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REGULAR ARTICLE

Biological nitrogen fixation and nitrogen and phosphorus budgets in farmer-managed intercrops of maize–pigeonpea in semi-arid southern and eastern Africa

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Abstract Biological nitrogen fixation (BNF), nitrogen (N), and phosphorus (P) imports-exports budgets were estimated at four locations, each with 20 farmer-managed fields for two years in a semi-arid Tanzania and Malawi. The ^{15}N isotope dilution method was used to quantify BNF by three pigeonpea (*Cajanus cajan* L. Millspp.) varieties intercropped with maize (*Zea mays* L.). The N and P accumulation in plant components of sole maize and intercrops of maize-pigeonpea systems were used to estimate the mean exports and imports of N and P. The proportion of N derived from air (%Ndfa) by the pigeonpea varieties ranged from 93.8% to 99.9% in Malawi and 65.6% to 99.3% in Tanzania. The amount of fixed N (BNF; kg N ha^{-1} yr^{-1}) varied from 37.5 to 117.2 in Malawi and 6.3 to 71.5 in Tanzania. The mean values for BNF during the two cropping seasons were 64.3 for Nyambi, 85.3 for Ntonda, 34.1 for Gairo and −54.3 for Babati sites. The mean N budget (kg ha^{-1}) was −26.1 in the sole maize plots and −40.3 for the intercrops at the two locations in Malawi, and −50.1 in the sole crop plots and −51.1 in the intercrops at the locations in Tanzania. In a scenario where all the aboveground material except the edible parts was returned to the soil, a positive value of 30.5 kg N for the intercrops was recorded compared with −8.9 kg N for the sole maize in Malawi. For the same scenario in Tanzania, the budget was more negative (−35.4 kg N) for sole maize compared with intercrops (−5.9 kg N). Including the roots in the calculations, did not change the differences between mono and intercrops. The P budget was negative irrespective of whether the aboveground biomass of maize and pigeonpea was incorporated or exported out of the fields, and the values were similar for intercrops and sole maize. The most negative N and P budgets were recorded in the two study areas where the extractable soil P status of the soils and the maize yields were high. These findings indicate that pigeonpea incorporated into maize-based cropping systems will maintain a very high %Ndfa (> 90%) in all plant parts and thereby contribute to improved N budgets but not increase the proportion of P mined of the soil.

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Introduction

Quantitative estimation of plant nutrient depletion from soils is useful for comprehending the state of degradation and for devising corrective measures. Field or farm level nutrient budgets are useful tools to assessing the sustainability of cropping systems (Francis 1990; Smalling et al. 1993a, b) although upscaling may be difficult (Schlecht and Hiernaux 2006). One of the main tenets of cereal–legume cropping system is that legumes contribute to soil fertility and the long-term sustainability of the system because legumes symbiotically fix a proportion of their nitrogen (N) requirements from the atmosphere (Giller 2001).

The maize–pigeonpea intercropping technology has a high potential of being adopted by farmers (Myaka et al. 2006), not because pigeonpea is a source of protein, a cash crop and as a food source but pigeonpea matures on residual soil moisture after most farmers have exhausted their maize stocks, thereby bridging the hunger period and providing food security to the rural farmers. In addition to the food security aspects, farmers in Tanzania and Malawi value the contribution from pigeonpea to the fuelwood supply (Odgaard et al. 2003, 2005).

Pigeonpea is one of the few crops with a potential to enhance soil fertility because of its complementarities with maize (McCown et al. 2002; Myaka et al. 2006). Pigeonpea is also known to increase the total plant available water and phosphorus (P) pools in the cropping system because of its deep rooting system, its potential ability to access sparingly soluble P sources (Ae et al. 1990) and to pump water from the deep to the surface soil layers (Ito et al. 1996). However, little attempt has been made to quantify the amount of biological fixed N (BNF) in the farmers' field and relate it to N and P budgets. Further, it remains unstudied how the inclusion of pigeonpea in maize-based cropping system influence the N and P budgets and long-term sustainability of the production system.

