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Biological nitrogen fixation and yield of pigeonpea and groundnut: Quantifying response on smallholder farms in northern Malawi

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The global nitrogen (N) cycle is markedly, and increasingly, influenced by anthropogenic inputs. A large unknown remains the quantity of biological N fixation (BNF) inputs derived from agriculture. This leads to major uncertainties in modeling reactive N interactions with climate change, and understanding N biogeochemical processes. Understanding N dynamics is central to enhancing productivity in cropping systems. To fill this gap, we used ¹⁵N natural abundance to quantify BNF and yield of groundnut and pigeonpea – on 18 on-farm sites in Ekwendeni, Northern Malawi. The study was conducted over the 2007/08 (2008) and 2008/09 (2009) cropping seasons under farmer management, for a range of edaphic environments. Overall, the soils are largely sandy with low to moderate organic carbon (0.12-1.56%), pH (5.5-6.5), and very low to moderately high inorganic P (3 to 85 mg kg⁻¹). Intercropping was efficient at utilization of growth resources than sole cropping as evidenced by land equivalent ration (LER) >1. The main drivers of BNF were plant density, inorganic P and interspecific competition. The proportion of N derived from the atmosphere (22-99%) was influenced by soil P status across seasons and crop species, but not by cropping system. The mean proportion of BNF was high in both groundnut (75%) and pigeonpea (76%). Total N fixed, on the other hand, differed with cropping system in the dry year, where intercropping was associated with low levels of N fixed by pigeonpea (15 kg N ha⁻¹) compared to sole pigeonpea (32 kg N ha⁻¹). A short rainfall season could not support biomass production of pigeon pease, and this has negative implications for relying on BNF to drive productivity on smallholder farms.

Key words: Intercropping, Groundnut, Pigeonpea, Nitrogen fixation, ¹⁵N natural abundance.

INTRODUCTION

Nitrogen (N) deficiency is a major factor limiting productivity of maize based systems on smallholder

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farms in Southern Africa. The major sources of N in agro-ecosystems are inorganic fertilizers, livestock manures, compost manures, and legumes. Legumes fix atmospheric N biologically into inorganic forms that can be used by plants (Giller, 2001).

Biological N fixation is important for small holder farmers as it is relatively cheaper source of N compared to inorganic fertilizers, less prone to losses through leaching and denitrification. In Malawi, farmers grow a diversity of legumes including groundnut, common beans, soybean, pigeonpea, cowpea and green manures such as velvet bean, fish bean and a number of agroforestry species. These legumes are planted in sole stands or intercropped with cereals or other legumes, and rotated with cereals. Intercropping is the growing of two or more crops simultaneously on the same piece of land (Hauggaard-Nielsen et al., 2008).

This helps to optimize the use of resources such as land, nutrients, labor and water. The traditional intercrop system consists of maize-legume intercrops at low density. The relative proportion of each component species depends on the main crop of interest to the farmers, complimentarity in growth habits and use of resources. Productivity of intercrops can be maximized with careful selection of component crops and appropriate agronomic practices (Szumigalski and Van Acker, 2008).

Legumes improve soil quality through BNF and crop residue incorporation, and increase productivity of cereal based systems (Kumar Rao et al, 1983, Sakala et al 2000). The amount of N fixed by legumes and residual benefits varies with plant species, agronomic practices and environmental factors. Groundnut can fix 32 to 206 kg N ha\(^{-1}\) (Giller et al., 1987; Unkovitch and Pate, 2000), and a net N contribution of 13 to 100 kg N ha\(^{-1}\) if crop residues are incorporated in the soil (Toomsan et al., 1995). Pigeonpea can fix 69 to 100 kg N ha\(^{-1}\) (Kumar Rao et al., 1987), and a net N contribution of 2 to 60 kg ha\(^{-1}\) depending on the genotype and environmental factors (Myaka et al., 2006; Egbe et al., 2007).

An intercrop of a legume and a cereal has rarely been considered in research, in contrast to an intercrop of a legume and a cereal which is widely grown and has a nutritional complementarity. This includes the nitrogen fixation capacity of the legume and the high nitrogen requirement of the cereal. Complementary growth forms can also be the basis for a successful intercrop, such as a slow growing, deep rooted perennial grown in mixtures with a fast growing and shallow rooted annual. In India, some farmers intercrop pigeon pea with groundnut at low density (Willey et al., 1981), and has been tested in Zimbabwe (Natarajan and Mafongoya, 1992) which is an example of a doubled up legume system.

