in a replicated 3×3 Latin square with 28-d periods. The experimental treatment was silage type and 3 different silages were included in the diets. The diets were formulated to be iso-NDF. Accordingly, each diet was formulated to contain 41.5% CS silage, 36.7% WPGS silage, or 28.0% FS silage, on a DM basis. Starch content was balanced by adding the appropriate amount of corn meal. Separate collection of total urine and feces was performed. Dietary forages were analyzed for in vitro NDF digestibility (6 and 24 h of incubation) to predict fiber digestion rate with 2 NDF pools (digestible and indigestible). Rumen digestibility of the potentially digestible NDF pool was predicted using CNCPS version 6.1, using the in vitro forage fiber digestion rate. The ttNDFD was predicted assuming that intestinal digestibility of the NDF amount escaping rumen digestion was 20%, according to the CNCPS model. Dry matter intake was decreased by approximately 1.8 kg/d in cows fed the FS diet compared with the other diets, probably for the greater particle size of FS diet. Hence, milk yield (kg/d) was lowest for FS (23.6), intermediate for WPGS (24.6), and highest for the CS diet (25.4). Milk urea N (mg/dL) was highest for FS (12.9), intermediate for WPGS (11.9), and lowest for CS (10.7) diet. In vivo ttNDFD (%) was 51.4 (CS), 48.6 (WPGS), and 54.1 (FS); this was probably due to a higher retention time of FS diet in the rumen rather than to a better quality of the FS silage, as confirmed by in situ and in vitro results. Urinary

N excretion (% N intake) was highest for FS (31.8), intermediate for WPGS (29.3), and lowest for the CS (27.5) diet. The predicted ttNDFD (37.7, 36.3, and 39.5% for CS, WPGS, and FS, respectively) were lower than the in vivo results. Providing an adequate starch supplementation, whole plant grain sorghum silage can replace corn silage in dairy cows TMR. Forage sorghum silage had rumen NDF digestibility comparable to the other silages; however, it had a negative effect on dry matter intake and milk production, probably due to an inadequate effect of processing.

Key words: sorghum silage, N balance, neutral detergent fiber digestibility, Cornell Net Carbohydrate and Protein System

INTRODUCTION

Corn silage (CS) is the main forage fed to dairy cows in the Po Plain (Italy) due to its high DM yield, high NE_L concentration, high potential intake, and optimum DM content at harvest. However, large amounts of N fertilizers and water are needed to achieve satisfactory yields, thus increasing the crop production costs and reducing the agricultural sustainability. Furthermore, in the European Union, the negative relationship between animal density and water quality led to a precautionary application threshold of 170 kg of manure N per hectare per year to protect water quality in the most vulnerable zones (European Commission, 1991). Nitrogen concentrations in ground and surface waters are determined by the combination of manure and N fertilizer; thus, the use of a low-N input crop is advisable. Sorghum is a crop with high biomass yield, low N fertilizer and water inputs, and good N efficiency (Gardner et al., 1994); therefore, it could be a valuable alternative to corn.

Another potential advantage of sorghum silage is the adequate rumen NDF digestibility (NDFD). Spanghero et al. (2009) reported an average in vitro NDFD of 48.9% for CS samples collected over 3 yr in the Po Plain; this value is close to the NDFD values reported by Sanderson (1993) for grain sorghum silage samples. Di Marco et al. (2009) found a wide range for in vitro NDFD (48 h) of forage sorghum (FS) silages (from 49.2

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to 63.8%) and the in vitro NDFD did not accurately predict the in vivo values. Fiber digestibility depends on potentially digestible NDF (**pdNDF**) and its rates of digestion (k_d) and passage (k_p); hence, accurate and precise predictions of the digestion kinetic parameters are important. Van Amburgh et al. (2003) proposed a mathematical approach to predict the pdNDF rumen k_d based on NDFD values determined at different times of incubation by an in vitro assay on CS samples. Therefore, the pdNDF k_d might be used within the Cornell Net Carbohydrate and Protein System (**CNCPS**) model (Fox et al., 2004; Tytlutki et al., 2008) to estimate NDF total-tract apparent digestibility (**ttNDFD**) assuming that the intestinal digestibility of the NDF amount escaping rumen digestion is 20% (Sniffen et al. 1992).

Several in vivo studies compared lactation performance and nutrients digestibility on dairy cows fed sorghum or CS diets (among these, Grant et al., 1995; Aydin et al., 1999; Oliver et al., 2004; Miron et al., 2007; Dann et al., 2008); however, in these studies, N-excretion was not determined. A previous research conducted in the Po Plain area (Colombini et al., 2010) showed that milk urea content was higher for cows fed a brown midrib (**BMR**) sorghum forage in comparison with CS, suggesting probably better N utilization at rumen level for the CS diet.

