Long-Term Effects of Legume-Based Cropping Systems on Soil Nitrogen Status and Mineralization in Vertisols

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Long-Term Effects of Legume-Based Cropping Systems on Soil Nitrogen Status and Mineralization in Vertisols

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Abstract

Vertisols in assured rainfall areas potentially allow double cropping or intercropping with grain legumes. The inclusion of grain legumes in rotations provides nitrogen (N) inputs into the system in addition to valuable grain yields. A cropping systems rotation experiment was established in 1983 on a Vertisol to quantify N-contribution of grain legumes to non-legumes in the rotation and short- and long-term changes in soil N-fractions. Different rotations influenced soil N-fractions to a different extent both in the short- and the long-term. In general the greatest positive effect on the N-economy of the systems was observed in rotations containing medium-duration pigeonpea. In these rotations, mineral-N at the beginning of the cropping season and mineralizable-N were higher in years following the legume. This was also reflected in the N-uptake of the sorghum following the legume. Mineral-N at the beginning of the cropping season fluctuated from year to year. Mineralizable-N in the topsoil (0-15 cm) increased over the 10 year period in rotations with pigeonpea intercrops from 4 to a maximum of 19 mg kg^{-1}. In addition to the build-up of mineralizable-N, total-N in the topsoil of these treatments also increased from 550 to a maximum of 645 mg N kg^{-1}. The build-up of soil fertility over several years increased N-availability and contributed to the sustainability of the system in a low nutrient input situation.

Introduction

Vertisols are one of the major groups of soils in the semi-arid tropics (SAT). In India, farmers have traditionally cultivated only a postrainy season crop on stored soil moisture in Vertisols. However, these soils have the potential to support double cropping or intercropping with crops in the rainy and postrainy seasons since their water-holding capacity is high due to the depth of the soil (> 1 m) and high clay content (> 50 %). But farmers did not crop during the rainy season because of difficulties in operation once the soil is wet. For two decades International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has advocated a Vertisol technology that involves dry seeding of rainy

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season crops followed by a sequential crop or intercropping of rainy season crops with one of the components being a long-duration crop (Virmani et al. 1989). A major constraint to the success of this technology is the need for nutrient inputs since Vertisols are often deficient in nitrogen (N) and phosphorus (P) (Burford et al. 1989). Nitrogen is required in large amounts for high productivity (e.g., 80 kg N ha^{-1} for rainfed rainy-season sorghum). But many farmers of the Indian SAT cannot afford to apply optimum amounts of N-fertilizer. In addition, they consider the risk of this investment too high as rainfall in this region is highly variable and unpredictable.

The inclusion of grain legumes in rotation either as a sole crop or as an intercrop provides N-inputs into the system. Grain legumes are more attractive to farmers than green manure legumes because of their high economic value. Legumes influence the N-economy of a system in two ways, they fix part of their N-requirement from atmospheric N_2 and therefore deplete available soil-N less than non-legumes, and they also provide part of the fixed-N upon mineralization of plant residues to the following non-leguminous crop (Peoples and Crasswell 1992). For agronomic purposes it is important to know when and how much N from this source becomes available to the following crops. But from a sustainability point of view it is also important to know how soil fertility is changed in the long-term if legumes provide the sole means of N-input into the system. To evaluate the N-contribution of legumes to non-legumes and short- and long-term changes in soil N-fractions, a cropping systems rotation experiment was established in 1983 with 10 different cropping system rotations on a Vertisol. The soil had an organic carbon content of 0.61% and a total nitrogen content of 550 mg kg^{-1}. Soil pH (H_2O) was 8.1. Due to the high clay content the cation exchange capacity was also high with 56.6 meq $100g^{-1}$. Electrical conductivity was 0.25 dS m^{-1}.

