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REGULAR ARTICLE

Productivity and residual benefits of grain legumes to sorghum under semi-arid conditions in southwestern Zimbabwe

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Abstract The productivity and residual benefits of four grain legumes to sorghum (*Sorghum bicolor*) grown in rotation were measured under semi-arid conditions over three cropping seasons. Two varieties of each of the grain legumes; cowpea (*Vigna unguiculata*); groundnut (*Arachis hypogaea*); pigeon pea (*Cajanus cajan*); Bambara groundnut (*Vigna subterranea*), and sorghum were grown during the first season. The same experiment was implemented three times in different, but adjacent fields that had similar soil types. At the end of the season the original plots were split in two and residues were either removed or incorporated into the subplots. The following season sorghum was planted in all subplots. In 2002/03 (314 mm rainfall) cowpeas produced the largest dry grain yield (0.98 and 1.36 t ha^{-1}) among the legumes. During the wettest year (2003/04, 650 mm rainfall) groundnut had the highest yields (0.76 to 1.02 t ha^{-1}). In 2004/05 (301 mm rainfall) most legume yields were less than 0.5 t ha^{-1}, except for pigeon pea. Estimates of % N from N_2-fixation from the legumes were 15–50% (2002/03), 16–61% (2003/04) and 29–83% (2004/05). Soil water changes during the legume growth cycle were proportional to varietal differences in total legume biomass. Sorghum grain yield after legumes reached up to 1.62 t ha^{-1} in 2003/04 compared with 0.42 t ha^{-1} when following sorghum. In 2004/05, sorghum yields after legumes were also higher (up to 1.26 t ha^{-1}) than sorghum after sorghum. Incorporation of crop residues had no significant effect on sorghum yield. Beneficial effect of legumes on yields of the subsequent sorghum crop were more readily explained by improvements in soil nitrogen supply than by the small observed changes in soil water relations. Our results demonstrate clear potential benefits for increasing grain legume cultivation in semi-arid environments through the use of improved germplasm, which also gave substantial increases in subsequent sorghum productivity (up 200% in a wet season and 30–100% in a dry season), compared with an unfertilized sorghum crop following sorghum.

Keywords Cereal · Crop rotation · Food security · Nitrogen fixation · Residues · Soil water

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Introduction

In many semi-arid regions of sub-Saharan Africa farmers typically use monocultures of cereal crops such as sorghum (*Sorghum bicolor* (L.) Moench) and pearl millet (*Pennisetum glaucum* (L.) R.Br.), while use of intercropping and sound crop rotations is either erratic or infrequent. Continuous crop cultivation with a lack of fallows and limited input use has greatly decreased inherent soil fertility which is a fundamental impediment to agricultural growth and food production. Fertilizers tend to be expensive, unavailable and unaffordable for the predominant smallholder farmers in such regions of sub-Saharan Africa (Buresh and Giller 1998). Legumes provide these farmers with an important alternative to diversify their farming systems and improve soil fertility via symbiotic N_2-fixation. Legumes also represent an important source of protein and supplemental income (Mapfumo and Giller 2001).

Sorghum and pearl millet are the main small grain cereals in the crop production system of the drier areas of semi-arid southern Africa, including Zimbabwe. Although yields of well-managed crops may range from 1.7 to 4.8 t ha^{-1}, the average yields of sorghum and pearl millet in Zimbabwe are currently 0.6 t ha^{-1} or less (Ahmed et al. 1997; Rohrbach et al. 2005). There is a critical need to increase productivity to improve local food security. Currently legumes play a minor role in the cropping systems of the semi-arid environments (Ahmed et al. 1997) and they receive less than 5% of the soil fertility inputs (Mapfumo and Giller 2001). A better understanding of the opportunities for, and of the constraints to the inclusion of grain and forage legumes in farming systems under semi-arid conditions of sub-Saharan Africa is required (Mapfumo and Giller 2001; Twomlow 2004).

Residual yield benefits to cereal crops from previous grain legumes are well-documented in other tropical regions (Giller 2001). The positive responses of cereals following legumes have been attributed largely to enhanced availability of nitrogen (N) to the cereal crop (Sanginga 2003). The N contribution to the cereal grown after the legume is largely dependent on how much of the N is removed and legumes with low N harvest indices thus have a greater potential for enhancing soil fertility (Giller and Cadisch 1995). Crop residues are commonly removed from the fields by farmers at harvest and stored for use as animal feed during the dry season.

Some studies attribute the residual benefits of legumes to other effects apart from nitrogen (Sauerborn et al. 2000; Sanginga 2003). Nielsen and Vigil (2005) indicated that soil moisture was an important factor in determining the residual benefits to cereals grown in rotation with green manure legumes in North America. Short duration, determinate legumes may result in more residual soil water for subsequent crops whereas long duration and/or indeterminate legumes may remove more water than cereal crops. In the face of restricted and uncertain rainfall, an improved understanding of the effects of legume–cereal rotations on water relations as well as N supply is required to evaluate the longer-term effects on soil productivity and yield stability of rotational systems.

The purpose of the study was to: (1) assess the productivity of indigenous and improved grain legumes under semi-arid conditions; (2) estimate N_2-fixation and possible N accumulation in the soil; (3) quantify the residual benefits of legumes to sorghum grown in rotation; and (4) assess the water dynamics during the rotation.

Materials and methods

Environmental conditions and experimental design

Experiments were conducted at Lucydale research site located within the Matopos Research Station farm (28°30′ E, 20°23′ S, 1,380 m above sea level) 45 km south of Bulawayo City. The soils of the site are classified as Eutric Arenosols (FAO/UNESCO) derived from granite (Moyo 2001). The upper slope consists of coarse grained, fersiallitic sandy clay loams while down slope soils are dominated by fersiallitic coarse grained loamy sands and light sandy loams (Hungwe et al. 1982). These soils are among the most common soil type cultivated by smallholder farmers in the communal areas of Zimbabwe (Mapfumo and Giller 2001), and in the drier south of the country tend to have more active clays than similar soils in the wetter north (Nyamapfene 1989) which are highly leached.

Eight short to medium duration legume varieties and one medium duration sorghum variety were selected for the experiments based on screening trials done during the previous seasons (Table 1). Sorghum was used as a reference crop during the legume phase.

