



# Role of biological nitrogen fixation in legume based cropping systems; a case study of West Africa farming systems

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## Abstract

Nitrogen (N) has been gradually depleted from West African soils and now poses serious threats to food production. Many ways of increasing N supply (e.g. judicious use of inorganic fertilizers and nitrogen-fixing plants) have been tried in West African farming systems. Herbaceous and woody legumes commonly contribute 40–70 kg N ha<sup>-1</sup> season. This represents about 30% of the total N applied as residues. Nevertheless and despite repeated demonstrations of the usefulness of green manures in enhancing soil fertility, their practices and adoption are still limited. Promiscuous soyabeans are being used to develop sustainable cropping systems in the moist savannah. Reliable estimates of N<sub>2</sub> fixed by soyabeans and their residual N benefits to subsequent cereal crops in the savannah zone of southern Guinea have only infrequently been made. The actual amounts measured varied between 38 and 126 kg N ha<sup>-1</sup> assuming that only seeds of soyabeans are removed from the plots, the net N accrual of soil nitrogen ranges between minus 8 kg N ha<sup>-1</sup> and plus 47 kg N ha<sup>-1</sup> depending on the soyabean cultivar. Residual soyabean N values of 10–24 kg N ha<sup>-1</sup> (14–36% of the total N in maize) were obtained in a soyabean-maize rotation. Although cereal yields following legume cultivation have been attributed to greater N accumulation, our data show that the relative increase in maize N was smaller than the relative increase in dry-matter yield. Hence, the increased yields of maize following soyabeans are not entirely due to the carry-over of N from soyabean residues (as well as to conservation of soil N) but to other rotational effects as well. It is thus clear that the N benefit of grain legumes to non-legumes is small compared to the level of N fertilizer use in more intensive cereal production systems but is nevertheless significant in the context of the low amounts of input in subsistence farming.

## Introduction

In response to increasing population pressures, agricultural production is intensifying across West Africa. In the Northern Guinea Savannah (NGS) of Nigeria such relatively new crops, as maize and soybean, are replacing sorghum, millet, and groundnut of traditional agriculture. As a result soil degradation and nutrient depletion have gradually increased and now poses serious threats to food production. For example, the reduction in the length of fallow from six to two years resulted in yield decreases of maize from 3 t

ha<sup>-1</sup> to about 0.7 t ha<sup>-1</sup> in the derived savannah of Benin (Houngnandan et al., 2000a).

Soils supporting maize (the most common cereal in rain-fed agriculture), must supply 50–60 kg N (usually as nitrate) and 30 kg P ha<sup>-1</sup> (in a form available to the plant) for each ton of grain produced per hectare (Weber et al., 1992; Weber, 1996). Obviously soils of the savannah cannot supply the quantities of N required and levels decline rapidly once cropping commences. Nitrogen depletion is at least 36 kg N ha<sup>-1</sup> per year and may even approach 80 kg N ha<sup>-1</sup> in some farmers' fields in the NGS in Nigeria (Vanlauwe et al., 1998). Depletion of organic matter is approximately 4% per year, resulting in very low organic

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carbon levels after 15–20 years of cultivation. Below 0.5% carbon, the soil supplies less than 50 kg N ha<sup>-1</sup> and this is sufficient for only about 1 t ha<sup>-1</sup> of maize grain at normal N use efficiency (Carsky and Iwuafor, 1999). Nitrogen supplied from the breakdown of indigenous organic matter must be supplemented from other sources.

Since the mid-1990s, it has become clear that to augment crop production to the yields needed to sustain the growing population without further degrading the soil, inorganic fertilisers are required. The results of a recent on-farm survey showed that more than 90% of farmers in some villages of the NGS in Nigeria used chemical fertilisers but up to 81% of maize fields received less than half of the recommended 120 kg N ha<sup>-1</sup> because of the high costs resulting from the removal of subsidies and inefficient marketing (Manyong et al., 2001). Similar results have been reported in the derived savanna in Benin (Houngnandan et al., 2000a). Because of the inherent characteristics of these soils and the relatively high cost of inorganic fertilisers, a consensus now exists in the research and development community that these inorganic inputs need to be complemented with organic matter.

Of the plant nutrients, N is unique in that its supply and replenishment of soil capital need not entail the direct application of external inputs. Nodulated roots as well as aboveground crop residues, left after the crop has been harvested, partially replenish soil organic N. If N availability limits crop productivity and legumes occupy a significant role within cropping systems, BNF has much to offer. It is the purpose of this review to show that these conditions are met within many farming systems in West Africa.

#### *Use of legumes and N input in maize-based cropping systems*

Traditional and modern West African farming systems almost invariably include legumes. In this sense, farmers recognise that legumes are valuable components. The benefits from BNF of legumes are both direct, due to intrinsic value of legumes, and indirect, as the inclusion of a legume affords greater yield stability in adverse growth conditions and benefit companion or following non-leguminous crops.

Farmers' perceptions of crop importance in improving or depleting soil fertility were investigated in the NGS in Nigeria (Manyong et al., 2000). Cereals, particularly maize and sorghum, were regarded as depleting soil nutrients while legumes (soybean,

*Table 1.* Total N, proportion and amounts of N<sub>2</sub> fixed by herbaceous and forage legumes grown at five sites representing three agro-ecological zones in the moist savannah of Nigeria, West Africa

	Total N (kg ha <sup>-1</sup> )	N <sub>2</sub> fixation	
		%Ndfa	(kg N ha <sup>-1</sup> )
<i>Aeschynomene histrix</i>	105	75	79
<i>Cajanus cajan</i>	113	77	86
<i>Centrosema brasilianum</i>	20	0*	0*
<i>Centrosema pascuorum</i>	216	88	190
<i>Chamaecrista rotundifolia</i>	144	82	117
<i>Crotalaria varicosa</i>	146	82	120
<i>Psophocarpus palustris</i>	102	74	76
<i>Lablab purpureus</i>	238	89	215
<i>Mucuna pruriens</i>	299	91	242
<i>Pseudovigna argentea</i>	86	69	107
<i>Pueraria phaseoloides</i>	193	86	167
<i>Spylosanthes hamata</i>	184	86	158

Source: Sanginga et al. (1996a).

\* No nodulation.

groundnut, and cowpea in that order) were regarded as beneficial. Farmers thus correctly perceive the role legumes play in enhancing of soil fertility.

From the mid-1980s to the early-1990s, the environmental degradation resulting from over-cropping (Sanchez, 1994) and the abolition of the fertilizer subsidies in West Africa, led to the development of farming systems where inputs of mineral fertilizers were minimized or even avoided (Swift, 1985). Alley cropping and live-mulch legume systems are excellent examples of such minimal or zero input technologies, and these will be discussed below.