Results from four rotations are reported in this paper: (1) sorghum in the rainy season followed by safflower in the postrainy season continuously (S+SF-S+SF); (2) sorghum in the rainy season followed by chickpea in the postrainy season in rotation with sorghum followed by safflower (S+CP-S+SF); (3) sorghum/pigeonpea intercrop in rotation with sorghum followed by safflower (S/PP-S+SF); (4) cowpea/pigeonpea intercrop in rotation with sorghum followed by safflower (C/PP-S+SF). For rotations with a different system in the second year than in the first, mirror images of these rotations were included in the trial, so that every year both phases of the rotation were available for sampling. Each plot was divided into four subplots receiving 0 (N_0), 40 (N_{40}), 80 (N_{80}), and 120 (N_{120}) kg N ha^{-1} applied to each non-legume crop as urea.

Yield and N-uptake of sorghum

Sorghum grain yield following a legume was in most years higher than following a non-legume. As an example, Figure 1 shows the sorghum grain yield following either the legume or the non-legume part of S/PP-S+SF and S+CP-S+SF rotations. The positive effect of the legume on the yield of the following non-legume was apparent, although dry matter yield and grain yield of sorghum in the four rotations differed from year to year. In case of the S+CP-S+SF rotation, the difference between yield after legume and non-legume

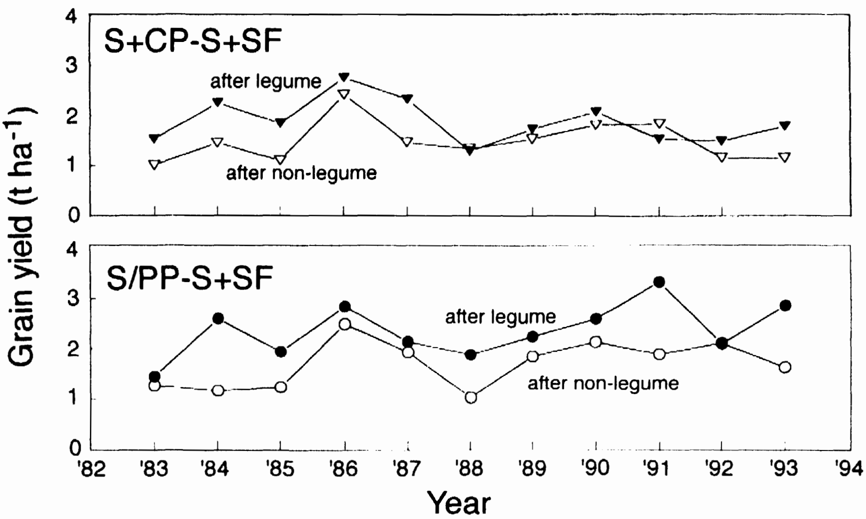

Fig. 1. Sorghum grain yield in N_0 treatments of S+CP-S+SF and S/PP-S+SF rotations following either the legume or the non-legume part of the rotation.

declines and becomes negligible after 1988. This coincides with declining chickpea yields in this rotation. Among the two systems, sorghum following S/PP always recorded higher grain yields than sorghum following S+CP, with the exception of 1987.

To better visualize long-term trends a 3-year shifting average of sorghum N-uptake was calculated for N_0. Sorghum N-uptake following a non-legume (Fig. 2a) showed clear