Experimental treatments were replicated three times using a randomised complete block design and plot size was 20×10 m. Plots were split into two 10×10 m subplots during the second season (sorghum crop). Residues (equivalent to plot stover yield in the

Table 1 Crop characteristics and corresponding agronomic practices of experimental crops

Crop	*Sorghum*	*Vigna unguiculata*		*Arachis hypogaea*		*Cajanus cajan*		*Vigna subterranea*	
Variety	SV 4	CBCI	86D 719	Nyanda	Natal Common	ICEAP 00535	ICPL 98091	Cream bambara	Maroon bambara
Source	AREX, Matopos	AREX Harare	IITA Nigeria	Seed Co Harare	Seed Co Harare	ICRISAT Kenya	ICRISAT Kenya	Market Bulawayo	Market Bulawayo
Growth habit	–	Determinate	Semi determinate	–	–	Determinate	Semi determinate	–	–
Duration (days)	Medium (110–120)	Short (60–90)	Short (60–70)	Short (70–90)	Medium (140)	Short (120)	Short (120)	Unknown	Unknown
Spacing (cm)	75×15	60×25	60×25	45×20	45×20	50×20	50×20	45×30	45×30
Plant population (m^{-2})	8.8	6.6	6.6	11.1	11.1	10	10	7.4	7.4
Seed rate (kg ha^{-1})	8	50	50	100	100	50	50	50	50

legume phase) were incorporated into one of the subplots in July (2003/04 season) and October (2004/05 season) while the above-ground residues were removed from the second subplot.

Field measurements and crop management

Initial soil analysis was conducted to assess phosphorus (P) availability in the soil across the fields before starting the experiments. As P availability was low (Olsen P extraction <0.1 mg kg^{-1}), a blanket rate of 200 kg ha^{-1} single super phosphate (18 kg P ha^{-1}) was applied and ploughed in to a depth of 0.20 m prior to planting the legume phase each season. During the 2002/03 season, soil samples were collected from the 0–0.15, 0.15–0.30, 0.30–0.60 and 0.60–0.90 m soil depths. During subsequent seasons a single layer, 0.30 m, was sampled. Each soil layer was analysed for pH (water), organic carbon, total and available P, and total N. The methods used to analyse pH, organic carbon and available P were those outlined by Okalebo et al. (1993), whereas nitrate N was analysed using the colorimetric method of Anderson and Ingram (1993).

Plant spacing was based on standard recommendations outlined in Table 1. Incorporation of the crop residues was done using a donkey drawn VS 200 mouldboard plough using a 0.20 m depth, a standard method used by local smallholders. Planting dates were; 19 December 2002 in the first season, 3 and 4 December 2003 in the second season, and 13 and 14 December 2004 in the third season. The first legume phase experiment was preceded by a millet breeding trial, the second by a 1-year fallow following a millet breeding trial and the third by a 2-year grass fallow. The overall experiment consisted of three seasons of legumes on three separate (but adjacent) experimental sites, two seasons of sorghum after legumes, and one legume–sorghum–sorghum sequence.

Local daily rainfall was measured throughout the cropping seasons. Soil water content was measured from the start of the 2002/03 season to the end of the 2003/04 cropping season. A Wallingford type neutron probe (Bell 1987) was used to measure soil water. Soil water measurements were taken once a week during the rainy season and biweekly or monthly during the dry season. Aluminium access tubes (45 mm internal diameter) were installed at the centre of each 10×10 m subplot. The installation depth depended on the presence of an irregular weathered quartz layer and tube depths ranged from 0.49 to 0.9 m with an average depth across all experiments of 0.69 cm. An additional tube was placed in a water-filled plastic drum for a weekly water count to check for instrument drift and provide the value RW used in Eq. 1, prior to taking field readings. Measurements were taken at 0.1-m increments, starting at 0.2 m below the soil surface. At each sampling date volumetric soil samples (0.05 m×0.15 m) were also collected from three positions in each plot to determine the volumetric water content of the surface layer (0–0.15 m), which cannot be measured accurately using the probe (Bell 1987). Neutron probe counts were converted to volumetric soil water content (θ) using the calibration curve for the Wallingford probe for sandy soils as outlined by Bell (1987). The equation for the curve is:

$$\theta = {}^{0.790R}\!/_{\mathrm{RW}} - 0.024 \quad (1)$$

Where R is the neutron probe count measured in the field and RW is the neutron probe count in a water filled drum. The volumetric soil water content was then converted to millimetres (mm) of soil water in each layer and values were integrated over the experimental soil profile. The presence of an irregular weathered quartz layer in the soil profile caused different offsets between sub-plots within the same experimental site. To compensate for this variation in observed soil water contents, instead of calculating absolute soil water contents, the measurements were used to calculate changes in soil water storage relative to the absolute water content on day 1 of sampling in each plot. This is an accepted practice when variations in profile characteristics with depth influence water storage in the profile and prevent calibration of the neutron probe for absolute values (e.g. Farahani et al. 1998).

Crops were kept free of weeds, disease and pests throughout each growing season, although a severe outbreak of aphids affected the cowpeas during the 2003/04 cropping season. At maturity the middle six rows were harvested, with a 1 m border left at each plot end. Grain and stover were separated and sub-samples were taken. The samples were dried at 70°C to constant weight and re-weighed to determine dry matter content and to calculate yield.

Nitrogen fixation was estimated using the ^{15}N natural abundance method as outlined by Boddey et al. (2000). Samples of legumes and sorghum (grain and stover) were dried in the oven at 70°C. The samples were then analysed for % N and ^{15}N using a 20–20 stable isotope mass spectrophotometer. Tissue ^{15}N enrichment was calculated using Eq. 2:

$$^{15}\mathrm{N}\,(^0\!/_{00}) = \frac{1000 \times \left(\mathrm{atom}\,\%^{15}\ \mathrm{N\ sample} - 0.3663\right)}{0.3663} \quad (2)$$

The amount of N fixed was then calculated using Eq. 3:

$$\%\ \mathrm{N\ from\ fixation} = 100 \times \left\lfloor \left(\delta^{15}\mathrm{N}_{\mathrm{referencecrop}} - \delta^{15}\mathrm{N}_{\mathrm{legume}}\right) / \delta^{15}\mathrm{N}_{\mathrm{referencecrop}} - \beta \right\rfloor \quad (3)$$

With β being the δ^{15}N of the legume when grown with N_2 as the sole source of N, and sorghum the reference crop. The β values for groundnut, pigeon pea and cowpea were obtained from literature (Boddey et al. 2000). The β value for groundnut was also used for Bambara groundnut.