The objectives of this study were to (1) compare the effects of diets based on corn, whole plant grain sorghum (**WPGS**; *Sorghum bicolor* L.), or FS (*Sorghum bicolor* × sorghum-sudangrass) silages on milk yield, nutrient digestibility, and N balance in dairy cows; and (2) determine the relationship between in vivo ttNDFD and the ttNDFD derived by the CNCPS model (v 6.1) using the k_d values determined in vitro for the forages of the diets.

MATERIALS AND METHODS

In Vivo Trial

Corn (hybrid Agrister; Limagrain Italy, Busseto, Parma, Italy), grain sorghum (*Sorghum bicolor* hybrid Silo 8416; Syngenta Seed Italy, Milano, Italy), and FS [*Sorghum bicolor* × sorghum-sudangrass hybrid Sweet Creek; Società Italiana Veterinaria Agricola Milano SpA (SIVAM), Casalpusterlengo, Lodi, Italy] were sown in adjacent fields in the Po Plain Valley on June 8, 2005. Corn and WPGS forages were harvested on October 4. The second cut of FS was used in the trial and it was harvested on September 23 and field-wilted for 72 h. Whole plant corn was ensiled in bunker silos, whereas WPGS and FS were ensiled in silo tube bags.

Six lactating primiparous Italian Friesian cows with mean BW of 600 kg (± 41), 178 DIM (± 13) and producing, on average, 28.4 kg of milk/d (± 2.57) at the start of the trial were used. Three diets with a different silage basis were tested: CS, WPGS, or FS. Diets were formulated using the CNCPS model version 5 (Fox et al., 2004) and balanced to have a content (% DM) of 11.0, 36.0, and 26.0 of MP, NDF, and starch, respectively. Because of the different fiber and starch contents, the 3 forages were included in the experimental diets in different proportions, as well as the corn meal necessary to compensate for the low starch content of the WPGS and FS silages.

The cows were fed the experimental diets in a 3 × 3 repeated Latin square design and each cow was fed the 3 diets in 3 consecutive periods of 28 d: 21 d of adaptation and 7 d of sample collection and data registration. Animals on trials were handled as outlined by the guidelines of the Italian law about animal welfare on experimental animals (Italian Ministry of Health, 1992). During the adaptation periods, cows were housed in tie-stalls and during the sample collection periods, cows were moved to individual metabolic stalls to allow urine and feces collection. Each metabolic chamber contained a 2.5 × 1.5-m stanchion, allowing the animal to stand or lie down. During the collection period, feces produced daily were measured as follows: feces left the chamber through openings on the floor in the back of the stanchion and were collected into tanks located underneath the floor of the chambers. Urine was collected through the use of the urine collection cup method of Fellner et al. (1988) modified to enable floor level urine collection. The pH of urine was maintained at <3.5 through the addition of adequate volumes of sulfuric acid 10% (vol/vol). During each of the 3 collection periods, urine and feces were weighed daily, sampled (5% of the total weight) and pooled per cow. All of the samples were stored at -20°C . Before analysis, feces were oven dried at 55°C until constant weight and ground through a 1-mm screen. A fresh subsample was used for the N analysis.

Cows had free access to water and were offered feed twice daily at 0800 and 1700 h; orts were recorded once daily and feeding rate adjusted to yield orts of approximately 10% of intake. Within each sample collection period, silages, TMR, and ort samples were sampled daily to obtain a composite sample and stored at -20°C . Weekly samples were also taken from alfalfa pellets, wheat straw, corn meal, solvent soybean meal, and concentrate mix. Samples were dried in a ventilated oven at 55°C for 48 h. After drying, TMR, silages, and orts were ground through a 1-mm screen (Pulverisette 14; Fritsch GmbH, Markt Einersheim, Germany).

Silages were also ground through a 2-mm screen for the in situ procedure.

Silages, TMR, Orts, and feces were analyzed for content of DM (method 945.15; AOAC, 1995); ash (method 942.05; AOAC, 1995); CP (method 984.13; AOAC, 1995); ether extract (method 920.29; AOAC 1995); starch (method 996.11; AOAC, 1998); NDF, corrected for insoluble ash and with the addition of α -amylase (**aNDFom**; Mertens, 2002), and ADF (Van Soest et al., 1991), using the Ankom 200 fiber analyzer (Ankom Technology Corp., Fairport, NY); ADL (Van Soest, 1963); and gross energy, using an adiabatic bomb calorimeter (IKA 4000; IKA Werke GmbH & Co. KG, Staufen, Germany). Silage samples were also analyzed for lactic acid, VFA, and ethanol (Fussell and Mc Calley, 1987), ammonium-N by direct distillation and titration using a Kjeltac 2300 analyzer (Foss Analytical A/S, Hillerød, Denmark), nitrogen bound to NDF and ADF (Licitra et al., 1996), and total ethanol-soluble carbohydrates (DuBois et al., 1956). Total mixed ration sample particle size was determined using the Penn State Particle Separator (Heinrichs and Kononoff, 2002).