#### *Herbaceous legumes*

##### *Nodulation and nitrogen fixation*

Herbaceous and shrub legumes for weed suppression and soil improvement are currently being introduced into the cropping systems of the moist savannah and humid zones of West Africa. If these legumes are not well managed, however, they may depend solely on available N. Despite the recent activity of various researchers in the agro-ecological zones of sub-Saharan Africa, an enormous number of legumes whose capacity to nodulate and fix N<sub>2</sub> has not been determined.

Recent estimates carried out using the total N difference method with 12 herbaceous and forage leguminous species grown in soil from five sites representing three distinct agro-ecological zones in the moist savannah in Nigeria indicate that except for *Centrosema brasilianum*, the average percentage of

N derived from the atmosphere by  $N_2$  fixation (Ndfa) was about 80% (Sanginga et al., 1996a). The amount of  $N_2$  fixed varied between 76 and 242 kg ha<sup>-1</sup> depending on the legume species (Table 1). In the Côte d'Ivoire, the mean % Ndfa in twenty one legumes was 68–73% at two sites with bi-modal rainfall but only 52–54% where there was a single rainy season (Becker and Johnson, 1998). The % Ndfa in the legumes showed a loose positive relationship with shoot N accumulation, indicating that poor nodulation and  $N_2$ -fixation was linked to poor growth in general. Thus, simple measurement of N accumulation in the legume might provide a useful indication of the amount of  $N_2$  fixed. Based on a number of characteristics including BNF and their potential uses, two species, *Mucuna pruriens* and *Lablab purpureus*, were selected for further studies. Work at one station in the derived savannah of Nigeria indicated that the proportion and amount of  $N_2$  fixed by *Mucuna* and *Lablab* depended on the cropping systems (live-mulching or *in situ* mulching) and field practices (inoculation with rhizobia or N fertiliser application). The quantity of N fixed by *Mucuna* in the N fertilized and rhizobia inoculated plots ranged from 133 kg to 188 kg N ha<sup>-1</sup>. In un-inoculated (*Lablab*) plots, the quantity ranged from 146 kg to 157 kg N ha<sup>-1</sup> (Ibewiro, 1998). This represents 64–75% of the plant total N for *Mucuna* and 62–70% for *Lablab*. Live-mulching of maize increased the proportion of  $N_2$  fixed by 14% (*M. pruriens*) and 20% (*L. purpureus*). Nevertheless, the amounts of N fixed by both legumes were significantly higher *in situ* than in the live-mulched systems. These data suggest that the competition for soil N with the associated maize could have stimulated N fixation.

Many studies have, however, shown a great disparity between results obtained on-station and in farmers' fields. Experiments conducted on fifteen farmers' fields located in three different villages (Eglimé, Zouzouvou and Tchi) in the derived savannah in southern Benin, indicated that the actual amount of  $N_2$  fixed by *M. pruriens* in farmers' fields at 20 weeks after planting averaged 50 kg N ha<sup>-1</sup> (range: 37–69 kg N ha<sup>-1</sup>) representing 54% (range: 48–60%) of the plant total N (Houngnandan et al., 2000b). These results suggest that in these farmers' fields, *Mucuna* cannot meet all its demands for growth and seed production by  $N_2$  fixation only. Many factors affect N-fixation and amongst them, Sanginga et al. (1996b) suggested that poor growth of *M. pruriens* in a number of soils could be due to lack of nodulation and effective  $N_2$  fixation. A short-term survey of several farmers' fields in the

derived savannah of Benin showed that *Mucuna* was only 79% nodulated. More commonly, a few nodules were found on the root systems, which is indicative of low rhizobial populations or the presence of inefficient or incompatible rhizobia. Thus, the actual contribution of  $N_2$  fixation even with *M. pruriens* may be small in a number of cases. Houngnandan et al., (2000b) and Sanginga et al. (1996b) demonstrated that the use of appropriate rhizobial strains could improve  $N_2$  fixation and the subsequent growth of *M. pruriens* in N-deficient soils or without adequate rhizobial populations. Nodulation and  $N_2$  fixation by many legumes are also limited by deficiencies in soil nutrients such as N, P, and micronutrients (Giller and Wilson, 1991; Sanginga et al., 1995). The nutrient deficiencies may restrict the development of a population of free-living rhizobia in the rhizosphere, limit the growth of the host plant, restrict nodulation itself, and result in impaired nodule function. Houngnandan et al. (2001) indicated that 36% lower biomass was obtained when P was deficient in the growing media.

#### *Phosphorus availability and nitrogen fixation*

Preliminary observations in the savannah of northern Guinea (Nigeria) have shown that legumes require about 30 kg P ha<sup>-1</sup> for optimal growth and  $N_2$  fixation (Weber et al., 1996). However, small-scale farmers use only limited amounts of P fertiliser for their food crops. Under these circumstances, it would be beneficial to select legume species or cultivars with low P requirements for growth, nodule development and  $N_2$  fixation.

Species are known to differ greatly in their ability to assimilate P especially at low P availability (Chisholm and Blair 1988; Sanginga et al., 1991b). Studies by Föhse et al. (1988) indicate that species differ in their ability to extract soil P depending upon the potential of roots to absorb P, their active lifetime and the amount of root per unit of shoot.

Pot and field experiments were carried out to examine variation among potential herbaceous and shrub legumes for their ability to nodulate and to efficiently use P. These legumes were grown at two P fertilizer rates (0 and 7 kg P ha<sup>-1</sup>) in soils collected from two fields with different cropping histories (compound and degraded fields) at Yamrat in the northern Guinea savannah of Nigeria. In the compound field, animal manure and household residues are applied annually whereas in the degraded field, cereals are grown continuously with minimal organic inputs. Significant differences in growth, P content and mycorrhizal in-

fection rate occurred among the different legumes as affected by P and cropping history. Legumes grown in soil from degraded fields responded more to P application than those grown in soil from compound field.

Habte and Manjunath (1987) demonstrated that plants with stronger mycorrhizal associations have a lower external P requirement than plants of the same type without an effective mycorrhizas. Our investigations show that differences between several species in their ability to be infected by mycorrhizae as well as the difference in P uptake and growth response to P could largely account for the difference in adaptation of these species to low P soils. For example, at the lowest P rate, species such as *L. purpureus* and *Cajanus cajan* had the highest mycorrhizal infection rate (average 20%) compared to 4–10% for the other legumes with *M. pruriens* and *Crotalaria ochroleuca* being the least affected. Legume species that respond to phosphorus e.g., *M. pruriens* var. *utilis* (black seed) and *C. ochroleuca*, had a low mycorrhizal infection rate compared with less P responsive species such as *L. purpureus* and *C. cajan*. A significant relationship was found between the extent of mycorrhizal infection and plant growth but not with nodulation of these legumes.

