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RESEARCH ARTICLE

Nitrogen rhizodeposition from soybean (*Glycine max*) and its impact on nutrient budgets in two contrasting environments of the Guinean savannah zone of Nigeria

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Abstract Nitrogen (N) rhizodeposition by grain legumes such as soybean is potentially a large but neglected source of N in cropping systems of Sub-Saharan Africa. Field studies were conducted to measure soybean N rhizodeposition in two environments of the Guinean savannah of Nigeria using ^{15}N leaf labelling techniques. The first site was located in Ibadan in the humid derived savannah. The second site was in Zaria in the drier Northern Guinean savannah. Soybean N rhizodeposition in the top 0.30 m of soil varied from 7.5 kg ha^{-1} on a diseased crop in Ibadan to 33 kg ha^{-1} in Zaria. More than two-thirds of soybean belowground N was contained in the rhizodeposits at crop physiological maturity, while the rest was found in the recoverable roots. Belowground plant-derived N was found to constitute 16–23% of the total soybean N. Taking rhizodeposited pools into account led to N budgets close to zero when all residues were removed. If residues were left in the field or recycled as manure after being fed to steers, soybean cultivation led to positive N budgets of up to +95 kg N ha^{-1}. The role and potential of grain legumes as N purveyors have been underestimated in the past by neglecting the N contained in their rhizodeposits.

Keywords ^{15}N · *Glycine max* · Guinean savannah · Leaf labelling · Legumes · Nitrogen · Rhizodeposition · Roots · Promiscuous soybean

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Introduction

Soybean (*Glycine max*) production has been rapidly expanding in the cereal-based systems of the Guinean savannah (Sanginga et al. 2003). Driving factors behind this rapid adoption have been the availability of new, well-adapted, varieties, the high market value of soybean grain, and the positive impact of soybean on subsequent cereal crops. Soybean in rotation may increase maize yield by as much as 140% compared to continuous maize cultivation (Carsky et al. 1997;

Sanginga et al. 2002; Osunde et al. 2003; Franke et al. 2004, 2008). Maize yield gains are largely due to increased soil N availability following soybean cultivation (Giller 2002). Legumes also affect cereal yield due to a set of complex interactions between N, P, diseases and pests dynamics, termed the net "rotation contribution" (Heichel 1987). To understand these mechanisms and their interactions, a fuller understanding of N dynamics is needed (Sanginga et al. 2002).

It remains unclear whether the cultivation of grain legumes, such as soybean, results in a net drain or gain of N in cropping systems (Vanlauwe and Giller 2006). A large proportion of N fixed by grain legumes such as soybean is exported from the field at grain harvest. According to previous studies, soybean cultivation results in a net N drain, if all residues are removed from the field. If residues are retained, soybean N budgets range from −35 to +50 kg N ha^{-1} depending on the cultivar and environmental conditions (Eaglesham et al. 1982; Sanginga et al. 1997, 2002; Ogoke et al. 2003; Singh et al. 2003). On-farm, these residues may be consumed by livestock and some of the legume N is thus returned to the field when the manure is recycled (Harris 1998); a situation seldom reproduced in experiments on-station.

Legumes also contribute fixed N through their roots and rhizodeposits. Rhizodeposits include roots exudates, fine roots, and root necrosis products accrued in the soil during plant growth (Hertenberger and Wanek 2004). Rhizodeposits are lost for analysis when root excavation is performed. Physical recovery of roots substantially underestimates the role of belowground plant organs in nutrient cycling (Polomski and Kuhn 2002). Methods using the stable isotope ^{15}N have been developed to quantify N of plant origin and trace its fate in the soil (McNeill et al. 1997; Khan et al. 2003; Yasmin et al. 2006).

Studies outside Africa indicate that belowground N contribution by legumes is potentially a large source of N in agro-ecosystems (Khan et al. 2003; Wichern et al. 2008). We are not aware of any published studies quantifying the belowground N contribution of a legume in Africa. However, to understand N dynamics in cropping systems, information on the nature and quantity of N contributed by the belowground fractions of leguminous crops is essential (Bationo et al. 2004). It would contribute to a better understanding of the residual effects of legumes on subsequent crops. It would also make the assessment of the sustainability of cropping systems based on N budgets more complete.