Cows were milked twice daily, yield was recorded at each milking, and milk samples were collected daily (2% of total weight) with the addition of potassium dichromate as a preservative and stored at 4°C before analyses. Milk samples were pooled for cow and period and analyzed for total N (method 991.20; AOAC 1995) at the end of each experimental period. In addition, during each of the 2 milkings at d 3 and 5, individual milk samples were collected and analyzed for protein, fat, lactose, and casein content using a Fourier transform infrared (FTIR) analyzer (MilkoScan FT6000; Foss Analytical A/S). Milk urea nitrogen content was determined by a differential pH technique (Luzzana and Giardino, 1999).

In Situ Rumen NDF Degradability

Fiber rumen degradability of the silages was determined with the in situ method according to the NRC (2001) model using 3 fistulated Italian Friesian dry cows fed a 75:25 forage:concentrate diet, on a DM basis. The forage was a grass hay and the diet had 12% CP, 55% NDF, and 1.30 Mcal of NE_L/kg of DM. Samples (2-mm grind size) were weighed (3.5 g) in duplicate in polyester bags with a pore size of 53 μ m and placed in the rumen for 9 different times (2, 4, 8, 16, 24, 36, 48, 72, and 168 h). The sample size-to-bag surface area was 14.5 mg/cm². Ruminal kinetic parameters were estimated, by nonlinear regression of SAS Institute (2001), according to the equation of McDonald (1981):

$$D(\%) = a + b \times \left(1 - e^{-k_d \times (t-l)}\right),$$

where D is the potential degradability, a is the readily degradable fraction, b is the potentially degradable fraction, k_d is the rate of degradation of fraction b, t (h) is the incubation time, and l (h) is the lag time of the degradation of fraction b.

Effective degradability (**ED**) was calculated with a k_p of 0.03/h as follows (McDonald, 1981):

$$ED(\%) = a + [b \times k_d / (k_d + k_p)] \times e^{-k_p \times l}.$$

In Vitro Protocol and Prediction of NDF Total-Tract Digestibility

The forage samples pooled by period (CS, WPGS, and FS silages, alfalfa, and wheat straw) and the TMR samples, collected in each experimental period, were analyzed for in vitro aNDFom rumen digestibility using the Ankom Daisy^{II} incubator (Ankom Technology Corp.) with 2 incubation times at 6 and 24 h. Samples (1-mm grind size) were weighed (0.250 g) in duplicate in Ankom F57 filter bags. Rumen fluid was collected from 3 fistulated Italian Friesian dry cows fed a 75:25 forage:concentrate diet, on a DM basis, as already mentioned. Two digestion jars were filled with prewarmed (39°C) Marten and Barnes (1980) buffer solution and placed into the Daisy^{II} incubator. Four hundred milliliters of filtered rumen fluid was introduced into each jar. Jars were divided vertically by using a perforated plastic separator; after 6 h of incubation, the jars were opened under CO₂ flow; the bags on one side of the jars were quickly collected, and the jars were closed again. The remaining bags were removed after 24 h of incubation. The bags removed from the jars were rinsed thoroughly with cold tap water and immediately analyzed for aNDFom content using the Ankom200 fiber analyzer. Incubations were repeated twice.

The digestion rates of pdNDF of the forages were estimated on the basis of in vitro NDFD values, as reported by Van Amburgh et al. (2003). The indigestible fiber pools (**iNDF**) of the forages were calculated as 2.4 times ADL (Chandler et al., 1980). Diets and animal inputs (such as BW, DMI, and milk production, among others) were entered in CNCPS model version 6.1 (Tylutki et al., 2008). Forage chemical composition and pdNDF k_d derived from in vitro analysis were also entered in the model; for the nonforage feeds, the library k_d values were used. Rumen digestibility of the pdNDF was predicted by the model. The ttNDFD was estimated assuming that intestinal digestibility of the

NDF amount escaping rumen digestion was 20%, according to Sniffen et al. (1992). The predicted ttNDFD was compared with the in vivo data.

Statistical Analysis

Statistical analysis was carried out using the GLM procedure of SAS (SAS Institute, 2001). In vivo data were analyzed with the following model:

$$Y_{ijk(t)} = \mu + S_i + A_{ij} + P_k + T_{(t)} + e_{ijk},$$

where $Y_{ijk(t)}$ is the dependent variable, μ is the overall mean, S_i is the square effect ($i = 1, 2$), A_{ij} is the animal effect within square ($j = 1, 3$), P_k is the period effect, $T_{(t)}$ is the diet effect ($t = 1, 3$), and e_{ijk} is the residual error.

