Available online at www.sciencedirect.com

ScienceDirect

Field Crops Research 103 (2007) 119–128

Field Crops Research

www.elsevier.com/locate/fcr

Determinants of ruminant nutritional quality of pearl millet [*Pennisetum glaucum* (L.) R. Br.] stover

I. Effects of management alternatives on stover quality and productivity

F.R. Bidinger [a], M. Blümmel [b,*]

[a] *International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502324, Andhra Pradesh, India*
[b] *International Livestock Research Institute (ILRI), Patancheru 502324, Andhra Pradesh, India*

Received 20 December 2006; received in revised form 16 May 2007; accepted 17 May 2007

Abstract

The paper investigates management and cultivar type effects on pearl millet stover yield and fodder quality. Sixteen pearl millet cultivars available to farmers in India were selected to represent three cultivar types: (1) traditional landrace germplasm from the arid/semi-arid millet production zones, (2) improved dual-purpose (grain and stover) open-pollinated varieties incorporating differing amounts of traditional landrace germplasm and (3) commercial, grain-type F1 hybrids, bred for use in the arid/semi-arid zone. The cultivars were grown for 2 years (2000 and 2001) at high fertility (HF: 65 kg N ha^{-1} and 18 kg P ha^{-1}) and low fertility (LF: 21 kg N ha^{-1} and 9 kg P ha^{-1}). Within each fertility level high (HP) and low (LP) plant population densities were established by varying sowing rate and then thinning to the target populations (HP: 11 plants m^{-2} and LP: 5 plants m^{-2}). Stover fodder quality traits (nitrogen concentration, sugar content, *in vitro* digestibility and metabolizable energy content) were analyzed using a combination of conventional laboratory analysis and near infrared spectroscopy. In general, fertility level and cultivar type had strong effects on grain and stover yields, and on a range of stover nutritional quality traits, but with significant year interactions. In contrast, the effect of population density on these variables was largely insignificant. Higher fertilizer application significantly increased grain and stover yields and stover nitrogen concentration, *in vitro* digestibility and metabolizable energy content. As a result, fertilization resulted in significant increases in the yields of both digestible and metabolizable stover. Landrace cultivars as a group produced higher quality fodder than modern hybrids, but at a significant cost in grain yield. Dual-purpose, open-pollinated cultivars were generally intermediate between the landraces and hybrids, in terms of both stover quality and grain yield, but produced the highest yields of both digestible and metabolizable stover. The paper discusses the implications of these findings for Indian pearl millet farmers with various resource levels and farming objectives.

Keywords: Pearl millet; Stover productivity; Stover nutritional quality; Management effects; Cultivar effects

---

1. Introduction

Pearl millet and sorghum stover provide a crucial fodder resource for ruminant animals in smallholder crop–livestock systems in most of the arid and semi-arid zones of the Indian subcontinent (Kelley and Rao, 1996). This is especially the case where (1) the dry season is too long ($\geq$6 months) for native pasture resources to maintain animals until the next rainy season, and/or (2) an increased population density has drastically reduced the area of fallow/common property land that traditionally provided dry season grazing. Analyses of the availability of feed resources, and specifically of crop residues, indicate a significant shortfall in the arid and semi-arid regions in which sorghum and pearl millet stover provide the major sources of crop residues (Kelley and Rao, 1996). Evidence for this increasing scarcity is provided by increasing straw-to-grain price ratios in several key urban stover markets, which reached 1–3 and less in the case of sorghum and 1–4 in the case of pearl millet by the mid 1990s (Kelley and Rao, 1996). In addition to the inadequate quantities of sorghum and pearl millet stover, the nutritional quality of the residues of both crops is characteristically poor by key criteria such as protein concentration, digestibility and metabolizable energy content (Sundstøl and Owen, 1984).

---

* Corresponding author. Tel.: +91 40 3071 3071.
E-mail address: m.blummel@cgiar.org (M. Blümmel).

0378-4290/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.fcr.2007.05.006

Farmers have two basic options for improving the quantity and fodder quality of stover produced: intensifying both crop and stover management, to increase production and/or feed value of the stover, and choice of specific cultivar or general cultivar type sown, to exploit genetic differences in quantity and/or quality of stover produced (Williams et al., 1997). Crop management alternatives that have been reported to affect stover productivity and quality include fertilization, planting density, timeliness of harvesting, and selective harvesting (see reviews by Bartle and Klopfenstein (1988) and Reddy et al. (2003)). The benefits of such practices need to be quantified in specific crop-livestock production systems, however, as these may vary significantly, and the economic returns, attendant risks and opportunity costs of practices that involve higher capital or labor inputs carefully assessed.

Traditional pearl millet landrace cultivars in typical mixed crop–livestock systems are universally dual-purpose, producing both grain for human use and fodder for maintaining farm animals, reflecting the almost equal importance of food and feed in these systems (Kelley et al., 1996). Although there is a wide choice of new cultivars of both sorghum and pearl millet available in India, many farmers perceive the stover of modem cultivars, bred primarily for a high grain yield, to be inferior to that of their own landraces in both nutritional quality, as well as in yield (Kelley and Parthasarathy Rao, 1994; Kelley et al., 1996). There is published information to indicate that there are significant differences in fodder quality among cultivars of both crops (Hall et al., 2004). This suggests that farmers may have the option to select cultivars with improved stover quality, if they are aware of such differences, and provided that such cultivars meet other system requirements (adaptation, disease resistance, grain quality, grain yield, etc.).

The objectives of the research reported in this paper were to assess the magnitude of the effects of selected crop management and genetic alternatives on both stover productivity and stover quality in pearl millet. This paper reports a first estimate of the relative importance of the major farmer-controlled crop management variables of fertility, plant population, cultivar type and time of harvest on stover productivity and on various measures of stover nutritional quality.