In the semi-arid regions of Africa, the gap between fertiliser inputs and nutrient removal is high because fertiliser input is less favoured for rainfed systems and dryland agriculture is more likely to have negative nutrient budgets than the irrigated systems. Smaling et al. (1993b) reported an average nutrient loss in sub-Saharan Africa of 22 kg N, 2.5 kg P and 15 kg K ha^{-1} yr^{-1}, although in a district study in Kenya, depletion of 112 kg N, 3 kg P and 70 kg K ha^{-1} yr^{-1} was observed (Smaling et al. 1993a). However, positive budgets of N and P were reported by Rego et al. (2002) for a two-year sorghum–pigeonpea–castor rotation system in farmers' field in India. Sanginga et al. (2003) reported budgets ranging from minus 8 kg N ha^{-1} to plus 47 kg N ha^{-1} for promiscuous soybean cultivars grown as sole crop. In the semi-arid eastern Africa where intercropping is practiced, not only the harvested products but the whole aboveground biomass of both the cereal and the legumes are mostly exported to the homesteads for multiple use.

The objective of the present study was to quantity the amount of atmospherically derived N fixed by different pigeonpea varieties intercropped with maize in farmer-managed fields and to estimate the potential contribution of BNF by pigeonpea to the overall N budgets of the cropping system. The BNF and N balances will be related to P balances as P deficiency is a common trait of the cereal systems in Africa. The study also aimed at identifying suitable pigeonpea varieties with high productivity and soil fertility impact. The yield and nutrient concentrations of the system have been reported elsewhere (Myaka et al. 2006).

Materials and Methods

Experimental areas and participating farmers

Four study areas were selected in Tanzania and Malawi. In Tanzania, the Babati district of the Manyara Region (until 2003 it was part of the Arusha Region) (04°14 S, 35°35 E) and the Gairo Division of the Kilosa District of the Morogoro Region (06°13 S, 36°53 E) were selected. In Malawi, Nyambi (14°39 S, 35°35 E) and Ntonda (15°53 S, 34°57 E) extension planning areas (EPAs) were selected. The Nyambi EPA is located within the Kawinga Rural Development Projects (RDPs) and the Liwonde Agricultural

Development Division (ADD). The Ntonda EPA is located within the Blantyre Shire highlands RDP and the Blantyre ADD. These areas were similar in terms of low fertiliser use in maize (*Zea mays* L.), the dominant food crop, but they differed in terms of traditions for using pigeonpea (*Cajanus cajan* L. Millsp). Gairo is considered a new area for pigeonpea production while Babati, Nyambi and Ntonda are traditional pigeonpea growing areas. The soils of Babati, and Ntonda are classified as ferrasols, Gairo as ferralic cambisols, and Nyambi as cambisols according to FAO/UNESCO (1990). Details of the rainfall pattern, the criteria for the selection of farmers has been described elsewhere (Myaka et al. 2006). The trials were continued on the same plots for three consecutive growing seasons for all farmers and crops but the ^{15}N treatments were applied for two consecutive years.

Plant material

Six pigeonpea varieties were planted on the farmers' fields at the four study locations. The varieties used were (i) in Babati: ICEAP00053, ICEAP00040 and Babati White; (ii) in Gairo: ICEAP00068, ICEAP00040 and Babati White (Local); and (iii) in Nyambi & Ntonda: ICEAP00040, ICEAP00020, and ICPL9145. ICEAP00040, ICEAP00053, ICEAP00020 and ICP9145 are long duration varieties while ICEAP00068 is a medium maturing variety. Babati White is a traditional variety found in the Babati area in Tanzania. A recommended maize variety for each area was used. In Gairo, a long duration and open pollinated maize variety ''*Staha*'' was used while in Babati an open pollinated variety ''*Kilima*'' was used. In Malawi, a hybrid maize variety ''*SC 627*'' was used at all sites.

Crop management

The experimental plots were primarily managed by farmers but the extension agents or technicians influenced the planting patterns. All data were collected by research technicians and processed at the research station. Each farmer planted three pigeonpea varieties intercropped with maize and one plot was planted with sole maize. This block of four plots of each 10 × 10 m in every farmer's field was non-replicated. Maize rows were spaced at 90 cm apart and pigeonpea was planted between these rows of maize. Within the rows, the recommended plant spacing was 60 cm and plants were thinned to two plants per planting station.