In situ/in vitro data were analyzed with the following model:

$$Y_{ij} = \mu + S_i + \text{cow/run}_j + e_{ij},$$

where Y_{ij} is the dependent variable; μ is the overall mean; S_i is the silage effect; cow/run_j is the effect with $j = 1, 3$ for in situ data and $j = 1, 2$ for in vitro data; and e_{ij} is the residual error.

Least squares means estimates are reported; separation of least squares means was conducted at $\alpha = 0.05$ using the PDIF option in the LSMEANS statement. For all statistical analyses, significance was declared at $P \leq 0.05$ and trends at $P \leq 0.10$.

RESULTS AND DISCUSSION

Silage and Diet Chemical Composition

Chemical composition of the experimental silages is reported in Table 1. Starch content was highest for CS, intermediate for WPGS silage, and lowest for FS silage. Fiber fractions had the opposite tendency: highest for FS silage, intermediate for WPGS silage, and lowest for CS. Forage sorghum ADL content was lower than the value reported by Aydin et al. (1999) for a non-BMR hybrid. The protein content was in the normal range (NRC, 2001) for the forages tested, with a slightly higher content for grain sorghum. Ash content was higher in FS. The ash content reported by NRC (2001) for FS silage (sudangrass) is 10.9% of DM and higher than a typical corn silage (4.3% of DM), thus decreasing the energy value of sorghum. The DM contents of sorghum silages were close to the value (25%) normally recommended (Castle and Watson, 1973) for optimum fermentation, as confirmed by low pH values and good fermentation characteristics. The ratio

of lactate:acetate indicated better fermentation for CS despite moderate ethanol content. In our study, the acetate content of grain sorghum was lower than the value reported by Miron et al. (2007) but higher than the value reported by Tabacco et al. (2009) for grain sorghum ensiled in the Po Plain. The aerobic stability of silages depends greatly on the concentration of acetic acid, which acts as inhibitor of the growth of spoilage organisms. Therefore, acetic acid increases the aerobic stability exponentially (Danner et al., 2003). The acetic content of the silages of our study was within the range suitable for good aerobic stability without affecting DMI negatively.

Considering the analysis of the experimental diets (Table 2), some differences from expected values were observed, particularly for aNDFom, starch, and ash contents in the FS diet throughout the experiment. The ash content of FS silage explained the lower NE_L content of the FS diet in comparison with the other diets. Dietary CP content was significantly ($P = 0.005$) lower for the CS diet and the difference is explained by the higher CP of corn meal (10.2% DM) in comparison with the CP content of the CS used in this experiment. This difference in CP content also is a consequence of the need to balance the diets for the MP, using the same ingredients.

Results of diet particle size distribution are reported in Table 3. Diet FS had a higher percentage retained on the screen of 19-mm size and similar to the value reported by Dann et al. (2008) for a diet with 45% FS (on a DM basis). A large range in the percentage of diet retained on the screen of 19-mm size (14.7 to 35.2%) was reported by Oliver et al. (2004) for sorghum silage diets (40% of DM). Guidelines for TMR are 2 to 8% of the particles in the upper sieve and no more than 20% in the bottom pan (Heinrichs and Kononoff, 2002). The data observed in this study indicate an excessive chop length at harvest for FS.

Milk Production

Results of DMI and milk production are reported in Table 4. A linear trend was observed for an effect of DMI ($P = 0.07$), depending on the kind of silage. Particularly, the FS diet resulted in a lower DMI, probably due to the greater particle size, as described in other studies in dairy cows (Schwab et al., 2002; Krause and Combs, 2003). As a consequence, milk yield was lower for FS in comparison with the CS diet ($P = 0.05$). Previous studies (Aydin et al., 1999; Oliver et al., 2004) showed a decrease in DMI and milk production in cows fed conventional FS hybrids. The cows fed the WPGS diet provided intermediate results in terms of milk yield. Fat yield (kg/d) was numerically higher for the

Table 1. Chemical composition of the experimental forages

Component	Corn silage	Whole plant grain sorghum silage	Forage sorghum silage
DM, %	34.1	29.0	31.8
CP, % of DM	8.7	12.3	10.5
Ash, % of DM	4.3	5.9	14.4
EE, ² % of DM	3.6	3.1	1.8
aNDFom, ¹ % of DM	39.5	45.2	62.5
ADF, % of DM	23.5	29.5	46.4
ADL, % of DM	2.9	4.8	5.4
NPN, % of total N	64.4	56.1	47.6
NH ₃ , % of total N	8.6	10.4	11.3
NDIN, % of total N	11.6	12.4	22.4
ADIN, % of total N	10.5	12.0	11.3
Starch, % of DM	31.5	20.8	3.4
Sugar, % of DM	2.9	2.6	2.3
pH	3.64	3.90	4.28
Lactate, % of DM	5.46	4.97	4.10
Acetate, % of DM	1.72	2.38	1.92
Propionate, % of DM	0.13	0.39	1.14
Butyrate, % of DM	ND ³	ND	ND
Ethanol, % of DM	1.78	0.64	0.13

¹NDF, corrected for insoluble ash and with the addition of α -amylase.