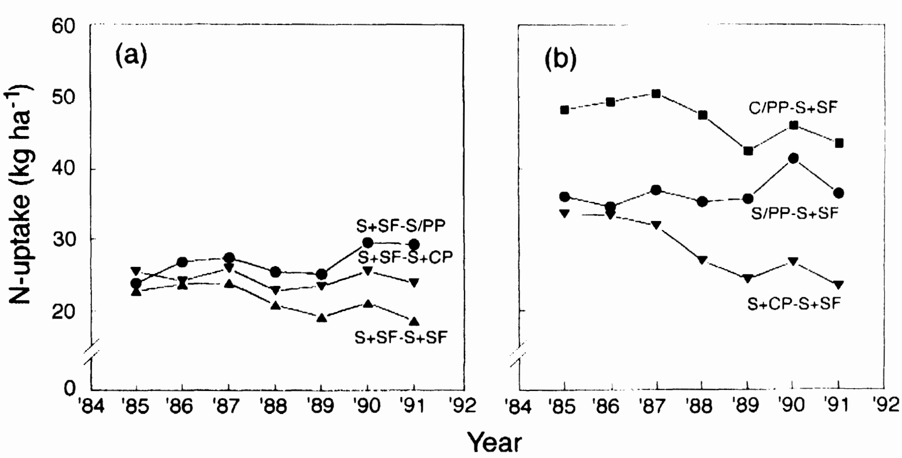

Fig. 2. Long-term trends of sorghum N-uptake in N_0 treatments following a non-legume (a) and a legume (b); shifting average over 3 years.

trends for the three system rotations. In the non-legume system (S+SF-S+SF), N-uptake declined, whereas in the S+CP-S+SF rotation it remained stable, and in the S/PP-S+SF it increased. These trends are indicators for the long-term effects of different rotations on soil N-availability. Sorghum N-uptake after legumes (Fig. 2b) was higher compared to uptake after non-legumes with the exception of the S+CP-S+SF rotation, as seen before. Sorghum N-uptake following C/PP was highest, but in this treatment as well as in sorghum following S+CP, a declining trend was observed (Fig. 2b), reflecting a decline in legume yields, biomass production, and N-yield. However, the sorghum N-uptake after S/PP remained stable over the 10-year period, although pigeonpea N-yields declined in this treatment as well.

There are several possible reasons for the increased yield of non-leguminous plants after legumes. Some of them have nothing to do with increased N-availability, such as decreased pest and disease pressure and reduction of allelopathic effects from cereal crop residues in wider rotations (Barber 1972; Sanford and Hairston 1984). Furthermore, 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 increase N-uptake.

From the N-response curves (Fig. 3) it becomes clear that in our case the legume benefits on sorghum were caused by increased N-availability, since yield was different only at low N-fertilizer levels where N-availability was limiting. At 120 kg N ha^{-1}, differences were not significant. If reduction of pest and disease pressure or removal of allelopathic effects would have been the responsible mechanism, the yield increase should have occurred over the entire range of N-fertilizer treatments. The reason that rotation benefits were not observed is most likely that the experiment was carried out under intensive pest

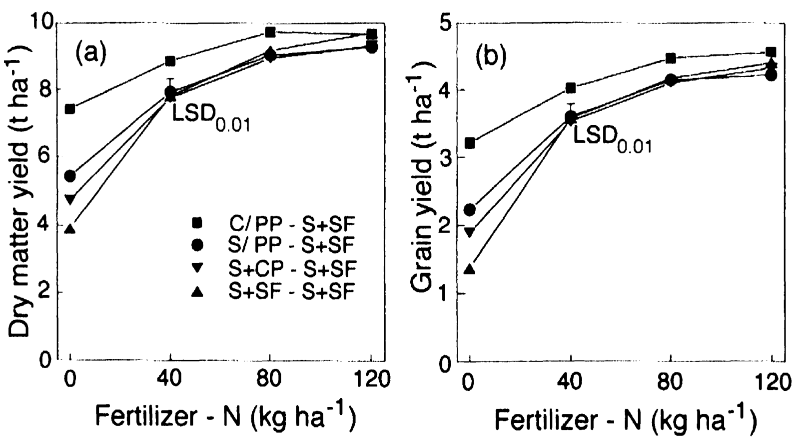

Fig. 3. Sorghum dry matter (a) and grain yields (b) following a non-legume system or 1 of 3 different legume systems at 0, 40, 80, and 120 kg N ha^{-1} fertilizer levels. A 10 year average.

control. Another indicator that improved N-availability was the reason for higher sorghum yields after legumes is the increased soil mineral-N and mineralizable-N content in years following S/PP and C/PP.