Initial soil sampling and ^{15}N application

Soils from the experimental areas were just before the onset of the rains on the first cropping season. Twenty samples were taken with soil augers (diameter of 2 cm) diagonally across the plots to a depth of 0.15 m from all plots. The samples were bulked and analysed for total C and total N, using an elemental analyzer (ThermoQuest S.p.A., Milano, Italy), and inorganic NO_3^- and NH_4^+ were analysed as described by Myaka et al. (2006). The $NaHCO_3$−extractable P was determined (Olsen et al. 1954; 0.5 g dry soil, 10 ml 0.5 M $NaHCO_3$ shaken for 1 h). Electric conductivity was determined in a 1:1 soil/water extraction (USDA 1954). The results are presented in Table 1.

At each study area, two farmers were selected for the estimation of BNF. A relatively constant ^{15}N enrichment of the plant available N pool over the growth season was targeted (Jørgensen et al. 2004) by dissolving ^{15}N-labelled ammonium sulphate (10 at % excess) with glucose, ratio 1:8 (v/v) and applied to the three pigeonpea microplots of size 4 m^2 during each of the two growing seasons. The amounts of N

Table 1 pH, EC and nutrient (N, C and P) concentrations in soils at the experimental sites at the onset of the trials

Country	Location	C (g kg^{-1})	N (g kg^{-1})	P (mg kg^{-1})	pH(H_2O)	EC (mS cm^{-1})
Malawi	Nyambi	9.0	0.62	11.0	5.64	1.32
	Ntonda	11.9	0.78	32.6	5.66	1.18
Tanzania	Gairo	12.2	1.12	7.34	6.30	2.20
	Babati	14.2	1.10	43.4	6.30	2.49

Values are means of 20 observations

applied equals 8 kg N ha^{-1}. To ensure that the crops were assessing the same sources, the ^{15}N-enriched solution was applied after sowing of the crops when the pigeonpea crops had emerged and the maize crop had reached a height between 10 and 20 cm.

Plant sampling and analysis

Except for the ^{15}N-labelled plots, plants from 10 m^2 of the experimental areas were sampled and weighed. Sub-samples of the maize plants were divided into grains, husk, and stovers. Sub-samples of the pigeonpea plants were divided into grains, pods, fresh leaves and stems. All samples were dried to constant weight at 60°C, ground to a fine powder (mesh 0.2 mm) and analysed. At randomly selected farms, the leaf litter was collected at regular intervals from a clearly marked area and dried to constant weight. After final sampling, all samples were pooled, ground to a fine powder and analysed.

Total N content of the plant material was analysed using an elemental analyser (Thermo- Quest S.p.A., Milano, Italy) and the P content was determined by dry-ashing at 550°C for 4 h; the ashes were then solubilised in 3 M HCl, dried and dissolved again in 1 M HNO_3 before filtering the solution. The P concentration in the plant digest was determined by UV–Vis spectrophotometry using the molybdophosphoric blue method of Murphy and Riley (1962).

For the ^{15}N-labelled plots, aboveground plants were sampled and separated into leaves, stems/stovers, grains, husks, dried to constant weight at 60°C, and ground to a fine powder (mesh 0.2 mm). Roots were excavated with augers, washed and dried.

Total-N and ^{15}N in plant sample parts were analysed using the Dumas combustion method by a system consisting of an ANCA Mass SL Elemental analyzer coupled with a 20–20 Tracermass Mass Spectrometer (Europa Scientific Ltd., Crewe, UK). The fractional contribution of fixed N derived from air (%Ndfa) in pigeonpea was calculated as (Peoples et al. 1989):

$$\%\text{Ndfa} = 1 - (\text{Atom\% excess of pigeonpea}) / (\text{Atom\% excess of maize}) \times 100$$

The proportion of N fixed was calculated for all the plant parts. The amount of N symbiotically fixed by pigeonpea (BNF, kg ha^{-1} yr^{-1}) was calculated by multiplying the total N in plant samples by the %Ndfa.