²Ether extract.

³Not detectable.

WPGS than the FS diet, whereas CS was intermediate ($P = 0.09$).

Milk protein yield (kg/d) was lower for FS than CS and intermediate for the WPGS diet ($P = 0.05$). Milk urea N was higher for the FS than the CS diet, in agreement with the results of Colombini et al. (2010) and Dann et al. (2008). Milk urea N is affected by several factors and, among these, dietary CP content (Broderick and Clayton, 1997) and fermentable energy of the diet (Oltner and Wiktorsson, 1983) are the most significant: lower-protein diets with rapidly fermentable carbohydrate content usually decrease the MUN content. In this study, the FS diet had a significantly higher CP content and a lower energy value than the CS diet. Moreover, the rumen starch digestion rate is usually higher in corn silage than in corn meal; Lanzas et al. (2007) reported a starch digestion rate (/h) of 0.25 for unprocessed corn silage (35% of DM) and a rate of 0.15 for corn grain ground fine. In the present study, corn meal was added in higher proportion in the FS diet than in the CS diet; hence, it can be hypothesized that in the FS diet, less energy was available in the rumen to convert ammonia into microbial protein. The WPGS diet was again intermediate with no difference compared with the other 2 dietary treatments.

Total-Tract Nutrient Digestibility

Nutrient digestibility is reported in Table 5. Organic matter, aNDFom, ADF, starch, and energy digestibilities were greater for the FS diet than the WPGS

and CS diets. Total-tract aNDFom digestibility of the WPGS diet (48.6%) was higher than the value reported by other studies (Grant et al., 1995; Oliver et al., 2004) and not different from the CS diet. The higher aNDFom digestibility of the FS diet (54.1%) is probably due to a higher retention time in the rumen rather than to a better quality of the forage fiber. This is confirmed by the theoretical dietary forage k_p calculated according to Fox et al. (2004) based on the measurements registered during the experiment (BW, DMI, and diet characteristics, including the physically effective NDF): 0.049, 0.042, and 0.035/h for CS, WPGS, and FS silages, respectively. The hypothesis that the higher ttNDFD of the FS diet is mainly due to the higher rumen retention rather than to a higher rumen fiber degradability is confirmed by the data obtained in situ and in vitro (Table 6), which did not show any difference in the rate of degradation or in the effective degradability of aNDFom among the 3 forages tested. Similarly, Aydin et al. (1999) indicated no difference in the k_d of NDF among conventional sorghum, BMR sorghum, and corn silages. The aNDFom k_d of FS (0.032/h) was similar to the value obtained for a BMR sorghum harvested in the Po Plain area in a study of Colombini et al. (2010) and higher than the value reported by Oliver et al. (2004) for conventional sorghum. A tendency ($P = 0.08$) existed for the potentially degradable fiber to be higher for CS than sorghum silages; this can be explained by the lower ratio ADL:NDF of CS (0.07) as compared with sorghum silages (0.11 and 0.09 for WPGS and FS silages, respectively).

Table 2. Composition of the experimental diets (% of DM, unless otherwise stated)

Composition	Diet ¹		
	CS	WPGS	FS
Ingredient			
Corn silage	41.5	—	—
Grain sorghum silage	—	36.7	—
Forage sorghum silage	—	—	28.0
Alfalfa pellets	13.6	13.6	13.6
Wheat straw	1.3	1.3	1.3
Corn meal	16.0	21.3	29.4
Soybean meal solvent	7.0	7.0	7.0
Concentrate mix ²	17.8	17.8	17.8
Salt ³	2.6	2.6	2.6
Vitamin-mineral mix ⁴	0.2	0.2	0.2
Chemical composition			
DM, %	55.5	53.6	61.8
Ash	7.1	7.8	9.7
CP	16.0	17.0	16.8
MP ⁵	10.9	10.9	11.0
EE ⁶	4.2	4.3	4.2
aNDFom ⁷	36.6	35.8	37.0
ADF	19.5	21.2	21.4
ADL	3.6	3.8	3.5
Starch	26.5	26.8	25.0
NE _L , ⁵ Mcal/kg of DM	1.71	1.68	1.63

¹CS = corn silage diet; WPGS = whole plant grain sorghum silage diet; FS = forage sorghum silage diet.

²Concentrate mix: 21% canola meal, 21% cotton seeds, 20% beet pulp, 19% barley meal, 8% soybean flakes, 8% sugar cane molasses, 2% urea, 1% yeast.

