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Stover quality of dual-purpose sorghums: genetic and environmental sources of variation

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Abstract

Improvement of the nutritive value of dual-purpose sorghum (*Sorghum bicolor* (L.) Moench) stover is an important objective for the semi-arid tropics where sorghum crop residue is extensively used for livestock feed. To identify the relative importance of genetic and environmental sources of variation for nutritive value, leaves and stems of six diverse dual-purpose sorghum cultivars were evaluated for in vitro gas production (Gas48hr), neutral detergent fiber (NDF), acid detergent fiber (ADF), lignin, nitrogen, and ash contents under two fertility and two plant-density regimes during 2 years in India. Substantial genotypic differences were observed for stem Gas48hr (25.7 to 33.0 ml in 200 g^{-1} dry matter (DM)) and NDF (564–687) content. Gas48hr and NDF content of stems exhibited more promise as selection criteria than those of leaves, as stems showed larger portion of variation attributed to genotypes, relatively less genotype by environment (GE) interactions, and were closely related to whole-plant values. Year, nitrogen fertilization and plant density showed very little influence on Gas48hr, NDF or ADF of leaves and stems. Gas48hr exhibited substantial GE interactions with all environmental factors, indicating the need for multi-environment testing to achieve progress. © 2001 Published by Elsevier Science B.V.

Keywords: Stover quality; *Sorghum bicolor*; Genetic variation; Genotype–environment interaction

1. Introduction

Sorghum stover (vegetative crop residue) is used extensively for livestock feed in the semi-arid areas of Asia (Kelly and Rao, 1993) and sub-saharan Africa (Leeuw, 1997; Powell, 1985; Sanford, 1989; Youngquist et al., 1990). Stover accounts for 35–49% of the total crop value in Asia (Kelly and Rao, 1993) . Furthermore, increasing animal numbers and stagnating area for forage in India (Kelly et al., 1993) suggest that the demand for sorghum stover as ruminant feedstuff is increasing, as reflected by a doubling of the relative value of sorghum stover to grain over the past two decades (Kelly and Rao, 1993). However, a major problem in realizing the feed potential from sorghum stover is the generally low levels of digestible energy, protein and certain minerals (Bartle and Klopfenstein, 1988).

Genetic variation for digestibility or fiber content of sorghum stover has been frequently reported both at flowering (Caravetta et al., 1990; Gupta and Sagar, 1987; Gupta et al., 1976; Lodhi and Dangi, 1981) and

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at harvest (Badve et al., 1994; Ross et al., 1983; Youngquist et al., 1990). Plant density has been shown to influence sorghum NDF and lignin levels at flowering (Caravetta et al., 1990; Masaoka and Takano, 1985). Nitrogen fertilitzation has been found to influence rate of NDF digestion and intake of warm season grasses (George and Hall, 1983; Puoli et al., 1991) and cool season grasses (Messman et al., 1991) but not the extent of digestion.

The importance of genotype relative to environmental effects in determining stover quality would determine the opportunities for improving quality either through breeding or crop management whereas genotype by environment interactions would limit gains from both approaches. Very little information exists, however, on the relative importance of these sources of variation for the nutritive value of stover from dual-purpose sorghums in tropical environments. There are reports that year and location effects are much greater than genotypic differences for forage sorghum (Arora et al., 1975) and dual-purpose sorghum (Badve et al., 1994). Badve et al. (1994) concluded that assessment of stover quality over specific environmental factors with a diverse set of genotypes was needed prior to initiating a breeding program for stover quality of sorghum.

The measurement of in vitro gas production alone or associated with other tests has been used to estimate the nutritive value of roughages (Hillman et al., 1993; Khazaal et al., 1993; Williams et al., 1995). The anaerobic digestion of cellulose and other types of fiber by ruminal microbes produces volatile fatty acids (VFA), CO_2, CH_4, and traces of H_2. Both in vivo and in vitro, the VFA react with bicarbonate buffer to release CO_2 so that gas production occurs simultaneously and in concert with fiber digestion. Measurement of gas evolution in vitro, therefore, can provide quantitative information about the rate and extent of cellulose digestion.

The objective of this study was to assess the relative importance of environmental, genotypic and genotype by environment variation for stover quality for a set of six contrasting dual-purpose sorghum varieties evaluated under contrasting soil fertility and plant density treatments. In this study, cumulative gas production at 48 h was used as one indicator of feed quality of non-grain plant components of contrasting genotypes of sorghum. Other indicators of quality included ADF, NDF, lignin, nitrogen and ash.