The objectives of this study were (1) to measure the contribution of rhizosphere processes to N fluxes following soybean cultivation in two contrasting environments of the Guinean savannah of Nigeria and (2) to establish N budgets for soybean cultivation taking into account the effect of rhizodeposition. The hypotheses behind this study are (1) that N rhizodeposited by grain legumes is a substantial but hitherto ignored source of N in cropping systems of the Guinean savannah, and that (2) studies using nutrient budgets to assess cropping systems' bio-physical sustainability have overestimated the extent of N mining in African cropping systems and underestimated the potential of soybean as net N supplier.

Material and methods

Experimental sites

Measurements of soybean below-ground N were made in 2005 in plots of long-term crop rotation experiments that were started in 1998 at two agro-ecologically distinct locations in Nigeria. One site was on the campus of the International Institute of Tropical Agriculture (IITA), Ibadan, Southwest Nigeria, in the derived savannah eco-zone (7°29′N, 3°53′E, 218 m above sea level). Ibadan has a bi-modal rainfall pattern peaking in June and October with a long-term mean annual rainfall of 1,290 mm and a growing period of 210–270 days. Soil type in Ibadan is Plinthic Luvisol (FAO 1988) with relatively high sand fraction, low N and soil organic matter content and moderate Bray-I P levels (Table 1). The other site was located at the Shika experimental farm of Ahmadu Bello University in Zaria, in the northern Guinean savannah eco-zone (11°12′N, 7°36′E, 680 m above sea level). Zaria has a mono-modal rainfall distribution, an annual mean rainfall of 1,050 mm and a growing season of 120–150 days. In Zaria, soil type was Haplic Lixisol (FAO 1988) with high silt and clay content. Soil is very low in N and organic carbon content and has low Bray-I P (Table 1). Soil samples were taken in 2005 before planting, at depths of 0–0.12 m and 0.12–0.24 m using a soil auger 22.5 mm in diametre. In each subplot, 12 samples were combined to one composite sample for analyses.

Table 1 Soil characteristics of maize–soybean plots within the crop rotation trials in Ibadan and Zaria, 2005

Soil parameter	Ibadan	Zaria
pH (H_2O)/0–0.12 m	5.85 (0.08)	5.6 (0.4)
pH (H_2O)/0.12–0.24 m	5.73 (0.11)	5.50 (0.14)
Org. C(%) / 0–0.12 m	16.8 (1.7)	15.2 (1.53)
Total N(%) / 0–0.12 m	1.75 (0.28)	1.33 (0.08)
Bray-I P (mg kg^{-1})/0–0.12 m	12.41 (2.05)	5.91 (0.95)
Exch. K (cmol kg^{-1})/0–0.12 m	0.26 (0.03)	0.28 (0.02)
Exch. Ca (cmol kg^{-1})/0–0.12 m	1.00 (0.17)	1.76 (0.14)
Exch. Mg (cmol kg^{-1})/0–0.12 m	0.31 (0.04)	0.57 (0.04)
Sand (%)/0–0.12 m	83	36
Silt (%)/0–0.12 m	10	46
Clay (%)/0–0.12 m	7	18

Standard error of the means (SEM) in parentheses

Soil particle size, pH (H_2O, 1:1 soil to water ratio), organic C content (Walkley–Black method), total N (Macro–Kjeldahl method), Bray-I extractable P and ammonium acetate-exchangeable K, Ca and Mg were determined at IITA's analytical services lab (IITA 1981). For a more detailed description of the long-term trials, see Franke et al. (2008).

Experimental setup

Below-ground N measurements were taken in 2005 from soybean plants rotated with maize. Measurements were taken in four plots (4.5 × 6 m) at each site. Phosphorus (P) and potassium (K) were applied annually at a rate of 17 kg P ha^{-1} as Triple Super Phosphate (TSP) and 33 kg K ha^{-1} as Muriate of Potash. From 2002 onwards in Zaria, P applications were increased to 40 kg P ha^{-1}, of which 20 was in the form of TSP and 20 kg ha^{-1} was applied as Single Super Phosphate (SSP), which also contained 28 kg S. Precipitation data were retrieved from nearby climate recording stations (Table 2).