³Salt: 30% sodium bicarbonate, 18% calcium carbonate, 18% potassium carbonate, 12% monocalcium phosphate, 9% potassium sulfate, 9% magnesium oxide, 4% sodium chloride.

⁴Provided (per kilogram): 17.5 mg of Zn, 1.75 mg of Cu, 0.75 mg of Mn, 0.3 g of I, 0.13 g of Se, 0.02 g of Co, 1900 KIU of vitamin A, 600 KIU of vitamin D, and 16,000 IU of vitamin E.

⁵Calculated according to Cornell Net Carbohydrate and Protein System (CNCPS) version 5.

⁶Ether extract.

⁷NDF, corrected for insoluble ash and with the addition of α -amylase.

Total-tract starch digestibility was very high and it was slightly lower, yet significant, for the CS and WPGS diets than the FS diet ($P < 0.01$). To improve

starch digestibility, processing of the grain is needed for all cereals to break the seed coat (Beauchemin et al., 1994), especially for corn and grain sorghum (Theurer et al., 1999). Taking this into account, a possible explanation that can be given is that a small proportion of the whole corn and sorghum grains was not broken by the on-board rollers during harvesting, resulting in an overall decrease in starch digestibility.

Fiber Digestibility Prediction Based on In Vitro Results

The in vitro NDFD at 24 h of in vitro incubation of TMR samples did not reveal ($P = 0.14$) any difference among the experimental diet values (43.0, 37.8, and 44.7% for CS, WPGS, and FS diets, respectively), which were lower than the in vivo results (Table 5). However, the rank of the 3 diets in terms of 24 h rumen fiber digestibility was again in favor of FS followed by CS and, with the lowest value, WPGS. The values obtained were lower than those of the in vivo, partly because of the shorter time used for the in vitro analysis (24 h) similarly to the results reported by Di Marco et al. (2009).

Considering the estimation of the fiber k_d of the 3 silages (Table 6), no significant difference ($P = 0.32$) was registered between the in situ and the in vitro method. Using the in vitro k_d values, the prediction of the rumen dietary NDFD was obtained by CNCPS model version 6.1 (Tylutki et al. 2008), whereas ttNDFD was estimated, as previously described, assuming that intestinal digestibility of the NDF amount escaping rumen digestion was 20% (Sniffen et al. 1992). The estimated ttNDFD values were 37.7, 36.3, and 39.5% for the CS, WPGS, and FS diets, respectively. This prediction gave lower values (on average, 37.8%) than those observed in vivo (on average, 51.4%). It must be recognized that some critical aspects exist in the prediction model applied. In this regard, the underesti-

Table 3. Diet particle size distributions

Particle size fraction, ¹ % retained (as-fed basis)	Diet ²					
	CS		WPGS		FS	
	Mean ³	SD	Mean	SD	Mean	SD
>19 mm	1.5	0.4	4.8	2.2	18.5	3.2
>8 to 19 mm	39.2	2.3	39.3	1.9	20.8	2.9
1.18 to 8 mm	33.9	1.6	28.5	1.8	30.0	0.9
<1.18 mm	25.4	3.9	27.4	2.7	30.8	2.7

¹Determined with the Penn State Particle Separator (Heinrichs and Kononoff, 2002).

²CS = corn silage diet; WPGS = whole plant grain sorghum silage diet; FS = forage sorghum silage diet.

³Mean of 6 composite samples (1 per cow per period).

Table 4. Dry matter intake and milk yield of the cows fed the experimental diets

Item	Diet ¹			SE	<i>P</i> -value
	CS	WPGS	FS		
DMI, kg/d	20.0	20.0	18.2	0.53	0.07
Milk yield, kg/d	25.4 ^a	24.6 ^{ab}	23.6 ^b	0.43	0.05
4% FCM, kg/d	25.6	25.8	24.1	0.48	0.07
4% FCM/DMI	1.28	1.29	1.32	0.03	0.63
Fat, %	4.08	4.33	4.16	0.08	0.14
Fat yield, kg/d	1.03	1.06	0.98	0.02	0.09
Protein, %	3.36	3.28	3.31	0.07	0.31
Protein yield, kg/d	0.85 ^a	0.81 ^{ab}	0.78 ^b	0.02	0.05
Casein, %	2.79	2.73	2.71	0.03	0.25
Casein, kg/d	0.71 ^a	0.67 ^{ab}	0.64 ^b	0.02	0.05
Lactose, %	5.11	5.09	5.10	0.03	0.57
Lactose yield, kg/d	1.29 ^a	1.25 ^{ab}	1.19 ^b	0.02	0.05
MUN, mg/dL	10.7 ^a	11.9 ^{ab}	12.9 ^b	0.5	0.05

^{a,b}Least squares means within a row with different superscripts are different ($P < 0.05$).

