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LONG-TERM EFFECTS OF GRAIN LEGUMES ON RAINY-SEASON SORGHUM PRODUCTIVITY IN A SEMI-ARID TROPICAL VERTISOL

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SUMMARY

In southern and central India, farmers crop Vertisols only in the post-rainy season, to avoid land management problems in the rainy season. In 1983 ICRISAT established a long-term trial seeking to intensify cropping. The trial included intercrops, sequential crops and appropriate Vertisol management technology to allow consecutive rainy-season and post-rainy season crops to be grown. Benefits provided by legumes to succeeding rainy-season sorghum (*Sorghum bicolor*) were analysed in relation to a non-legume system of sorghum + safflower (*Carthamus tinctorius*). Rainy-season sorghum grain yield production was sustained at about 2.7 t ha^{-1} over 12 years within a continuous sorghum–pigeonpea (*Cajanus cajan*) intercrop system. With a cowpea–pigeonpea intercrop system, succeeding sorghum benefitted each year by about 40 kg N ha^{-1} (fertilizer nitrogen (N) equivalent). Without N fertilizer application the sorghum grain yield was around 3.3 t ha^{-1}. Legume benefits were less marked in the chickpea (*Cicer arietinum*)-based rotation than in the pigeonpea system, in which a 12-year build up of soil total N (about 125 $\mu g\ g^{-1}$) was observed. Although sorghum benefitted from this system, pigeonpea yields declined over time due to soil-borne fungi and nematodes. Wider rotations of crops with pigeonpea may help to overcome these problems, while sustaining sorghum production.

INTRODUCTION

In semi-arid India, the majority of Vertisols are left fallow during the rainy season and then cropped during the post-rainy season with the stored soil moisture. In central India the main crops are sorghum (*Sorghum bicolor*), chickpea (*Cicer arietinum*) and to a lesser extent safflower (*Carthamus tinctorius*); they may be grown as sole crops or in intercropping combinations. In the North Central Plains, the main crop is wheat (*Triticum aestivum*), most often as a sole crop but sometimes intercropped with chickpea (Willey *et al.*, 1989).

Although the rainy-season fallowing is prevalent throughout the Vertisols the reasons for its occurrence vary. In areas of low (500–750 mm) and erratic rainfall, rainy-season cropping is risky despite good moisture-holding capacity of soil. On the other hand in wetter areas (>750 mm) this soil becomes too sticky and difficult to manage, and crops may suffer from waterlogging. Vertisols in these areas could be cropped during the rainy and post-rainy seasons due to high water

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holding capacity and by making use of rainfall (Virmani *et al*, 1978); at the same time soil erosion could be reduced by cropping during the rainy season instead of leaving the land fallow. ICRISAT's early research concentrated on the Vertisols of high rainfall areas and developed 'Vertisol technology' by which crop intensification was made possible. The three important components of this improved technology, improved genotype, improved management of both land and crop, and the use of fertilizer, were examined individually and in combination on the maize (*Zea mays*)–pigeonpea (*Cajanus cajan*) intercrop. The effect of fertilizer was much more striking in combination with improved genotype or improved management, where the yields increased by two- to three-fold. These results highlight the importance of fertilizer application and the synergistic effects that can occur among various inputs when they are used in combination.

Vertisols are generally deficient in nutrients. Fertilization is needed because the improved cropping systems, during the rainy and post-rainy seasons, have greater nutrient demands than the traditional single-season cropping system, particularly when crops in both the seasons are non-legumes (for example, maize–safflower or sorghum–safflower). Responses to nitrogen (N) fertilization were much higher than with any other nutrient, and the response in the rainy season was greater than in the post-rainy season. Other studies have confirmed that the cereals in intercrops respond to fertilizer N in the same way as in sole crops (Rego, 1981). Seasonal differences in rainfall and its distribution influenced the nitrogen responses (Burford *et al.*, 1989).

Nevertheless there remains some caution over the use of fertilizers under rainfed dryland conditions because of variability in responses between years and locations. Legume-based systems have been particularly successful in providing N inputs where fertilizer was of marginal economic benefit (Donald 1964; Russell 1984), and legumes were grown for their grain as part of the crop production system. The yield thus removed a substantial proportion of the N fixed, especially by improved cultivars with a high harvest index. Perhaps this logic led to a lower priority being given to research on the possible beneficial effects of biological N fixation by grain legume crops. A grain legume like pigeonpea has only a low harvest index, sometimes less than 0.20 for the medium- to long-duration types, and in addition sheds its senescing leaves from flowering onwards. Although farmers remove stalks from the field, they remove relatively little N in this process because stalks have a very low N content. Addition of N by fallen leaves and flower parts alone may add 40–60 kg N ha^{-1} to the soil (Sheldrake and Narayanan, 1979). Besides leaf fall, root material and nodules remaining in the soil have shown good residual effects on the subsequent cereal crop (Kumar Rao *et al.*, 1983), these are equivalent to a fertilizer application of 30–40 kg N ha^{-1}. While this is not large, even a moderate input is valuable for a crop such as sorghum which is very responsive to N inputs; this input could also double the yield because the soil appears to supply as little as 30 kg N ha^{-1} to cereal crops. Such results have led to the establishment at ICRISAT of a long-term experiment to examine the yields and residual effects of various combinations of crops in order to assess optimum combinations of legumes with sorghum for maintaining productivity. The experiment was established in 1983 on a Vertisol and there were three objectives: to quantify the benefits of grain legumes to non-legumes in the cropping system rotations; to monitor long-term changes in soil quality for sustainable crop production; and to identify improved and sustainable cropping system options for crop intensification and to enhance crop productivity.

MATERIALS AND METHODS

An experiment with 10 different cropping system rotations was established in 1983 on a Vertisol (for soil properties see Table 1) at the ICRISAT Centre (lat 18°N, long 78°E), Patancheru, India. Treatment details are given in Table 2. The design was split-plot with cropping systems as main plots and levels of N fertilizer application as subplots. Five of the cropping systems were continuous and another five were rotated in a two-year cycle. All the cropping systems, except the rainy-season fallow system, had two crops, grown either as intercrops, dry-sown simultaneously or as sequential crops with the first crop dry-sown seven to ten days before the onset of the south–west monsoon and the second crop sown immediately after the harvest of the first crop in each year. The cropping treatments included continuous systems like the traditional fallow during the rainy season and sorghum during the post-rainy season (F + S), improved systems like a sorghum–pigeonpea intercrop (S/PP), and rainy-season sorghum followed

Table 1. Soil properties at a depth of 0–15 cm in a Vertisol at the experimental site at ICRISAT in 1983.