In this study, BNF and yield of intercropped groundnut and pigeonpea legumes was investigated. We hypothesized that N fixation rate per area basis will be higher under groundnut – pigeonpea intercrop (GNPP) than if either is sole cropped.

**MATERIALS AND METHODS**

**Site description**

Participatory on-farm researcher designed farmer managed trials were conducted in Ekwendeni area of Mzimba District, northern Malawi (33°53’E and 11°20’S; altitude 1200 m) in 2008 and 2009 growing seasons. Note that the growing season usually starts around November of the previous year but we refer to the season in terms of the year in which the majority of the season occurs. The annual precipitation is 800 to 1200 mm, with a unimodal distribution from November/December to March/April. Ekwendeni soils are classified as ferruginous latosols (Young and Brown, 1962).

In the 2008 crop season, rainfall was considerably below average at 669 mm. This was much less than 800 to 1200 mm, the expected range for this agro-ecological zone. Precipitation was high (45-50% of total) between last half of December 2007 to end of January 2008 which caused sheet erosion on some farm sites depending on the slope of the field, and could have resulted in leaching of some nutrients (personal observations).

Another concern was poor seedling development at some sites possibly due to saturated soil. From the second half of February 2008, the area experienced a dry spell and this coincided with grain and pod filling growth stages in maize and groundnut respectively while pigeonpea was still at vegetative stage. Scattered rain showers fell in March 2008 but this was not adequate to support optimum growth of the crops. In the 2009 season (November 2008 to April 2009), the area received 826mm of rainfall, and this was adequate for growth of legumes and maize.

**Experiment description and data collection**

The treatments for the cropping seasons 2008 and 2009 consisted of five cropping systems: three sole crops, maize (Zea mays), groundnut (Arachis hypogaea) and pigeonpea (Cajanus cajan); and two intercrops, maize-pigeonpea and groundnut-pigeonpea. The varieties grown were CG7 groundnut, ICEAP00040 pigeonpea and ZM621 maize. CG7 groundnut is characterized by bunch growth habit and high oil content averaging 48% and a yield potential of 2500 kg ha\(^{-1}\) (Malawi Government Ministry of Agriculture, Irrigation, and Food Security, MaAIFS, 2005). Pigeonpea is a semi perennial legume that grows up to 2-4 m high (Werner, 2005). It has a deep root system and initial growth rates are slower compared to groundnut or maize.

The experiment was laid out as a randomized complete block design with six treatments. Each treatment was replicated 18 times on farm, one replicate per farm. Treatment plot size was 10m by 10m, and consisted of 11 rows (aligned on a ridge following farmer practice in Malawi), each 10m long and spaced at 0.90m. The net plot used for measurements of grain and biomass consisted of the interior 8m of 7 centrally located ridges, to reduce border effects by not monitoring the external 1m of row.

The goal for the planting pattern for intercrops was based on maximizing the plant population of the main crop for all cropping systems. The legumes were seeded at a 0.20m and 0.90m within row spacing for groundnut and pigeonpea respectively to achieve 43,210 plants ha\(^{-1}\) (0.90x0.2x1) and 55555 plants ha\(^{-1}\) (0.90x0.2x1) for intercropped and sole groundnut respectively, with an additional 37000 plants ha\(^{-1}\) of maize or pigeonpea in the intercrops. Maize and pigeonpea were seeded alternately in the intercrop, along rows in stations of three plants each, spaced at 0.45m intervals.

The planting pattern for maize and pigeonpea was an additive
design, sole crop and intercrop all planted at 37000 plants ha\(^{-1}\) density for both crops. Planting was done in December 2007 and 2008. All plots received a uniform basal application of 10 kg N ha\(^{-1}\) at one week after planting based on observations that soils were highly N deficient, to improve uniformity of plant stands and early vigor. All field management practices were conducted by participating farmers. In the 2009 crop season, year one treatments were replicated in time by planting adjacent plots. The varieties and planting pattern were the same as described for year 1.

### Soil sampling and analysis

At planting in December of 2007, composite soil samples (8 to 10 subsamples) were collected from each farm using a Z-scheme to ensure random collection. Two depths were sampled, 0 to 15 cm and 15 to 30 cm, for site characterization.