The amount of N fixed was also calculated using the N difference method (Giller 2001). The method assumes that both legumes and the reference plants take up similar N amounts from the soil. Therefore, the difference between total N in the legume and N taken up by the reference plant (sorghum) is estimated to be equal to the total N fixed by the legume.

Statistical analysis

Grain, stover and N yield, and water data from both the legumes and sorghum were first tested for normality before carrying out analysis of variance (ANOVA) in Genstat 8.1. The legume varieties and season were the treatments in the legume analysis, while the replicates were the blocks. In the sorghum analysis residues were added as a third treatment. Standard errors of the differences (SED) of legume variety means are presented. Water data was also analysed using ANOVA.

Results and discussion

Initial soil characteristics

The soils at Lucydale were acidic (Table 2), but historically the acidity has had no drastic effect on crop growth at the site, possibly due to the fact that the clay fraction, although small, is still active (Nyamapfene 1989) and not as highly leached as the clay fractions of similar soils in wetter areas of the country. Total nitrogen contents were below the range for sandy clay loams (0.06–0.10%) previously reported for upland soils of medium to low rainfall

Table 2 Initial soil characteristics at the start of experimentation in each season

Season	Soil depth (m)	pH	Organic carbon (g kg^{-1})	Available N (mg kg^{-1})	Total N (%)	Olsen P (mg kg^{-1})	Total P (%)
2002/03	0–0.15	3.7	7.8	7.3	0.04	12.2	0.10
	0.15–0.30	3.8	7.5	5.7	0.04	5.8	0.09
	0.30–0.60	4.8	5.9	1.5	0.03	2.2	0.08
	0.60–90	5.3	3.3	0.7	0.03	2.0	0.05
2003/04	0–0.30	3.8	2.5	3.6	0.06	25.4	0.06
2004/05	0–0.30	4.0	4.3	1.4	0.04	0.5	0.01

Number of samples in the 0–0.30 m depth per season=27

In 2004/05 samples were collected before applying SSP fertilizer.

areas of Zimbabwe (Hungwe et al. 1982). The surface layer nitrate–nitrogen concentrations however tended to reflect the preceding cropping activity on the three sites, namely a millet breeding trial in season 1 (high), a fallow after a millet breeding trial in season 2 (less) and a grass fallow in season 3 (least). Organic carbon was below 1%, and generally similar to that found in larger fields of the smallholder farming areas of Zimbabwe (Mtambanengwe and Mapfumo 2005; Zingore et al. 2006).

Seasonal rainfall

Rainfall was highly variable and subsequent cumulative rainfall values during the cropping season were 314, 650, and 301 mm. Figure 1 shows cumulative daily rainfall measured across the three seasons.

The cropping season average total rainfall for Matopos (590 mm based on 50 year average) was exceeded only in the 2003/2004 season. A 'typical' rainy season in Matopos begins in late October/early November, and ends in April. During the 2002/03 season, enough rainfall for planting was received by 19 December 2002 and rainfall was evenly distributed until March after which crops matured under conditions of terminal drying. The 2003/04 rainy season started early in October and crops were planted on 3 and 4 December 2003. Ample rainfall during December and January allowed for good crop establishment during the critical growth stages while rainfall was also evenly distributed throughout the rest of the season (Fig. 1). The last season of experimentation (2004/05) had erratic rainfall. The rainy season started late and planting started in mid December (13 and 14). The

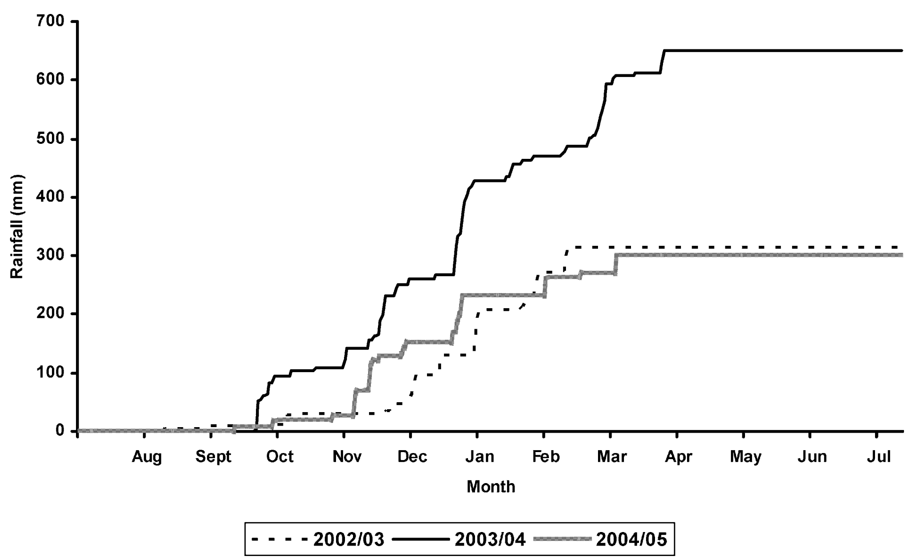


Fig. 1 Seasonal rainfall at Lucydale from the 2002/03 to the 2004/05 season. The long-term average for Matopos weather station located at 5 km distance is about 590 mm per annum

Table 3 Legume grain and stover yield, grain N and stover N, and total N yield measured across three seasons at Lucydale