Soil series	pH (H_2O)	EC (dS m^{-1})	CEC (meq 100 g^{-1})	C_{org} (%)	N (mg kg^{-1})
Kasireddipalli	8.1	0.25	56.6	0.61	550

Table 2. Main plots (three replicates): cropping system rotations.

Year 1 Rainy/Post-rainy†	Year 2 Rainy/Post-rainy†	Year 1 Abbreviation‡	Year 2 Abbreviation‡
Fallow + sorghum	Fallow + sorghum	F + S†	F + S
Sorghum/pigeonpea	Sorghum/pigeonpea	S/PP‡	S/PP
Sorghum + chickpea	Sorghum + chickpea	S + CP	S + CP
Sorghum + safflower	Sorghum + safflower	S + SF	S + SF
Mungbean + sorghum	Mungbean + sorghum	M + S	M + S
Fallow + sorghum	Fallow + chickpea	F + S	F + CP
Sorghum/pigeonpea	Sorghum + chickpea	S/PP	S + CP
Cowpea/pigeonpea	Sorghum + safflower	C/PP	S + SF
Sorghum + chickpea	Sorghum + safflower	S + CP	S + SF
Sorghum/pigeonpea	Sorghum + safflower	S/PP	S + SF

† In subplots non-legumes only were given 0 (N_0), 40 (N_1), 80 (N_2) and 120 (N_3) kg N ha^{-1};
‡ + = sequential system, oblique (/) = intercrop system.

by post-rainy season chickpea (S + CP), rainy-season mung bean (*Vigna radiata*) followed by post-rainy season sorghum (M + S), rainy-season sorghum followed by a non-legume safflower during post-rainy season (S + SF). Besides post-rainy season sorghum, chickpea and safflower were included in these treatments to assess their ability to utilize residual soil moisture. Mung bean was included as a short-duration legume, to explore the possibilities for crop intensification and to avoid fallowing in the rainy season. The five rotational systems were fallow + sorghum rotated with fallow + chickpea (F + S–F + CP), sorghum–pigeonpea followed by sorghum + chickpea (S/PP–S + CP), cowpea (*Vigna unguiculata*)–pigeonpea intercrop rotated with sorghum + safflower (C/PP–S + SF), sorghum–pigeonpea followed by sorghum + safflower (S/PP–S + SF) and sorghum + chickpea rotated with sorghum + safflower (S + CP–S + SF). All these five rotations had their mirror images (for example, S/PP–S + SF and S + SF–S/PP) so that in any given year both phases of the rotations were grown. Main plot size was 12 × 12 m. Each plot was divided into four subplots receiving 0 (N_0), 40 (N_1), 80 (N_2) and 120 (N_3) kg N ha^{-1} applied to each non-legume crop as urea.

Land management

The experiment was laid out on a broad-bed (100 cm) and furrow (50 cm) type of seedbed, designed across a major slope and along the minor slope to facilitate draining of excess runoff water. Primary tillage and intercultivation were done with a tropicultor, an animal-drawn wheeled tool carrier. Mould-board ploughing twice on the beds immediately after harvest of the preceding post-rainy season crop under receding soil moisture conditions helped to make further land preparation possible before the onset of the monsoon. Cultivation in the first fortnight of May to break big clods, and finally shaping the beds with a bed-former while clearing furrows with ridgers on both sides, produced an ideal seedbed.

Crop management

Almost every year, rainy-season sowing was done in the first week of June, just before the onset of the monsoon. Dry seeding was done at a depth of 5 to 7 cm; the basal dose of fertilizer was applied simultaneously in a band 5 cm away and 5 cm below the seed furrow. However, row spacing and numbers of rows varied depending on the cropping treatments in order to maintain the optimum plant population. In the sorghum–pigeonpea intercrop, the sorghum plant population was the same as in sole sorghum, and pigeonpea had the recommended population for pigeonpea. In the cowpea–pigeonpea intercrop each component crop was also sown at the recommended rate. Therefore, the intercrops had additional plant populations in the systems. Gap filling was carried out within a week after emergence and thinning was done within 10–15 days after emergence. Weeding and intercultivation was carried out twice during rainy season cropping and once during post-rainy season including fallow treatments. Crops and variety of each crop across all cropping treatments were kept the same over the years with the exception of sorghum varieties during the post-rainy season. The hybrid CSH 8R was replaced by a variety SPV-421 after four cycles (eight years) due to non-availability of that particular hybrid sorghum seed. The varieties were rainy season sorghum CSH-6, cowpea EC-6216, pigeonpea ICPL-1, mungbean PS-16, post-rainy season sorghum CSH8R (eight years) followed by SPV 421, safflower Manjira, followed by sunflower Mordon, and chickpea Annigiri.

After 10 years safflower was replaced by sunflower because the former crop was almost wiped out due to a soil-borne fungus (*Fusarium oxysporum*) resulting in wilt and the premature death of plants. The problem was very serious in the continuous sorghum + safflower treatment. Intensive pest control measures were taken based on pest surveillance reports.

Fertilizer

Phosphorus (P) in the form of single superphosphate was applied as a basal dressing of 20 kg P ha^{-1} for both the crops in sequential rotation and for intercropping systems. Zinc sulphate was applied at 50 kg ha^{-1} once in three years. Zinc sulphate was broadcast whereas single superphosphate was band-placed. For the non-legumes nitrogen was band-placed as urea, but none of the leguminous crops in any of the systems were supplied with nitrogen irrespective of the N treatment. During the rainy season 20 kg N ha^{-1} was band-placed as a basal application and the remainder was band-placed as a top dressing three weeks after crop emergence; in the post-rainy season the entire dressing amount of N was band-placed at the time of sowing.

This paper is intended to emphasize the long-term effects of legumes on rainy-season sorghum productivity and as such the results of treatments having rainy-season sorghum as one of the components of the systems are discussed in detail.