2. Materials and methods

2.1. Genetic materials

Six tall (2.0–2.8 m) sorghum cultivars were chosen for this study to represent the diversity of origin of current dual-purpose landrace and bred varieties. They include two landrace cultivars of commercial importance in India in the post-rainy (M 35-1) and the rainy season (Local Yellow), CSV 15 a released dual-purpose variety from the All India Coordinated Sorghum Improvement Program, ICSV 735 and ICSV 89057, ICRISAT varieties developed for midge (*Contarinaria agricola*) resistance, and ICSV 700, a sweet stemmed ICRISAT variety selected for stem borer (*Chilo partellus*) and shootfly (*Arthrigona soccata*) resistance. The landrace cultivars belong to the botanical race Durra, whereas the four bred cultivars belong to the Caudatum race that predominates among breeding materials in the region.

2.2. Field evaluations

Field experiments were conducted in 1995 and 1996 at ICRISAT, Patancheru, India in fields with Patancheru Series Udic Rhodustalf soils. The 1995 field had been previously cropped with pearl millet (*Pennisetum glaucum* (L.) R. Br.) for two seasons, whereas the 1996 field had been fallow and cropped with groundnut (*Arachis hypogaea* (L.)) the prior two seasons. A split-split-plot design in four randomized complete blocks was used in each year with fertility treatments (9 and 78 kg N ha^{-1}) as whole plots, plant density (7.5 and 17.5 plants m^{-2}) as sub-plots, and cultivar as sub-sub-plots. Only two replicates were used in 1995 due to poor and non-uniform growing conditions on the field margins. All plots received a basal application of 50 kg DAP (9 kg N, 23 kg P_2O_5) ha^{-1}. The high fertility plots received three topdressings of 55 kg urea ha^{-1} at approximately 24-day intervals with the first one at 2 weeks after sowing. Two plant densities were established by oversowing all plots and thinning plants to 9.5 cm (high density) and 22.2 cm (low density) within rows of 0.6 m row width. Cultivar plots were seven rows of 9 m in 1995 and six rows of 4 m in 1996.

At physiological maturity a sub-sample of six representative plants was taken from each net-plot of 1.0 m × 5 rows (3.0 m^2) in 1995 and 1.5 m × 4 rows

(3.6 m^2) in 1996 for leaf and stem measurements. Leaf blades were removed leaving the sheath connected to the stem. Leaf blades and stems were dried at 60°C for 48 h and ground with a 0.5 mm sieve in a Cross Beater Mill (Model 16-153).

2.3. Quality determinations

Leaves and stem plant parts of sorghum genotypes were incubated with ruminal fluid obtained from four bullocks (average liveweight = 387.5 kg, S.D. = 40.3) before the morning feeding and adapted to a diet of sorghum residues for a minimum of 3 weeks. Ruminal fluid was collected before the morning feeding with in vitro gas production from incubated feeds was estimated as described by Osuji et al. (1993). Two-hundred milligrams of each sample, standards (groundnut hay, pearl millet, foxtail millet, sorghum, and starch) and blanks were incubated in triplicate with 30 ml of rumen fluid mixture as described in Osuji et al. (1993) including a buffer solution made up with sodium hydrogen carbonate. Cumulative fermentation gas was measured at 3, 6, 12, 24, 36, 48, 72 and 96 h after incubation. Whole-plant Gas48hr was computed as the weighted average, by proportion of plant part in total dry matter, of stem and leaf Gas48hr. Gas production of feed samples were corrected for gas production in the appropriate blank. In addition, average gas production from a set of standard samples of sorghum, pearl millet and finger millet straw and groundnut hay incubated in every batch were used to correct for possible differences occurring between batches. However, the correction factor was small with the coefficient of variation between batches being less than 5%.

Nitrogen (N) was determined (Technicon Auto Analyzer) in dry feed material and was expressed on an absolute dry matter (DM) basis. Acid and neutral detergent fibers (ADF, NDF) and lignin were determined by the method of Van Soest and Robertson (1985). DM and ash were determined according to AOAC (1980).