Legumes also differ in their ability to fix N<sub>2</sub> under low P conditions. The percentage of Ndfa by the legumes mentioned above was generally high (on average 80%) and comparable with values reported for herbaceous legumes used as cover crops or pastures elsewhere (Date, 1991; Sylvester-Bradley, 1984). In terms of % Ndfa and total N fixed under low P soil levels, *L. purpureus* out-performed all other species and is obviously well-suited to N and P deficient soils. Although *M. pruriens*, that is being adopted by farmers in some areas of the moist savannah, has comparable % Ndfa rates, its optimum rate of BNF and shoot dry matter production strongly depends on the availability of P. Species such as *M. pruriens* and *C. ochroleuca*, which require P application for maximum yield, are better suited to soils with higher P availability.

#### *Nitrogen fixation in cropping systems*

Legume cover crops that provide live or dead mulch, are effective in suppressing weeds, fixing atmospheric N, adding organic matter to the soil, improving its chemical and physical properties, and minimising soil erosion (see Lal et al., 1979; Wilson et al., 1982). Early studies conducted at IITA showed that herbaceous legumes yield between 30 and 300 kg N ha<sup>-1</sup>

and contribute N to subsequent or associated cereal crops grown in live or dead mulch (Mulongoy and Akobundu, 1985). These N inputs are sufficient to reduce, if not eliminate, the need for application of chemical N fertilizers. More recently, cover and forage legumes have been shown to significantly enhance grain yields of a subsequent maize crop (Versteeg et al., 1998). On severely depleted soils previously yielding only 480 kg ha<sup>-1</sup>, maize yields were increased to 1140 kg ha<sup>-1</sup> due to the production by *M. pruriens* of between 0.4 and 8.7 t biomass ha<sup>-1</sup> (and 12–193 kg N ha<sup>-1</sup>) in the aboveground biomass. Houngnandan et al. (2000c) observed increases in maize grain yield from 1.6 to 2.7 kg<sup>-1</sup> following *M. pruriens* compared with maize following maize or natural fallow on 10 farmers' fields in Zouzouvo and Eglimé (derived savannah, southern Benin). Yields of upland rice increased linearly with the amount of N added by a wide range of green manures across four sites in Côte d'Ivoire (Becker and Johnson, 1998). Studies on integrated soil management with leguminous cover crops (*Crotalaria*, *Lablab*, and *Mucuna*) conducted in the NGS of Nigeria indicated that the N fertiliser replacement value of legume rotations varied between 6 and 14 kg N ha<sup>-1</sup> (Carsky et al., 1999b). Without N application to the test crop, maize grain yields following legume fallow were 235–265 kg ha<sup>-1</sup> higher than after natural fallow. The benefits of a legume fallow to subsequent maize crops were mostly related to above-ground N of the previous legume.

In an attempt to quantify the amount of N released from the residues of *Lablab* and *Mucuna*, Ibe-wiro (1998) calculated that at 84 days after planting, a maize crop (in the derived savannah of Nigeria) had utilised 13–36% of N released from *M. pruriens* amounting to 13 kg N ha<sup>-1</sup> in live mulch and 63 kg N ha<sup>-1</sup> in *in situ* mulch systems. In contrast the second maize crop recovered 16–25% of N released from *M. pruriens* at 168 days. Similar maize N recovery values were 9–62 kg N ha<sup>-1</sup> from *Lablab* representing 28–35% of total N released from the residues. The apparent recovery of legume N by the following maize crop varied between 12 and 36% and was higher for *Lablab* than for *Mucuna* (on-station trial in the NGS in Nigeria – Vanlauwe et al., 2000). After grain removal, *M. pruriens* planted in farmers' fields in the derived savannah of Benin led to a net N contribution ranging from –46 to +20 kg N ha<sup>-1</sup> (Houngnandan et al., 2000c).

## Woody legumes

### Nodulation and nitrogen fixation

Geographical restriction on nodulation occurs among nitrogen fixing trees (NFTs) used in agro-forestry systems. Some NFTs nodulate in some areas, but not in others, and not all species within a genus e.g. *Acacia* can be nodulated by the same bacterial strain. *Leucaena leucocephala* for example, was nodulated in two out of 11 sites in Nigeria, and in one out of four sites in Zaire but did not nodulate in Zimbabwe (Sanginga et al., 1987). Sanginga et al. (1989) showed that *Rhizobium* strain IRC 1047 induced high shoot dry weight on *L. leucocephala* grown in soil that previously supported *L. leucocephala* although it was less effective in other soils. Also, *Rhizobium* strain TAL1145 (a *L. leucocephala* isolate from Hawaii) was completely ineffective in Nigerian soils. It is therefore important to determine the degree of host specificity of selected NFTs and to develop rhizobial strains that nodulate and fix N<sub>2</sub> with many of the useful species. It has been known for many years the small proportion of Caesalpinoid legumes nodulate compared with species of Mimosoid and Papilionoid (Allen and Allen, 1981; Halliday, 1984; Puepke and Broughton, 1999).

Measurements of BNF in alley cropping systems show that some tree species such as *Acacia mangium*, *Gliricidia sepium*, and *L. leucocephala*, are capable of deriving between 100 and 300 kg N ha<sup>-1</sup> yr<sup>-1</sup> from atmospheric N<sub>2</sub>, while species such as *Faidherbia albida* and *Acacia senegal* might fix less than 20 kg N ha<sup>-1</sup> yr<sup>-1</sup>. Species such as *Albizia lebbek* appear to be intermediate, fixing between 60 and 120 kg N ha<sup>-1</sup> (Kadiata et al., 1996). Moreover, significant differences in % Ndfa have been reported among provenances or iso-lines of other nitrogen fixing trees. For example, despite the generally poor N<sub>2</sub> fixation (average 20%) ascribed to *F. albida* (Sanginga et al., 1990), vast differences exist between provenances. One provenance derived 36% of its total N from fixation; another fixed only 6% of its N requirements under identical conditions. Similar variations in the proportions and amounts of N<sub>2</sub> fixed have been observed for *G. sepium* growing under identical conditions. Ndfa ranged from 26 to 68% among the 25 provenances examined (Sanginga et al., 1991a). Other tree species, such as *Senna siamea* and *S. spectabilis*, are also used in alley cropping, although they do not nodulate and therefore do not fix N<sub>2</sub> (Sanginga et al., 1990).