Mineral and mineralizable-N in soil

If N is the limiting nutrient for plant growth and N is not applied to plant, N-uptake depends on the mineral-N supply by the soil. The mineral-N supply by soil is determined by the mineral-N content in soil at the beginning of the cropping season and the mineralization/immobilization and N-loss mechanisms operative during the cropping season.

Soil samples were taken in 1983, 1988, 1991, and 1993 during the dry season (May). Mineral soil-N was determined in dried soil after extraction with 2 M KCl by steam distillation (Keeney and Nelson 1982). Mineralizable-N was determined after anaerobic incubation (Keeney and Bremner 1966) by the same method.

On average, top soil mineral-N content in N-0 treatments at the beginning of the growing season was higher in S/PP-S+SF and C/PP-S+SF treatments in years following the legume system (Fig. 4). But only in the S/PP-S+SF treatment was the mineral-N content always higher. Differences in NH_4-N content between rotations were not significant at any depth, and differences in NO_3-N content were significant to a 60-cm depth. In the total profile an additional amount of, on average, 24 and 16 kg N ha^{-1} in the S/PP-S+SF and C/PP-S+SF, respectively, was available at the beginning of the cropping season in years following the legume. Mineralizable-N in the topsoil at the beginning of the growing season was also increased in years following the legume. An additional amount of 4 kg N ha^{-1}

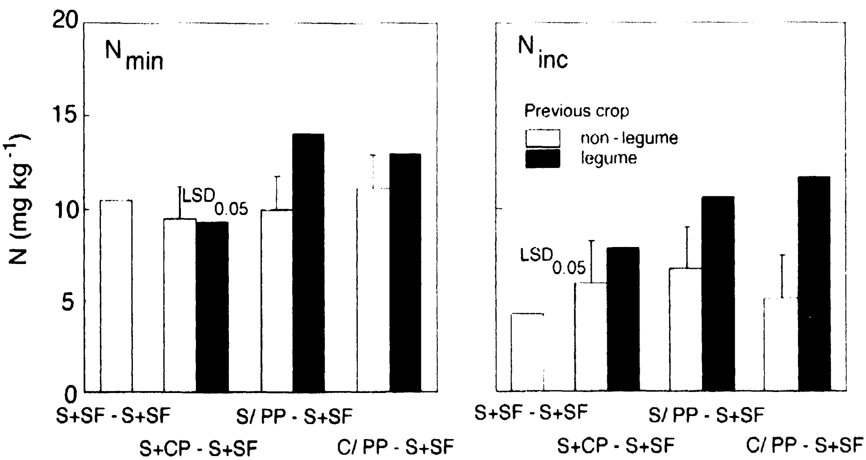

Fig. 4. Mean mineral-N (N_{min}) and mineralizable-N (N_{inc}) in the topsoil (0-15 cm) of N_0 treatments.

was found in S+CP-S+SF, 8 kg in S/PP-S+SF, and 14 kg in C/PP-S+SF.

For the evaluation of the long-term effects of rotations on the soil mineral-N content, the treatment and its mirror image (i.e., S/PP-S+SF and S+SF-S/PP) was averaged. Mineral-N content fluctuated from year to year but no consistent long-term trend for any rotation became obvious (Fig. 5). However, the mineralizable-N in the top soil showed some clear treatment effects after 10 years. The C/PP-S+SF treatment resulted in the highest mineralizable-N, at 19 mg kg^{-1}, followed by S/PP-S+SF, at 12 mg kg^{-1}. The S+CP-S+SF treatment recorded 11 mg kg^{-1} of soil. The non-legume treatment S+SF-S+SF had the lowest mineralizable-N content with 6 mg kg^{-1} soil.

The relationship between mineral-N and mineralizable-N at the beginning of the cropping season and N-uptake of sorghum is shown in Figure 6. With a linear regression, which seemed appropriate owing to the low amount of N in the N-0 treatments, mineral-N and mineralizable-N explained only 30% and 34% of the sorghum N-uptake, respectively.