The proportions of N derived from fertiliser (%Ndff) were calculated as:

$$\%\text{Ndff} = (\text{Atom\%excess in plant material}) / (\text{Atom\%excess in fertilizer}) \times 100$$

Nitrogen and P budgets

A simple input/output model was used in calculating the N and P budgets. The inputs were fertiliser and non-fertiliser (BNF) and the outputs were nutrients removed in harvested products. More that 95% of the farmers did not use any fertilizer during the 2 year. Thus, fertilizer uses were assumed to be nil and nutrient losses out of the systems (leaching, erosion, overland and lateral transport) were not included.

In the budgets, tree scenarios were examined. In the first scenario (budget 1) it is assumed that all the aboveground biomass is exported from the fields and only the fallen leaves are incorporated into the soil. In the second scenario, all the aboveground biomass (except the edible portions) of the maize and pigeonpea are returned to the soil. In the third scenario it is assumed that all the aboveground biomass is exported from the fields and the roots and fallen leaves are incorporated into the soil. It is assumed that the roots constitute 33% of the N and P accumulated in the maize (Anderson 1988; Mengel and Barber 1974) and pigeonpea shoots (Vesterager et al. 2006) following an allometric relation between shoot and roots (Wilson 1988).

Statistical methods and calculations

At each farm there was one plot with sole maize and three plots with intercropped pigeonpea and maize. The three intercropped plots were averaged to determine the yield of pigeonpea and maize in the mixture. Harvest indices of N, P and biomass were only calculated for the first two cropping seasons. An analysis of variance was carried out on the data using the GLM procedure of the SAS software (SAS Institute Inc. 1993). Mean comparisons for the individual treatments was done using a Waller–Duncan *t*-test.

Results

Soil characteristics at the selected locations

Soils at the selected sites in Tanzania contained slightly more $NaHCO_3$−extractable P than those in Malawi but in particular the electric conductivity and total N and total C content of the soils were higher in Tanzania (Table 1). The $NaHCO_3$−extractable P was 32.6 μg kg^{-1} at the Ntonda and 43.4 μg kg^{-1} at the Babati sites compared with 11 μg kg^{-1} at Nyambi and 7.3 μg kg^{-1} at Gairo. The soils at the sites in Malawi are more acidic (pH 5.6) than those in Tanzania (pH 6.3). Further they contained only half the amounts of soluble salts that those in Tanzania. The locations in Tanzania are characterized by a bimodal whereas those in Malawi have a unimodal rainfall pattern with onset of in November or December in both locations. Total N and C content values from plots planted with maize and pigeonpea did not differ ($P > 0.10$) from plots planted with sole maize (Table 1).

N and P accumulation and BNF

The enrichment of the plant available N was aimed relatively constant by applying sucrose together with^{15}N while at the same time a sufficient high enrichment was needed to label the absorbing plants. This aim was reached by obtaining of 0.5–0.7 at % in maize (data not shown). The N fertiliser use efficiency (%Ndff) varied among sites and years between 1% and 4.2% (data not shown). A moderate and relatively constant enrichment in combination with a low %Ndff are good indicators that an appropriate balance between release and mobilisation was obtained. This is important as the growth pattern of maize and pigeonpea differs.

The weighted means for the different plant organs of the proportion of N derived from air (%Ndfa) by the pigeonpea varieties ranged from 94% to 99% in Malawi and 66% to 99% in Tanzania. These values tended to be slightly higher in grain ($P > 0.05$) than in stems and roots, although the %Ndfa values did not differ ($P < 0.05$) among the tested varieties during the two cropping seasons.

The mean values of the amount of N fixed (kg ha^{-1}) for the two cropping season were 64.3, 85.3, 34.1 and 54.3 for the Nyambi, Ntonda, Gairo and Babati sites, respectively (Table 2). The BNF by pigeonpeas were highest at the Ntonda (115 kg N ha^{-1}) sites because the Ntonda site out-yielded the other sites in terms of pigeonpea biomass production during the 2002 cropping season (see Myaka et al.