These were air dried and sieved through a 2 mm sieve. Soil texture was determined using the hydrometer method (Anderson and Ingram, 1989). Particulate organic matter (POM) were analyzed on ungrounded soil samples using a modification of the light-large particulate organic matter (POM) fractionation method described by Cambardella and Elliott (1993) and Cambardella and Elliot (1992).

Sodium polytungstate was recycled according to Six et al. (1999). After POM extraction and weighing, the sample was ground into powder with a clean mortar and pestle. POMC and POMN were determined using a dry combustion C and N Analyzer (Costech ECS 4010, Costech Analytical Technologies, and Valencia, CA). The remaining soil samples were ground and sent to A and L Great Lakes Lab in Fort Wayne, Indiana, United States of America, for analysis of the following variables: pH in a 1:1 ratio in H\(_2\)O, inorganic P (Bray P), and Mehlich 3 extraction of Ca, K, Mg (Mehlich, 1984).

### Plant sampling and analysis

#### Assessment of nitrogen fixation by legumes

**Plant sampling for N fixation measurements:** Two 1 m x 1 m quadrants were demarcated in each plot for BNF measurements. At harvest, these plants were harvested and separated into grain and leafy biomass. Dried grain samples were ground into fine powder using a Wiley mill to pass a sieve size of 1 mm, then carefully sub sampled and weighed into capsules before \(^{15}\)N and \(^{14}\)N mass spectrophotometer analysis conducted at University of California Davis, USA. The proportion of N fixed through BNF was determined using \(^{15}\)N natural abundance method. The proportion of N derived from atmosphere (%Ndfa) was calculated according to Shearer and Khol (1986) and Peoples et al., (1989) as follows:

\[
\%\text{Ndfa} = \frac{100 \left( \delta^{15}N_{\text{ref}} - \delta^{15}N_{\text{legume}} \right)}{\delta^{15}N_{\text{ref}} - B}
\]

Where \(\delta^{15}N_{\text{ref}}\) is the \(^{15}\)N natural abundance of grain of the reference plant (maize) grown on same soil as the legume; \(\delta^{15}N_{\text{legume}}\) is the \(^{15}\)N natural abundance of the grain of the legume crop; B is the \(\delta^{15}N\) of the test legume where the only N source is atmospheric N. The lowest \(\delta^{15}N\) for each legume was used as B value (Hansen and Vinther, 2001).

### Plant biomass

Plant biomass at early vegetative stage and at harvest was determined from the net plot of 57.6 m\(^2\) (8 middle ridges x 8 m x 0.90 m). Groundnut and maize were harvested in June whilst pigeonpea was harvested in September after full physiological maturity. As described above, quadrant samples were removed from the net plot to measure N fixation, and grain yields were adjusted for this removal. Grain moisture was determined by wet weight basis of oven dried sub sample of grain. Grain yields were reported on an adjusted basis at 8% and 15% moisture content for groundnut and pigeonpea, respectively.

### Statistical analysis

Soil nutrient and physical properties were analyzed using a one way ANOVA for location. Whereas plant analysis, biomass yield were analyzed as a RCBD using SAS proc mixed procedure for a two-way model, cropping system by year as factors (SAS Institute, 2001). Where variances were not homogenous, data were analyzed with unequal variances assumption. All data were analyzed in SAS proc mixed procedure. Significant differences were determined at p=0.05.

### RESULTS

#### Soil characterization

Table 1 shows results on soil chemical properties and texture. Soil pH ranged from 5.5 to 6.5 at 0 to 15 cm depth with a mean of 5.8±0.3. The soils are largely light textured with 18±7.7% and 74±9.8% clay and sand respectively. Soil organic carbon (OC) was low in the range of 2.0 to 16 g kg\(^{-1}\), with a mean of 6.4± 3.1g kg\(^{-1}\); and total N (0.7±0.05 g kg\(^{-1}\)). Inorganic P was highly variable (3 to 85 mg kg\(^{-1}\)) at 0 to 15 cm depth. The mean CEC was 5.8±1.6 and 4.9±1.4 cmol kg\(^{-1}\) at 0 to 15 cm and 15 to 30 cm soil depths respectively. Exchangeable cations (calcium, potassium and magnesium) were adequate for growth of the maize, groundnut and pigeonpea (Table 1).