The additional amount of mineral-N plus mineralizable-N was 4 kg N ha^{-1} after S+CP, 32 kg N ha^{-1} after S/PP, and 30 kg N ha^{-1} after C/PP which agree in the order of magnitude with the increase in sorghum N-uptake following the legumes. However, the relationship between mineral-N or/and mineralizable-N and sorghum N-uptake is not good enough for predictive purposes. Using these two parameters in a multiple linear regression model did not improve the prediction of N-uptake. Doughton and Mackenzie (1984) found a better relationship using an asymptotic equation for predicting grain yield from soil mineral and fertilizer-N. But the reason for the better fit was a wider range of N-supply (0 - 240 kg N ha^{-1} compared to 0 - 50 kg N ha^{-1} in our case), which they obtained by adding applied fertilizer-N to the soil mineral-N values. We concluded that mineralization, which is not correctly reflected in the measured mineralizable-N at the beginning of the growing season, and N-loss mechanisms must play an important role for N-availability in these soils and cropping systems.

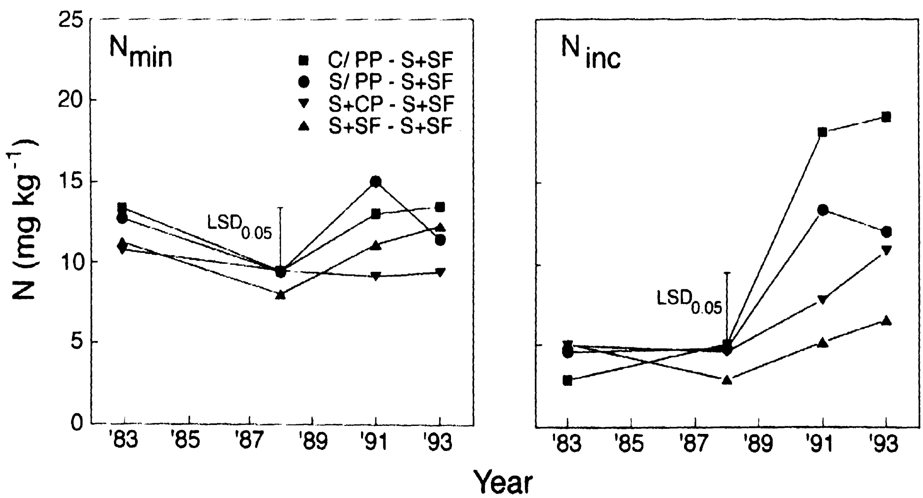

Fig. 5. Mineral-N (N_{min}) and mineralizable-N (N_{inc}) in the topsoil (0-15 cm) of N_0 treatments during the course of the experiment.

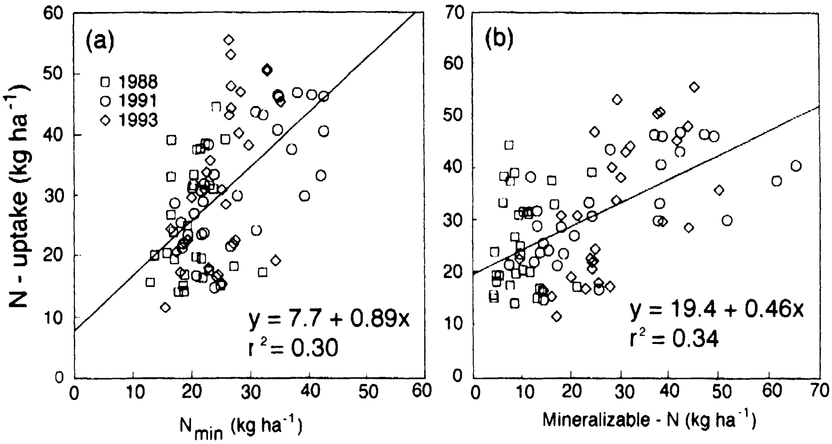

Fig. 6. Relationship between N-uptake of sorghum and mineral-N (a) and mineralizable-N (b) at the beginning of the cropping season in N_0 treatments.