2.4. Statistical analyses

Data on different quality traits for each individual year were analyzed by fitting the additive linear model appropriate to a split-split-plot design using the general linear regression procedure in Genstat 5, Release 4.1. The plant density (D), fertility (F), and genotype (G) effects in the model were assumed fixed. A pooled analysis over the 2 years was conducted using the general linear regression procedure by treating year (Y) effects also as fixed. The mean squares (MS) in the resulting ANOVA were used to estimate the components of MS by the method of moments using the expected mean squares (EMS) under a fixed-effects model. The estimates of components of MS were used to assess the relative importance of variation among genotypic, environmental (E), and genotype–environment interaction (GEI) effects. The E component includes the effects of Y, D, F, Y × D, Y × F, D × F, and Y × D × F. The GEI component includes the effects of G × Y, G × D, G × F, G × Y × D, G × Y × F, G × D × F, and G × Y *imes*D × F. For any individual year, all effects including Y are dropped. The relative importance of GEI was estimated by the ratio of estimates GEI to G component of MS.

3. Results

3.1. Environments

Productivity differed greatly between years, with mean biomass production from feed samples of 6.19 t ha^{-1} in 1995 and 9.79 t ha^{-1} in 1996 ($P < 0.01$). The years did not differ for climate (rainfall of 998 mm in 1995 and 931 mm in 1996) but there were differences for date of sowing (11 days later date in 1995) and cropping history (1995 crop following two seasons of millet, 1996 crop following fallow and a prior groundnut crop). The high fertility treatment increased biomass production ($P < 0.01$), but there was a year by fertility interaction ($P < 0.05$) with a larger response in 1995 (from 4.70 to 7.67 t ha^{-1}) than in 1996 (from 9.32 to 10.26 t ha^{-1}). The plant densities achieved were consistent over years, with 7.29 and 7.67 plants m^{-2} in low-density, and 16.44 and 16.46 plants m^{-2} in high-density in 1995 and 1996, respectively. Biomass production was greater ($P < 0.05$) in high plant density but compensatory growth in the low density treatments resulted in yields that were only 0.85 and 0.78 t ha^{-1} lower than those of the high density treatments in 1995 and 1996, respectively.

3.2. Sources of variation for quality traits

Gas48hr showed little response to the environmental factors of year, fertility level and plant density with only a significant ($P < 0.05$) year by density interaction for stems (Table 1). Year or year by fertility interactions were significant sources of variation for stem NDF, ADF, lignin and ash and leaf ADF, lignin, and nitrogen (Table 2). Fertility level only showed significance for stem ash and leaf lignin. Plant density influenced the nitrogen contents of leaves and stems and stem ash.

Genotype was a major source of variation for most measures of stover quality. The genotypic variance components were highly significant ($P < 0.001$) for all quality measures of stems (Table 1) and for NDF and ADF of leaves (Table 2). Genotype means for stem Gas48hr ranged from 25.7 to 33.0 ml in 200 mg^{-1} DM (Table 3). The range among genotypes was much larger for stems as compared to leaves for NDF, ADF and lignin (Table 3).

The year–genotype interactions were very important for most stem quality traits (Table 1) and leaf Gas48hr (Table 2). There were no correlations between years for Gas48hr for stems ($r = 0.08$) or leaves ($r = -0.14$) with major rank changes occurring between years (Table 4). Fertility–genotype interactions were also important for stem Gas48hr and year–fertility–genotype interactions for stem ADF and lignin (Table 1). Whereas every form of genotype–environment interaction (GEI) was significant for leaf Gas48hr, none were significant for leaf NDF and ADF (Table 2).

The importance of GEI relative to genotypic variation differed greatly by year and by trait (Table 5). Whereas GEI for Gas48hr was absent (GEI/G ratio less than 1.0) in 1995, it was much more prominent than genotypic variation in 1996 and pooled over years for both stems and leaves. Compared to Gas48hr, the GEI of the chemical parameters were much lower, and could be considered absent for stem NDF, ADF and leaf ADF and ash. GEI was generally much more

Table 1
Sorghum stem mean squares (MS) and components of mean squares (CMS) for Gas48hr and five indirect quality traits over 2 years