#### Plant growth in 2008 and 2009

Biomass of pigeonpea and groundnut at early vegetative stage (eight and half weeks after planting) averaged 8.9±1.7 g plant\(^{-1}\) and 17±3.4 g plant\(^{-1}\), respectively, with no effect observed of cropping system. The mean biomass/plant of sole and intercropped groundnut at harvest were 63±20 and 53± 20g respectively. However, in pigeonpea, intercropping reduced pigeonpea biomass by 30 to 60%, p=0.0023 (Figure 1). In 2008/09 season, similar observations were made on late season growth of pigeonpea.

#### Grain yield of groundnut and pigeonpea

Table 2 shows results on leafy biomass and grain yield of
Table 1. Soil chemical properties and texture of on-farm experimentation fields (Baseline analysis sampled early December, 2008. N=18).

| Variable            | 0-15cm         |                | 15-30cm         |                |
|---------------------|----------------|----------------|-----------------|----------------|
|                     | Mean           | Range          | Mean            | Range          |
| pH (in H₂O)         | 5.8 ±0.3       | 5.5-6.5        | 5.9±0.4         | 5.1-6.9        |
| OC (g kg⁻¹)         | 6.5±2.1        | 3-11           | 5.0±2.2         | 2-11           |
| Total N (g kg⁻¹)    | 0.5 ±0.1       | 0.4-0.8        | 0.5 ±0.2        | 0.3-1.1        |
| POMC (g kg⁻¹)       | 0.4 ±0.01      | 0.20-0.94      | 0.2 ±0.12       | 0.03-0.45      |
| POMN (g kg⁻¹)       | 0.02±0.01      | 0.008-0.04     | 0.01±0.002      | 0.003-0.04     |
| Bray P (mg kg⁻¹)    | 10 ±8.4        | 3-85           | 3±1.9           | 1-66           |
| Sand (%)            | 74 ± 9.8       | -              | 72±10.7         | -              |
| Clay (%)            | 18 ± 8.2       | -              | 21±8.8          | -              |

Key: POMC=particulate organic matter carbon; POMN=particulate organic matter nitrogen, units for POMC and POMN are g per kg POM.

Figure 1. Pigeonpea growth at vegetative stage (8.5 weeks after planting) and at harvest in 2007/08 season (Key: PP=sole pigeonpea; PPGN=pigeonpea intercropped with groundnut; PPMZ=pigeonpea intercropped with maize. Standard error presented as error bar).

groundnut and pigeonpea. In groundnut, cropping system and season interactions were significant, \( p=0.0026 \). Sole cropped groundnut yielded 84% higher in 2008/09 season than 2007/08. The yield of groundnut haulms varied with season and cropping system \( (p<0.001) \). Sole groundnut produced more haulms \( (2.5 \text{ t ha}^{-1}) \) compared to intercropped groundnut \( (1.7 \text{ ton ha}^{-1}) \).

Across seasons, the quantity of haulms was 89% higher in a 2009 than in 2008. In pigeonpea, grain yield averaged 284 kg ha\(^{-1}\) and was not affected by cropping system or season. However, leafy biomass of pigeonpea was significantly affected by cropping system \( (p<0.0001) \) and season \( (p=0.03) \). Sole cropped pigeonpea produced 100% more leafy biomass than intercrop. In a wetter season, pigeonpea produced higher biomass than in 2008 season. The land equivalent ratio was equal to 1.52 indicating total productivity was 52% higher under groundnut-pigeonpea intercropping than...
sole cropping, that is, 52% more land would be required in sole stands to produce same yields as in intercropping (Table 2).

**Biological nitrogen fixation of groundnut and pigeonpea**

**Nodule number and weight**

Cropping system had no effect on nodule numbers per plant and nodule weight of both legumes at eight weeks after planting (WAP). The mean nodule number per plant were 91±8; and 10±1.4 for groundnut and pigeonpea respectively. However, in groundnut, the nodules were bigger (p=0.004) in a wetter season (2009) than 2008 (2.7 vs 1.7mg); and no season effects observed in pigeonpea. The average nodule weight in pigeonpea was 9.6mg.