RESULTS

Sorghum production

Legume annual contribution. The treatments were grouped into two sets, in one set legume-based cropping systems were rotated with a non-legume system of S + SF while in the second set legumes were grown every year as in S/PP or the S + CP continuous system. In Fig. 1a the sorghum grain yields of S + SF systems following different legume-based systems from 1984 to 1994 in zero N plots have been compared. This was possible because of the mirror images of both the phases of the cropping system rotation. The sorghum grain yield after the C/PP system was the highest every year, and this was followed by the sorghum grain yield following the S/PP system. The S + CP system was similar to the S/PP system in its effects on following sorghum grain yields until 1987 but from then onwards its effects were only marginally better than those of the continuous S + SF system. Even though these effects are clear, there were year-to-year differences, which were consistent in these treatments. In order to smooth these year effects, three-year moving averages are shown in Fig. 1b. The same trend as was observed in Fig. 1a is

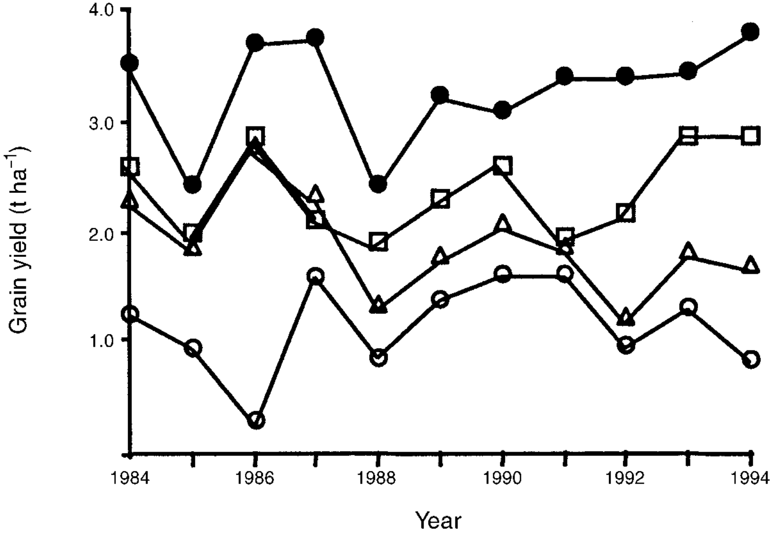

Fig. 1a. Rainy season sorghum grain yield as affected by preceding legume-based cropping system (● C/PP; □ S/PP; △ S + CP) compared with a non-legume cropping system (○ S + SF) grown without nitrogen application during 1984–94 at ICRISAT. See Table 2 for details of cropping systems.

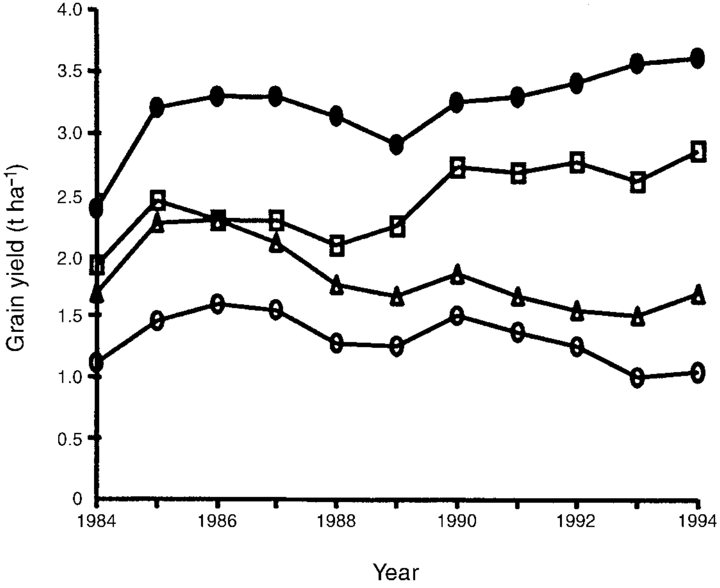

Fig. 1b. Three-year moving average of sorghum grain yield as affected by preceding legume-based cropping system (● C/PP; □ S/PP; △ S + CP) compared with a non-legume cropping system (○ S + SF) grown without nitrogen application during 1984–94 at ICRISAT. See Table 2 for details of cropping systems.

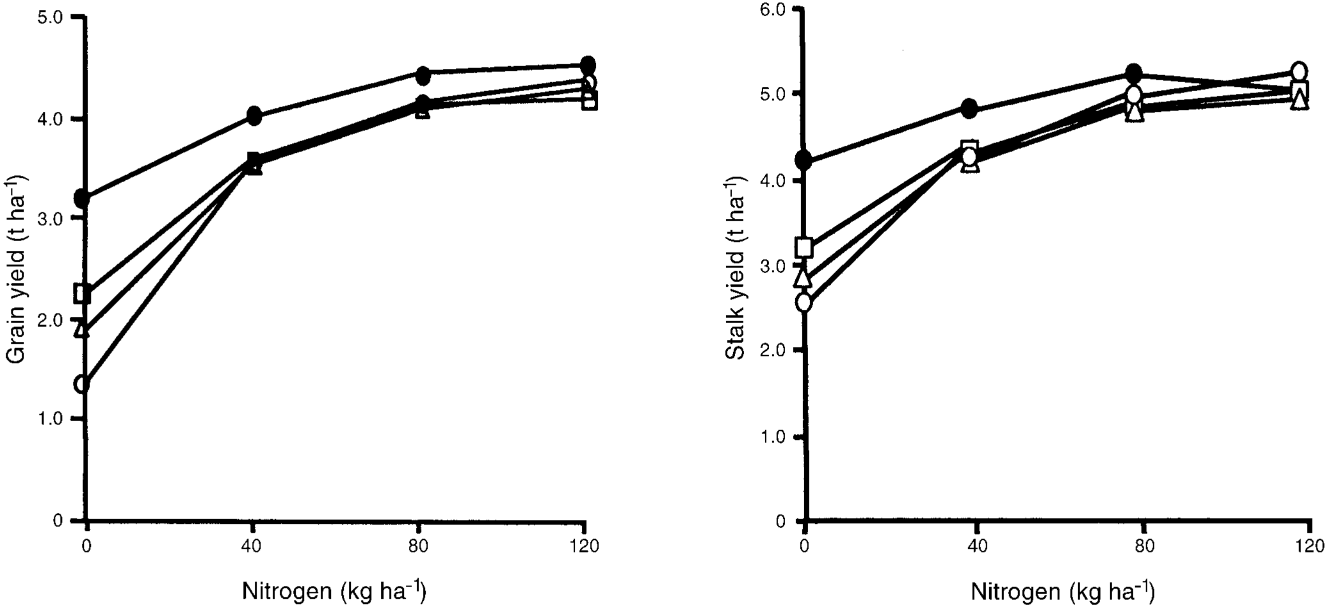

Fig. 1c. Rainy season sorghum grain yield and stalk yield (mean of 12 years) as affected by preceding legume (● C/PP; □ S/PP; △ S + CP) and non-legume (○ S + SF) cropping systems with different levels of fertilizer nitrogen at ICRISAT. See Table 2 for details of cropping systems.