¹CS = corn silage diet; WPGS = whole plant grain sorghum silage diet; FS = forage sorghum silage diet.

mation of the predicted NDFD can be explained by an overestimation of the k_p . A recent meta-analysis study (Krizsan et al., 2010) showed that the k_p values estimated from the rumen evacuation technique were lower than those predicted from the CNCPS according to Seo et al. (2006), based on studies with external markers. Furthermore, the k_p values in the model are referred to the whole feed, and not to the single fractions, with a consequent great influence, particularly on fiber, due to its slower k_p in comparison with the soluble and with the readily degradable fractions. The reticulo-rumen is a system with selective retention of feed particles; not considering this aspect leads to serious underestimation of NDF digestibility (Huhtanen et al., 2006).

Another questionable point is the assumption that indigestible NDF is equal to 2.4 times ADL for any feed. Raffrenato et al. (2008) showed that the ratio between ADL and iNDF is not constant. Particularly, it is higher in forages with high ADL and NDF and lower

in most CS and grasses. A wrong evaluation of iNDF results in a bias in the predicted k_d value. Particularly, an overestimation of iNDF determines an overestimation of the k_d , and vice versa. Moreover, in the present study the use of dry cows as donor animals might have affected the in vitro NDFD and, consequently, the k_d values, as suggested by Ward (2009) who showed that the inoculum obtained from dry cows gave NDFD values lower (on average, -10%) than the values obtained using the inoculum from lactating cows. Furthermore, the forage-to-concentrate ratio of the diets fed to the donor animals can affect the in vitro results. Nagadi et al. (2000) showed that bacterial DM and gas production increased as the ratio of concentrate to hay increased in the donor sheep diets, suggesting a 60:40 hay-to-concentrate ratio in the donor animal diets (lower than that used in the present study: 75:25).

Finally, it is known that NDF actually is composed of several pools with different degradation rates (Mertens

Table 5. Total-tract digestibility (%) of the experimental diets

Item	Diet ¹			SE	<i>P</i> -value
	CS	WPGS	FS		
OM	70.4 ^b	69.5 ^b	71.7 ^a	0.51	0.05
CP	66.0	64.5	66.3	1.43	0.66
EE ²	75.5	75.7	78.0	0.51	0.60
aNDFom ³	51.4 ^b	48.6 ^b	54.1 ^a	0.94	0.01
ADF	37.8 ^b	40.4 ^b	44.7 ^a	1.67	0.05
Starch	97.3 ^b	96.6 ^b	98.1 ^a	0.23	0.01
Energy	68.6 ^b	67.7 ^b	70.2 ^a	0.470	0.01

^{a,b}Least squares means within a row with different superscripts are different ($P < 0.05$).

¹CS = corn silage diet; WPGS = whole plant grain sorghum silage diet; FS = forage sorghum silage diet.

²Ether extract.

³NDF, corrected for insoluble ash and with the addition of α -amylase.

Table 6. In situ and in vitro aNDFom rumen degradability of the experimental forages

Item	Diet			SE	P-value
	Corn silage	Whole plant grain sorghum	Forage sorghum		
In situ					
a, ¹ % aNDFom	2.8	2.1	2.0	0.52	0.58
b, ² % aNDFom	77.8	70.5	71.4	1.31	0.08
a+b, % aNDFom	80.6 ^a	72.6 ^b	73.4 ^b	0.97	0.03
24-h NDFD, ³ %	30.0	31.5	36.2	3.73	0.57
48-h NDFD, ⁴ %	51.2	54.3	51.9	1.23	0.37
Lag, h	2.8 ^a	2.8 ^a	2.0 ^b	0.38	0.05
k _d , ⁵ /h	0.021	0.029	0.032	0.003	0.19
ED, ⁶ %	32.5	33.4	36.8	1.19	0.62
In vitro					
24-h NDFD, ³ %	30.2	29.1	36.7	1.27	0.14
Lag, h	6.0	5.8	5.6	0.19	0.45
k _d , ⁵ /h	0.026	0.028	0.034	0.001	0.23

^{a,b}Least squares means within a row with different superscripts are different ($P < 0.05$).

¹Soluble fraction.

²Potentially degradable fraction; aNDFom = NDF, corrected for insoluble ash and with the addition of α -amylase.

³Rumen aNDFom digestibility after 24 h of in situ or in vitro incubation.

⁴Rumen aNDFom digestibility after 48 h of in situ incubation.

⁵Degradation rate of potentially degradable fraction.

⁶Effective fiber degradability with a passage rate of 0.03/h.

and Ely, 1982; Ellis et al., 2005; Huhtanen et al., 2008; Raffrenato et al., 2011). This was not considered in the current study, as the model used (Van Amburgh et al., 2003) predicts a k_d for a single pool of potential digestible NDF assuming a first-order model (i.e., the k_d is constant during fermentation) and a fixed iNDF.