2. Materials and methods

2.1. Management treatments

The experiment was designed as a simple three level factorial combination of fertility level, plant population and cultivar type, repeated for 2 years, to compare the relative importance of each of these effects on stover productivity and quality. The experiment was conducted in both years in a sandy alfisol field (Udic Rhodustalf) in which high and low fertility treatments (blocks within replications) have been maintained for more than 10 years by differential annual fertilizer application. The field was divided into four replications with the long-term fertility treatments randomized with in each replication. Each fertility block was further subdivided at random into two plant population treatments, and the 16 genotypes were assigned at random to each replication × fertifertility block × population block combination. The crop was entirely rainfed in both years, sown on 0.6 m ridges that were made annually. All fertilizer was banded mechanically either into the center of the ridges (pre-plant) or the side of the ridges (side-dressing). Sowing was done with a precision planter modified to sow 4-row plots of 5 m length. Weed control was done by a combination of mechanical cultivation and one hand weeding. There were no significant pest or disease problems in either year.

The high fertility (HF) treatment received 150 kg ha^{-1} of 28–28–0 ($N–P_2O_5–K$) banded into the ridges before sowing and 50 kg ha^{-1} of urea side-dressed at approximately 20 days after emergence (for a total of 65 kg N ha^{-1} and 18 kg P ha^{-1}). The low fertility (LF) treatment received only 75 kg ha^{-1} of 28–28–0 banded into the ridge before planting (for a total of 21 kg N ha^{-1} and 9 kg P ha^{-1}). The HF treatment represented fertilization levels used in research plots and the LF treatment approximated levels used on farmers' fields (where fertilizer is applied at all). Plant population treatments were managed by varying sowing rate and then thinning to the target populations about 15 days after seedling emergence. Because of the common 60 cm row spacing in both population treatments, treatment differences were within-row spacing differences, with consequently different rectangularity. The high population treatment was approximately 11 plants m^{-2} (15 cm between plants = 4:1 rectangularity) and the low population treatment was 5 plants m^{-2} (33 cm between plants = 2:1 rectangularity).

The 16 (determined by the area available in the permanent fertility blocks) cultivars used in the experiment were selected to represent 3 cultivar types: (1) traditional landrace germplasm from the arid/semi-arid pearl millet production zone bordering the Thar desert in NW India/SE Pakistan, (2) improved dual-purpose (grain and stover) open-pollinated varieties incorporating differing amounts of traditional landrace germplasm and (3) commercial, grain-type F1 hybrids, bred for use in the arid/semi-arid zone. The landrace materials and dual-purpose cultivars were mainly selected and/or bred by a collaborative program between ICRISAT, the Rajasthan Agricultural University and the Central Arid Zone Research Institute, targeting the arid zone (Yadav and Weltzien, 1998). The hybrids were bred either by ICRISAT, the Indian Agricultural Research Institute, or the Haryana Agricultural University, and released by the government of India after testing by the All-India Coordinated Pearl Millet Improvement Program for suitability for cultivation in the arid/semi-arid zone.

2.2. Field data collection

Time to flowering was recorded as the time to stigma emergence in 50% of the main shoot panicles in the whole plot. At harvest, 30–35 days after flowering of the longest-duration genotype, panicles with grain were harvested from a bordered 3 m length of the center two rows of each plot, by manually cutting at the base of the panicle. These were counted, oven dried at 70 °C for 3–4 days, weighed and mechanically threshed, and the grain weighed. The data were used to calculate panicle number per unit area, grain yield per unit area and grain yield per panicle. The stover was harvested from the same area by cutting at ground level and tying in a bundle. The fresh weight of the bundle was recorded, a subsample of at least 1 kg was taken and its fresh weight also recorded. In 2000, this subsample was divided into leaf blade and stem (plus leaf sheath) fractions, and these were manually cut into smaller pieces, oven dried and weighed. In 2001, this subsample was mechanically chopped, dried and weighed without dividing into leaf and stem fractions. A second, smaller subsample was taken and divided into leaf and stem (plus sheath) fractions and these were dried, weighed and the data used to estimate percentages of leaf and stem. Subsample fresh and dry weights were used to estimate stover moisture percentage, which was used to calculate stover dry weights per unit area on an oven dry basis. Leaf and stem fractions of the stover were calculated from the appropriate subsamples in each year, also on an oven dry basis. Total biomass per unit area was calculated from stover and panicle weights, and harvest index from the ratio of grain and biomass yields.

2.3. Stover quality analyses

Stover nitrogen concentration (N × 6.25 equals crude protein content), sugar content, percentage *in vitro* digestibility and metabolizable energy content (megajoule per kg) were analyzed for stover quality assessment. These stover quality analyses were done independently on the leaf and stem samples from each plot, and a weighted average (using the stover leaf and stem percentages in the subsamples) calculated to represent the whole stover values. All samples were analyzed by near infrared spectroscopy (NIRS), calibrated for this experiment against conventional wet laboratory analyses. The NIRS instrument used was a FOSS Forage Analyzer 5000 with software package WinISI II. Out of a total of 1024 stover samples, 220 were selected for calibration and validation procedures using the WinISI II samples selection program with a Global H value of 1.3. One hundred and ten samples each were randomly allocated to the development of calibration and validation procedures. Validation procedures were blind-predictions of laboratory measurements by the NIRS equations developed in the calibration procedures. Relationships between blind-predicted and measured variables were described by R^2 and standard error of prediction (SEP). Relationships between laboratory values and NIRS blind-predicted values were $R^2 = 0.99$ (SEP = 0.07) for nitrogen concentration, $R^2 = 0.79$ (SEP = 1.6) for *in vitro* digestibility, $R^2 = 0.93$ (SEP = 0.21) for metabolizable energy content. Sugar content was predicted at a later stage and only 180 samples were available for the calibration and validation procedures. The relationship between laboratory sugar values and NIRS blind-predicted values was $R^2 = 0.85$ (SEP = 0.49).