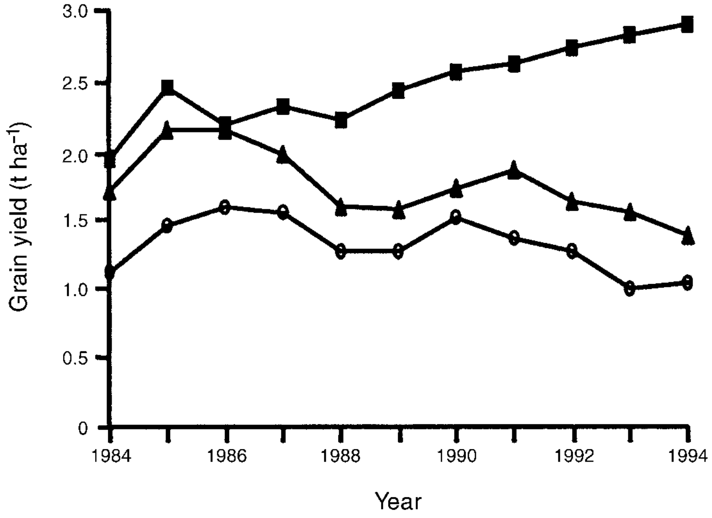

Fig. 2. Effect of continuous legume-based cropping systems (■ S/PP; ▲ S + CP) on companion or succeeding sorghum grain yield (three-year moving average) compared with sorghum grain yield in a continuous non-legume system (○ S + SF) without nitrogen application at ICRISAT. See Table 2 for details of cropping systems.

repeated in Fig. 1b but with more clarity. It can be seen from the figures that both pigeonpea-based systems were not only superior to the other two systems but also that these systems showed upward increases in the grain yields of the following sorghum from 1989 onwards. This indicated a cumulative beneficial effect whereas the other two systems showed a downward trend indicating a non-sustainable system. It can be seen from Fig. 1c that the legume effect of the C/PP system on the grain and stalk yields of following sorghum were equivalent to applied N at a rate of 40 kg ha^{-1}. Effects of continuous legume-based systems on companion or succeeding sorghum are shown in Fig. 2 together with sorghum in a continuous sorghum + safflower system. The S/PP system was superior to the S + CP system in its effects on sorghum grain yields. The sorghum grain yield in the continuous S/PP system increased steadily from 1989 onwards indicating the long-term cumulative benefits of the legume. While the S + CP system was superior to the continuous S + SF system, both systems showed a downward trend of sorghum grain yields, indicating that both these systems are not sustainable in the long term. The S + CP system was almost as good as the S/PP system from 1984 to 1986 but then it showed a declining productivity trend.

Rotational effects of grain legumes on sorghum grain yields in continuous vs. rotation systems. In Fig. 3 the sorghum grain yields in the S/PP and S + CP continuous systems are compared with the same systems rotated with the non-legume S + SF system. As the two phases of these rotations were not significantly different for any given year the mean of sorghum grain yield from both phases was taken (that is, sorghum grain yield from S/PP + S + SF divided by two).

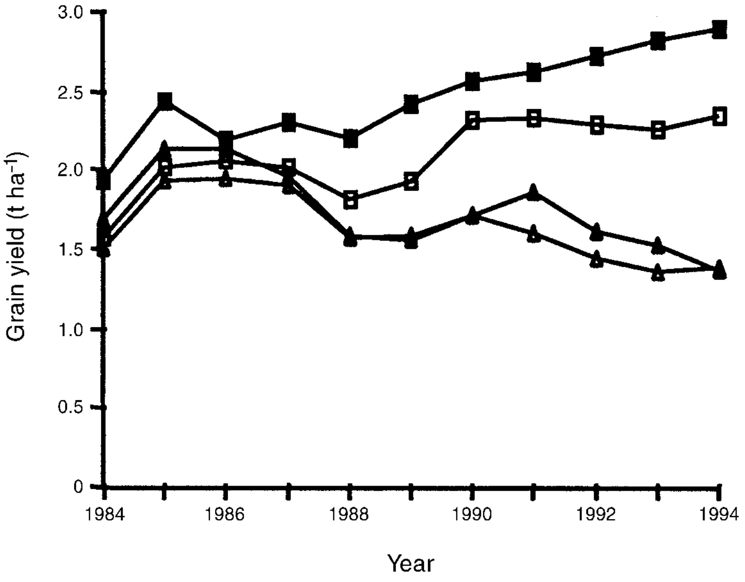

Fig. 3. Sorghum grain yield (three-year moving average) as affected by intensive (■ S/PP; ▲ S + CP legume every year) and less intensive (□ S/PP–S + SF; △ S + CP–S + SF legume alternate year) legume-based rotations of pigeonpea and chickpea grown at ICRISAT. See Table 2 for details of rotations.

These sorghum yields can be considered as rotational sorghum yields for any given year. It is clear from the graph that sorghum grain yields in continuous S/PP were the best followed by the S/PP–S + SF rotational system. Continuous S + CP and S + CP–S + SF were similar in their effect on sorghum grain yield. S/PP–S + SF and the continuous S/PP system either increased or maintained sorghum yield.

Effects of grain legumes on nutrient uptake

Nutrient uptake of sorghum. The uptake of N, P and potassium (K) by sorghum in the S + SF system following the C/PP, S/PP, S + CP and S + SF systems are shown in Fig. 4a;b;c. The uptake of N by sorghum following C/PP was highest in all years from 1984 to 1994. The effect of S/PP on the uptake of N by following sorghum was lower in all years while the S + SF system resulted in the lowest N uptake by the following sorghum crop. The P and K uptakes followed similar trends to that of N uptake. These nutrient uptake trends closely followed the grain yield trend of sorghum as shown in Fig. 1a. The average N, P and K uptakes are given in Table 3. The uptake of N by sorghum following a 100% legume (C/PP) system was 28 kg N ha^{-1} higher than that of sorghum following a non-legume (S + SF), the uptake of which was only 20 kg N ha^{-1}. The uptake of sorghum following S/PP was 15 kg N ha^{-1} more, while that of the following S + CP system was 7 kg N ha^{-1} more than that of sorghum after the S + SF system. Higher P and K uptakes were also recorded by sorghum following the C/PP system. This was followed by sorghum after the S/PP system.