Table 2 Biological nitrogen fixation by pigeonpea varieties over two cropping seasons

Country	Location	Variety	Proportion of atmospheric derived N, weighted mean		Amount of atmospheric derived N (kg ha^{-1})	
			2002	2003	2002	2003
Malawi	Nyambi	ICEAP00040	0.957 (0.002)	0.997 (0.001)	91.5 (2.0)	45.6 (3.6)
		ICEAP00020	0.962 (0.003)	0.999 (0.001)	76.5 (7.2)	45.0 (3.1)
		ICP9145	0.963 (0.001)	0.997 (0.002)	76.2 (26.5)	50.7 (6.1)
	Ntonda	ICEAP00040	0.961 (0.003)	0.967 (0.003)	118.4 (0.9)	61.7 (4.2)
		ICEAP00020	0.938 (0.002)	0.956 (0.008)	117.2 (19.2)	70.6 (2.7)
		ICP9145	0.969 (0.013)	0.967 (0.004)	108.6 (38.6)	37.5 (2.3)
Tanzania	Gairo	ICEAP00040	0.891 (0.004)	0.726 (0.015)	47.8 (4.5)	20.0 (2.3)
		ICEAP00068	0.841(0.010)	0.658 (0.023)	17.6 (7.1)	6.3 (3.4)
		Babati White	0.957 (0.007)	0.656 (0.09)	68.2 (6.7)	44.9 (5.2)
	Babati	ICEAP00040	0.957 (0.023)	0.964 (0.030)	60.3 (26.1)	49.8 (7.6)
		ICEAP00053	0.954 (0.006)	0.978 (0.014)	71.5 (3.5)	43.7 (7.5)
		Babati White	0.954 (0.003)	0.993 (0.009)	59.0 (6.3)	41.5 (–)

The varieties consisted of three groups: (i) one improved variety grown across all sites (ICEAP00040), (ii) local varieties (ICP9145 or Babati White), or (iii) specific improved varieties specifically targeting the environmental conditions of individual sites. Means ± SE, $n = 4$.

2006 for details). The Gairo site received the lowest rainfall during the experimental period among the sites, thus accounting for the lowest amount of N fixed by pigeonpea. The variety ICEAP00040 outyielded ($P < 0.05$) all the other varieties in all the locations in terms of amount of N fixed. The variety ICEAP00068 performed poorly although its a short duration cultivar that was introduced to the Gairo site because of the location's short rainfall pattern. In terms of location, the mean amount of BNF was higher in Malawi (75.0) than in Tanzania (44.2).

Nitrogen and P budgets

The N and P budgets for three management scenarios in the intercrops of maize–pigeonpea and sole maize are presented in Tables 3 and 4. Exporting all aboveground material (Budget 1) gave a mean N budget (kg ha^{-1}) of –26.1 in the sole maize plots and −40.3 for the intercrop in the two locations in Malawi, and −50.1 in the sole crop plot and −51.1 in the intercrop plots in the locations in Tanzania during the two cropping seasons (Table 3). If only the grains were exported, all budgets were improved ($P < 0.05$; Budget 2; Table 3). Further in such scenario, inclusion of the pigeonpea improved the balance with 30–40 kg N ha^{-1}; that is from −8.8 kg N to 30.5 kg N ha^{-1} in Malawi and from −35.4 to −5.9 kg N ha^{-1} in Tanzania for the sole maize and the intercrops, respectively. At the two locations in Malawi, the N budget (kg ha^{-1}) was higher ($P < 0.05$) in Ntonda than in Nyambi for the intercrops but the values did not differ ($P > 0.05$) in the sole maize plots. At the locations in Tanzania, the intercrops did not differ ($P > 0.05$) but sole maize depleted the soil more ($P < 0.05$) in Babati than in

Table 3 Cropping systems budgets from nitrogen imports and exports in sole maize and in maize–pigeonpea intercrops in Malawi and Tanzania averaged over two cropping seasons for three scenarios