A long duration soybean (*Glycine max*) variety (TGx 1448-TI; 120 days) was cultivated on flat land in Ibadan and on ridges in Zaria, following local practices. The soybeans were not inoculated with *Bradyrhizobium* spp. Planting was done when rains were well established and risks of early crop failure were minimized (Table 3). At both sites, prior to planting, ten PVC cylinders (0.245 m in diameter, 0.340 m high) were inserted amongst four plots. They were placed on the top of the rows or ridges, 0.30 m deep into the soil. Ninety percentages of soybean roots are typically found in the top 0.15 m of soils (Mitchell and Russell 1971). Two soybean plants were grown in each cylinder. Chicken fence was placed around the cylinders to protect the seeds and seedlings.

Table 2 Precipitation at experimental sites in Ibadan and Zaria, 2005

	Ibadan (mm)	Zaria (mm)
April	188	64
May	140	281
June	305	154
July	196	179
August	53	254
September	273	117
October	188	32
November	11	0

^{15}N leaf labelling

A multiple direct ^{15}N labelling strategy was used with the two plants in the cylinder being enriched in ^{15}N on two occasions at the beginning of the growing season. Plants were enriched in ^{15}N by dipping the central leaflet of the 3rd or 4th leaf in 2.5 ml of a 0.5% urea solution (99.7% atom ^{15}N) kept in 10 ml vials. The tip of the leaflet was cut and inserted in the vial so as to be in contact with the solution. The vials were sealed using inert plastic material to protect the content from rain and avoid ^{15}N urea solution losses. Sticks were planted close to the cylinder to hold the vials in place. Vials were attached to the sticks using thin metal wire.

Labelling started at the 6th node stage in Ibadan and the 4th node stage in Zaria (Table 3). All plants at a location were labelled simultaneously. After 7 days, the vials were removed. The labelled leaflets were detached from the leaves and taken away with the vials. A week later, new vials containing 2 ml of fresh urea solution were installed on new leaves for another 7 days.

Sampling procedures for labelled systems and controls

Ten cylinders were installed at each site distributed amongst the four plots: six cylinders contained labelled plants, while the four others were kept as controls. Four plots of the rotation experiment were used; two plots had three cylinders and the other two

Table 3 Timing of operations at both Ibadan and Zaria sites, 2005, expressed in days after planting (DAP)

Manipulation	Ibadan	DAP	Zaria	DAP
Planting	May 17	–	June 25	–
Labelling starts	June 26	40	July 15	20
Labelling ends	July 20	64	August 8	44
Harvest of plants within cylinders	September 29	135	October 11	108
Harvest of plants in the plots	October 8	145	November 19	147

plots contained two cylinders. Every plot had one of the four control cylinders.

Sampling procedures for the labelled plant–soil systems and the controls were identical. The crops were harvested at physiological maturity. All cylinders were excavated at harvest. The soil column from the cylinders was split using cutlasses. Two soil and root sampling depths were obtained: 0–0.15 and 0.15–0.30 m. All soil in the cylinders was dry-sieved using 2 mm mesh and all visible roots were collected. Rocks that were present in the soil of Ibadan were removed. The sieved soil was thoroughly mixed and a 50 g sub-sample was taken and dried to constant weight at 60°C for 48 h. The soil was crushed using a hand mortar. Beans, residues and roots were dried, weighed and ground with a rotary mill (Wiley Mill, A.H., Thomas, Philadelphia, PE, USA) to pass a 1 mm sieve first and then a 0.5 mm sieve. Four and five of the six labelled cylinders from Ibadan and Zaria, respectively, were analyzed for ^{15}N enrichment and their data presented. The four control cylinders were fully analyzed at each site. Subsequently, soils, pods, residues, and roots samples were weighed in tin capsules and analysed for N content and ^{15}N enrichment by flash combustion on an elemental analyzer (EA1110, Carlo Erba, Milan, Italy) coupled in continuous flow mode with an isotope ratio mass spectrometres (Finnegan Mat, Bremen, Germany).