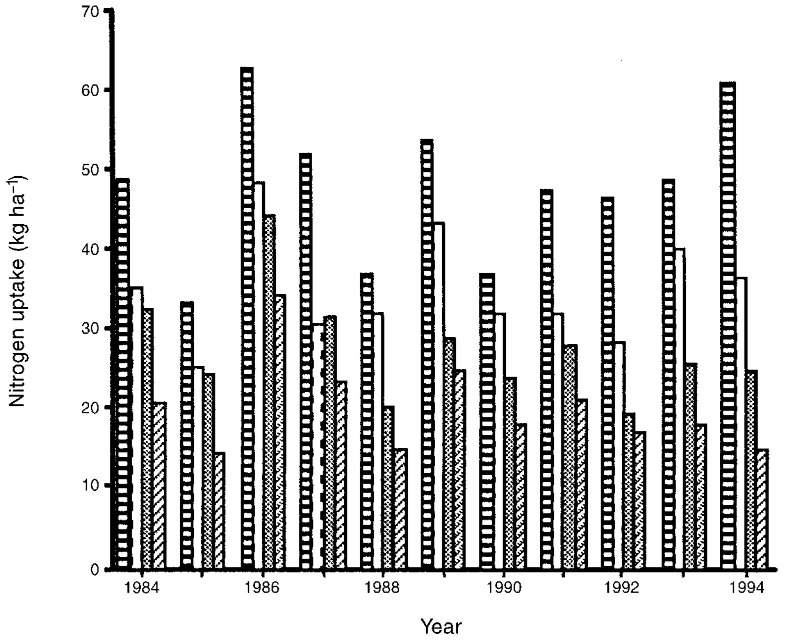

Fig. 4a. Total plant uptake of nitrogen by sorghum in a sorghum + safflower system following different legume (▤ C/PP; □ S/PP; ▩ S + CP) and non-legume (▨ S + SF) systems without nitrogen application during 1984–94 at ICRISAT. See Table 2 for details of cropping systems.

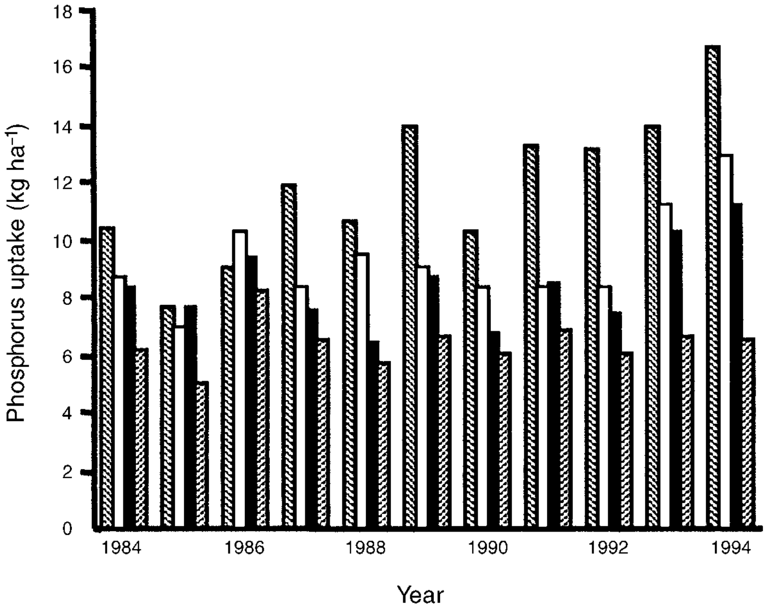

Fig. 4b. Total plant uptake of phosphorus by sorghum in a sorghum + safflower system following different legume (▧ C/PP; □ S/PP; ■ S + CP) and non-legume (▨ S + SF) systems without nitrogen application during 1984–94 at ICRISAT. See Table 2 for details of cropping systems.

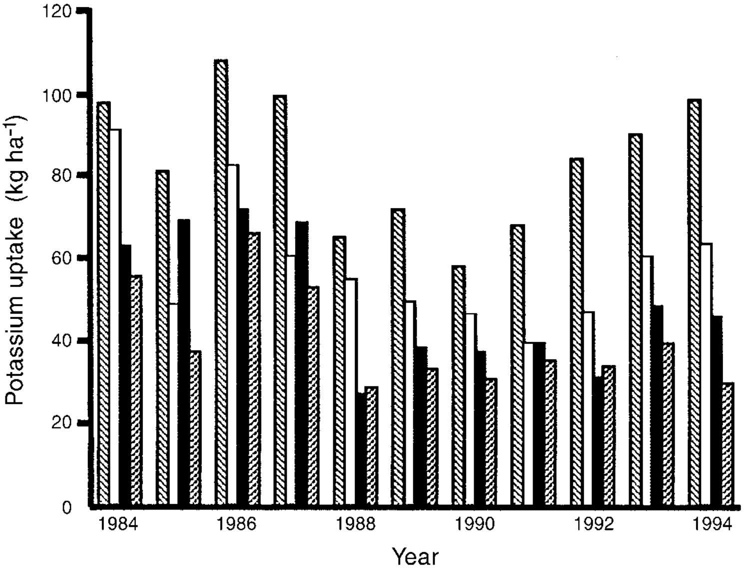

Fig. 4c. Total plant uptake of potassium by sorghum in a sorghum + safflower system following different legume (▧ C/PP; □ S/PP; ■ S + CP) and non-legume (▨ S + SF) systems without nitrogen application during 1984–94 at ICRISAT. See Table 2 for details of cropping systems.

Nutrient uptake of different cropping systems. Figure 5a;b;c depict the cumulative N, P and K uptakes for 12 years in the zero N treatment plots of different cropping systems.