Season	Crop	Variety	Grain yield (t ha^{-1})	Stover yield (t ha^{-1})	Grain N (%)	Stover N (%)	Grain N yield (kg ha^{-1})	Stover N yield (kg ha^{-1})	Total N yield (kg ha^{-1})
2002/03	Bambara	Bambara cream	0.07	3.21	4.2	3.1	3	99	102
	Bambara	Bambara maroon	0.13	3.19	4.4	2.8	5	90	95
	Groundnut	Natal Common	0.47	3.09	3.4	2.8	16	87	103
	Groundnut	Nyanda	0.51	3.64	2.9	2.7	15	98	113
	Cowpea	CBC1	0.98	1.56	4.2	3.5	41	55	96
	Cowpea	86D 719	1.36	2.09	4.2	3.5	57	74	131
	Pigeon pea	ICPL 87091	0.11	2.78	3.6	2.7	4	75	79
	Pigeon pea	ICEAP00535	0.33	2.52	3.7	2.7	12	68	80
	Sorghum	SV4	1.98	3.64	1.6	0.4	32	15	47
2003/04	Bambara	Bambara cream	0.38	2.09	3.8	2.1	14	44	58
	Bambara	Bambara maroon	0.58	1.83	3.8	2.2	22	40	62
	Groundnut	Natal Common	0.76	1.98	3.8	2.4	29	48	77
	Groundnut	Nyanda	1.02	1.96	3.8	2.0	39	40	78
	Cowpea	CBC1	0.20	0.33	3.7	3.2	7	10	18
	Cowpea	86D 719	0.22	1.12	4.5	2.6	10	30	39
	Pigeon pea	ICPL 87091	0.66	1.71	3.7	2.3	24	39	63
	Pigeon pea	ICEAP00535	0.53	1.75	3.7	2.6	20	46	66
	Sorghum	SV4[a]							
2004/05	Bambara	Bambara cream	0.06	0.97	4.0	2.1	3	21	23
	Bambara	Bambara maroon	0.05	1.09	4.1	1.8	2	20	22
	Groundnut	Natal Common	0.18	0.98	3.8	1.9	7	19	26
	Groundnut	Nyanda	0.37	0.98	3.8	1.9	14	18	33
	Cowpea	CBC1	0.35	1.03	4.0	2.2	14	23	37
	Cowpea	86D 719	0.46	1.11	3.7	2.2	17	25	42
	Pigeon pea	ICPL 87091	0.58	1.17	3.3	2.0	19	24	43
	Pigeon pea	ICEAP00535	0.53	1.33	3.1	1.9	16	25	41
	Sorghum	SV4	0.61	2.18	1.2	0.6	8	13	20
P values		Variety	<0.001	<0.001	<0.001	<0.001	<0.001	0.080	0.002
		Season	<0.001	<0.001	NS	<0.001	<0.001	<0.001	<0.001
		Season×Variety	<0.001	NS	0.002	NS	<0.001	NS	0.076
SED		Season×Variety	0.12	0.46	0.27	0.25	4.8	13.65	8.15

NS not significant

[a] No yield

crops received only 24 mm in the first month of establishment while in January 2005 the rainfall total was 80 mm, but the whole amount fell within 1 week (January 15–19). Thereafter only a few light showers were received.

Legume grain yield

Legume grain yields were significantly different across seasons ($P<0.001$) and within seasons ($P<0.001$) when variety means were compared. All grain and stover yield weights are reported as oven dry values (Table 3). All legumes generally yielded higher than current reported yields in smallholder farms in dry regions, by about 20–300% except for the Bambara groundnut.

Cowpeas produced the highest grain yields during the dry 2002/03 season; CBCI (0.98 t ha^{-1}) and 86D 719 (1.36 t ha^{-1}). In a wetter 2003/04 season the cowpeas were severely attacked by aphids, resulting in poor grain yields. In 2004/05 cowpea produced 0.35–0.46 t ha^{-1}. Average yields in smallholder farms in dry regions are currently 0.3 t ha^{-1} (Nhamo et al. 2003).

Groundnut yields were influenced by rainfall across the three seasons. The two groundnut varieties consistently exceeded 0.4 t ha^{-1}, except in the 2004/5 season when Natal Common yielded only 0.2 t ha^{-1}. The national average yields of groundnut in Zimbabwe's smallholder farming systems are also low (0.3 t ha^{-1}; Nyakanda and Hildebrand 1999), but the yields we obtained were substantially better than smallholder farm yields of between 0.26 and 0.36 t ha^{-1} obtained in higher rainfall areas of the country (Waddington and Karigwindi 2001). Mupangwa and Tagwira (2005) suggested that groundnut yields could be improved through the use of phosphorus. Soil analysis and grain production results from smallholder farms in southwestern Zimbabwe have indicated that P is probably not a major limiting factor for legumes in the drier environment (Ncube et al. 2007). Therefore, the current poor groundnut yields in dry regions are probably more related to unimproved germplasm interacting with limited water availability rather than poor soil fertility per se.

Pigeon pea varieties consistently yielded more than 0.5 t ha^{-1} across the three seasons, although the variety ICPL 87091 performed poorly in 2002/03 where it produced 0.11 t ha^{-1}. Pigeon pea is a relatively new crop in Zimbabwe. Mapfumo and Mtambanengwe (2004) reported average yields of about 0.7 t ha^{-1} for the short duration variety ICPL 87109 in sub-humid eastern Zimbabwe. Chikowo et al. (2004) reported pod/seed yields of less than 0.5 t ha^{-1} in the same higher rainfall region. The yield potential of pigeon pea is largely unknown in semi-arid regions of Zimbabwe, but the crop has so far shown potential in the region. The two varieties used in this experiment were selected because they had produced high yields of 0.8 (ICPL 87091) and 0.9 (ICEAP 00535) t ha^{-1} on clay soils at the Matopos Research Station (Ncube et al. 2003).

Bambara groundnut performed very poorly in all three seasons, with maximum grain yield of 0.38 and 0.58 t ha^{-1} for the two cultivars in 2003/04. Bambara groundnut is an underutilized and largely unimproved crop that has received little attention from breeding programmes (Azam-Ali et al. 2001; Giller 2001). We used seed of landraces from the local market in our study. It is striking that Bambara groundnut performed so poorly in the two dry seasons (2002/03 and 2004/05), yet Collinson et al. (1996) suggested that Bambara groundnut is resistant to drought stress. Studies of the crop under semi-arid conditions in Botswana reported high grain yields of 0.4 to 1.5 t ha^{-1} (Karikari and Tabona 2004), though the crop was irrigated at emergence. The poor yields in our study were due to unimproved germplasm with consistently low harvest indices (0.02–0.24) across seasons.