Country	Location	Cropping system	N imports (kg ha^{-1})	N exports (kg ha^{-1})	Budget 1 (kg ha^{-1})	Budget 2 (kg ha^{-1})	Budget 3 (kg ha^{-1})
Malawi	Nyambi	Intercrops	59.1 (3.8)	80.3 (3.1)	−49.3 (4.6)	17.9 (4.3)	−2.3 (4.3)
		Sole maize	2.3 (0.2)	30.3 (3.9)	−28.0 (3.9)	−6.4 (2.4)	−18.0 (2.6)
	Ntonda	Intercrops	79.5 (5.4)	99.1 (3.5)	−31.2 (2.7)	43.0 (5.0)	25.5 (4.2)
		Sole maize	2.3 (0.2)	26.4 (2.8)	−24.1 (2.8)	−11.4 (2.0)	−15.4 (1.9)
Tanzania	Gairo	Intercrops	55.1 (2.4)	61.0 (3.1)	−34.8 (11.7)	2.3 (11.3)	−7.8 (9.7)
		Sole maize	2.3 (0.2)	36.9 (3.5)	−34.6 (3.5)	−22.1 (2.4)	−22.4 (2.3)
	Babati	Intercrops	49.9 (4.7)	119.5 (4.2)	−67.5 (7.9)	−14.1 (8.5)	−16.0 (8.0)
		Sole maize	2.3 (0.2)	67.7 (3.5)	−65.5 (3.5)	−48.6 (3.6)	−43.1 (2.3)

Means ± SE, n = 20 and 60 for sole maize and intercrops, respectively.

Table 4 Cropping systems budgets from phosphorus imports and exports in sole maize and in maize–pigeonpea intercrops in Malawi and Tanzania averaged over two cropping seasons

Country	Location	Cropping system	P imports (kg ha^{-1})	P exports (kg ha^{-1})	Budget 1 (kg ha^{-1})	Budget 2 (kg ha^{-1})	Budget 3 (kg ha^{-1})
Malawi	Nyambi	Intercrops	1.2 (0.1)	10.1 (0.5)	−8.9 (0.5)	−2.8 (0.3)	−5.6 (0.3)
		Sole maize	0.3 (0.1)	6.3 (0.7)	−6.0 (0.7)	−1.5 (0.3)	−3.9 (0.5)
	Ntonda	Intercrops	1.2 (0.1)	18.1 (0.5)	−16.9 (0.5)	−4.8 (0.3)	−10.9 (0.3)
		Sole maize	0.3 (0.1)	7.9 (0.9)	−7.6 (0.9)	−3.8 (0.8)	−5.0 (0.6)
Tanzania	Gairo	Intercrops	1.2 (0.1)	6.9 (0.7)	−5.7 (0.7)	−2.2 (0.2)	−3.5 (0.5)
		Sole maize	0.3 (0.1)	4.6 (0.4)	−4.3 (0.4)	−3.2 (0.3)	−2.8 (0.3)
	Babati	Intercrops	1.2 (0.1)	26.3 (1.9)	−25.1 (1.9)	−16.8 (0.6	−16.4 (1.3)
		Sole maize	0.3 (0.1)	19.1 (1.1)	−18.8 (1.1)	−15.5 (1.1)	−16.4 (0.7)

Means ± SE, n = 20 and 60 for sole maize and intercrops, respectively

Gairo. In a third budget, taking the root systems into consideration as a residue residing in the systems, following an allometric root:shoot relation, but still exporting all aboveground plant material, lead to an higher ($P < 0.05$) input into the systems (Budget 1 vs. Budget 3). It differ however only little for the sole maize due to the residues being rather N depleted so the root pool made little impact (Budget 2 vs Budget 3). This contrast to the intercrops where the pigeonpeas' N rich residues were reflected in the root systems leading to improvements ($P < 0.05$) of the balances.

Farmers in Babati apply farm yard manure once every third year to the plots and the maize yield were more than twice the values recorded in Gairo. The P partial budgets for the intercrops were highly negative in Ntonda (−17 kg ha^{-1}) and Babati (−25 ha^{-1}) where the initial P content in the soil was high as compared with Nyambi (−9) and Gairo (−6) with low $NaHCO_3$−extractable values.