The highest amount of N uptake (878 kg N ha^{-1}) was observed in the C/PP–S + SF system while the lowest (336 kg N ha^{-1}) was recorded in the continuous S + SF system. The S/PP–S + SF system had an uptake of 761 kg ha^{-1} while S + CP–S + SF took 544 kg N ha^{-1}. When the N uptakes of the legume components are compared the 100% legume C/PP recorded the highest level (337 kg N ha^{-1}) closely followed by the pigeonpea of the S/PP system (304 kg N ha^{-1}). The chickpea of the S + CP system took up only 159 kg N ha^{-1}. A sizeable part of this N uptake by legumes must have come from biological nitrogen fixation (BNF) and may not have much effect on the mining of soil N. There was also evidence of a build-up of soil total-N in plots cropped with those systems (Fig. 6). The N uptake

Table 3. Average nutrient uptake (kg ha^{-1}) of succeeding sorghum crops in selected cropping systems grown without fertilizer nitrogen application for 12 years at ICRISAT.

	Cropping system†			
Nutrients	C/PP–S + SF	S/PP–S + SF	S + CP–S + SF	S + SF–S + SF
Nitrogen	48	35	27	20
Phosphorus	12	9	8	6
Potassium	84	58	49	40

† See Table 2 for details of cropping systems.

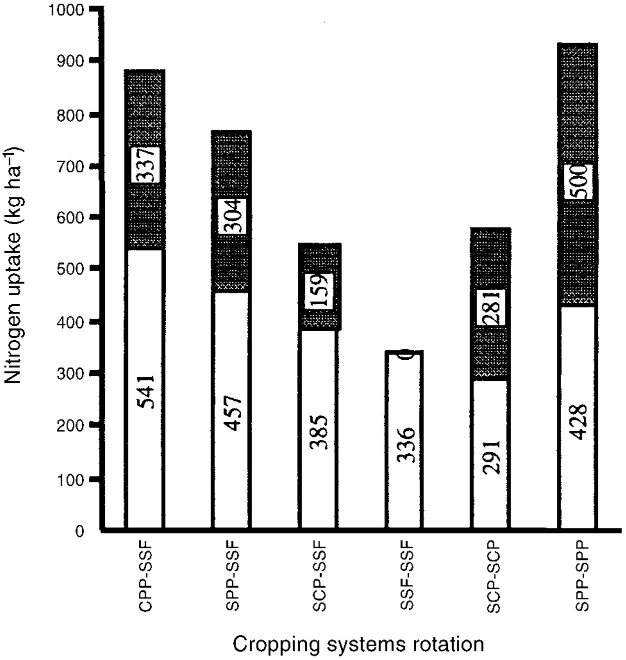

Fig. 5a. Cumulative uptake of nitrogen by crops in different cropping systems grown for 12 years at ICRISAT and represented as ▨ legume and ☐ non-legume crop uptake in subplots where no fertilizer nitrogen was applied. See Table 2 for details of cropping systems.

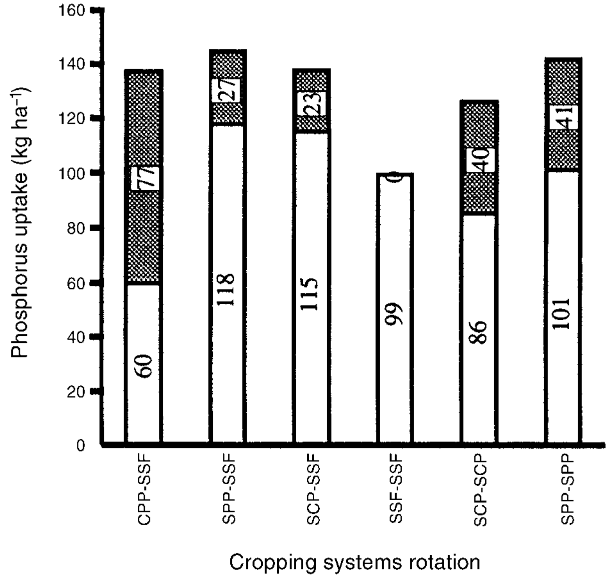

Fig. 5b. Cumulative uptake of phosphorus by crops in different cropping systems grown for 12 years at ICRISAT and represented as ▨ legume and ☐ non-legume crop uptake in subplots where no fertilizer nitrogen was applied. See Table 2 for details of cropping systems.

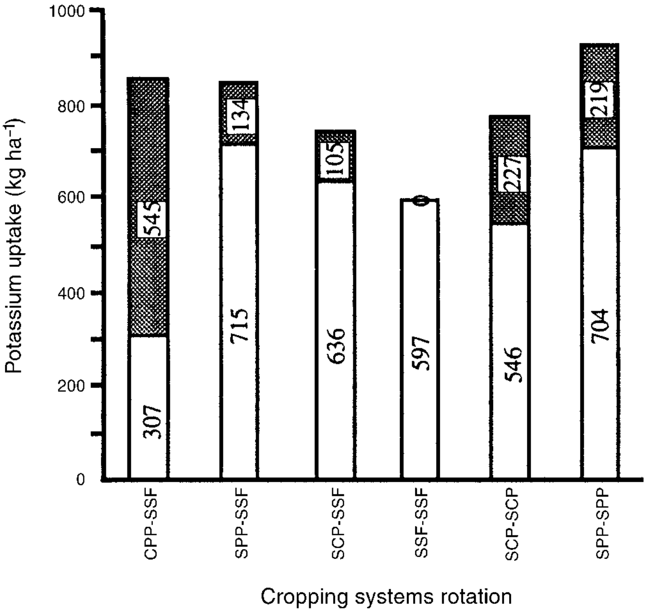

Fig. 5c. Cumulative uptake of potassium by crops in different cropping systems grown for 12 years at ICRISAT and represented as ░ legume and ☐ non-legume crop uptake in subplots where no fertilizer nitrogen was applied. See Table 2 for details of cropping systems.