Legume nitrogen accumulation and N_2-fixation

Nitrogen content in the grain was significantly different between the legume varieties ($P<0.001$), while stover nitrogen content varied between both legume varieties ($P<0.001$) and the seasons ($P<0.001$). A high proportion of N that was produced by the legumes accumulated in the stover and was returned to the soil as residues. Legume N accumulation in stover at the end of the 2002/03 season was 87 and 98 kg ha^{-1} (groundnut), 55 and 74 kg ha^{-1} (cowpea), 75 and 68 kg ha^{-1} (pigeon pea), 90 and 99 kg ha^{-1} (Bambara groundnut). During 2003/04 overall N accumulation was less and the corresponding values were; 40 and 48 kg ha^{-1}, 10 and 30 kg ha^{-1}, 39 and 46 kg ha^{-1} and 40 and 44 kg ha^{-1} respectively. In the 2004/05 season the stover N yield values ranged between 18–25 kg ha^{-1} (Table 3). These amounts were all greater than the amount of N accumulated in sorghum stover during the same period. Chikowo et al. (2003)

reported net stover N addition of 82 and 17 kg ha^{-1} for pigeon pea and cowpea respectively in a higher rainfall region of Zimbabwe. Kumar Rao et al. (1996) harvested 25–93 kg ha^{-1} N from pigeon pea varieties in semi-arid India, whereas Toomsan et al. (1995) recorded 21–166 kg ha^{-1} N in groundnut stover in farmers' fields in the northeast of Thailand. There is little information on Bambara groundnut N yields, but despite the low grain yield of Bambara groundnut in our study the amounts of N accumulated in stover were substantial in each of the three seasons.

The ^{15}N signatures of sorghum (reference plants) were greater than the $\delta^{15}N$ signatures of all the legumes showing that the sorghum solely depended on soil N for its N uptake (Table 4). However, the short season cowpea variety CBC1 also gave relatively high $\delta^{15}N$ signatures (and correspondingly low fixation estimates). The highest signatures were recorded from the first experiment (2002/03) when the three experiments were compared. Using the ^{15}N natural abundance method we estimated that the legumes derived 15–50% (19–62 kg N) of their N from N_2-fixation in 2002/03: groundnut 19 and 41%, cowpea 15 and 17%, pigeon pea 28 and 30% and Bambara groundnut 34 and 50% (Table 4). In 2003/04 the legumes fixed 16–61% (4–57 kg N ha^{-1}) while in 2004/05 the legumes fixed 29–83% (10–35 kg N ha^{-1}). Chikowo et al. (2004) reported 84% (97 kg N ha^{-1}) fixation for pigeon pea and 58% fixation (28 kg N ha^{-1})for cowpea in sub-humid eastern Zimbabwe. Similar proportions of N_2-fixation (45–68%) have been reported in groundnut (Bell et al. 1994; Gathumbi et al. 2002), whereas in this study groundnut values ranged between 19 and 83% across the three seasons (Table 4).

The values of N derived from N_2-fixation were similar to those calculated using the N difference method for most of the legumes in the 2003/04 and 2004/05 seasons, indicating that the ^{15}N natural abundance method and the N difference method could give fairly similar estimates of N_2-fixation even under dry conditions. However, the N difference estimates of N_2-fixation were much higher in the 2002/03 season, particularly in the cowpea varieties and the groundnut Natal Common. It is not clear why the two methods differed so much during this season for these particular legumes. The differences were probably caused by high $\delta^{15}N$ values measured in samples from these legumes in 2002/03, but it is not clear why these high values arose.

The 2004/05 season had significantly less N fixed (mean 23 kg N, $P<.001$) compared to the other two seasons (means 39 kg N in 2002/03 and 38 kg N in 2003/04). The low N fixation in 2004/05 was probably related to the poor rainfall distribution and plant moisture stress in that season. Symbiotic N_2-fixation is highly sensitive to moisture stress (Ledgard and Steele 1992; Giller 2001). The persistently poor N_2-fixation by CBC1 was probably also due to it being a determinate variety.

Rotation sorghum grain yield and nitrogen uptake

There was an overall increase in sorghum yield following legumes, even in the drier seasons (Table 5), while the yield increases over mono-cropped sorghum were on average 200% in the wetter 2003/04 cropping season. In a drier 2004/05 season the yield increases were lower, but still more than 30% and up to 100% in a few plots. The response of sorghum to residual effects of legumes was strongly related to the previous legume variety in 2003/04 ($P<0.05$).

Many studies of residual effects of legumes on subsequently planted cereals attribute yield benefit to N accumulation during the legume phase, and subsequent uptake by the following cereal (Giller 2001; Sanginga 2003). Cowpea and groundnut varieties accumulating most N during the 2002/03 season being generally followed by the highest yielding sorghum crop in 2003/04 seems to be in agreement with these findings (Tables 4 and 5). The highest sorghum yield in 2003/04 was 1.62 t ha^{-1}, following Natal Common, sorghum after 86D 719 was 1.59 t ha^{-1}. In general all legume varieties that accumulated substantial N during the legume phase showed relatively high yields of subsequent sorghum crops in the wetter 2003/04 season (Fig. 2). However, during the drier 2004/05 season there was no relationship between N yield in the previous season and sorghum grain yield showing that moisture availability was probably playing a more determinant role.

Some studies have demonstrated that residual effects of legumes cannot be attributed to contributions of N only. Other potential benefits include: a better supply of other nutrients such as cations like potassium, calcium and magnesium (Sauerborn et al. 2000); an N sparing effect (where legumes depend on fixed nitrogen and thus leave more available soil N to be taken up by the next crop: Herridge et al. 1995). A

Table 4 Legume nitrogen fixation estimates across three seasons at Lucydale

Crop	Variety	β value	$\delta^{15}N$ (‰)	N from N_2-fixation (%)	Total N in crop (kg ha^{-1})	Total N+root N (kg ha^{-1})	Total N fixed (kg ha^{-1})	Total N fixed (by difference; kg ha^{-1})
2003/03								
Bambara groundnut	Bambara cream	0.66	3.82	34	102	133	45	72
Bambara groundnut	Bambara maroon	0.66	3.06	50	95	124	62	63
Groundnut	Natal Common	0.66	4.54	19	103	134	25	73
Groundnut	Nyanda	0.66	3.49	41	113	147	60	86
Cowpea	CBC1	−1.66	4.41	15	96	125	19	64
Cowpea	86D 719	−1.66	4.22	17	131	170	29	109
Pigeon pea	ICPL 87091	−0.90	3.54	28	79	103	28	42
Pigeon pea	ICEAP 00535	−0.90	3.69	30	80	104	31	43
Sorghum	SV4		5.44		47	61		
2003/04								
Bambara groundnut	Bambara cream	0.66	2.64	61	58	76	46	50
Bambara groundnut	Bambara maroon	0.66	3.06	52	62	81	43	55
Groundnut	Natal Common	0.66	3.58	39	77	100	39	74
Groundnut	Nyanda	0.66	2.83	56	78	102	57	76
Cowpea	CBC1	−1.66	4.54	16	18	23	4	−3
Cowpea	86D 719	−1.66	1.60	56	39	51	28	25
Pigeon pea	ICPL 87091	−0.90	2.45	57	63	82	47	56
Pigeon pea	ICEAP 00535	−0.90	1.93	49	66	86	42	60
Sorghum	SV4[a]		5.70		20	26		
2004/05								
Bambara groundnut	Bambara cream	0.66	3.86	40	23	30	12	4
Bambara groundnut	Bambara maroon	0.66	4.09	35	22	28	10	2
Groundnut	Natal Common	0.66	2.28	66	26	34	22	7
Groundnut	Nyanda	0.66	1.49	83	33	42	35	16
Cowpea	CBC1	−1.66	3.54	29	37	48	14	21
Cowpea	86D 719	−1.66	2.28	46	42	55	25	28
Pigeon pea	ICPL 87091	−0.90	3.21	46	43	55	26	29
Pigeon pea	ICEAP 00535	−0.90	2.77	40	41	54	22	27
Sorghum	SV4		5.96		20	26		
P values	Variety		0.004	<0.001	0.092	<0.001	<0.001	
	Season		<0.001	<0.001	<0.001	<0.001	<0.001	
	Variety×season		0.012	0.042	0.001	NS	NS	
SED	Variety×season		0.68	12.67	13.47	12.39	9.47	