Laboratory analyses for the calibration and validation of the NIRS were done as follows. Nitrogen (N) was determined (Technicon Auto Analyzer) in duplicate samples and corrected for percentage dry matter (DM). For analysis of *in vitro* digestibility and metabolizable energy content, rumen inoculum for the *in vitro* incubations was obtained from two rumen cannulated steers (local Indian breed) maintained on stover supplemented with concentrate. Briefly, a mixture of rumen fluid and particulate matter (approximately 60:40) was collected into CO_2-filled thermos bottles, transferred to and homogenized in a household blender, strained and filtered through glass wool. All handling of rumen inoculum was carried out under continuous flushing of CO_2. Portions of about 200 mg air-dry stover sample were accurately weighed (in duplicate) into 100 ml calibrated glass syringes (Menke and Steingass, 1988) that were incubated according to the procedure of Blümmel and Ørskov (1993). A total of 30 ml of medium consisting of 10 ml of rumen inoculum and 20 ml of bicarbonate–mineral–distilled water mixture was injected into the syringes. Three blanks containing 30 ml of medium only were included at the beginning and at the end of the incubation syringes. *In vitro* gas production measurements were conducted in N supplemented incubation medium containing ammonium bicarbonate. *In vitro* digestibility was calculated based on gas volumes produced after 24 h of incubation following Menke and Steingass (1988) as: 15.38 + (0.8453 × ml of gas produced after 24 h per 200 mg sample) + (0.595 × % crude protein on a dry matter basis) + (0.181 × % ash on a dry matter basis). Metabolizable energy content was calculated following Menke and Steingass (1988) as: 2.2 + (0.136 × ml of gas produced after 24 h per 200 mg sample) + (0.0057 × crude protein (g kg^{-1})).

2.4. Statistical analyses

Field and laboratory results were analyzed according the field design, using the GLM procedure of SAS. In the analysis, replicate was considered as nested within year and the replicate (year) MS used as an error term for testing the significance of the year MS (1 and 6 d.f.). Fertility level was considered as the main plot of a split-split–split-plot design; the MS for fertility and year × fertility were tested against the fertility × replica-replication (year) MS (1 and 6 d.f.). Plant population was considered as the sub-plot; the population, population × year and population × fertility MS were tested against the combined replication (year) × population and replication (year) × population × fertility MS (1 and 12 d.f.). Genotype was considered as the sub-sub plot, with genotype sums of squares partitioned into an effect of cultivar type (2 d.f.) and genotype within cultivar type (13 d.f.). MS for cultivar type (and genotype) and their interactions with year, fertility and plant population were tested against the residual MS (360 d.f.). Standard errors for means of each factor were calculated from the square root of the actual error term used for testing the significance of that factor.

There was a strong positive effect of genotype time to flowering on several of the stover quality variables (later flowering = higher quality), which was possibly a proxy for the effects of variation in the time between genotype physiological maturity and harvest, as all genotypes were harvested at the same time, regardless of their time to flowering/maturity. The delay between estimated physiological maturity (flowering + 25 days) and actual harvest was calculated for all plots and G, G × E and residual variance components estimated with and without delay as a source of variation in the variance components model, using GENSTAT REML analysis, with delay as a fixed variable and all other sources of variation as random variables. Changes in genetic variances for individual traits, when delay was included as a source of variation, were interpreted as an effect of delay in harvest on the measured trait.

3. Results and discussion

3.1. Year and management effects on crop growth and productivity

Mean time to flowering (data not presented) and mean total biomass yield did not differ between years, but panicle number per plant, grain yield and stover yield did (Table 1). Mean grain yields were 42% lower, and mean stover yields 27% higher in 2000 than in 2001 (Table 2), due to major differences in harvest index in the 2 years (26.5% versus 41.4%). The apparent cause of the year effect was the difference in productive tiller numbers (2.0 panicles plant^{-1} versus 3.2 panicles plant^{-1}; Table 2), rather than in plant numbers (7.3 plants m^{-2} versus 7.7 plants m^{-2}), or in individual panicle productivity (11.9 g grain panicle^{-1} versus 13.2 g grain panicle^{-1}) in the 2 years (data not presented). It was likely that early growth conditions were more favorable in 2001 than in 2000, resulting in a greater number of tillers reaching flowering, a greater potential sink size, and consequently a greater fraction of the total biomass partitioned to grain.

Fertility level, as expected, affected all productivity variables measured (Table 1). Total biomass was 50% higher in the high fertility (HF) treatment, and grain and stover yields were, respectively, 56 and 47% higher (Table 2). The higher grain yields in the HF treatment were due mainly to the greater numbers of productive tillers (3.0 panicles plant^{-1} versus 2.2 panicles plant^{-1}; Table 2), rather than to differences in grain yield per panicle (13.1 g grain panicle^{-1} versus 12.0 g grain panicle^{-1}). Greater stover yields in the HF treatment were also a consequence of the greater productive tiller numbers in this treatment as stover mass per tiller was similar in both treatments (18.0 g stover shoot^{-1} versus 17.4 g stover shoot^{-1}, data not presented). Fertility × year interactions were significant for most yield variables (Table 1).

In contrast to the major effect of fertility on productivity, plant population had no significant effects on any of the productivity variables, apart from panicle number plant^{-1} (Table 1), despite the large differences in actual plant numbers (10.3 plants m^{-2} versus 4.7 plants m^{-2}). Productive tiller number plant^{-1} was significantly greater in the low population (LP) than in the high population (HP) treatment (3.52 versus 1.72). The LP treatment largely compensated in productive tiller numbers for reduced plant numbers (16.4 panicles m^{-2} versus 18.0 panicles m^{-2} in the LP and HP treatments, respectively; data not presented). This difference in productive tillers m^{-2} was still significant ($P < 0.003$), but a secondary difference in panicle productivity between the LP and HP treatments (13.5 g grain panicle^{-1} versus 11.6 g grain panicle^{-1}, $P < 0.0001$), resulted in a complete compensation in grain yield in the LP treatment (Tables 1 and 2). Population × year and population × fertility interactions were not significant for any variables apart from panicles plant^{-1}.