Calculations of rhizodeposition and ^{15}N partitioning

^{15}N enrichment is expressed as $\delta\,^{15}$N (‰) relative to the natural enrichment of atmospheric N (0.3663 atoms %):

$$\delta^{15}\mathrm{N} = \frac{(\mathrm{ratio}^{15}\mathrm{N}/^{14}\mathrm{N\,sample} - \mathrm{ratio}^{15}\mathrm{N}/^{14}\mathrm{N\,atmosphere})}{\mathrm{ratio}^{15}\mathrm{N}/^{14}\mathrm{N\,atmosphere}} \times 1000 \quad (1)$$

Determination of plant-derived N in soil is based on the assumption that plant exudates and root necrosis products have the same enrichment as the roots at sampling (Khan et al. 2003). The proportion of soil N derived from rhizodeposition (% Ndfr) was thus calculated from the ratio of the enrichment of labelled soil over that of labelled roots. To do this, the enrichment of labelled soil and of labelled roots was corrected against the enrichment of the same N pool in the controls (Schmidtke 2005) as in

$$\%\ \mathrm{Ndfr} = \frac{\delta^{15}\mathrm{N\,Soil\,Labelled} - \delta^{15}\mathrm{N\,Soil\,Control}}{\delta^{15}\mathrm{N\,Root\,Labelled} - \delta^{15}\mathrm{N\,Root\,Control}} \times 100\% \quad (2)$$

The proportion of soil N derived from rhizodeposition (% Ndfr) was multiplied by the total soil N to determine the quantity of soil N coming from rhizodeposition. Values obtained for below-ground measurements in the cylinder were converted to a per area unit basis by multiplying them by the ratio of the aboveground biomass in the plots over biomass in the cylinders. ^{15}N Recovery was calculated by adding up ^{15}N excess in the soil and in the different plant organs.

Symbiotic nitrogen fixation

SNF in the soybean was measured using the isotope dilution method (IAEA 2001) using four replicates in each site. In each of the four soybean plots of each site, a 2 m^2 microplot was sprayed with 0.1 g N m^{-2} (98 atom% ^{15}N) of potassium nitrate diluted in 10 l of water with dextrose added to obtain a C:N ratio of 10:1. Dextrose was added to immobilise the ^{15}N and obtain a constant enrichment of the plant available N throughout the season (Giller and Witty 1987). The solution was mixed to 2 kg of soil per meter square of microplot and left to incubate for two weeks. The enriched soil was spread over the microplot one week before planting and mixed with the top few cm of soil.

Half the micro-plot was cropped with upland rice (*Oryza sativa*) as the non-fixing reference plant, while soybean was grown in the other half. The upland rice cultivar (IITA-321) was a long duration type reaching maturity at about the same time as soybean. Soybean and rice in the micro-plots were harvested just prior to the removal of the cylinders. Plant samples consisting of grain and residues together were dried and ground using a rotary mill to pass a 0.5 mm sieve. The ^{15}N enrichment of the samples was measured using an isotope ratio mass spectrometer. The proportion of legume N derived from atmospheric N_2 (% Ndfa) was calculated as follows:

$$\%\,\mathrm{Ndfa} = \frac{(\delta^{15}\mathrm{N\,rice} - \delta^{15}\mathrm{N\,soybean})}{\delta^{15}\mathrm{N\,rice}} \times 100 \qquad (3)$$

The amount of N fixed by soybean was determined using the % Ndfa multiplied by the total soybean N:

$$\mathrm{Total\ N\ fixed} = \%\,\mathrm{Ndfa} \times (\mathrm{N_{roots}} + (\mathrm{N_{rhizodeposits}}) + \mathrm{N_{residues}} + \mathrm{N_{beans}})/100 \qquad (4)$$