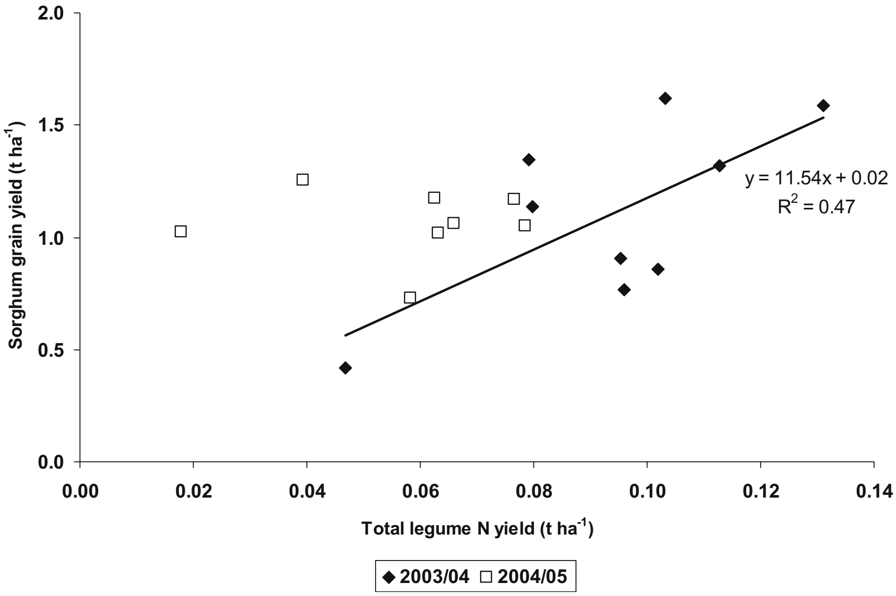
[a] No sorghum yield, therefore the value is an average of the 2002/03 and 2003/04 values

Table 5 Rotation sorghum grain and stover yield, nitrogen uptake and total N yield across two seasons at Lucydale

Season	Previous crop	Residues	Grain N (%)	Grain yield (t ha^{-1})	Grain N (kg ha^{-1})	Stover N (%)	Stover yield (t ha^{-1})	Stover N (kg ha^{-1})	Total N yield (kg ha^{-1})
2003/04	Bambara cream	+	1.8	0.86	15	0.6	1.76	11	26
	Bambara maroon	+	1.6	0.91	15	0.7	2.30	16	31
	Natal Common	+	1.6	1.62	25	0.6	2.25	14	39
	Nyanda	+	1.6	1.32	21	0.5	3.63	19	41
	CBC1	+	1.6	0.77	13	0.5	2.28	12	25
	86D 719	+	1.5	1.59	24	0.5	3.23	16	40
	ICPL 87091	+	1.7	1.34	23	0.5	3.11	14	37
	ICEAP00535	+	1.7	1.13	20	0.7	2.88	19	39
	SV4	+	1.8	0.42	8	0.9	1.35	12	20
	Bambara cream	−	1.5	0.56	9	0.6	2.00	11	20
	Bambara maroon	−	1.6	1.33	21	0.6	2.21	14	35
	Natal Common	−	1.6	0.82	13	0.7	2.54	18	31
	Nyanda	−	1.7	1.28	22	0.5	3.20	15	36
	CBC1	−	1.5	1.37	21	0.5	3.08	15	35
	86D 719	−	1.7	1.57	27	0.5	3.09	17	44
	ICPL 87091	−	1.7	1.21	21	0.7	3.59	23	44
	ICEAP00535	−	1.6	1.34	22	0.6	2.63	17	38
	SV4	−	1.5	0.36	6	0.7	0.80	6	11
2004/05	Bambara cream	+	1.6	0.73	12	0.7	1.44	10	22
	Bambara maroon	+	1.7	1.17	20	0.5	1.56	8	27
	Natal Common	+	1.4	1.17	17	0.5	1.85	10	27
	Nyanda	+	1.4	1.05	14	0.5	2.02	9	24
	CBC1	+	1.6	1.02	16	0.5	1.66	8	24
	86D 719	+	1.5	1.26	19	0.6	1.75	10	28
	ICPL 87091	+	1.6	1.02	16	0.6	1.93	11	28
	ICEAP00535	+	1.5	1.06	16	0.6	1.77	11	27
	SV4	+	1.4	0.77	11	0.5	1.14	6	17
	Bambara cream	−	1.6	0.95	15	0.7	1.54	11	26
	Bambara maroon	−	1.5	1.02	16	0.5	1.85	10	25
	Natal Common	−	1.4	1.09	16	0.5	1.29	7	23
	Nyanda	−	1.4	1.22	17	0.4	2.12	9	26
	CBC1	−	1.3	0.94	12	0.5	1.63	9	21
	86D 719	−	1.5	1.03	16	0.6	1.83	11	27
	ICPL 87091	−	1.5	1.22	18	0.5	1.90	9	27
	ICEAP00535	−	1.6	0.92	14	0.6	1.75	11	26
	SV4	−	1.6	0.52	8	0.5	1.05	5	14
P values	Variety (V)		NS	<0.001	0.005	NS	<0.001	NS	0.019
	Residues (R)		0.057	NS	NS	NS	NS	NS	NS
	Season (S)		<0.001	NS	NS	NS	<0.001	<0.001	0.002
SED	VxRxS		0.11	0.37	6.21	0.16	0.72	6.11	10.87