Source	d.f.	Gas 48h		NDF		ADF		Lignin		Nitrogen		Ash	
		MS	CMS	MS	CMS	MS	CMS	MS	CMS	MS	CMS	MS	CMS
Year (Y)	1	254	4	9748*	146*	5030*	77*	428*	6*	0.05	0.00	1320*	19*
Error 1	4	22	1	408	0	86	0	42	0	0.20	0.00	109	3
Fertility (F)	1	1	0	4535	24	1365	8	335	4	4.56	0.06	336*	4*
Y × F	1	18	1	5072	70	11088*	322*	651	19	0.09	0.00	3	0
Error 2	4	3	0	2818	133	771	0	58	3	0.31	0.00	29	1
Density (D)	1	50	0	1964	10	3253	33	9	0	3.97*	0.05*	362***	5***
Y × D	1	111*	3*	28	0	884	1	2	0	0.06	0.00	402***	12***
F × D	1	73	2	27	0	5	0	158*	4*	0.36	0.00	0	0
Y × F × D	1	8	0	963	0	1799	59	11	0	0.05	0.00	6	0
Error 3	8	19	0	1223	47	859	71	24	0	0.45	0.03	14	0
Genotype (G)	5	116***	4***	36845***	1496***	30244***	1242***	511**	20**	3.48***	0.30***	353***	13***
Y × G	5	116***	9***	5321***	411***	4024***	336***	143***	11***	0.51	0.02	62	2
F × G	5	91**	6**	1553	51	220	0	31	1	0.37	0.01	93	4
Y × F × G	5	29	1	1376	81	2190***	329***	163***	27***	0.66*	0.07*	25	0
D × G	5	68*	4*	1656	60	384	0	35	1	0.13	0.00	84	3
Y × D × G	5	32	2	1147	39	542	20	17	0	0.31	0.01	18	0
F × D × G	5	55*	6*	749	0	1052*	103*	84**	11**	0.10	0.00	29	0
Y × F × D × G	5	47	9	1760	307	548	42	24	1	1.02**	0.28**	96	19
Error 4	80	22	22	942	942	435	435	21	21	0.27	0.27	45	45

* Significant at $P < 0.05$.
** Significant at $P < 0.01$.
*** Significant at $P < 0.001$.

Table 2
Sorghum leaf mean squares (MS) and components of mean squares (CMS) for Gas48hr and five indirect quality traits over 2 years

Source	d.f.	Gas 48hr		NDF		ADF		Lignin		Nitrogen		Ash	
		MS	CMS	MS	CMS	MS	CMS	MS	CMS	MS	CMS	MS	CMS
Year (Y)	1	41	0	1277	16	17	0	1642**	25**	129.6*	1.9*	1068	10
Error 1	4	24	0	226	0	1044	17	23	0	5.6	0.1	433	2
Fertility (F)	1	6	0	3182	23	1244	9	168*	2*	16.2	0.2	274	0
Y × F	1	9	0	5772	134	4100*	108*	418**	13**	0.3	0.0	7	0
Error 2	4	32	2	1496	49	633	0	15	0	2.7	0.0	392	8
Density (D)	1	28	0	3590	37	57	0	4	0	41.8*	1.0*	1294	14
Y × D	1	3	0	2954	57	120	0	24	0	0.7	0.0	1402	31
F × D	1	21	0	1111	6	1238	16	121	2	14.8	0.3	113	0
Y × F × D	1	128	7	1202	18	187	0	3	0	0.0	0.0	25	0
Error 3	8	12	0	911	0	668	0	34	3	5.0	0.2	296	5
Genotype (G)	5	42*	1*	5198***	174***	5515***	199***	51*	1*	11.4*	0.3*	1090**	34**
Y × G	5	143***	12***	1065	4	666	0	18	0	10.3*	0.6*	218	0
F × G	5	78***	5***	1388	31	1021	23	43*	2*	2.3	0.0	137	0
Y × F × G	5	51**	7**	1939	172	639	0	59**	8**	12.6**	1.7**	79	0
D × G	5	83***	6***	1660	53	840	8	26	1	1.7	0.0	256	0
Y × D × G	5	51**	7**	316	0	372	0	17	0	7.9	0.8	229	0
F × D × G	5	128***	19***	763	0	1065	54	17	0	9.2*	0.9*	195	0
Y × F × D × G	5	144***	49***	815	0	407	0	34	7	2.8	0.0	290	8
Error 4	80	15	15	1022	1023	741	742	16	16	3.8	3.8	269	270

* Significant at $P < 0.05$.
** Significant at $P < 0.01$.
*** Significant at $P < 0.001$.

prominent for the leaf quality parameters as compared to stem parameters, and most dramatically for Gas48hr.

The ratio of environmental to genotypic components of mean squares indicates that environment was also a prominent determinant of Gas48hr and lignin, and particularly for leaves (Table 5).