Calculation of N budgets

Nitrogen budgets of soybean were calculated based on the amount of N fixed minus the N contained in the parts harvested (residues and beans) and removed from the field. The total amount of N fixed varied according to whether or not the N contribution of roots and rhizodeposits were considered in the calculations. It was assumed that the proportion of N fixed in the roots and the rhizodeposits was the same as in the aboveground plant material. Four N budgets were calculated based on different scenarios: N budget (1), below-ground fractions not included, beans and residues removed. N budget (2), below-ground fractions included, beans and residues removed. N budget (3), below-ground fractions included, beans harvested and residues recycled through manure. N budget (4), below-ground fractions included, beans harvested and residues incorporated in the soil.

$$\mathrm{N\ budget\ (1)} = (\%\ \mathrm{N\ fixed} \times \mathrm{Plant\ N})/100 - (\mathrm{N_{residues}} + \mathrm{N_{beans}})$$

$$\mathrm{N\ budget(2)} = (\%\,\mathrm{N\ fixed} \times (\mathrm{Plant\ N\ incl\ BGN}))/100 - (\mathrm{N_{residues}} + \mathrm{N_{beans}})$$

$$\mathrm{N\ budget(3)} = (\%\,\mathrm{N\ fixed} \times (\mathrm{Plant\ N\ incl\ BGN}))/100 - (\mathrm{N_{residues}} + \mathrm{N_{beans}}) + (\mathrm{N_{residues}} \times 0.5_{(\mathrm{manure})}*)$$

$$\mathrm{N\ budget\ (4)} = (\%\ \mathrm{N\ fixed} \times (\mathrm{Plant\ N\ incl\ BGN}))/100 - (\mathrm{N_{beans}})$$

At both locations, aboveground soybean residues were fed to steers over the dry season and the manure was collected and applied in the field at subsequent planting. Plant residue and manure analyses suggested that the carry-over rate of N from residues at harvest to manure at planting was 0.50 (Franke et al. 2008), and this rate was used in N budget (3).

Data handling

Means of biomass production by the different plant organs, their N content and the ^{15}N enrichment were calculated from measurements in the cylinders. Results were presented with their corresponding standard errors of means (SEM).

Results

In 2005, crops were planted following large rainfall in the beginning of May in Ibadan, and in the second half of June in Zaria. Crops established readily at both sites. The precipitation was close to seasonal averages (Table 2).

Biomass yield, N yield and symbiotic N fixation

In Ibadan, biomass production of grain and residues was low with 0.85 mg grain ha^{-1} and 0.70 mg residues ha^{-1} (Table 4). The crop accumulated 55 kg aboveground N ha^{-1}. Soybean was heavily infested with diseases in Ibadan (Franke et al. 2008) and as a result, biomass production was reduced and leaves prematurely shattered.

Soybean produced higher yields in Zaria: 1.5 mg dry matter (DM) ha^{-1} of grain and 3.7 mg DM ha^{-1} of residues (Table 4). Residue production was exceptionally high for a soybean crop in this region. Accordingly, a high aboveground N accumulation of almost 160 kg N ha^{-1} was recorded (Table 5). Soybean consistently derived 80% of its N from the atmosphere at both sites (Table 6).

Labelling and plant and soil ^{15}N enrichment

The ^{15}N labelling of soybean at both sites resulted in high ^{15}N enrichment in the labelled cylinders, compared to the natural enrichment of samples taken from control cylinders. The soil and plant enrichment was sufficient to measure rhizodeposition (Table 4). 1.8 and 2.3 mg of ^{15}N were recovered per plant in Ibadan and Zaria, respectively (Tables 4, 5). The plant enrichment was higher in Ibadan than in Zaria because of the higher biomass and N content of plants in Zaria (Tables 4, 5).

Nitrogen rhizodeposition

Approximately 70% of the soybean belowground N (0–0.30 m) was contained in the rhizodeposits at both sites with the remaining 30% found in the recoverable roots (Table 5). Most of the roots and the rhizodeposited N were found in the top soil (0–0.15 m) (Table 4). In Ibadan, the equivalent of 20% of the aboveground soybean N was contained in belowground N fractions, roots and rhizodeposits. In Zaria, the equivalent of more than 30% of the aboveground N was measured in the roots and rhizodeposits (Table 5). Soybean rhizodeposits contained 7.5 kg N ha^{-1} in Ibadan and 33 kg N ha^{-1} in Zaria (Table 5).