The observed effects of year, fertility and plant population treatments on crop productivity in this experiment were largely predictable. In each case, one of the alternatives (2001, HF and LP) was more favorable than the other (2000, LF and HP) for initial crop growth, which resulted in a greater rate of tiller survival/growth/productivity. This is the main mechanism of adjustment to varying environmental resources in this crop

Table 1
Analysis of variance for effects of year and management alternatives on pearl millet agronomic traits and stover dry matter (DM), digestible dry matter (DDM) and metabolizable energy (ME) yields

Source of variation	d.f.	Panicles plant^{-1}	Biomass yield (g m^{-2})	Grain yield (g m^{-2})	Stover yield (m^{-2})		
					DM yield (g)	DDM yield (g)	ME yield (MJ)
Year	1	****	NS	****	*	*	**
Fertility	1	****	****	****	****	****	***
Fertility × year	1	NS	*	*	**	**	*
Population	1	****	NS	NS	NS	*	**
Popln × year	1	****	NS	NS	NS	NS	NS
Popln × fertility	1	***	NS	NS	NS	NS	NS
Cultivar type	2	****	****	****	**	***	****
Cult × year	2	****	****	****	****	****	****
Cult × fertility	2	*	*	****	NS	NS	NS
Cult × population	2	****	*	*	NS	NS	NS
CV (%)		17.2	14.2	16.3	17.9	18.5	26.0

Data are probability levels for the ratio of the effect mean square to the appropriate error mean square.
NS $P > 0.05$.
* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
**** $P < 0.0001$.

Table 2
Main effect least square means and standard errors (S.E.) for the effects of year and management alternatives on pearl millet agronomic traits and stover dry matter (DM), digestible dry matter (DDM) and metabolizable (ME) yields

Effect	Panicles plant^{-1}	Biomass yield (g m^{-2})	Grain yield (g m^{-2})	Stover yield (m^{-2})		
				DM yield (g)	DDM yield (g)	ME yield (MJ)
2000	1.99	545	147	342	129	1.67
2001	3.24	608	255	269	107	1.48
S.E.	±0.034	±24.6	±8.1	±16.9	±6.8	±0.029
High fertility	3.02	692	245	364	142	1.81
Low fertility	2.20	461	157	247	103	1.34
S.E.	±0.038	±10.5	±2.9	±7.0	±2.5	±0.042
High population	1.72	581	196	313	125	1.64
Low population	3.52	572	206	298	120	1.51
S.E.	±0.059	±10.9	±4.4	±6.1	±2.5	±0.029
Landraces	2.66	510	147	303	124	1.59
Dual-purpose OPVs	2.38	597	210	314	126	1.66
Hybrids	2.81	662	247	300	118	1.47
S.E.	±0.046	±8.3	±3.3	±5.6	±2.3	±0.032
Trial mean	2.6	575	201	304	122	1.58

(Bidinger and Raju, 2000; Carberry et al., 1985). The outcome of increased early tiller growth differed among the comparisons. Under high fertility the early growth advantage persisted throughout the season, as the advantage of a higher soil nutrient level continued throughout the season, leading to higher biomass, grain and stover yields. In the low population treatment the greater (per plant) tiller numbers and tiller growth led to a full compensation for the differences in plant numbers in biomass, grain and stover yields, as the initial advantage of extra radiation per plant in the LP treatment declined as the canopy closed by flowering. In 2001, the apparent early advantage persisted in terms of a greater productive panicle number and grain yield, but not in terms of either total biomass or stover yield. The difference appears to have been in the greater number of tillers that were able to continue development through to flowering and grain yield in 2001, where fewer succeeded in 2000, which resulted in a lower grain yield but a higher stover yield in this year (non-productive tillers were included in the stover fraction at harvest). Year thus differed from fertility and plant population, as the differences between grain and stover yields were opposite for the 2 years, where they were consistent for both the fertility and plant population treatments.

The choice of cultivar type had a highly significant effect on all crop productivity variables (Table 1). The landrace-type cultivars produced the least biomass (Table 2), which was likely a reflection of, first, their lack of adaptation to the environment of peninsular India (these landraces originated in the more arid north-west of the country), and secondly, a lower partitioning of biomass (HI of 28.5%) to grain than the other two cultivar types (HI $>$ 35%), as the landrace-type cultivars had not been selected specifically for grain yield. The dual-purpose, open-pollinated variety cultivars, with better levels of adaptation to the environmental conditions of the experiment and a history of selection for both grain and stover yields, produced significantly greater biomass and grain yields than the landrace-type cultivars, but had similar stover yields (Table 2). For the grain-type hybrid cultivars, the combination of heterosis (which increased total biomass) and a history of selection for a greater partitioning of biomass to grain (HI of 38.8% for the hybrids versus 34.5% for the dual-purpose varieties) resulted in the hybrid cultivar type producing the greatest grain yields without significant costs in stover yields (Table 2). Cultivar type × year interactions were also significant for all productivity variables, and both cultivar type × fertility and cultivar type × plant population interactions were significant for biomass and grain yields (Table 1). To maximize productivity, cultivar choice should therefore focus first on adaptation—the ability to produce biomass in the target environment. Within this requirement, the partitioning of the biomass between grain and stover – harvest index – can be selected to meet the farmers' relative requirements for grain and for stover. The advantage of heterosis in hybrid cultivars, however, is that it allows farmers to maximize grain yield without necessarily sacrificing stover yield (Bidinger et al., 2003).