Nitrogen Utilization and Excretion

Dietary effects on variables related to N utilization and excretion are reported in Table 7. Nitrogen intake was not different among diets, as the higher CP content of the FS diet was offset by the lower DMI of this diet.

Table 7. Nitrogen balance of the cows fed the experimental diets

Item	Diet ¹			SE	P-value
	CS	WPGS	FS		
N intake, g/d	513	542	493	16.2	0.17
Fecal excretion					
DM, kg/d	6.3	6.5	5.8	0.21	0.09
Total N, g/d	174	191	166	7.09	0.08
Total N, % of N intake	34.0	35.5	33.7	1.43	0.66
Urinary excretion					
Urine, kg/d	13.8	15.6	16.7	0.205	0.07
Total N, g/d	138	157	158	6.14	0.10
Total N, % of N intake	27.5	29.3	31.8	1.17	0.08
Manure excretion					
Total N, g/d	313 ^b	348 ^a	323 ^b	6.59	0.01
Total N, % of N intake	61.5	64.8	65.5	1.45	0.18
Milk excretion					
Total N, g/d	133	126	122	3.47	0.13
N, % of intake	26.1	23.5	24.9	0.76	0.11
N balance					
N retained, g/d	66.9	66.8	47.5	11.7	0.43
N retained, % of N intake	12.4	11.7	9.6	1.77	0.54

^{a,b}Least squares means within a row with different superscripts are different ($P < 0.05$).

¹CS = corn silage diet; WPGS = whole plant grain sorghum silage diet; FS = forage sorghum silage diet.

Feces produced were lower for cows fed the FS diet ($P = 0.09$) due to the lower DMI. A trend ($P = 0.08$) was observed for lower fecal N excretion (g/d) for the FS diet in comparison with the WPGS diet, but the N fecal excretion as a proportion of N intake was not different among diets.

The excretion of urine (kg/d) was lowest for CS, intermediate for WPGS, and highest for the FS diet ($P = 0.07$). Dietary CP concentrations have been shown to affect urine excretion (Sannes et al., 2002; Broderick, 2003; Wattiaux and Karg, 2004) because a greater urine volume is required for excreting the excess N consumed by cows (Holter et al., 1982). Cows fed the FS diet, despite the numerically lowest N intake, had a urinary N excretion (g/d) similar to cows fed the WPGS diet in absolute value, and numerically higher as a percentage of N intake (29.3 vs. 31.8% for WPGS and FS, respectively), probably because of a less efficient N utilization at rumen level, with a consequent increase in the urine volume. The average urinary excretion was close to the value (16.3 kg/d) reported by ASAE (2001) and lower than the average value (24.1 kg/d) reported by Nennich et al. (2005) on the analysis of a wide data set; however, the average milk production of this latter data set (32.7 kg/d) was higher than the average value obtained in our study.

A trend occurred for a reduction of urinary N (g/d) with the CS diet ($P = 0.10$) in comparison with the other diets. Bacterial MP (% total MP), estimated by CNCPS model version 6.1, was higher for the CS diet (54.4%) than for the WPGS and FS diets (48.4% for both), indicating a greater microbial protein synthesis at rumen level with the CS diet. As a consequence, urinary N excretion (% N intake) was highest for FS, intermediate for WPGS, and lowest for the CS diet ($P = 0.08$). The average urinary N excretion is lower than the percentage reported by Kebreab et al. (2010; 38% of N intake) but similar to the value reported by Colmenero and Broderick (2006) for a diet with a 16.5% CP content on a DM basis.

Total N excretion (manure N, g/d) was highest for the WPGS diet in comparison with the other diets ($P = 0.01$) and this difference is mainly due to the higher N intake of the WPGS diet; overall N manure excretion as a proportion of N intake was not different among diets and it was close to the average value reported by Kebreab et al. (2010) on a wide data set derived from in vivo experiments. N retention was similar in all dietary treatments and positive. The positive N balance is probably due to an overestimation of N retention, which, in turn, is consistent with the findings of Spanghero and Kowalski (1997) reported in a review of many nitrogen balance experiments on lactating cows. However, despite the possible little bias in terms of the

absolute values, the rank of the 3 dietary treatments in terms of N utilization is valid.

CONCLUSIONS

With adequate starch supplementation, whole plant grain sorghum silage can replace corn silage in dairy cow TMR without any negative effect on milk production. Forage sorghum had NDFD comparable to the other silages; however, it was probably chopped too long, with a negative effect on DMI and milk production. In this experiment, the predicted ttNDFD values were lower than those in vivo. However, because several factors affect total-tract fiber digestibility and data in the literature are not always consistent, further investigation, particularly in vivo studies, are needed to better understand and predict ttNDFD.

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