Nitrogen budgets

N budget (1) (all grain and residues removed and the N contribution of rhizodeposits ignored) showed a net removal of N from the soil at both locations: −9 kg ha^{-1} in Ibadan and −22 kg ha^{-1} in Zaria (Table 6). N budget (2) (including N contribution from rhizodeposits) resulted N balances close to zero in terms of N removal or accrual at both locations. N budget (3) (including the contribution from rhizodeposition as well as N transfer from manure returned to the plot) revealed that soybean cultivation led to a net accrual of N at both locations: +4 kg N ha^{-1} in Ibadan and +50 kg N ha^{-1} in Zaria. In N budget (4) (all residues left in the field), N budgets reached +10 kg N ha^{-1} in Ibadan and +95 kg N ha^{-1} in Zaria. The values from N budget 4 may be considered as an upper limit of N contribution from soybean at harvest.

Table 4 Accumulation of soybean biomass on a per hectare basis and soybean ^{15}N enrichment of the controls and of the labelled plants in Ibadan (derived savannah), mean ± SEM ($n = 4$), and in Zaria (Northern Guinean savannah), mean ± SEM ($n = 5$)

	Soybean biomass (kg/ha)	^{15}N enrichment	
		$\delta^{15}N$ Control	$\delta^{15}N$ Labelled
Ibadan			
Grain	856 ± 132	6.59 ± 269	269 ± 31
Residues	680 ± 92	5.24 ± 1.67	416 ± 82
Roots/0–0.15 m	228 ± 24	5.83 ± 1.35	368 ± 75
Soil/0.15–0.30 m	–	8.91 ± 1.13	23 ± 3
Roots/0.15–0.30 m	28 ± 8	2.88 ± 1.58	405 ± 67
Soil/0.15–0.30 m	–	16.36 ± 0.58	24 ± 2
Zaria			
Grain	1,540 ± 100	−0.40 ± 0.3	81 ± 16
Residues	3,770 ± 370	−0.5 ± 0.5	137 ± 42
Roots/0–0.15 m	620 ± 80	2.8 ± 0.6	177 ± 42
Soil/0.15–0.30 m	–	5.2 ± 0.2	23 ± 4
Roots/0.15–0.30 m	90 ± 20	3.0 ± 1.10	177 ± 35
Soil/0.15–0.30 m	–	7.4 ± 0.5	15 ± 2

Table 5 Nitrogen accumulation in soybean and soybean rhizodeposits per unit area in Ibadan (derived savannah), mean ± SEM ($n = 4$), and Zaria (Northern Guinean savannah), mean ± SEM ($n = 5$)

	Soybean N (mg/cylinder)	Soybean N (Kg/ha)	Soybean N (% of total N)
Ibadan			
Grain	1,032 ± 106	41.3 ± 4.3	63.57 ± 4.58
Residues	317 ± 47	12.7 ± 1.4	19.94 ± 4.07
Roots/0–0.15 m	70 ± 10	2.8 ± 0.4	4.45 ± 0.93
Roots/0.15–0.0.30 m	7 ± 4	0.3 ± 0.2	0.41 ± 0.14
Rhizodeposition/0–0.15 m	137 ± 7	5.5 ± 1.3	8.46 ± 2.11
Rhizodeposition/0.15–0.0.30 m	51 ± 17	2.0 ± 0.7	3.17 ± 1.19
Total below-ground	264 ± 40	10.56 ± 1.51	16.48 ± 2.50
Total	1,613 ± 86	64.53 ± 3.45	100
Zaria			
Grain	1,571 ± 190	62.8 ± 7.6	31.09 ± 3.71
Residues	2,264 ± 221	90.6 ± 8.8	44.32 ± 2.26
Roots/0–0.15 m	291 ± 34	11.7 ± 1.4	5.78 ± 0.68
Roots /0.15–0.30 m	40 ± 10	1.6 ± 0.4	0.79 ± 0.20
Rhizodeposition /0–0.15 m	666 ± 101	26.6 ± 0.4	14.90 ± 2.29
Rhizodeposition /0.15–0.30 m	158 ± 89	6.3 ± 3.6	3.12 ± 1.36
Total below-ground	1,156 ± 209	46.2 ± 8.4	23.30 ± 4.0
Total	4,991 ± 270	199.6 ± 10.8	100