(+) Residues added; (−) residues removed

Fig. 2 Relationship between total nitrogen harvested during the legume phase and grain yield harvested during the sorghum phase at Lucydale for the 2003/04 and 2004/05 sorghum crops



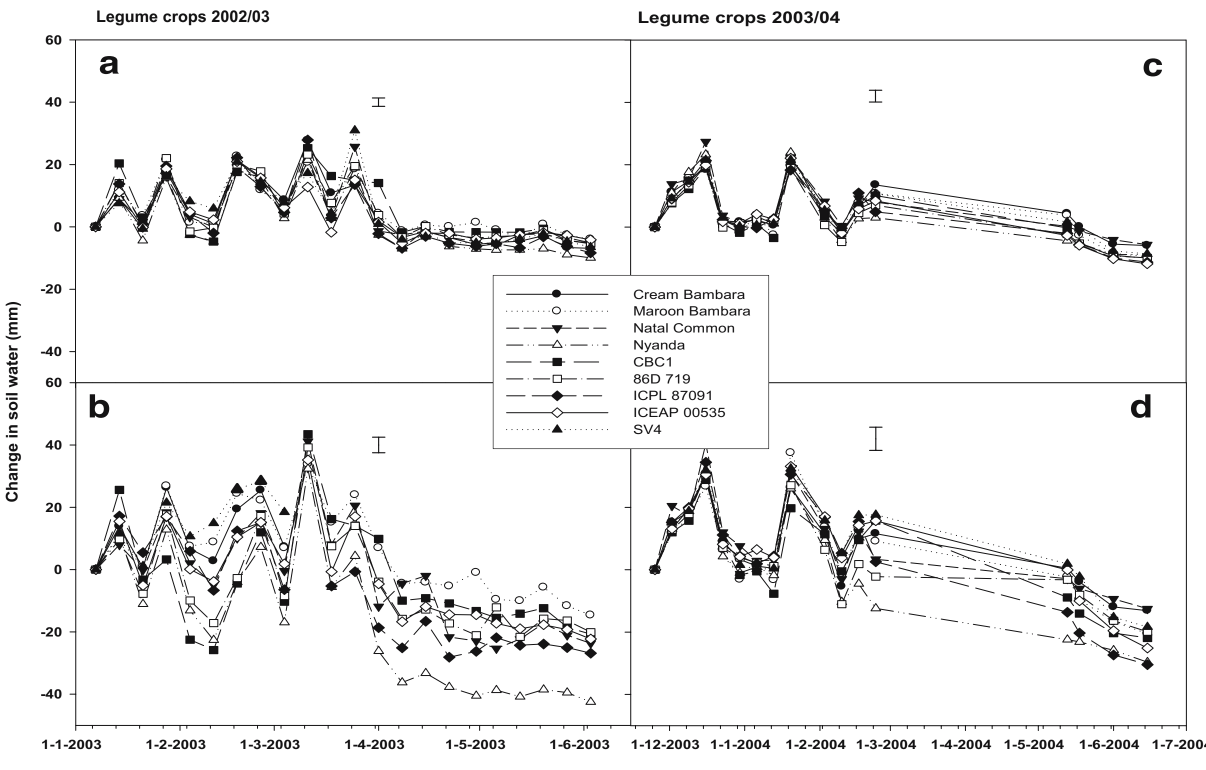
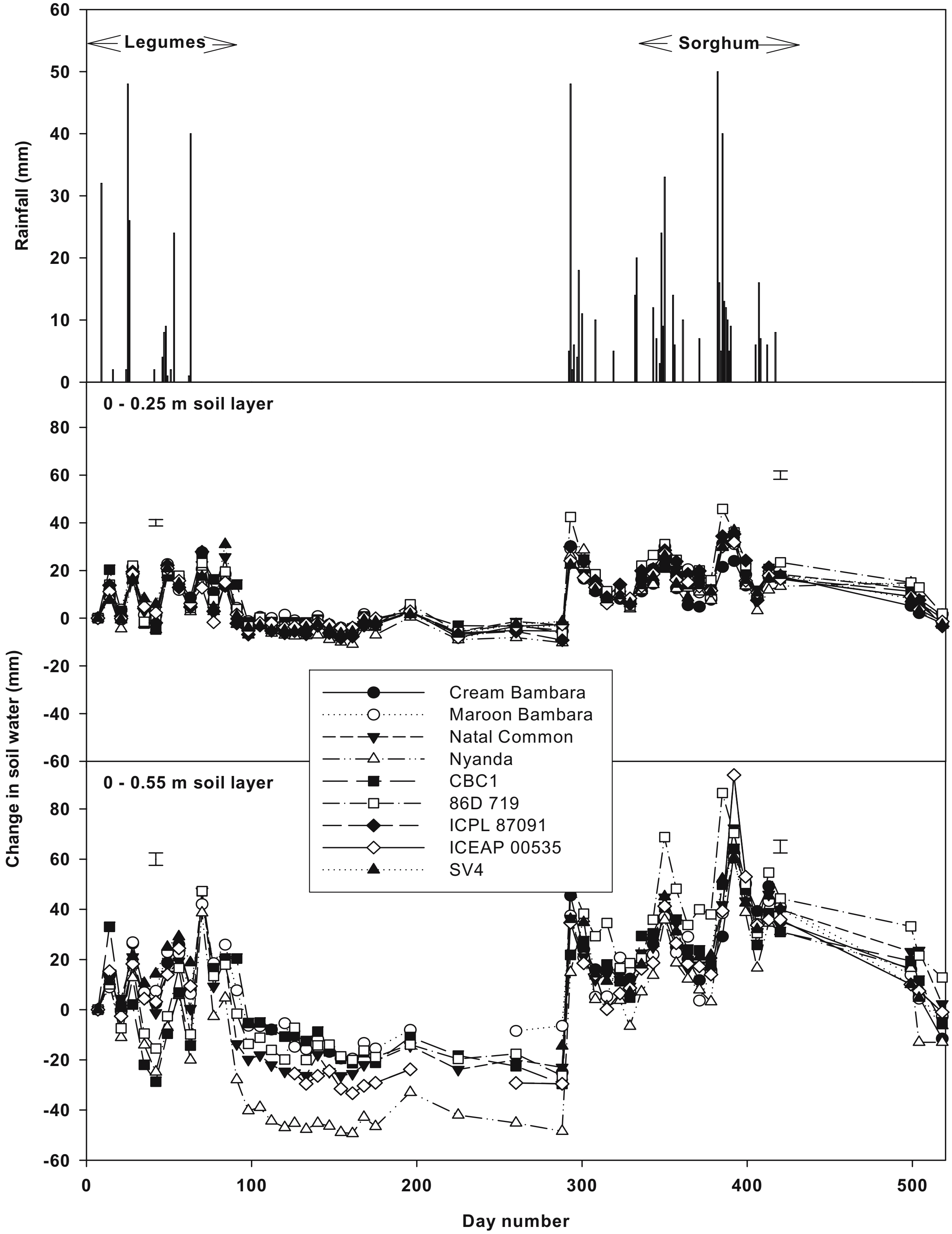