Measuring BNF in trees poses problems that are associated with their perennial nature, massive size, and great difficulty of obtaining representative samples. Strategies for obtaining representative samples (as opposed to destructive sampling), the application of <sup>15</sup>N procedures, and the selection criteria for appropriate reference plants have been discussed (Sanginga et al., 1995). Data obtained using <sup>15</sup>N labelling techniques have indicated that up to 50% or more of the tree's N may be stored below ground. In this case, quantification of N<sub>2</sub> fixed that disregard roots, and nodules, would result in serious underestimation of the amount of N<sub>2</sub> fixed. Cutting or pruning of tops of NFTs in alley cropping systems can cause considerable sloughing-off of roots and nodules. N<sub>2</sub> fixation is therefore reduced in proportion to the severity of pruning. The effect of three successive prunings on N uptake, fixation and distribution in *L. leucocephala* was investigated in a greenhouse experiment (Sanginga et al., 1990) and validated in the field using provenances of *G. sepium*. Two iso-lines, un-inoculated or inoculated with three different *Rhizobium* strains were labelled with <sup>15</sup>N, and grown for 36 weeks during which they were cut every 12 weeks. Cutting affected the distribution of <sup>15</sup>N in the different plants parts. Live nodules showed the lowest atom% <sup>15</sup>N excess values (0.087), followed by leaves (0.490), branches (0.522), stems (0.591), and roots (0.857). The total N<sub>2</sub> fixed in the roots was about 60% of that fixed in the whole plant, while the shoots contained only 40% of the fixed N. It was concluded that N reserves in roots and nodules constitute substantial N sources. Timing and severity of pruning may thus allow transfer of fixed N<sub>2</sub> to associated crops.

### Phosphorus as a factor limiting nitrogen fixation

*L. leucocephala* is particularly susceptible to low soil fertility (Ahmad and Ng, 1981; Halliday, 1981). Sanginga et al. (1985) observed that *Acacia holocericia*, *F. albida*, *G. sepium*, and *L. leucocephala* need about 80 kg P ha<sup>-1</sup> for good establishment in Nigerian soils, especially when it is effectively nodulated. Adding P fertiliser or selecting NFT genotypes or provenances tolerant to low P soils are being used to ameliorating P-deficiencies. Variability in growth, P use efficiency and N<sub>2</sub> fixation amongst leguminous trees used in alley cropping systems has been reported (Sanginga et al., 1994). Kang et al. (1995) also showed large differences in early growth of woody species in response to P application. For example, 25 provenances of *G. sepium*, as well as 11 cultivars of *L.*

*leucocephala* and *F. albida* were examined for growth, P uptake and P use efficiency in low P soils both in pot and field experiments (Sanginga, 1992; Sanginga et al., 1991b, 1994b). Differences in P use efficiency at both low and high soil P levels were crucial to early growth and disappeared after the first year. Selection of provenances tolerant to low soil P levels can thus be confined to juvenile plants.

Unfortunately, the results of the pot experiment were not completely duplicated in the field experiments. Differences between *G. sepium* provenances to P uptake and growth were largely related to differences in physiological P use efficiency and root length, especially at low P. In general, nodulation was improved by P application, but varied among provenance. *G. sepium* fixed approximately 61% and 40% of its N from atmospheric N<sub>2</sub> in pot and field, respectively. The percentage of N fixed was affected by the low rate of P application (20 Kg P ha<sup>-1</sup>). The same study also indicated differences between NFTs in their capacity to form mycorrhizal infections. Work on exotic and indigenous NFT species conducted at IITA (Nigeria) showed that mycorrhizal infection increased root P and dry weight, as well as uptake of immobile elements like Zn and Cu (Osonubi et al., 1991).

Tree growth is stimulated by the 'tripartite' symbiosis of plant- bacteria-mycorrhiza. Inoculation of *L. leucocephala* by species of *Glomus* doubled plant growth, increased nodule fresh weight and nitrogenous activity by as much as 50% (Purcino et al., 1986). In a P-deficient soil, De la Cruz et al. (1988) obtained little increase in the N per plant in *Acacia auriculiformis*, *A. mangium* and *Albizia falcata* inoculated with only *Rhizobium*. Inoculation with *Rhizobium* and selected arbuscular mycorrhizal fungi (AMF) stimulated BNF. Nitrogen fixing and non-N<sub>2</sub> fixing legumes such as *G. sepium* and *S. siamea* have been used in alley cropping systems for soil improvement and food. Often their establishment is limited by P and moisture deficiencies in degraded soils. Osonubi et al. (1991) examined the effects of an AMF (*Glomus deserticola*) on the performance of hedgerow trees of *G. sepium* and *S. siamea* both alone and inter-planted in a fallowed alley cropping experiment on a degraded Alfisol in south-western Nigeria. Percentage root infection by AMF fungi was higher in inoculated plants than in un-inoculated ones irrespective of whether they were inter-planted or alone. Inoculation with *G. deserticola* increased dry matter accumulation and nutrient uptake (N, P, mg and K) but there was no significant

interaction between mycorrhizal inoculation and inter-planting. Inoculation with *G. deserticola* reduced leaf shedding of *G. sepium* by 50% but did not have the same effect on *S. siamea*. Both tree species extracted more water from 0 to 30 cm depth when inoculated.

*Contributions of nitrogen fixation in cropping systems*  
Prunings taken from *Sesbania rostrata* planted as hedgerows in an alley cropping system (at two different population densities) provided 3 and 4 t ha<sup>-1</sup> of dry matter (Mulongoy, 1986). When returned to the soil their decomposition released 70 kg N ha<sup>-1</sup> during the rice-growing season, and stimulated yield increase of 20–50%. Many others have also observed the beneficial effects of green manures in rice (e.g. Ladha, 2003; Rinaudo et al., 1982). Observations in southern Nigeria indicate that five annual prunings of *L. leucocephala* grown in hedgerows yielded between 150 and 560 kg N ha<sup>-1</sup> yr<sup>-1</sup> depending on hedgerow spacing, pruning regime, and soil type (Duguma et al., 1988; Kang et al., 1981). Sanginga et al. (1988) reported N yields ranging between 448 and 598 kg N ha<sup>-1</sup> yr<sup>-1</sup> from *L. leucocephala* inoculated with an effective strain of *Rhizobium* grown in a woodlot on an Alfisol in Nigeria. Tree species such as *Gliricidia sepium*, *Flemingia macrophylla*, and *Sesbania sesban* also have large N yields compared to the non-leguminous species, e.g., *Dactyladenia barteri* and *Alchornea cordifolia*. Leguminous tree fallows of several species including *Cajanus*, *Crotalaria*, *Sesbania*, and *Tephrosia* accumulate 100 – 200 kg N ha<sup>-1</sup> in 6 months to 2 years. When incorporated into the soil before planting, this biomass increases maize yields two to four times. NFT fallows provide such other benefits as capturing leached nitrates and other nutrients, controlling striga, improving soil physical properties, and sequestering carbon. At the end of the fallow period, the trees can be felled for firewood (Sanchez and Jama, 2000).

Despite the high N yield of species such as *L. leucocephala* and *G. sepium*, supplemental N application is still required to obtain high yields in the subsequent maize crop (Kang et al., 1981). Part of the problem lies in the low N-use-efficiency of prunings (Mulongoy and Van der Meersch, 1988; Sanginga et al., 1995). Large quantities of N are harvested with hedgerow prunings (< 300 kg N ha<sup>-1</sup> yr<sup>-1</sup>) but the direct N contribution to crops is commonly in the range of 40–70 kg N ha<sup>-1</sup> season. This represents about 30% of N supplied in prunings although recoveries as low as 5–10% have been reported (Vanlauwe et al., 1998).