4. Discussion

The absence of fertility and plant-density main effects for Gas48hr of stem or leaves suggest that little opportunity exists to enhance nutritive value of sorghum stover through manipulation of these agronomic factors. The significant year–density interaction for stem Gas48hr shows that plant density was important but not consistent in its effect over years. Other studies have also found that soil nitrogen had little influence on digestion parameters (Messman et al., 1991; Puoli et al., 1991; Walli et al., 1994).

The highly significant differences among genotypes for stem Gas48hr over environments indicates that genetic improvement of stover quality of dual-purpose sorghums should be possible. The extensively cultivated dual-purpose cultivar ''Local Yellow'' was ranked lowest for stem Gas48hr and had below average stem Gas48hr values in all environments. Thus varietal improvement could contribute to raising the nutritional quality of sorghum crop residues above current levels. The magnitudes of genotypic differences found in this study should prove meaningful for animal performance, as small changes of in vitro dry matter digestibility of 3–4% units have been observed to result in improvements of 17–24% in daily gains and production per hectare (Vogel and Sleper, 1994).

However, the very large genotype-environment interactions (GEI) observed in this study could seriously reduce the realized gains for stover digestibility

Table 3
Genotype means, ranges and standard error of differences over years, fertility and density levels for leaf and stem quality parameters

Genotype	Gas48hr	NDF	ADF	Lignin	Nitrogen	Ash
Stem parameters[a]						
M35-1	30.9	576	370	47.6	3.2	41.4
Local Yellow	25.7	687	462	60.7	2.9	47.9
CSV 15	27.7	619	421	53.3	2.4	51.1
ICSV 735	30.1	598	390	51.7	2.7	45.2
ICSV 700	33.0	564	349	46.2	3.2	42.7
ICSV 89057	26.3	604	410	51.1	2.4	51.8
Range	7.4	123	113	14.5	0.9	10.4
Mean	28.9	608	400	51.8	2.8	46.7
S.E. differences	1.7	11	7	1.6	0.2	2.3
Leaf parameters[a]						
M35-1	33.7	663	403	45.1	11.2	92.9
Local Yellow	32.0	660	406	44.7	11.6	96.3
CSV 15	32.1	687	442	48.8	9.6	87.8
ICSV 735	30.7	696	424	47.0	10.1	85.2
ICSV 700	32.7	697	403	43.4	9.8	77.8
ICSV 89057	25.9	697	442	45.8	10.6	99.8
Range	7.7	37	39	5.5	2.0	22.1
Mean	31.2	683	420	45.8	10.5	90.0
S.E. differences	1.4	11	10	1.4	0.7	5.5

[a] Units of measure: Gas48hr (ml in 200 mg^{-1} DM), NDF, ADF, lignin, nitrogen, ash (mg g^{-1} DM).

Table 4
Genotype × fertility, genotype × density, and genotype × year means for Gas48hr for stems and leaves

Genotype	Fertility		Density		Year	
	High	Low	High	Low	1995	1996
Stems						
M35-1	33.8 (1)[a]	27.9 (5)	30.8 (3)	31.0 (2)	33.4 (1)	28.4 (5)
Local Yellow	26.4 (5)	24.9 (6)	25.4 (5)	25.9 (6)	25.4 (4)	25.8 (6)
CSV 15	27.0 (4)	28.8 (4)	29.3 (4)	26.5 (5)	25.2 (5)	30.7 (4)
ICSV 735	31.2 (3)	28.9 (3)	32.8 (2)	27.3 (4)	29.3 (3)	30.8 (3)
ICSV 700	32.9 (2)	33.1 (1)	34.2 (1)	31.8 (1)	32.3 (2)	33.7 (1)
ICSV 89057	23.1 (6)	29.6 (2)	23.8 (6)	29.0 (3)	20.0 (6)	32.7 (2)
S.E. differences	2.54		2.65		2.91	
Leaves						
M35-1	34.6 (1)	32.6 (2)	33.6 (2)	33.6 (1)	34.0 (2)	33.2 (1)
Local Yellow	34.4 (2)	29.8 (5)	34.8 (1)	29.4 (4)	34.1 (1)	30.1 (6)
CSV 15	31.8 (4)	32.9 (1)	32.3 (5)	32.4 (2)	32.2 (4)	32.5 (3)
ICSV 735	30.3 (5)	31.2 (4)	33.2 (4)	28.3 (5)	29.7 (5)	31.8 (5)
ICSV 700	33.9 (3)	31.5 (3)	33.4 (3)	31.9 (3)	32.5 (3)	32.8 (2)
ICSV 89057	23.8 (6)	28.0 (6)	23.7 (6)	28.1 (6)	19.6 (6)	32.2 (4)
S.E. differences	2.24		2.13		2.38	

[a] Genotype rank within environment.