3.2. *Year and management effects on stover quality*

The 2 years differed in the leaf percentage and digestibility percentage of the stover but not in stover nitrogen percentage, sugar percentage or ME content (Table 3). The leaf percentage of the stover was considerably higher in 2000 than in 2001 (39.8% versus 25.3%; Table 4). This is consistent with the lower fraction of tillers that reached a productive stage in 2000, as non-productive tillers were generally included as a part of the "leaf" fraction, as they had little or no stem tissue. This procedure did result in the leaf sheaths of the non-productive tillers being considered leaf, where the sheaths were grouped with the stem fraction in the case of the productive tillers. As leaf tissue was generally more digestible than stem tissue (42.4% for the leaf versus 40.3% for the stem), the total stover harvested in 2000 had a significantly greater digestibility

Table 3
Analysis of variance for effects of year and management alternatives on measured pearl millet stover quality traits

Source of variation	d.f.	Leaf percentage	Nitrogen percentage	Digestability percentage	Soluble sugars percentage	ME content (MJ kg^{-1})
Year	1	**	NS	***	NS	NS
Fertility	1	NS	****	****	*	***
Fertility × year	1	**	NS	NS	NS	*
Population	1	NS	****	**	NS	NS
Popln × year	1	NS	NS	NS	NS	NS
Popln × fertility	1	NS	NS	NS	NS	NS
Cultivar type	2	**	NS	****	****	****
Cult × year	2	NS	NS	NS	NS	NS
Cult × fertility	2	NS	*	*	NS	*
Cult × population	2	NS	NS	NS	NS	NS
CV (%)		16.3	13.9	3.1	20.2	5.72

Data are probability levels for the ratio of the effect mean square to the appropriate error mean square.

NS $P > 0.05$.

* $P < 0.05$.

** $P < 0.01$.

*** $P < 0.001$.

**** $P < 0.0001$.

(42.2% versus 40.0%) than the stover of the 2001 harvest (Table 4). Sugar concentration and ME content were unaffected by the differences in leaf percentage between the 2 years, however, presumably because these were more dependant upon stem tissue than leaf tissue.

Fertility had a highly significant effect on all observed stover quality parameters apart from leaf percentage (Table 3). Stover N concentration was markedly higher in the HF treatment, as expected (0.98% versus 0.68%), but digestibility (39.8% versus 42.3%), sugar concentration (3.2% versus 3.5%) and ME content (5.3 MJ kg^{-1} versus 5.7 MJ kg^{-1}) were all lower in the HF than in the LF treatment (Table 4). The fact that fertility affected three estimates of stover quality suggests that the fertility effect on quality was real. Year × fertility effects were not significant for any of the stover quality measures, apart from leaf percentage and ME content (Table 3). In the HF treatment mean grain yield was 56% higher than in the LF treatment (Table 2), which suggests a more complete translocation of soluble nutrients from stems and leaves to grain in the HF treatment resulting in lower stover sugar concentration, *in vitro* digestibility and metabolizable energy content in HF compared to LF treatment (Table 4).

Plant population affected stover N concentration and stover digestibility, but not sugar concentration or ME content (Table 3). Stover of the LP treatment had a higher N concentration (0.886% versus 0.794%) and a higher stover digestibility (41.3% versus 40.8%) than that of the HP treatment (Table 4). These differences between plant population treatments in stover digestibility, but not in sugar concentration or ME content, were generally similar to the year differences, but in the case of plant population, were

Table 4
Main effect least square means and standard errors (S.E.) for the effects of year and management alternatives on pearl stover quality variables

Effect	Leaf percentage	Nitrogen percentage	Digestibility percentage	Soluble sugar percentage	ME content (MJ kg^{-1})
Year 2000	38.9	0.887	42.2	3.34	5.50
Year 2001	25.3	0.782	40.0	3.34	5.56
S.E.	±1.80	±0.0438	±0.24	±1.192	±0.081
High fertility	32.7	0.980	39.8	3.17	5.34
Low fertility	31.4	0.679	42.3	3.51	5.72
S.E.	±0.55	±0.0128	±0.018	±0.082	±0.032
High population	31.9	0.794	40.8	3.28	5.50
Low population	32.2	0.866	41.3	3.41	5.56
S.E.	±0.26	±0.0178	±0.12	±0.051	±0.024
Landraces	30.9	0.824	41.5	3.66	5.66
Dual-purpose OPVs	32.6	0.822	41.2	3.43	5.58
Hybrids	32.7	0.844	40.5	2.93	5.36
S.E.	±0.50	±0.0118	±0.13	±0.109	±0.025
Trial mean	32.2	0.829	41.1	3.35	5.53

accompanied by parallel differences in N concentration of the stover, which was not the case between years. There were no significant interactions of plant population and year or fertility treatment on any of the measured stover quality variables (Table 3).

The fertility and population treatments and the 2 years thus present contrasting pictures in terms of the relationships or consistency of the various stover quality measures. This is most easily seen in the case of the treatment (or year) with the highest digestibility in each of the three paired comparisons (Table 4). Stover from the LF treatment had a higher digestibility, sugar concentration and ME content than that from the HF treatment, but a lower N concentration. Similarly, stover from the LP treatment also had the higher digestibility in the population treatment comparison, but there was no difference in sugar concentration or ME content, and a higher, rather than a lower, N concentration. Stover from the year 2000 had a higher digestibility than that from the year 2001 in the year comparison, and no differences in sugar concentration or ME content (similar to the pattern of the LP treatment). However, in this comparison stover from 2000 had a similar N concentration to that produced in 2001. Higher stover digestibility in 2000 was also associated with a higher leaf fraction, which was not the case in either the fertility or the plant population treatment comparisons).