The amount of N that becomes available to the following crop depends largely on the amount of N in legume residues (Chapman and Myers 1987). In addition, growing a leguminous crop can enhance soil N-mineralization and thereby increase N-availability for the succeeding crop (Birch and Dougall 1967). Using the N in legume residues for the prediction of N-availability to non-leguminous crops in legume-based rotations is a cheaper and probably more promising way than soil analysis for mineral and mineralizable-N as it was discussed above. This is especially so if legume yield data are used in a N-availability model based on organic matter turnover that takes N-losses into account.

Long-term changes in total soil-N

The occurrence of legume benefits does not necessarily indicates a positive N-balance of legume crops. Higher soil mineral-N content after legumes can be due to the N-savings effect of legumes. The amount of mineral-N remaining in soil after a legume crop will always be greater than that after a non-legume crop with an equal amount of N in harvest products because the legume will satisfy part of its N-requirement through atmospheric N_2- fixation. Senaratne and Hardarson (1988) quantified N-savings on the order of 18 to 23 kg N ha^{-1} by pea and faba bean when compared with barley. But the N-budget was negative when all above-ground crop residues were removed. Incorporation of crop residues made the N-budget positive (59 kg N ha^{-1}) in the case of faba bean and balanced the budget in the case of peas.

In addition to the effect of partial or complete removal of crop residues, the N-balance of grain legumes depends on N-harvest index of the total plant (including roots) and soil N-status. Short duration pigeonpea with a N-harvest index of 54% had a negative N-balance of -32 kg N ha^{-1} even when crop residues remained in the system. In contrast, late maturity pigeonpea with a N-harvest index of 21% had a positive N-balance of 41 kg N ha^{-1} under these conditions (Kumar Rao and Dart 1987). Higher soil N-availability reduced the N-balance of cowpea from +52 to 0 kg N ha^{-1} due to reduced N_2-fixation (Eaglesham et al. 1982).

Long-term changes in total soil N-content give some indication of the N-balance in systems of the present study. Total-N was determined with a modified Kjeldahl method in order to account for nitrate and nitrite in the samples (Dalal et al. 1984). The cropping systems under study did influence the total-N in the surface soil (0-15 cm). The C/PP-S+SF and S/PP-S+SF rotation increased the total soil-N from 550 to 645 and to 629 mg N kg^{-1}, respectively, in 10 years (Fig. 7a). A slight decline was observed in the S+CP-S+SF and S+SF-S+SF rotations. In Figure 7b the rotation effects at different levels of mineral fertilizer application are compared for total-N build-up after 10 years. Differences in total soil-N due to fertilizer-N occurred only between the N_0 and the fertilized treatments (N_{40}, N_{80}, N_{120}) in the non-legume system (S+SF-S+SF). Increasing N-fertilizer level did not increase total-N build-up. The build-up of total soil-N in the legume system (C/PP-S+SF) was considerably larger than that due to fertilizer application. Most probably mineral fertilizer-N is subjected to a larger extent to losses than the organically combined N resulting from legume crop residues.

The observed increase in total soil-N under pigeonpea based rotations indicates a positive N-balance for these rotations (C/PP-S+SF and S/PP-S+SF) even though all standing-crop residues were removed and average sorghum N-uptake was considerable