**Proportion of nitrogen (N) derived from the atmosphere and N fixation by groundnut and pigeonpea**

The proportion of N derived from the atmosphere (%Ndaf), total N fixed by legumes and correlation matrix between N fixed and selected variables are shown in Tables 3 and 4. In groundnut, the %Ndaf ranged from 29 to 99% with a mean of 78% with no effect of cropping system. For sole groundnut, the %Ndaf was positively correlated to crop N (r=0.98), POM (r=0.68), inorganic P (r=0.59) and plant density (r=0.65) (Figure 2). The relationship between total N fixed (kg ha⁻¹) and plant density was described by following fitted regression model:

\[
\text{Total N fixed} = -93.404 + 0.003 \text{ plant density}
\]

However, no linear relationship was observed between the total N fixed per unit area and inorganic P or density when groundnut was intercropped with pigeonpea.

In pigeonpea, the %Ndaf ranged from 41 to 99%, mean =76±20. This did not differ between sole and intercropped pigeonpea. In 2008, the %Ndaf was positively correlated with total N fixed, r=0.73 and 0.68 for sole pigeonpea and pigeonpea intercropped with maize (PPMZ) respectively. Similar findings for %Ndaf were observed under sole pigeonpea and pigeonpea intercropped with groundnut (PPGN) in 2009. Inorganic P was positively correlated with total N fixed, r=0.86 for PPMZ in 2008, r=0.59 for PPGN (Table 4), r=0.78 and 0.65 for sole pigeonpea in 2008 and 2009 respectively (Table 3 and Figure 3).

On area basis, total N fixed ranged from 21 to 86, mean= 53 kg ha⁻¹ under sole pigeonpea; 34 to 148, mean = 72 kg ha⁻¹ for GNPP (Table 3); and 4 to 26 kg ha⁻¹, mean=12 kg ha⁻¹ for PPMZ. However, there were no differences in total N fixed by sole groundnut and GNPP. A trend of higher total N fixed under GNPP than PP was observed (p=0.094). Total N fixed in aboveground leafy biomass of pigeonpea was twice as much in 2009 season than 2008 probably due to adequate soil moisture with

### Table 2. Effect of cropping system on leafy biomass and grain yield of groundnut and pigeonpea, 2007/08 and 2008/09 cropping seasons.

| Crop          | Cropping system | Grain yield (kg/ha) | Leafy Biomass | 2008 | 2009 | 2008 | 2009 | Mean |
|---------------|-----------------|---------------------|---------------|------|------|------|------|------|
|               |                 |                     |               |      |      |      |      |      |
| Groundnut     | Sole            | 598⁸A              | 1101⁸A        | 1895 | 3156 | 2569B|      |      |
|               | Intercropped    | 435⁸B              | 650⁸B         | 1275 | 2042 | 1659A|      |      |
| Mean          |                 | 516                | 876           | 1585A| 2599B| -    |      |      |
| Pr>F          | Season (A)      | <0.0001            | -             | -    |      |      |      |      |
|               | Cropping system (B) | <0.0001       | -             | -    |      |      |      |      |
|               | A × B           | 0.0026             | -             | 0.247| -    |      |      |      |
| Pigeonpea     | Sole            | 310                | 302           | 3410 | 4341 | 3876B|      |      |
|               | Intercropped    | 238                | 284           | 1443 | 2320 | 1881A|      |      |
| Mean          |                 | 274                | 293           | 2416A| 3333B| -    |      |      |
| Pr>F          | Season (A)      | 0.738              | -             | 0.03 | -    |      |      |      |
|               | Cropping system (B) | 0.425               | -             | <0.0001| -    |      |      |      |
|               | A × B           | 0.816              | -             | 0.947| -    |      |      |      |

Means in a row or column per variable category followed by same upper lower or upper case letter are not statistically significant at p<0.05; in pigeonpea, the biomass includes the leafy biomass and stems (2008= 2007/08 cropping season; 2009=2008/09 cropping season).
the high precipitation. A short rainfall season could not support biomass production of pigeonpea and this has negative implications for relying on BNF to drive productivity on smallholder farms. Defoliation in senesced leaves was estimated at 41% and 57% for PPGN and sole PP. The

Table 3. Biological nitrogen fixed (proportion and total) in grain and leafy biomass by sole and intercropped groundnut and pigeonpea.