Table 2. Estimates of N<sub>2</sub>-fixation by grain legumes grown as the sole crop in the moist savannah of West Africa.

Grain legume	N <sub>2</sub> fixed		References
	Ndfa	Kg N ha <sup>-1</sup>	
<i>Arachis hypogaea</i> (groundnut)	67–81	11–63	Garry (1992)
	28–52	38–79	Badiane and Gucye (1992)
	ND	101	Dakora et al. (1987)
<i>Glycine max</i> (soyabean)	26–64	24–168	Sanginga et al. (1997)
	50–60	65–115	Okereke and Eaglesham (1992)
	84–87	114–188	Eaglesham et al. (1982)
<i>Vigna unguiculata</i> (cowpea)	57–58	ND	Okereke and Eaglesham (1992)
	61–76	47–105	Eaglesham et al. (1982)
	54–70	66–120	Eaglesham et al. (1982)
	ND	201	Dakora, et al. (1987)
	70	15–31	Sanginga et al. (2000)

The low N recovery in NFT-maize systems is partly due to the lack of synchronisation of N release from hedgerow trees and the N demand of the associated food crop. Much of the N not taken up by the associated crop is immobilised in soil organic matter or assimilated by the hedgerow trees and thus remains in the system (Vanlauwe et al., 1998), although a sizeable proportion is also lost from the system through de-nitrification, volatilisation, and leaching.

### Grain legumes

Single developments such as improved crop genotypes has contributed most to increased productivity in modern agriculture. Farmers readily adopt new legume varieties since additional costs are low and existing cropping systems are not affected. Amongst the grain legumes used in the West African region, cowpea and groundnut are predominant (Weber, 1996).

Experimental estimates of the proportion of plant N derived from N<sub>2</sub> fixation and the amounts of N<sub>2</sub> fixed by important grain legumes in the moist savannahs are presented in Table 2. It appears that potential BNF for most species is in the range of 11–201 kg N ha<sup>-1</sup> crop<sup>-1</sup>. Since crop N is partitioned either into seeds or vegetative parts at harvest, not all of the N<sub>2</sub> fixed is returned to the soil. With protein levels of 20–40% of dry weight, legumes sequester up to 60 kg N ha<sup>-1</sup> for every ton of seeds harvested. Earlier field studies performed in Nigeria showed that soyabeans derived less than 60% of their N from fixation and resulted in a negative contribution of –36 kg N

ha<sup>-1</sup> to the N balance compared to a positive balance of 53 kg N by *Vigna unguiculata* (cowpeas) in the cropping systems (Eaglesham et al., 1982). Estimates of the benefits of cowpeas to soil N supply are 80 kg ha<sup>-1</sup> when residues from two successive cowpea crops are left in the field (Horst and Hardter, 1994) and 60 kg ha<sup>-1</sup> when residues from one cowpea crop were incorporated into the soil (Dakora et al., 1987).

The production and utilization of soyabean has expanded approximately 10-fold in Nigeria over the past 10–15 years (Sanginga, 1998). This crop, that was once a minor component of the cropping system (2% of the crops grown in the Kaya village Nigeria, in 1986, accounted for 25% in 1997 becoming the second crop after maize. Major expansion in soyabean production has occurred in Benin, Côte d'Ivoire, Ghana and Togo, in recent years.

### Nitrogen contributions of promiscuous soyabeans in cropping systems

#### *Nodulation and effectiveness of promiscuous soyabeans*

In 1978, the IITA soyabean programme targeted the improvement of BNF for soybeans through breeding of 'promiscuous' soybean varieties that nodulate with indigenous soil bradyrhizobia (Kueneman et al., 1984). Selection of progeny from crosses between Asian and American varieties was based on good nodulation in local soils (using visual scores for nodule mass). IITA identified several effective promiscuous soyabean varieties amongst 400 soybean accessions grown at five locations that had soils which were poor in N and had never been planted to soyabean. The elite 'promiscuous free-nodulating' soybean varieties were also extensively tested on farms. Smallholders in Nigeria, are widely adopting these 'free nodulating soyabean cultivars' such as the high yielding TGX 1448 – 2E breeding line.

Unfortunately, studies on rhizobia associated with these 'free nodulating soyabean cultivars' have been spasmodic. Results of laboratory and field evaluations of early soyabean rhizobial collections from Nigeria which covered the period 1979–1983 (Eaglesham, 1985, Pulver et al., 1985; Rao et al., 1981) may be summarized as follows: (i) Local strains that nodulate promiscuous soyabean comprise only approximately 10% of the total *Bradyrhizobium* population of the soil (rhizobia in these regions predominantly infect

cowpeas and only rarely US soybean cultivars). (ii) The cowpea rhizobial population shows a range of effectiveness on cowpea, and the same is true of rhizobia on soybean. The isolates are equally variable in terms of colony morphology, tolerance of environmental stresses, and production of pink nodules. (iii) A number of isolates are potentially useful for promiscuous soybeans, and (iv) Significant yield responses were observed following inoculation of non-promiscuous lines, but responses were small and generally not significant for promiscuous lines.

Active field studies on the soil microbiological aspects of soybean inoculation stopped at IITA in 1983. Apparently, none of the *Bradyrhizobium* strains that were in use before 1983 have been tested for compatibility with recent selections from the breeding programme (Sanginga et al., 1996c). Knowledge of the indigenous rhizobia that nodulate promiscuous soybeans are limited and their symbiotic properties may differ between locations. Recently Abaidoo (1998), Sanginga et al. (1996c) and Sanginga et al. (2000a) concluded that it may be impossible to produce a soybean which will nodulate effectively with indigenous rhizobia in all locations in the Guinean savannah. BNF by soybeans is often insufficient to support high yields in many parts of Africa, *Bradyrhizobium* populations that nodulate these soybeans were designated *Bradyrhizobium* sp. (TGx) and their phylogenetic, genetic, and phenotypic relationships to *B. japonicum* and other *Bradyrhizobium* spp. strains were examined (Abaidoo, 1998). *Bradyrhizobium* sp. (TGx), and *B. japonicum* populations were detected in 72% and 37% of the soil samples, respectively. *Bradyrhizobium* sp. (TGx) populations were generally low, and significantly less than the total bradyrhizobia populations in 57% of the samples. Populations sizes of less than  $10 \text{ cell g}^{-1}$  soil were common, occurring in 43–100% of soil samples analysed depending on the geographic origin. Forty-one percent of the *Bradyrhizobium* sp. (TGx) populations were ineffective on TGx 1456–2E while 33% were effective on TGx 1456–2E, but ineffective on a North American soybean genotype.