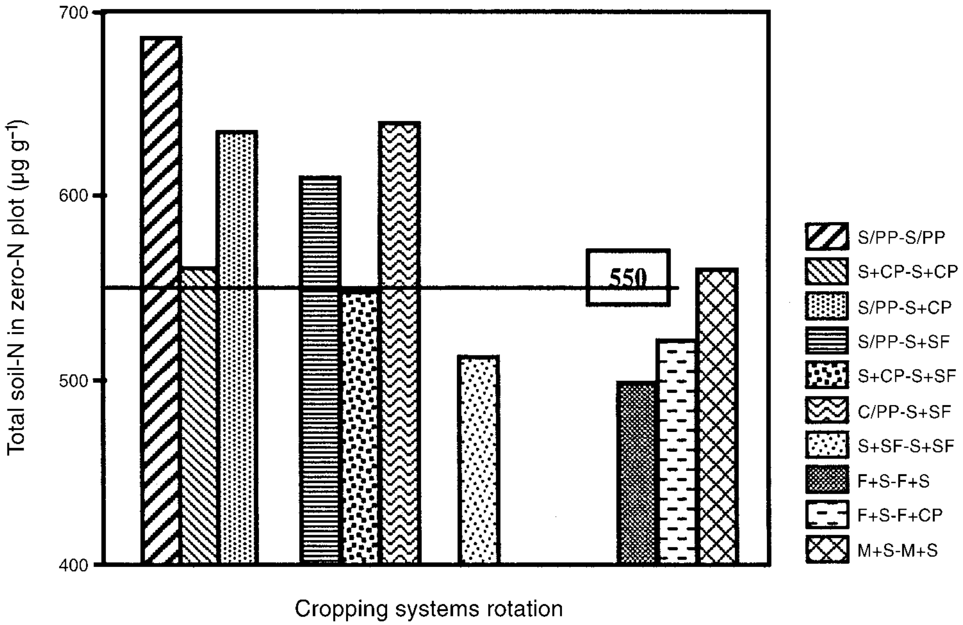

Fig. 6. Changes in soil total-N as affected by different cropping systems rotations over 10 years at ICRISAT.

by the non-legume components of different systems is very revealing. The uptake of six crops of S + SF in the C/PP–S + SF system after 12 years was 541 kg N ha^{-1} while that of 12 crops of S + SF in the S + SF–S + SF system was only 336 kg N ha^{-1}. Thus an extra 205 kg N ha^{-1} were removed by the non-legume S + SF of the C/PP–S + SF system. The uptake of twelve crops of sorghum and six crops of safflower was 457 kg N ha^{-1} in S/PP–S + SF while that of the same crops for the same period was only 385 kg N ha^{-1} in the S + CP–S + SF system.

The continuous S + SF system had the lowest P uptake (99 kg ha^{-1}) while the remaining three cropping systems had 38–46 kg ha^{-1} more P uptake than the S + SF system and did not differ significantly in their P uptakes. Again the legume and non-legume P uptakes were more or less equal (56% vs. 44%) in the C/PP–S + SF system while in the remaining systems, these values were 19% vs. 81% and 17% vs. 83% for the S/PP–S + SF and S + CP–S + SF systems respectively. This indicates that legume and non-legume crops had similar P uptakes.

Both the pigeonpea-based systems had similar K uptakes whereas the continuous non-legume systems resulted in a K uptake of 597 kg ha^{-1} (Fig. 5c). Unlike P, no K was applied to these crops and so these uptakes came entirely from the soil pool.

DISCUSSION

During the eleven-year period yield and N uptake of sorghum was higher in most years following pigeonpea-based systems. Initially, in a chickpea-based system, sorghum yield and N uptake were also higher directly after the legume, but this effect ceased after four years. Even in a continuous pigeonpea-based sorghum–pigeonpea system the sorghum grain yield was not only higher when compared with the sorghum grain yield of the non-legume continuous sorghum plus safflower system, but also showed an upward yield trend, which clearly indicated a sustainable yield increase. There are several possible reasons for the increased yield of non-leguminous plants after legumes. Increased nitrogen availability is considered one of the important factors responsible for the beneficial effect of the legume on the following non-legume crop (Sen *et al.*, 1962; Jones, 1974; Senaratne and Hardarson, 1988; Rego and Seeling, 1996). The improved grain yield of the non-legume has also been attributed to other factors, which have nothing to do with increased nitrogen availability, namely decreased pest and disease pressure and the reduction of allelopathic effects from cereal crop residues (Barber, 1972; Sanford and Hairston, 1984). Improvement of soil structure and water-holding capacity by legume crops and their residues (Toogood and Lynch, 1959; Hearne, 1986; Buresh and De Datta, 1991) influence a number of factors affecting plant growth, among which improved root growth and activity can also improve nitrogen uptake.

From the N response curves (Fig. 1c) presented in Rego and Seeling (1996) it was clear that the legume benefits on sorghum were caused by increased N availability. Sorghum grain yield was different at low N fertilizer levels where N availability was limiting, but the differences were not significant at 120 kg N ha^{-1}. If reduction of pest and disease pressure or removal of allelopathic effects had been responsible, the yield increases would have occurred over the entire range of N fertilizer treatments. As intensive plant protection measures were followed during crop growth, any benefits from reduced pests and diseases were ruled out. There was another indication that improved N availability was the reason for higher sorghum yields after legumes, and this was the increased soil mineral and mineralizable N content in the years following S/PP and C/PP. The additional amounts of mineral plus mineralizable N after S + CP, S/PP and C/PP on average were 4, 32 and 30 kg N ha^{-1} respectively which agreed in order of magnitude with the increase in sorghum N uptake following the legumes.

Including legume crops in the rotation changes the N budget of the system in two ways. One is soil N conservation as a consequence of the N-saving effect of legumes. This is because part of the N uptake by legumes will be met by their own fixation of atmospheric N; therefore a legume will mine soil N to a lesser extent than a non-legume if the harvested N in both cases is equal. Senaratne and Hardarson (1988) quantified N savings in the order of 18–23 kg N ha^{-1} by pea and faba bean when compared with barley. This can occur even when there is a negative N balance, indicating that N removal by legumes exceeds N fixation.

In situations where there is a positive N balance as a result of ploughing back crop residues either purposely or naturally, total soil N increases and additional N might become available for the succeeding crop. In the case of the pigeonpea crop, which has a medium duration of about 180 days, a considerable amount of leaf fall takes place which amounts to 30–40 kg N ha^{-1} (Sheldrake and Narayanan, 1979). An increase in total soil N under pigeonpea-based rotations which indicates a positive N balance was also observed by Rego and Seeling (1996). This positive N balance occurred despite removal of all standing crop residues and increased N uptake by sorghum (47 kg N ha^{-1} in the C/PP–S + SF system and 35 kg N ha^{-1} in the S/PP–S + SF system compared with 27 kg N ha^{-1} in the S + CP–S + SF system). The total soil N content under the S + CP–S + SF and S + SF–S + SF rotations was not very different after 10 years although a slight decline was observed. Kumar Rao and Dart (1987) reported that late-maturing pigeonpea with an N harvest index of 21% had a positive N balance of 41 kg N ha^{-1} while short-duration pigeonpea with an N harvest index of 54% had a negative N balance of -32 kg N ha^{-1}.