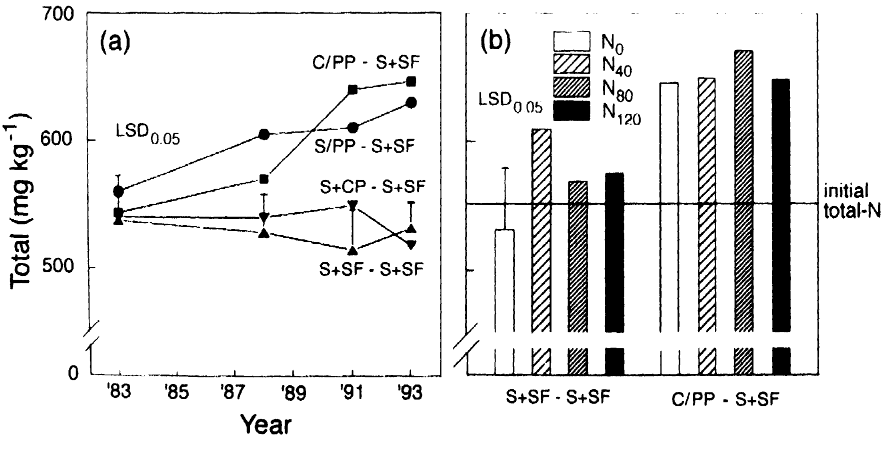

Fig. 7. Total soil-N content in the topsoil (0-15 cm) of N_0 treatments under different rotations (a) and total soil-N content under different N-fertilizer treatments after 10 years (b).

/ith 46 kg N ha^{-1} at N_0 of C/PP-S+SF and 31 kg N ha^{-1} at N_0 of S/PP-S+SF. One reason for his might have been N in fallen leaves, which returned 30% of the total N-uptake before iarvest. Furthermore, pigeonpea can obtain up to 88% of its N-uptake from atmospheric N_2-fixation (Kumar Rao et al. 1987). In the N-0 treatment, which did not receive mineral-N iddition for 10 years, it can be expected that N_2-fixation is at its maximum.

After 10 years, the total soil-N content under S+CP-S+SF and S+SF-S+SF rotations was not very different (Fig. 7a). A slight decline was observed in both treatments. The decline of total soil-N under S+SF-S+SF at N_0 was much lower than expected. In 10 years, a total of 300 kg N ha^{-1} was removed from soil in harvested plant parts. But total-N in the top soil declined only by 53 kg N ha^{-1}. Possibly the N-depletion was partly balanced through N-deposition by rainfall, which at ICRISAT Asia Center can contribute up to 12 kg N $ha^{-1}a^{-1}$ (K. V. S. Murthy, ICRISAT, personal communication, 1995). Another N-source might be non-symbiotic nitrogen fixation. But the amount of fixed-N in association with sorghum roots is at less than 0.5 kg ha^{-1}, which is rather small (Lee et al. 1994).

In legume-based cropping systems, particularly the pigeonpea-based system, the fallen leaves and root mass undergo mineralization during the following crop season and supply mineral-N to the sorghum. However, part of the N remains in the soil organic N-pool. For this reason we observed more dry matter, grain yield, and N-uptake following legume-based systems, and at the same time increased mineralizable and total soil-N in the long-term. This increased content of mineralizable and total soil-N results in enhanced N-availability to non-legume crops leading to higher productivity on a sustainable basis.

Conclusion

Medium duration pigeonpea as a component of intercropping systems consistently benefitted the succeeding sorghum during the experimentation period of 10 years. Pigeonpea not only increased N-availability to sorghum, and thereby supported a sustainable sorghum yield of on average 2.7 t ha^{-1} in a rotation without mineral-N inputs, but also increased total soil-N. A low N-harvest index and considerable returns of N through leaf fall during its growth are the reasons for beneficial effects of pigeonpea on crop productivity and soil fertility. Chickpea when compared to pigeonpea produced lower amounts of biomass and the beneficial effects were smaller. We are convinced that medium duration pigeonpea is especially suited for cropping systems in low input dryland agriculture. However, we have noticed decreased pigeonpea yields during the course of the experiment mainly due to build-up of soil borne diseases, such as fusarium wilt, and of parasitic nematodes and insect pests (Helicoverpa) damage of pigeonpea grains. This problem may be alleviated either by increasing the length of rotation or by changing to wilt-resistant varieties that are now available.

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