On the basis of 16S rDNA-RFLP analyses, many of the *Bradyrhizobium* sp. (TGx) strains were phylogenetically related to *Bradyrhizobium* spp. while only a few were closely related to *B. japonicum*. Similar relationships were identified based on randomly amplified polymorphic DNA, intrinsic antibiotic resistance patterns, and the genomic arrangement of *nifDH* gene sequences. Unfortunately, the sizes and  $\text{N}_2$  fixation effectiveness of the *Bradyrhizobium* sp.

(TGx) populations are insufficient to support high non-fertilised soybean yields. The diversity amongst the *Bradyrhizobium* sp. (TGx) populations raises the question of whether indigenous bradyrhizobia are capable of sustaining high soybean yields.

#### *Measuring $\text{N}_2$ fixation and the relevance of the plant host*

Despite active research on this subject since 1977, quantification of  $\text{N}_2$  fixed by promiscuous soybeans in the field in the different agro-ecological zones of West Africa remains little better than an informed guess. This is largely because of the methods used. The assessment of  $\text{N}_2$  fixation in promiscuous soybeans is based on scoring nodules from 1 to 5. In turn, this results from the finding that nodule scores correlate significantly with nodule weight (Kueneman et al., 1984). Almost the only advantage of this procedure is that it is easy to apply to large numbers of breeding lines.

Using the  $^{15}\text{N}$  isotope dilution method on five promiscuous IITA soybean lines over two seasons at Mokwa, in the southern Guinea savannah of Nigeria, BNF was found to average  $91 \text{ kg N ha}^{-1}$ . This represents 46% of the plant total nitrogen (Sanginga et al., 1997). In other countries, soybeans have been shown to fix (using the  $^{15}\text{N}$  isotope dilution method)  $85\text{--}154 \text{ kg N ha}^{-1}$  in Brazil,  $26\text{--}57 \text{ kg N ha}^{-1}$  in Thailand,  $78 \text{ kg N ha}^{-1}$  in Australia (Peoples and Crasswell, 1992),  $92 \text{ kg N ha}^{-1}$  in Hungary,  $114 \text{ kg N ha}^{-1}$  in the USA, and  $71 \text{ kg N ha}^{-1}$  in Sri Lanka (Rennie et al., 1982). Depending on available soil N, an average figure of  $100 \text{ kg N ha}^{-1}$  or 50% on average of Ndfa is probably possible with soybeans. Thus, the IITA promiscuous soybeans are as efficient in supporting  $\text{N}_2$  fixation and deriving benefit from fixed  $\text{N}_2$  as other soybean lines grown in other countries. Nevertheless, the proportion and amount of Ndfa differed significantly for the lines used in this study and ranged from 38 to  $126 \text{ kg N ha}^{-1}$  under identical soil N and *Bradyrhizobium* treatments (Sanginga et al., 1997). In the Mokwa trial, major sources of N for the five IITA promiscuous lines were both atmospheric fixed N (Ndfa –  $85 \text{ kg N ha}^{-1}$ , 46% of plant total N), and N derived from the soil (Ndfs –  $75 \text{ kg N ha}^{-1}$ , 43% of the plant total N). The contribution from labelled N to total N was small and amounted to only  $20 \text{ kg N ha}^{-1}$  or 11% of plant total N (Table 5). These results suggest that the current generation of promiscuous soybeans cannot meet all their demand for growth and seed-

Table 3. %Ndfa by selected *Glycine max* breeding lines grown for two seasons in three sites with low soil N in the Guinea savannah of Nigeria

Breeding lines	Site			Means
	Gidaway	Mokwa	Zaria	
<b>High fixers</b>				
1485-1D	63	71	55	64
1830-20E	67	74	42	61
1526-5E	60	64	57	60
1789-7F	54	75	43	58
1799-8F	44	72	53	57
<b>Intermediate</b>				
1838-10E	47	50	39	46
1831-28E	39	54	38	44
1837-6E	40	52	36	43
1833-20E	36	60	33	43
SAMSOY-2	34	54	38	42
<b>Lower fixers</b>				
1838-5E	45	34	21	33
1805-33F	37	27	36	33
1740-3F	32	37	27	32
1837-2E	29	35	32	32
1814-2E	23	32	37	31
<b>Means</b>	41	55	39	45
LSD 5%	26	25	19	13

Source: Sanginga et al. (2000) (Unpublished data).

Table 4. Performance of the three best breeding lines and two controls (TGX 1448 - 2E and Samsoy 2) in the Advanced Extra Late Maturity Soybean Trial at three locations (Abcokuta, Mokwa, and Zaria) in Nigeria in 1998

Variety	Grain yield (Kg ha <sup>-1</sup> )	Fodder yield (kg ha <sup>-1</sup> )	Ndfa
Tgx 1856 - 1E	1148	2482	54
Tgx 1864 - 15F	1136	2604	55
Tgx 1861 - 3F	458	2826	56
Tgx 1448 - 2E	1134	1908	63
Samsoy - 2	912	1093	56
Prob. of F	NS	0.0021	NS
CV	49.0	36.7	20.9

Source: Dashiell and Sanginga (1998) (Unpublished data).

Table 5. %Ndfa by five soybean lines grown in the field at Mokwa, southern Guinea savannah in Nigeria

Soybean lines	Sources of N					
	Proportion (%)			Amounts (kg ha <sup>-1</sup> )		
	Ndfa	Ndff	Ndfs	Ndfa	Ndff	Ndfs
IAC 100	36	10	54	38	6	55
TGX 1519 - 1D	43	13	43	67	8	64
TGX 1456 - 2E	50	10	40	81	9	64
TGX 1660 - 19F	52	12	36	125	9	92
Br 17060	50	10	43	110	9	95
LSD 5%	8	2	9	17	1	20

Source: Sanginga et al. (1997).

Ndfa: Nitrogen derived from atmosphere.

Ndff: Nitrogen derived from fertilizer.

Ndfs: Nitrogen derived from soil.

development only by N<sub>2</sub> fixation. Breeding for higher Ndfa should thus continue along with the development of efficient *Bradyrhizobium* strains.

Unfortunately, <sup>15</sup>N techniques are difficult to apply and for that reason easier but no less precise techniques have been sought and the relative abundance of ureides derived from N<sub>2</sub> fixation versus nitrate absorbed from the soil has been used to estimate BNF in field-grown soybeans (Herridge, 1982; Herridge et al., 1988; Herridge and Peoples, 1990). Ureide based methods were calibrated against the <sup>15</sup>N isotope dilution technique on 190 breeding lines (known to be high yielding and possessing other desirable agronomic traits) grown in the field at three sites. As the relationships between the two methods for measuring N<sub>2</sub> fixation were highly significant, the ureide method has since been used routinely in all programmes.