The N, P and K uptakes by the sorghum in pigeonpea systems was consistently higher than in the other systems, which again supports the idea that more N was available for sorghum in pigeonpea systems and resulted in better uptake of other nutrients that were not limiting, finally resulting in higher sorghum productivity on a sustainable basis. Chapman and Myers (1987) reported that the amount of N which becomes available to the following crop depends largely on the amount of N in legume residues. It is clear from this study that, as its productivity declined, chickpea produced smaller amounts of biomass than pigeonpea, which may have been the reason for the low productivity of sorghum in the chickpea system compared with the pigeonpea system. In addition growing leguminous crops can enhance soil N mineralization and thereby increase N availability for the succeeding crop (Birch and Dougall, 1967).

CONCLUSION

Medium-duration pigeonpea increased the total-N of the soil and also increased N availability for succeeding sorghum, thereby supporting sustainable sorghum yields averaging 2.7 t ha^{-1} in a rotation without mineral N inputs. As discussed above a low N harvest index and considerable *in situ* N recycling through leaf fall during its growth were the reasons for higher N inputs by pigeonpea than by chickpea. Even though medium-duration pigeonpea appeared to be ideally suited for different cropping systems in semi-arid tropical India, not only as a supplier of protein-rich grains but also a means of N supply in low-input dryland agriculture, the two-year narrow rotations showed decreasing pigeonpea yields due to a resistant insect, *Helicoverpa*, and a slight build up of pigeonpea wilt and nematodes. Thus, the optimum rotation may not be one of growing pigeonpea as often as every second year; instead it may be better included in a wider rotation system. However, in terms of sorghum productivity, it is an improved but also a sustainable system.

REFERENCES

Barber, S. A. (1972). Relation of weather to the influence of hay crops on subsequent corn yields on a Chalmers silt loam. *Agronomy Journal* 64:8–10.

Birch, H. F. & Dougall, H. W. (1967). Effect of a legume on soil nitrogen mineralization and percentage nitrogen in grasses. *Plant and Soil* 27:292–296.

Buresh, R. J. & De Datta, S. K. (1991). Nitrogen dynamics and management in rice–legume cropping systems. *Advances in Agronomy* 45:1–59.

Burford, J. R., Sahrawat, K. L. & Singh, R. P. (1989). Nutrient management in Vertisols in the Indian semi-arid tropics. In *Proceedings of an IBSRAM Workshop on Management of Vertisols for Improved Agricultural Production, 18–22 February 1985*, 147–159 (Eds J. R. Burford & K. L. Sahrawat). Hyderabad, India: ICRISAT.

Chapman, A. L. & Myers, R. J. K. (1987). Nitrogen contributed by grain legumes to rice grown in rotation on the Cununurra soils of the Ord Irrigation Area, Western Australia. *Australian Journal of Experimental Agriculture* 27:155–163.

Donald, C. M. (1964). The impact of cheap nitrogen. *Journal of the Australian Institute of Agricultural Science* 26:317–338.

Hearne, A. B. (1986). Effect of preceding crop on the nitrogen requirements of irrigated cotton (*Gossypium hirsutum* L.) on a Vertisol. *Field Crops Research* 13:159–175.

Jones, M. J. (1974). Effects of previous crop on yield and nitrogen response of maize at Samaru, Nigeria. *Experimental Agriculture* 10:273–279.

Kumar Rao, J. V. D. K. & Dart, P. J. (1987). Nodulation, nitrogen fixation and nitrogen uptake in pigeonpea (*Cajanus cajan* (L.) Millsp) of different maturity groups. *Plant and Soil* 99:225–266.

Kumar Rao, J. V. D. K., Dart, P. J. & Sastry, P. V. S. S. (1983). Residual effect of pigeonpea (*Cajanus cajan*) on yield and nitrogen response of maize. *Experimental Agriculture* 19:131–141.

Rego, T. J. (1981). Nitrogen response studies of intercropped sorghum with pigeonpea. In *Proceedings of International Workshop on Intercropping, 10–13 January, 1979*, 210–216 (Ed. R. W. Willey). Hyderabad, India: ICRISAT.

Rego, T. J. & Seeling, B. (1996). Long-term effects of legume-based cropping systems on soil nitrogen status and mineralization in Vertisols. In *Dynamics of Roots and Nitrogen in Cropping Systems of Semi-arid Tropics*, 469–479 (Eds O. Ito, C. Johansen, J. J. Adu-gyamfi, K. Katayama, J. V. D. K. Kumar Rao & T. J. Rego). Ohwashi, Tsukuba, Japan: Japan International Research Center for Agricultural Sciences.

Russell, J. S. (1984). Nitrogen in dryland agriculture. In *Proceedings of the International Congress on Dryland Farming*, 202–226. Adelaide, Australia: South Australia, Department of Agriculture.

Sanford, J. O. & Hairston, J. E. (1984). Effects of N-fertilization on yield, growth and extraction of water by wheat following soybeans and grain sorghum. *Agronomy Journal* 76:623–627.

Senaratne, R. & Hardarson, G. (1988). Estimation of residual N-effect of faba bean and pea on two succeeding cereals using ^{15}N-methodology. *Plant and Soil* 110:81–89.

Sen, S., Bains, S. S. & Mathew, B. P. (1962). Phosphate manuring of legumes. IX. Direct and indirect manuring of cereals in rotation with rabi legumes. *Journal of the Indian Society of Soil Science* 10:283–288.

Sheldrake, A. R. & Narayanan, A. (1979). Growth, development and nutrient uptake in pigeonpea (*Cajanus cajan*). *Journal of Agricultural Science*, Cambridge 92:513–526.

Toogood, J. A. & Lynch, D. L. (1959). Effect of cropping systems and fertilizers on mean weight–diameter of aggregate of Breton plot soils. *Canadian Journal of Soil Science* 39:151–156.

Virmani, S. M., Sivakumar, M. V. K. & Reddy, S. J. (1978). *ICRISAT Research Report 1.* Hyderabad, India: ICRISAT.

Willey, R. W., Singh, R. P. & Reddy, M. S. (1989). Cropping systems for Vertisols in different rainfall regions in the semi-arid tropics. In *Proceedings of an IBSRAM Workshop on Management of Vertisols for Improved Agricultural Production*, 119–131. Hyderabad, India: ICRISAT.