Choice of cultivar type significantly affected leaf percentage, digestibility, sugar concentration and ME content, but not N concentration (Table 3). Stover from the landraces had a lower leaf percentage, but a higher sugar concentration and ME content than that of either the dual-purpose varieties or the hybrids, and a higher stover digestibility than that of the hybrids (Table 4). Stover from the dual-purpose varieties had a similar leaf percentage as that of the hybrids, but a higher digestibility, sugar concentration and ME content (Table 4). The general ranking of quality among the three cultivar types is thus the inverse of their ranking for grain yield (Table 2). Apparently greater partitioning of dry matter to the grain in the hybrids (and to a lesser extent in the dual-purpose varieties), results in a reduction in the concentration of more highly digestible materials (e.g. sugars) remaining in the stem, and thus the lower the digestibility and the ME content of the stover. These differences are consistent with reports that arid zone farmers consider their own pearl millet landraces have better stover quality that the available hybrids (Kelley and Parthasarathy Rao, 1994; Kelley et al., 1996). There were no significant interactions of either cultivar type and year or cultivar type and plant population for any of the stover quality measures, but there were significant cultivar type × fertility interactions for nitrogen concentration, digestibility and ME content (Table 3). The comparison of individual genotype effects is presented in the second paper of this series.

3.3. *Year and management effects on stover nutrient yields*

The most important management factors in terms of animal production are those that affect the overall yields of digestible dry matter (DDM) and ME per unit area, as it is these that will have the greatest impact on maintenance of animal weight during the dry season, especially for farmers with limited land areas from which to produce fodder to feed their animals. The 2 years differed in both DDM and ME yields (Table 1). DDM yield in 2000 exceeded that in 2001 by 17% (129 g m^{-2} versus 107 g m^{-2}) and ME yield in 2000 exceeded that in 2001 by 13% (1.67 MJ m^{-2} versus 1.48 MJ m^{-2}; Table 2). The largest factor was the difference in stover yield (342 g m^{-2} versus 269 g m^{-2}) in the 2 years, but digestibility (42.2% versus 40.0%), if not ME content, was also higher in 2000 than in 2001 (Table 3). Similarly, the HF treatment produced a significantly greater stover DDM (142 g m^{-2} versus 103 g m^{-2}) and ME (1.81 MJ m^{-2} versus 1.34 MJ m^{-2}) yields than the LF treatment (Tables 1 and 2). In the case of the fertility treatments, however, the effect was due entirely to the greater stover productivity in the HF treatment, as both digestibility and ME content were greater in the LF than in the HF treatment (Tables 2 and 4). There were also significant interactions of year and fertility for both stover DDM and stover ME yields (Table 1). Plant population had smaller effects on both stover DDM and ME yields than did fertility, but the differences in DDM and ME yields between HP (125 g m^{-2} and 1.64 MJ m^{-2}) and LP (120 g m^{-2} and 1.51 MJ m^{-2}) treatments were significant. The lack of a large population effect (compared to the effects of year and fertility) on either DDM or ME yield was primarily because plant population had no significant effect on stover yield itself (Table 1). There were no significant interactions between plant population and either year or fertility (Tables 1 and 2) for either DDM or ME yield.

There were significant differences among cultivar types for stover DDM and ME yields, and interactions of cultivar type and year for both DDM and ME yields (Table 1). The hybrids produced slightly less stover DDM than either the landraces or the dual-purpose varieties (118 g m^{-2} versus an average of 125 g m^{-2}), due to both their lower stover yield and lower stover digestibility (Table 2). The hybrids also produced a lower stover ME yield (1.47 MJ m^{-2}) than both the dual-purpose varieties (1.66 MJ m^{-2}) and the landraces (1.59 MJ m^{-2}), also due to their lower total stover yield (Table 2). In both cases however, the differences for these variables were not large in percentage terms (about 10%) and the lower stover DDM and ME yields of the hybrids would have been more than offset for most farmers by their higher grain production (Table 2), at least in the favorable peninsular India test environments used in this study. Therefore, at least among the cultivar types and range of production environments used in this experiment, there were no major advantages in terms of either stover DDM or stover ME yields to the selection of dual-purpose cultivars or landraces over the hybrid cultivars, despite the differences among cultivar types in digestibility and ME content (Table 4). There were, however, significant cultivar type × year interactions for both stover DDM and ME yields (Table 1), suggesting that this conclusion may need to be considered in terms of specific environments.

3.4. *Effects of delay in harvest and stover quality*

There were a number of significant correlations between time to flowering and stover productivity and quality measures among genotypes (data not presented). Some of these were intuitive, such as the relationship between later flowering and higher biomass ($r = 0.52$, $P < 0.05$) and stover ($r = 0.84$, $P < 0.001$) yields. However, stover of later flowering genotypes had a higher leaf percentage ($r = 0.59$, $P < 0.05$), which would not be expected as greater biomass would normally be associated with greater stem mass (Craufurd and Bidinger, 1988). Also, later flowering cultivars had higher digestibility ($r = 0.74$, $P < 0.001$) and sugar concentration ($r = 0.73$, $P < 0.002$), for which the reasons were not obvious. As harvesting of all genotypes was done at the same time, earlier-flowering genotypes would have stood in the field for a longer time after physiological maturity than would have later-flowering ones, and may have been more subjected to both weathering and/or lignification of cell walls (Zerbini and Thomas, 2003). Therefore, some of the apparent relationships of flowering and stover quality (such as leaf percentage or digestibility) might be an artifact of the variation in delay between physiological maturity and harvest among individual genotypes. Although it is not possible to unequivocally distinguish the effects of time to flowering and delay in harvest (as the two are perfectly correlated), an attempt was made to assess the magnitude of the possible effect of delay in harvest on stover quality by estimating the G and G × E components of variance for various stover quality measures with and without the delay in harvest as a source of variation in the variance components model.