Table 5
Magnitude of GEI and E components of mean squares relative to G components of mean squares as ratios of GEI/G and E/G

Trait	Leaf						Stem					
	GEI/G			E/G			GEI/G			E/G		
	1995	1996	Pooled	1995	1996	Pooled	1995	1996	Pooled	1995	1996	Pooled
GAS48hr	0.1	126.4	90.6	0.2	5.9	7.0	0.6	8.5	9.2	0.6	0.0	2.3
NDF	1.2	1.3	1.5	1.4	1.0	1.7	0.3	0.1	0.6	0.3	0.0	0.2
ADF	0.8	0.8	0.4	0.8	0.1	0.7	0.1	0.3	0.7	0.3	0.1	0.4
Lignin	1.3	–[a]	12.6	0.8	–[a]	29.3	0.7	1.4	2.5	0.3	0.9	1.6
Nitrogen	3.7	2.2	12.4	1.3	1.5	10.7	4.2	0.4	1.3	2.2	0.5	0.4
Ash	0.0	3.3	0.2	0.1	5.8	1.6	1.1	1.2	2.2	0.2	2.9	3.1

[a] Infinite.

of dual-purpose sorghums in the semi-arid tropics. The GEI accounted for much more of the variation for Gas48hr than did genotype (Table 5) and involved interactions with all of the environmental factors studied, year, plant density and fertility (Tables 1 and 2).

The different patterns of variation for Gas48hr between years in our study possibly involves responses to differing edaphic conditions due to sowing date and cropping history differences. In vitro digestibility involves the fermentation of all substrates in the feed, and is influenced by the content and digestibility of fiber, content of non-structural carbohydrate, and presence of anti-nutritional factors. The genotype interactions with year for Gas48hr may reflect altered predominance of these factors. The relationship between digestibility and fiber content did appear to differ between years, with substantial correlations between stem Gas48hr and NDF, ADF and lignin in 1995 (-0.63^{**} to -0.82^{**}) and weak to no correlations in 1996 (-0.32 to -0.41^{*}). Although few studies have been specifically designed to examine genotype by year interactions for stover quality, there are reports of highly significant genotype by year interactions for in vitro digestibility (Youngquist et al., 1990) or NDF digestion kinetic parameters (Jung et al., 1998) while other studies failed to find major GY interactions for stover digestibility (Badve et al., 1994; Ross et al., 1983).

The important genotype interactions with each of the environmental factors in this study suggests that opportunities to exploit GEI by targeting more homogeneous environmental sub-sets are limited. Testing in multiple environments would help assure gains in the target environments but would increase the cost per unit gain. However, the following selection approaches could be considered to maximize gains per research cost.

Emphasis on stem digestibility. The greater genotypic variation for stem Gas48hr and its relatively lower level of GEI as compared to leaf Gas48hr indicate that selection for stem Gas48hr should be much more effective. Also stem Gas48hr values were more closely related to whole-plant Gas48hr ($r = 0.98^{**}$) than leaf Gas48hr ($r = 0.64^{**}$), which reflects the low leaf to stem ratio at harvest of these dual-purpose sorghums (Rattunde, unpublished data).

Multi-stage testing. Testing and selection of early generation materials for stover digestibility could be done in a single low productivity environment representative of the median of dual-purpose sorghum field conditions (Powell, 1985). Testing of the limited number of more promising later generation progenies could be done with multiple environments. Another approach would be to initially conduct indirect selection on traits such as NDF or ADF that did not exhibit GE interactions in this study, followed by multi-environmental tests of digestibility for a reduced number of genotypes.

Application of molecular techniques. Marker-assisted selection could offer a powerful tool for selection when quantitative trait loci (QTL) for digestibility are identified and characterized for their GEI. Results from maize are encouraging where, of the seven and six QTL for in vitro digestible organic matter in two test-cross populations of maize, only one QTL in one of the populations showed significant QTL environment interaction (Luebberstedt et al., 1997).

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