Discussion

Biomass yield, N yield and symbiotic N fixation

The current soybean variety is a product of a breeding Programme at the International Institute of Tropical Agriculture (IITA) in the 1980s and 1990s aiming to produce well-adapted grain and dual-purpose varieties with a good capacity to nodulate with indigenous soil *Bradyrhizobia*. The high SNF and residues and grain production measured in this experiment in Zaria is an indication of the program's success in developing "promiscuous" soybean cultivars. The soybean N accumulation at Zaria was in line with other studies on aboveground soybean N in Africa (Sanginga et al. 1997; Osunde et al. 2003; Ojiem et al. 2007). Some experiments reported cases of soybean crops containing up to 250 kg aboveground N ha^{-1} (1997; 2007). The high SNF measured in this experiment was probably the result of favourable growing conditions, regular P, K and S fertilizers additions and a low soil mineral N content.

Plant diseases in Ibadan left the plants stunted with few leaves, affecting the rhizodeposition and N budgets. Diseases were not a problem when the experiment started in 1998, but they have built up since then, stressing the need for a constant breeding effort to adapt varieties to the southern, more humid, zones of the Guinean savannah.

Rhizodeposition

The results confirmed the hypothesis that rhizodeposition of N represents a substantial N input in the Guinean savannah, as 16–23% of the total accumulated crop N was found belowground (Table 5). This is in agreement with findings from other environments where soybean rhizodeposition was studied (Australia: Rochester et al. 1998; Brazil: Araujo et al. 2006). Wichern et al. (2008) concluded in a recent review that grain legumes on average have 33% of the total crop N in pools located belowground. It is also a common finding in rhizodeposition studies that most rhizodeposited N is found in the upper section of soil (Khan et al. 2003, Araujo et al. 2006).

We found that most of the belowground N (70% in Ibadan and Zaria) was stored in the rhizodeposits. Also other studies observed that, at physiological maturity, most belowground N in legumes, up to 90% in some cases, is found in the rhizodeposits (Khan et al. 2003; Mayer et al. 2003; Araujo et al. 2006; Wichern et al. 2008). This confirms that physically

Table 6 Soybean N budgets and its components in the top 0.30 m of soil and soybean N fixation in Ibadan (derived savannah), mean ($n = 4$), and in Zaria (Northern Guinean savannah) mean ($n = 5$)

	[a]Budget (1) kg ha^{-1}	[b]N-budget (2) kg ha^{-1}	[c]N-budget (3) kg ha^{-1}	[d]N-budget (4) kg ha^{-1}
Ibadan				
Grain N (kg ha^{-1})	−41.3 (4.3)	−41.3 (4.3)	−41.3 (4.3)	−41.3 (4.3)
Residues N (kg ha^{-1})	−12.7 (1.4)	–12.7 (1.4)	−12.7 (1.4)	−12.7 (1.4)
Roots N (kg ha^{-1})	+3.1 (0.4)	+3.1 (0.4)	+3.1 (0.4)	+3.1 (0.4)
Rhizodeposited N (kg ha^{-1})	–	+7.50 (1.8)	+ 7.50 (1.8)	+7.50 (1.8)
N in manure (kg ha^{-1})	–	–	+6.3	–
(%) Ndfa (%)	80 (3)	80 (3)	80 (3)	80 (3)
N fIxed (kg ha^{-1})	45.7	51.7	51.7	51.7
N Budget (kg ha^{-1})	−8.7	−2.7	4.0	10.4
Zaria				
Grain N (kg ha^{-1})	−62.8 (7.6)	−62.8 (7.6)	−62.8 ± 7.6	−62.8 ± 7.6
Residues N (kg ha^{-1})	−90.6 (8.8)	−90.6 (8.8)	−90.6 ± 8.8	−90.6 ± 8.8
Roots N (kg ha^{-1})	+13.3 (1.6)	+13.3 (1.6)	+13.3 ± 1.6	+13.3 ± 1.6
Rhizodeposited N kg ha^{-1})	–	+33.0 (6.8)	+33.0 (6.8)	+33.0 (6.8)
in manure (kg ha^{-1})	–	–	+45.3	–
(%) Ndfa (%)	79 (3)	79 (3)	79 (3)	79 (3)
N fixed (kg ha^{-1})	132	158	158	158
N budget (kg ha^{-1})	−22	4	50	95.5