The data shown in Table 3 illustrates that different lines of promiscuous soybeans growing in the same soil can vary considerably in their ability to fix N. This is the basis of the selection criteria used in the soybean breeding programs at IITA. With very few exceptions, the relative differences were reproducible across sites.

On average, the proportion of Ndfa estimated by the ureide method by the soybean breeding lines ranged from 31 to 64% and was higher at Mokwa (55%; range 27-74%) than at Gidaway (41%; range 23-67%) or Zaria (39%; range 21-59%). In some sites up to 70% of the plant total N was fixed N<sub>2</sub>. These values are much higher than has previously been reported for soybeans in the Guinea savanna (Eaglesham et al., 1982; see Sanginga et al., 1997).

#### Phosphorus as a limiting factor to nitrogen fixation

While crops often perform poorly on soils with low levels of available P, many such soils contain considerable reserves of P which are fixed in unavailable forms. Often wild plants and weedy species, perform well on these soils. Some of these efficient plants are simply better at obtaining P from the available pool.

for example, by exploring more soil via a more extensive root system or through mycorrhizal associations. Evidence is now mounting that other plants are able to draw on the normally unavailable P pool by modifying their rhizosphere through the excretion of organic acids and enzymes which convert the fixed P into soluble forms which are useable by the plant. Species or genotypes that are productive under these conditions may be able to access normally unavailable organic P, fixed soil P and sparingly soluble fertiliser P. *Cajanus cajan* is an example from the Leguminosae. There has been relatively little effort in tropical Africa to define areas where P-deficiency is acute or to characterise the soil P chemistry there in order to assess where P-efficient plants may overcome the short-term effects of this limitation.

One of the strategies adopted at IITA to allow crops access to fixed soil P or sparingly soluble P fertilizers has been to exploit the genotypic variation that exists between and within legume species. Inter- and intra-specific differences in P uptake, accumulation and use have been reported for grain legumes including promiscuous soyabeans and cowpeas growing in P deficient soils in the Guinea savannah (Abdelgadir, 1998; Sanginga et al., 1999). Mechanisms by which these legumes exhibit differential abilities to grow at low or high P supply are poorly understood.

#### *BNF in farmers' fields*

Even BNF measured in fields at research stations is not always a good indication of what will happen in farmers' fields. For this reason, IITA has carried out on-farm research at Kaya village in the northern Guinea savannah of Nigeria with 24 farmers since 1998. Special emphasis was given to selected germ-plasms (improved promiscuous soybean TGX 1448-2E and a local var. Samsoy) and inoculation. Soybean grain yield varied between 667 and 3715 kg ha<sup>-1</sup> while the percentage of Ndfa ranged from 42 to 72%. Ndfa averaged 65% for TGX 1448-2E and 62% for local varieties planted in farmers' plots. These values were higher than the 57% (for TGX 1448-2E), and 47% obtained by the local variety managed by the farmer. Large variations also occurred in the weight of nodules (0.59 g to 8.6 g plant<sup>-1</sup>).

The local soyabean variety responded to inoculation in 14 out of the 24 fields with an average increase of 24% in grain yield (above that of the un-inoculated controls). TGX 1448-2E responded to inoculation in only nine cases. With or without inoculation, the in-

duced improved germ-plasm produced 33% more grain than the local varieties. Local soybeans grown in the researcher-managed plots (on farmers' land) yielded 38% more grain when un-inoculated, and 43%, when inoculated, over yields that the farmers' were able to produce themselves. This shows that poor management is one of the factors that contributes to low yields in farmers' fields (Sanginga et al., 2000b).

#### *N balances in maize-based cropping systems*

In a recent study conducted at Mokwa, we hypothesised that genotypic variation in uptake of soil N exists between promiscuous soyabean cultivars and those with a low N harvest index (Sanginga et al., 1997). Assuming that only the seeds of soyabean were removed from the plots, it was estimated that the net N accrual to soil ranged between minus 8 kg N ha<sup>-1</sup> and plus 47 kg N ha<sup>-1</sup> depending on the soybean lines (Sanginga et al., 1997). This information could be useful in developing management practices, including the application of fertilizer, to increase soybean yields by optimizing N<sub>2</sub> fixation and N nutrition.

Clearly, if promiscuous soyabeans are to contribute substantial amounts of N to the soil, the proportion of Ndfa must be considerably greater than the total nitrogen harvest index. An early maturing breeding line, IAC100, that fixed only 36% of its total N (Table 5) would require Ndfa values greater than 60% or a low nitrogen harvest index to avoid a net loss of N from the system. Late maturing lines such as TGX 1660-19F contribute more residual N (43 kg N ha<sup>-1</sup>) than the early maturing cultivars (30 kg N ha<sup>-1</sup>) which also have the lowest N harvest index. Carsky et al. (1997) showed in the same region that the maize yield after following the late maturing soybean var. TGX 1660-19F was similar to the application of 40 kg N ha<sup>-1</sup> while that of the earlier maturing variety 1456-2E was equivalent to the application 15-20 kg N ha<sup>-1</sup>. As minimising the N harvest index is not in the farmers' interest, efforts should be directed towards increasing Ndfa which is more a characteristic of late maturing than early varieties.

All estimates made above do not take into consideration N contribution from roots. Nevertheless, N added to the soil through root turnover and nodule decay represents a potential N gain that is not accounted for (see Bergersen et al., 1985; Buresh and De Datta, 1991). Leaf fall was estimated by Ogoke (1999) at 1-2 t ha<sup>-1</sup> at four-savannah sites in Nigeria. It ranged from 0.55 t ha<sup>-1</sup> for early var. TGX 1485 - D to 1.56

Table 6. The effect of five soybean lines on grain yield, total N and N input into maize grown subsequently in the field at Mokwa, southern Guinea savannah, Nigeria

Soybean lines/Maize	Maize		
	Maize Grain yield (kg ha <sup>-1</sup> )	Maize Total N (kg ha <sup>-1</sup> )	Soybean N* input to maize (kg ha <sup>-1</sup> )
<b>Soybeans</b>			
IAC 100	1541 <sup>b**</sup>	57 <sup>b</sup>	16 <sup>b</sup>
TGX 1519 – 1D	2425 <sup>ab</sup>	68 <sup>a</sup>	27 <sup>a</sup>
TGX 1456 – 2E	3021 <sup>a</sup>	67 <sup>a</sup>	26 <sup>a</sup>
TGX 1660 – 19F	1458 <sup>b</sup>	58 <sup>b</sup>	17 <sup>b</sup>
<b>BR 17060</b>	<b>1986<sup>ab</sup></b>	<b>64<sup>a</sup></b>	<b>23<sup>a</sup></b>
<b>Maize</b>			
Oba super 2 (8644–27) (Ref 1)	1326 <sup>c</sup>	35 <sup>c</sup>	ND
Oba super 1 (9021–18) (Ref 2)	1131 <sup>c</sup>	40 <sup>c</sup>	ND
TZE comp (Ref 3)	1200 <sup>c</sup>	47 <sup>c</sup>	ND

\*Nitrogen input into maize was calculated by the total N difference method using means of the three reference maize cultivars.