Delay in harvest was a significant source of variation for leaf percentage and nitrogen concentration in pearl millet stover, borderline for stover digestibility, but not significant for either sugar concentration or ME content (Table 5). The consequence of including delay in harvest in the variance components model was a massive decrease ($\geq$80%) in the magnitude of genetic variance for the two most affected variables (leaf percentage and N concentration; Table 5). Effects of delay in harvest on genetic variances for the other stover quality variables were mixed, ranging from a reduction of 20% for digestibility to an increase of 18% for sugar content (Table 5). Inclusion of delay as a source of variation in the variance components model also reduced G × E variance estimates for leaf percentage (−42%), sugar concentration (−86%) and ME content (−85%), but increased G × E for digestibility (+38%). The very large negative effect of removing differences in delay in harvest on genetic variance for stover leaf percentage suggested that the delay in harvest was likely associated with a loss in leaf tissue due the effects of weathering and/or late-onset foliar disease. Loss of leaf tissue would also have resulted in significant loss of stover N, as the N concentration of the leaves is considerably higher than that of the stems (1.65% versus 0.43%, data not presented). The negative effect of eliminating the delay in harvest on genetic variance for digestibility may or may not have been primarily due to the loss of the more digestible leaf fraction, as progressive lignification of both leaf and stem tissue in the earlier-flowering genotypes could also have increased genetic variance for digestibility, where genotypes had unequal time between maturity and harvest (see review by Zerbini and Thomas, 2003).

If the delay hypothesis is correct, farmers' ability to maximize stover nitrogen (i.e. protein) concentration and to a lesser degree, digestibility, will depend another factor—timely harvesting. Alternatively, if the positive relationship of quality and flowering time is real (i.e. not an artifact of differential delay in harvest), then stover quality in early-maturing genotypes may be inherently lower than that in later-maturing ones. This implies that stover DDM and ME yields will be even more limited in such genotypes, as stover dry matter yield is also largely controlled by crop duration. Unfortunately, early-maturing genotypes are typically a requirement for arid zone production environments with short rainy seasons, in which animal production is often the main economic activity and pearl millet stover an essential dry season feed. Current research is examining ways to improve stover quantity in such

Table 5

Evaluation of the effects of including the delay between physiological maturity and the time of harvest as a fixed effect in the components of variance model for pearl millet stover quality traits

	Leaf percentage	Nitrogen percentage	Digestibility percentage	Sugar percentage	ME content (MJ kg^{-1})
Significance of delay effect					
Wald statistic	7.18	6.61	3.07	0.28	1.30
χ^2 probability	0.007	0.01	0.08	0.60	0.26
Genotype variance G[a]					
Without delay in model	0.148	1.56	1.224	0.256	0.0444
With delay in model	0.030	0.21	0.984	0.301	0.0389
Fractional change in G	−0.80	−0.86	−0.20	+0.18	−0.04
G × E variance[a]					
Without delay in model	0.500	1.24	0.980	0.0655	0.0129
With delay in model	0.292	1.26	1.354	0.0094	0.0019
Fractional change in G × E	−0.42	+0.02	+0.38	−0.86	−0.85
Residual variance[a]					
Without delay in model	3.82	20.0	1.92	0.623	0.129
With delay in model	3.83	20.3	1.93	0.585	0.121

Variance component (σ^2), estimates were based on the following model $\sigma^2_{\mathrm{g}} + \sigma^2_{\mathrm{gy}}/\mathrm{y} + \sigma^2_{\mathrm{gf}}/\mathrm{f} + \sigma^2_{\mathrm{gp}}/\mathrm{p} + \sigma^2_{\mathrm{gyf}}/\mathrm{yf} + \sigma^2_{\mathrm{gyp}}/\mathrm{yp} + \sigma^2_{\mathrm{gfp}}/\mathrm{fp} + \sigma^2_{\mathrm{gyfp}}/\mathrm{yfp} + \sigma^2_{\mathrm{E}}/\mathrm{ryfp}$, where g, y, f, p, E and r refer to genotype, year, fertility level, plant population, error and replication, respectively.

[a] Variance values presented for leaf percentage and nitrogen percentage are actual variances $\times 10^{-3}$.

environments (Bidinger et al., 2003; Hash et al., 2003). Improvement in stover quality will also have major benefits for small farmers in other pearl millet production environments.

4. Conclusions

The most significant management option available to farmers for increasing pearl millet stover DDM yield and stover ME yield is adequate fertilization. Although higher fertilizer application had small, but significant, negative effects on stover digestibility, sugar concentration and metabolizable energy content, these were more than offset by large increases in total stover dry matter production. Higher fertility also had a major positive effect on stover nitrogen concentration. This latter would likely have a significant effect on voluntary feed intake by ruminant livestock, especially where stover is fed without supplementation with either a concentrate or a higher N legume straw, as N levels in the stover from the LF treatment ($<0.7\%$) are well below those required by rumen microbes (Van Soest, 1994). The economic returns to fertilizer application on pearl millet in arid and semi-arid zone areas are often modest, or even negative in poor years, because of the overwhelming influence of soil moisture on grain and stover yields. However, the improvement in both quantity and quality of stover with fertilization (in addition to the expected improvement in grain yield in seasons with adequate rainfall) should add weight to the economic benefits of fertilization, particularly for farmers whose income is more dependant to the sale of animal products than on the sale of grain. The favorable (and increasing) stover to grain price ratios for pearl millet in urban markets (Kelley and Rao, 1996), also suggests that the opportunity for direct cash sales of surplus stover can also fund the greater use of fertilizers on pearl millet for some farmers.

Increasing plant population, in contrast, had little effect on DDM and ME yields, despite a 2-fold difference in plant numbers, at least under the conditions of this experiment, in which the LP treatment still produced the same biomass and stover yields as the HP treatment. Stover from the lower plant population treatment did have slightly numerically higher values for almost all stover quality traits, but differences were only significant for N concentration and digestibility. As in the case of the fertility comparison, differences in stover quality values were offset by differences in productivity, and stover DDM and ME yields were actually marginally higher in the HP treatment. As changes in plant population are virtually a no-cost management option (in comparison to fertilization), it is unfortunate that there appears to be little potential for improving pearl millet stover quality via this route.