The P budgets (Table 4) were negative irrespective of whether residues were exported from the fields or incorporated (Budget 1 vs. Budget 2), whether the root systems were included or not (Budget 1 vs. Budget 3), and did not differ much ($P < 0.05$) between the intercrops and the sole maize plots. The highest negative values N and P balance were recorded in the two study areas where the initial soil P was high and where the maize yield were high. The pigeonpea varieties had no effect ($P > 0.05$) on the N and P budgets for the intercrops and they are thus combined in the presented data (Table 3 and 4).

Discussion

Pigeonpea plays an important role in production, consumption and cash income in the households of eastern and southern Africa (Mergeai et al. 2001). This study was conducted under farmers' conditions on realistic soil and climatic variations.

Biological Nitrogen Fixation by pigeonpea cultivars as input to the N budget in farmer-managed fields

It is not the practice of the farmers in the study areas to cultivate pigeonpea as sole crops. Therefore this study did not compare the N fixing ability of pigeonpea as sole crop but only when it was intercropped with maize. Under the farmer-managed conditions, more than 90% of the N in pigeonpea consistently was derived from the atmosphere when intercropped with maize across environments, except at Gairo in the second production year (Table 2).

The isotope ^{15}N dilution method is based on the assumption that both crops, the reference crop and the N fixing legume, have access to the same N pools in the soil (Peoples et al. 1989). The low %Ndff for maize in pure stands indicates that a relative constant enrichment of the N pools in the upper soil layer was achieved. A potential source of error would be if pigeonpea could access a pool of N located below maize rooting depth. The %Ndff for pigeonpea were in all cases less than 0.3% which indicate an inferior competitive ability for the available inorganic N compared to maize. Thus, it is expected that only in cases where a significant pool of N could be located directly below maize rooting depth at the end of the growth season the estimates of %Ndfa could be invalidated.

The amount of N fixed by pigeonpea ranged between 6 and 117 kg N ha^{-1} in the current study. These values compares favourably with values of 50–76 kg ha^{-1} reported by Katayama et al. (1995) in an sorghum–pigeonpea intercrop although Tobita et al. (1994) and Adu-Gyamfi et al. (1996) reported values in the range of 75–165 and 123–170 kg ha^{-1}, respectively. In general, ICEAP 00040 was the best variety for intercropping with maize in terms of grain yield and BNF stability in the study environments.

With a consistently high proportion of %Ndfa, the amount of N fixed was related to the biomass production of the crops, and particularly to the available P in the soil. In particular P stress could be expected under some of the farmers' conditions and Høgh-Jensen et al. (2006) identified less than 10 mg $NaHCO_3$−extractable P kg^{-1} soil as the critical level where pigeonpea grain content of P is becoming affected. This is condition is found for the Gairo area (Table 1) but the crop seems to maintain its N fixing apparatus under these conditions. This agrees with Høgh-Jensen et al. (2002) who studied the effects of P deficiency at legumes and concluded that P deficiencies were regulated on whole-plant level, i.e. first affecting the growth regulatory mechanisms. This agrees with the lower values for %Ndfa at Gairo in the second production year because the pigeonpea crops accumulated less biomass and the absorbed soil N would then constitute a relatively larger proportion of the crop N.

ICEAP 00068 was the only early duration cultivar that was included in the study at the Gairo location. The aim was to study how farmers could take advantage the earliness to bridge the hunger gap but it tended to perform poorly because it matures earlier than the other varieties which may leads to shading effects from the maize canopy. Further, ICEAP 00068 was suffering from the low and variable rainfall patterns as it only was able to set one set of flowers in contrast to the other varieties tested.

Effects of incorporation of pigeonpea in maize-based cropping systems on N and P budgets

The large negative values for N (-31 to -68 kg ha^{-1}) and P (-6 to -17 kg ha^{-1}) in Budget 1 (Tables 3 and 4) indicate that there was a net removal of N and P from the intercropped system. The N and P removal were highest in the locations where the initial soil fertility and maize biomass were large. In situations where the aboveground biomass of both the legume and the cereal were removed from the field, high negative values were observed. It was only when the aboveground biomass (except the edible portions) of the maize and the pigeonpea in the sole and intercrop were retained that the benefits of the intercrop over the sole crop were visible.