\*\* Values followed by the same letters are not significantly different at  $P = 0.05$ .

t ha<sup>-1</sup> for late TGX 1670-1F at one site and not affected by variety at other sites. Litter dry matter was also increased by P application. Since fallen leaves and nodulated roots contain up to 40 kg N ha<sup>-1</sup> these too are substantial and hitherto unaccounted inputs.

#### Contribution of soybeans N to subsequent maize crops

Yields of maize improve in a rotation system with soybeans (Carsky et al., 1997; Kaleem, 1993), often by as much as 80%. Experiments were conducted for two years in five farmers' fields at Zonkwa (southern Guinea savannah) and in four farmers' fields at Zaria (northern Guinea savanna) to assess the residual effect of two promiscuous soybean cultivars (TGX 1485–1D and TGX 1448–2E) to maize. Grain yields of maize grown after soybeans was increased by an average of 25% (Sanginga et al., 2000, unpublished results). The increased maize yields are possibly due to enhanced N availability following soybeans, but could also be due to the reduction of diseases etc. For example, Carsky et al (2000) reported reduced *Striga hermonthica* parasitism on maize following soybeans compared with a sorghum control. Thus the benefits of bringing grain legume into cereal production systems might be higher than expected from the legumes net N contribution to the system.

The <sup>15</sup>N isotope dilution technique was used to estimate the amounts of N contributed to maize by soybean using three different maize cultivars as ref-

erence plants. Results showed that maize grown after soybean had a significantly higher grain yield (20–23% increase) compared to maize after maize, so confirming the observations of Carsky et al. (1997) and Kaleem (1993) in the same agro-ecological zones. Residual N values between 10 and 24 kg were obtained by the indirect <sup>15</sup>N labelling method in the first crop representing 14–36% of the maize total N ha<sup>-1</sup> (Table 6), while the total N difference method gave values varying between 16 and 23 kg N ha<sup>-1</sup>. Highly variable results have been reported, however, and the quality of the residues is clearly important. Nitrogen recoveries as low as 5–10% have been reported in alley cropped maize with *L. leucocephala* (Sanginga et al., 1995; Vanlauwe et al., 1998). It is apparent that the 26 kg N ha<sup>-1</sup> difference between maize following soybeans (line TGX 1456–2E, for example), could not explain the 1802 kg ha<sup>-1</sup> grain yield difference in maize after maize (Table 6). Also, yield increases occurred even in situations where the N contribution of soybean was estimated to be negative, such in the case of soybean line IAC 100. Hence, the increased yields of maize following soybean were not due entirely to the carry-over of N from the soybean residue and to the soil N-conserving effect (Giller and Wilson, 1991) but are probably also due to 'other effects' which enabled the subsequent crop to exploit the soil better when preceded by legumes than by cereals.

What are termed 'other effects' merit careful investigation so as to understand the mechanism by which legumes benefit a succeeding crop. Senaratne and Hardarson (1988) reported that the N benefit to subsequent crops after grain legumes was due to a lower uptake of soil N by legumes relative to cereals, and a carry-over of N from the legume residue, both leading to a greater uptake of residual soil N by the subsequent crop compared to crops grown after non-legumes. For the subsequent crop, it is important that the residual N benefit after legumes should be evident in the mineral (available) N pool. The availability of N for a subsequent crop will be influenced by the amount of plant residues left, the availability of N from the plant residues induced mineralisation of soil organic matter, and the extent to which soil N was depleted by the preceding crop.

It has been difficult to explain the rotation effect based solely on N availability in maize soybean cropping systems in the moist savannah zone of sub-Saharan Africa. Although AMF undoubtedly contribute to plant growth by reducing stresses resulting from other nutrient deficiencies (mainly P and drought),

their roles in the maize/soybean rotation cropping systems of the Guinea savannah have not been fully elucidated. Pot and field experiments were conducted for two years on thirteen farmers' fields, each with different cropping histories in two agroecological zones (Zaria, northern Guinea savannah and Zonkwa, southern Guinea savannah) in Nigeria.

The colonisation by AMF of promiscuous soybean roots ranged from 7 to 36%, while in maize it varied between 17 and 33%. Most of the variation was attributable to the soil type and its cropping history. Infection rates of soybeans were higher (13% increase) in Zonkwa if the preceding crop was maize instead of soybean. Inoculation with bradyrhizobia increased both the infection rate (by 25%) and the diversity of AMF species (19% more than in uninoculated soybeans). Four AMF genera comprising twenty nine species were found at the two sites (Zaria and Zonkwa). *Glomus* was the dominant genus (56%) followed by *Gigaspora* (26%), *Acaulospora* (14%) while *Sclerocystis* was the least represented (4%).

### Remaining gaps and future research needs

Increasing protein production on African farms thus involves breeding legumes with a higher harvest-index that derive a larger proportion of their nitrogen from biological fixation. These, coupled with management strategies that combine organic inputs (e.g. soybean residues in rotations with maize) promise yield increases similar to those now being produced in the northern Guinea savannah. There, the yield of maize grown after soybeans and receiving 45 kg N ha<sup>-1</sup> as urea is similar to that of maize grown after maize but receiving 90 and 120 kg N (as urea) ha<sup>-1</sup> (Sanginga et al., 2000, unpublished results). Furthermore, the indirect benefits from BNF to companion or following species are small but are significant especially in the context of subsistence farming in the tropics. Both yields and sustainability are improved since organic matter levels in the soil are maintained, depending on the starting condition which is on average, about 1% organic carbon in the moist savanna of West Africa.

Means of transferring these technologies to farmers need to be improved especially since farmers' practices and cropping histories are usually ignored in designing research imperatives. Furthermore, the effects of soil factors such as low P and water availability that are crucial to the establishment and growth of legumes, have not been examined in detail in any

regions of the moist savannas. A holistic approach on entire cropping systems is thus needed to:

- breed promiscuous soybean lines that derive an even higher percentage of their nitrogen from the air, this being done through breeding programs and the alleviation of environmental constraints.
- select more competitive and efficient (brady)rhizobia that can serve as inoculants,
- improve management practices that affect BNF and its transfer to maize. Emphasis should be directed towards selected germ-plasms and residue management (both above and below ground),
- investigate the role of P in improving N-use efficiency of legumes in cropping systems (especially selection of legumes with improved P uptake from poorly available sources, such as organic P or bound P),
- determine the effects of cropping sequences on N balances and the organic fertility of the soil, and devise management options for farmers' and
- investigate the long-term benefits of legume/cereal rotations in terms of yield stability.

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