Choice of cultivar type was complicated in this experiment by tradeoffs between grain and stover yields in the hybrid and dual-purpose cultivar types, and by the lack of adaptation of the arid zone landrace cultivars to the environment in which the experiment was conducted. The dual-purpose cultivars (and the landraces) had significantly higher stover digestibility, sugar contents and ME contents than did the hybrids, but this was at the cost of significantly lower grain yield. Since most pearl millet farmers depend upon both grain (for food) as well as stover from their pearl millet crop, growing a dual-purpose variety for reasons of increased stover yield/quality, but at the cost of a lower grain yield, may be problematic. This is certainly questionable for farmers who have the environmental resources to exploit significant differences in potential grain yield between cultivar types. However, dual-purpose varieties may be reasonable for farmers in more marginal areas in which on-farm grain yields are not likely to differ between dual-purpose varieties and hybrids, or in arid areas in which presently available hybrids are not as well adapted to severe stress as are local landraces, and therefore have no overall grain yield advantage (Khairwal and Yadav, 2005).

Finally, the experiment produced a suggestion that timely harvest of the pearl millet crop (soon after physiological maturity) may enhance at least stover leaf percentage and nitrogen concentration, and possibly stover digestibility as well. Early harvest is more difficult in more humid environments, especially with early-maturing cultivars, as few if any farmers have the ability to dry panicles/grain once these are harvested, and most prefer to harvest only when the grain is sufficiently field dry to thresh and store. Timely harvest, however, is a common practice in more arid areas, where drying is less of a problem, and where farmers appear to recognize the value of retaining as much leaf material as possible in the stover.

References

Bartle, S.J., Klopfenstein, T.J., 1988. Nonchemical alternatives for improving crop residue feed quality: a review. J. Prod. Agric. 1, 356–362.

Bidinger, F.R., Raju, D.S., 2000. Mechanisms of adjustment by different pearl millet plant types to varying plant population densities. J. Agric. Sci. (Camb.) 134, 181–189.

Bidinger, F.R., Yadav, O.P., Sharma, M.M., van Oosterom, E.J., Yadav, Y.P., 2003. Exploitation of heterosis for simultaneous improvement in both grain and stover yields of arid zone pearl millet (*Pennisetum glaucum* (L.) R. Br.). Field Crops Res. 83, 13–26.

Blümmel, M., Ørskov, E.R., 1993. Comparison of *in vitro* gas production and nylon bag degradability of roughages in predicting feed intake in cattle. Anim. Feed Sci. Technol. 40, 109–119.

Carberry, P.S., Campbell, L.C., Bidinger, F.R., 1985. The growth of pearl millet as affected by plant population. Field Crops Res. 11, 193–205.

Craufurd, P.Q., Bidinger, F.R., 1988. Effect of duration of the vegetative phase on shoot growth, development and yield in pearl millet (*Pennisetum americanum* (L.) Leeke). J. Exp. Bot. 39, 124–139.

Hall, A., Blümmel, M., Thorpe, W.I., Bidinger, F.R., Hash, C.T., 2004. Sorghum and pearl millet as food-feed-crops in India. Anim. Nutr. Feed Technol. 4, 1–15.

Hash, C.T., Bhasker Raj, A.G., Lindup, S., Sharma, A., Beniwal, C.R., Folkertsma, R.T., Mahalakshmi, V., Zerbini, E., Blümmel, M., 2003. Opportunities for marker-assisted selection (MAS) to improve the feed quality of crop residues in pearl millet and sorghum. Field Crops Res. 84, 79–88.

Kelley, T.G., Parthasarathy Rao, P., 1994. Yield and quality characteristics of improved and traditional sorghum cultivars: farmers' perceptions and preferences. In: Joshi, A.L., Doyle, P.T., Oosting, S.J. (Eds.), Variation in the Quantity and Quality of Fibrous Crop Residues. Proceedings of a National Seminar held at the BAIF Development Research Foundation, Pune, India. Indo-Dutch Project on Bioconversion of Crop Residues, Pune, India, pp. 133–145.

Kelley, T.G., Parthasarathy Rao, P., Weltzien R., E., Purohit, M.L., 1996. Adoption of pearl millet cultivars in an arid environment: straw yield and quality considerations in western Rajasthan. Exp. Agric. 32, 161–172.

Kelley, T.G., 1996. Availability and requirement of different sources of livestock feed in India with special reference to sorghum and millet straw. In:

Global Agenda for Livestock Research, Proceedings of the Consultation for the South Asia Region, 8–6 June 1995, ICRISAT Asia Center, Patancheru, International Livestock Research Institute, Nairobi, Kenya, pp. 53–65.

Khairwal, I.S., Yadav, O.P., 2005. Pearl millet improvement in India—retrospect and prospects. Indian J. Agric. Sci. 75, 183–191.

Menke, K.H., Steingass, H., 1988. Estimation of the energy feed value obtained from chemical analysis and *in vitro* gas production using rumen fluid. Anim. Res. Dev. 28, 7–55.

Reddy, B.V.S., Sanjana Reddy, P., Bidinger, F., Blümmel, M., 2003. Crop management factors influencing yield and quality of crop residues. Field Crops Res. 84, 57–77.

Sundstøl, F., Owen, E. (Eds.), 1984. Straw and Other Fibrous By-products as Feed. Elsevier, Amsterdam.

Van Soest, P.J., 1994. Nutritional Ecology of the Ruminant, second ed. Cornell University Press, Ithaca, New York.

Williams, T.O., Fernandez-Rivera, S., Kelley, T.J., 1997. The influence of social-economic factors on the availability and utilization of crop residues as animal feeds. In: Renard, C. (Ed.), Crop Residues in Sustainable Mixed Crop/Livestock Farming Systems. CAB International, Wallingford, UK, pp. 25–40.

Yadav, O.P., Weltzien, E., 1998. New pearl millet populations for Rajasthan, India. Integrated Systems Project Report Series No. 10. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India, 88 pp.

Zerbini, E., Thomas, D., 2003. Opportunities for improvement of nutritive value in sorghum and pearl millet residues in South Asia through genetic enhancement. Field Crops Res. 84, 3–15.