Fig. 3 Change in soil water during the legume phase of the 2002/03 cropping season [for the 0–25 (**a**) and 0–55 cm (**b**) soil layer] and the 2003/04 cropping season [0–25 (**c**) and 0–55 cm (**d**)]. Each point is an average of measurements in three plots. *Error bars* represent standard errors of differences between means of soil water changes for the varieties (n=1,430)


Legumes
Sorghum
Rainfall (mm)
0 - 0.25 m soil layer
0 - 0.55 m soil layer
Change in soil water (mm)
Cream Bambara
Maroon Bambara
Natal Common
Nyanda
CBC1
86D 719
ICPL 87091
ICEAP 00535
SV4
Day number

◀ **Fig. 4** Rainfall events and comparison of relative change in soil water during the 2002/03 (legume phase) and the 2003/04 (sorghum phase) cropping seasons for sorghum plots with no residues only. Each point is an average of measurements in three plots. *Error bars* represent standard errors of differences between means of soil water changes for the legume varieties (n=459)

further benefit could be arbuscular mycorrhiza infection and the suppression of root nematodes by legumes (Bagayoko et al. 2000).

The removal or addition of legume residues had no effect on sorghum yields (Table 5). Given the amount of N added to the plant–soil system with incorporated legume stover (up to 100 kg ha^{-1}), this is a surprising result. One explanation could be that the belowground N contribution and fallen leaves from the senescencing legumes supplied sufficient N to meet the requirements of the following sorghum crops.

Previous legume varieties had no effect on the N content of sorghum grain harvested in the subsequent season (Table 5). However, there were significant differences ($P<0.001$) between seasons while residue removal resulted in a slight decrease in N content ($P=0.057$). The stover N content of sorghum was also not affected by residue removal. Total N accumulation was 35 kg ha^{-1} (2003/04) and 26 kg ha^{-1} (2004/05) in plots previously planted with legumes compared with 11 and 20 kg N ha^{-1} (2003/04) and 14 and 17 kg ha^{-1} (2004/05) for sorghum-based rotations. Differences were significant between previous legume varieties ($P<0.05$) and seasons ($P<0.01$).

There were weakly significant differences between the mean grain yields of the second sorghum crop ($P=0.058$) during the 2004/05 cropping season (data not shown). Sorghum grain yields after the legumes ranged from 0.7 to 1.5 t ha^{-1}, whereas that of sorghum after sorghum was 0.9 t ha^{-1}. The N content of grain was not affected by preceding crop varieties and residue handling in the second sorghum crop grown in 2004/05. However, stover N content was influenced by residue incorporation or removal two seasons prior in 2002/03. Sorghum grain and stover N content was generally greater in plots where residues were incorporated. As a result, total N accumulation by sorghum was also greatest in plots with residues. The yield was significantly different between previous variety ($P<0.05$) and residue treatments ($P<0.05$).

Soil water changes during the rotation

Soil water changes in the upper 0.25 m and 0.55 m soil layers during the legume phase were strongly influenced by legume variety and rainfall events during the cropping season for both years (Fig. 3a–d).

All legume varieties showed similar water use patterns in the upper 0–0.25 m soil layer in 2002/03 and 2003/04, and sorghum also closely followed the same pattern. The changes in water use were stronger in the relatively dry 2002/03 season (Fig. 3a,b) compared with the wetter 2003/04 season (Fig. 3c,d). However, for the deeper soil profile (0–0.55 m) legumes used more water during the growing period than sorghum (Fig. 3b,d). At the end of the growing period (April), varieties such as Nyanda and ICPL 87091 depleted more water from greater soil depths (0.55 m) than the other legume varieties. Nyanda had highest biomass production of legumes, whereas the pigeon pea variety ICPL 87091 was a long duration growing type.

The change in soil water during the sorghum phase did not show much dependence on the previous legume varieties in the 0–0.25 m soil layer (Fig. 4). The soil column in plots previously planted with legumes recharged to the same water content as with sorghum at the start of the rainy season in the upper layer. Even for the 0–0.55 m layer, observed differences in soil water content at the end of previous legume phase disappeared with the first single large rainfall event in October 2003, reflecting the low water holding capacity of the soil. Also noteworthy is the lack of differences in soil water use in the 0–0.55 m layer during growth of the sorghum crops, since there were quite large differences in sorghum biomass production between treatments (Table 5). However, the high and consistent rainfall in this season largely explains this observation. Whether or not similar effects would occur during seasons with poor initial and subsequent rainfall is an important question for further research, well suited to application of a calibrated cropping systems model (Ncube 2007).

Conclusions

Legume productivity was dependent on the variety grown and the amount and distribution of rainfall. New varieties of groundnut (Nyanda), cowpea (86D 719, CBC1) and pigeon pea (ICPL87091, ICEAP00535) were well adapted to the dry environments and yielded up to double or three times the grain yield achieved with traditional varieties. The legumes also fixed large proportions of their N from the atmosphere. Legume plots that produced the highest total N yield generally enhanced N supply and sorghum grain yields in the subsequent cropping season, by up to 200% in a wet season and 30 to 100% in a very dry season. All plots showed similar water recharge at the start of the sorghum phase indicating that the legumes had little direct impact on soil water storage to the following sorghum for this soil type. There is need to further study water dynamics in the rotation in order to fully understand the interactions between water and N use. The long-term bio-economic sustainability of the rotations also needs further assessment.

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