The minuses and pluses signs indicate whether the plants constituents were left in the field (+) or removed (−) SEM in parentheses

[a] N budget (1) = (%N fixed × Plant N)/100 − (N residues + N beans); all residues removed, BGN not taken into account

[b] N budget (2) = (%N fixed × Plant N incl BGN)/100 − (N residues + N beans); all residues removed, BGN taken into account

[c] N budget (3) = (%N fixed × Plant N incl BGN)/100 − (N residues + N beans) + (N residues × 0.5 manure); BGN taken into account, residues removed, then fed to steers and returned as manure

[d] N budget (4) = (%N fixed × Plant N incl BGN)/100 −(N residues + N beans) + (N residues × 0.5 manure); all residues left in the field, BGN taken into account

recovering roots greatly underestimates plant belowground N contribution. The measurements of rhizodeposited N depended on the assumption that the ^{15}N enrichment of the roots is representative of the enrichment of rhizodeposits. If roots were more enriched than the rhizodeposits, rhizodeposition has been underestimated, or vice versa.

Additional studies on belowground N dynamics of legumes in Africa carried out on diverse sites under realistic conditions could reveal more on the role of rhizodeposition and belowground N pools. Furthermore, more information is needed on the transfer of rhizodeposited N to the next crop and the influence of management on rhizodeposition and N transfer. This is especially relevant since aboveground legume N dynamics are often poorly correlated with yield dynamics of subsequent cereals (Sanginga et al. 2002; Ncube et al. 2007; Franke et al. 2008).

N budgets

The second hypothesis tested in this study was that belowground N pools are important for evaluating the rotational effects of soybeans in cropping systems of the Guinean savannah. This study underlined that N budgets associated with soybean cultivation improve if belowground N pools are taken into account. So far, N budgets have been constructed for soybean in the Guinean savannah without taking rhizodeposited N into account (Eaglesham et al. 1982; Sanginga et al. 1997, 2002; Singh et al. 2003; Ogoke et al. 2003). The N budgets obtained from these studies were always negative if residues were removed from the field. In the present study, even after removal of residues, budgets were close to balance at both sites if rhizodeposition was included (N budget (2)). N budget (3), in which the residues were fed to animals and the manure was returned, was the most realistic scenario for the Guinean savannah. N budget (4) (all residues left in the field) provided an estimate of the upper potential contribution of soybean in these environments. In reality, most plant biomass, and its N content, left in the field from the previous cropping season is lost over the dry season due to strong winds, free-roaming ruminants, bush fires and termites (Schulz et al. 2001).

Nutrient budgets have been used in sustainability assessment of cropping systems at various scales (Stoorvogel et al. 1993; Harris 1998). However, errors can arise when important processes are ignored. The results of the present study suggest that N rhizodeposition from soybean and grain legumes is such a neglected process.

Conclusions

Belowground plant-derived N was found to constitute 16–23% of the total soybean N. Rhizodeposited N pools were about twice as large as N pool in recoverable roots. Incorporating belowground N contribution of soybean, and presumably other legumes, into nutrient balances will improve the overall field N balance and affect the common assumption that agricultural soils are being nutrient mined in Africa (Smaling et al. 1997). Greater knowledge of belowground N pools of legume crops is needed to improve our understanding and utilisation of N effects and other rotational effects of grain legumes in African cropping systems.

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