Information is needed on the potential impact of rhizodeposition, i.e. a pool of plant-derived N located in the soil media following leaching of N compounds (Paynel et al. 2001; Rovira 1959) as well as degradation processes of dead nodules and dead above- or belowground plant tissue (Dubach and Russelle 1994; Høgh-Jensen and Schjoerring 2001; Steele 1992; Tobita et al. 1994). The use of the allometric relation between roots and shoots in Budget 3 is considered robust (Anderson 1988) but due to the importance of below-ground pools on the N budgets when including a N rich legumes in the systems (Table 3), future studies should try to qualify the importance of these pools.

If all residues are retained in the system (Budget 2) a mean positive N budget of 30.5 kg ha^{-1} was recorded in Malawi where maize grain yields were low. However, in Tanzania the mean N budget was negative (-5.9) because the grain seed yields of maize were higher. Thus, the inclusion of legumes in cropping system can lead to either a positive of negative N budgets. Whereas negative budgets were reported for pigeonpea (Kumar Rao et al. 1987), soybean (Myers 1997), and groundnuts (Rego et al. 2002), positive budgets have also been reported for the same crops (Rego et al. 2002; Sanginga et al. 2003). In the semi-arid areas where maize stovers and pigeonpea husk to a large extent are used for livestock feed, and pigeonpea stems are the source of fuelwood for the farmers, the continuous inter-cropping of pigeonpea and maize will result in N mining of the system unless occasional application of fertilizer and/or manure is practiced (Table 3, Budget 1). Nevertheless, the continuous cropping of sole maize without adequate restoration of soil fertility will further exacerbate the problem and threaten sustainability of the production systems in the study area which represent the variability in soil and climatic conditions typical for semi-arid Sub-Saharan Africa (Sanchez 2002; Sanginga 2003).

The continuous depletion of P in sole maize was enhanced by including pigeonpea in the systems irrespective of residue management. Ae et al. (1990) has reported that the cultivation of pigeonpea may increase the total P availability in cropping systems with low amounts of soluble P sources. However such an effect has not been quantified under field conditions and any such effect could not be detected in our study either. On the contrary, yields of pigeonpea were very low in the Gairo site where pigeonpea was introduced for the first time, where soil P availability were low and where rainfall were lowest. The easy accessible P pools in Gairo as defined by $NaHCO_3$−extraction does not account to more than approx. 30 kg P ha^{-1} in the upper 0.3 m soil layer. The depletion rate indicated by Budget 1–3 (Table 4) suggests that agronomic interventions are required to sustain crop production in the medium-to-long term under such conditions.

In the current study, the farmers' practice was not to apply any commercial fertilisers but in Babati farm yard manure was applied occasionally to some fields. The maize stovers were all grazed and/or removed in Tanzania while the stovers were incorporated in Malawi shortly after harvest while the soil still was partly moist. The pigeonpea stems were always utilized outside the field as fuelwood but the leaves were generally retained in the field.

The most realistic of the above discussed scenarios are thus Budget 3.

Questions have been raised as to whether nutrient budgets provide the information required for understanding the status and dynamics of the soil fertility across the farming systems and whether such analysis provide reliable direction and support to policy formulation on soil fertility management (see e.g. Schlecht and Hiernaux 2006 and references herein). Obviously some processes are left out, like leaching and surface run-off, and the values can only by difficulties be aggregated and upscaled (Smaling et al. 1993a, b; Færge and Magid 2004). Likewise, knowledge on some processes is scarce as for example discussed above regarding rhizodeposition. However, the aims of using nutrient budgets are to provide useful information to farmers and policy makers on the fertility status of the soil and the need for restoration if crop productivity is to be sustained based (Francis 1990; Myers and Johansen 2002). Simple budgets, based on farm-gate exports and imports of nutrients, as applied in the current study, demonstrates the benefits on the N budgets of including pigeonpea in the maize-based cropping systems of semi-arid southern and eastern Africa and they underlines the importance of crop residue management.

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