| Season | Cropping system | % Ndfa | N fixed in grain (kg/ha) | N fixed in leafy biomass (kg/ha) | Total N Fixed (kg/ha) | Range, total N fixed (kg/ha) | Estimated N fixed in defoliated PP leaves* (kg/ha) |
|--------|-----------------|--------|--------------------------|---------------------------------|----------------------|-----------------------------|---------------------------------|
| 2008   | Groundnut (GN)  | 78     | 17b                      | 21c                             | 50c                  | 21-102                      | -                               |
|        | Pigeonpea (PP)  | 76     | 2a                       | 15b                             | 31b                  | 11-64                       | 8.6                             |
|        | GNPP            | -      | 16b                      | 19bc                            | 42bc                 | 23-69                       | 6.2                             |
|        | Pr>F            | -      | <0.0001                  | 0.0005                          | <0.0002              | -                           | -                               |
| 2009   | Groundnut (GN)  | 73     | 28b                      | 33                              | 62                   | 21-96                       | -                               |
|        | Pigeonpea (PP)  | 75     | 8a                       | 34                              | 53                   | 21-86                       | 13.4                            |
|        | GNPP            | -      | 23b                      | 39                              | 72                   | 34-148                      | 6.5                             |
|        | Pr>F            | -      | <0.001                   | 0.726                           | 0.238                | -                           | -                               |

2008 = 2007/08 season; 2009= 2008/09 season; GNPP= groundnut intercropped with pigeonpea; B values obtained from lowest 15N of legume (Hansen and Vinther, 2001). B values in 2008 are -0.45, -0.38 and -0.80 for sole GN, GNPP and sole PP. B values in 2009 are -0.26 and -0.21 for sole GN and GNPP; and -0.83, -0.74 for sole PP and PP intercropped with GN; Means in a column by year category followed by same letter are not statistically significant at p=0.05; *The estimated N fixed in defoliated leaves calculated based on determined proportion of defoliation in pigeonpea at harvest, 41% and 57% for intercropped and sole cropped ICEAP00040 pigeonpea.

Table 4. Correlation matrix of nitrogen fixation with Ndfa, Bray P and crop N of sole and intercropped pigeonpea and groundnut, 2007/08 and 2008/09 seasons.

| Season | Variable | N fixed by pigeonpea | N fixed by groundnut |
|--------|----------|-----------------------|----------------------|
|        |          | Sole PP | PPGN | PPMZ | Sole GN | GNPP |
| 2008   | N fixed  | 1.000   | 1.000 | 1.000 | 1.000   | 1.000 |
|        | Bray P   | 0.780** | 0.175 | 0.857*** | 0.587* | 0.352 |
|        | Ndfa     | 0.731*  | 0.488 | 0.676* | 0.428 | 0.296 |
|        | Crop N   | 0.911*** | 0.92*** | 0.599* | 0.98*** | 0.93*** |
| 2009   | N fixed  | 1.000   | 1.000 | nd   | 1.000   | 1.000 |
|        | Bray P   | 0.646*  | 0.590* | nd   | 0.263   | 0.170 |
|        | Ndfa     | 0.598   | 0.566* | nd   | 0.337   | 0.868*** |
|        | Crop N   | 0.894*** | 0.904*** | nd   | 0.614*  | 0.981*** |

2008 = 2007/08 season; 2009= 2008/09 season; Values in bold are significant. Level of significance *p=0.05; ** p=0.01; *** p=0.0001; GN= groundnut; PP = pigeonpea; PPGN= pigeonpea intercropped with groundnut; GNPP= groundnut intercropped with pigeonpea; PPMZ=pigeonpea intercropped with maize; nd=no data for PPMZ in 2009.
estimates of N fixed in defoliated leaves are included in Table 2.

DISCUSSION

Soil fertility

Soil fertility was low and variable among smallholder farms and this is consistent with findings from earlier studies (Snapp 1998, Mhango et al., 2013). Inorganic P was variable and low, and yet this is important for BNF (Jemo et al, 2006). The high correlation of inorganic P and total N fixed by pigeonpea in maize-pigeonpea intercrops (Table 3) suggests interspecific competition and that the two crops were accessing P from same pools during part of their growth cycles. In contrast, groundnut and pigeonpea may access P from different pools because of the differences in growth habits. Phosphorus is important for root development and growth.
of legume species. Positive correlations observed between inorganic P and N fixed by pigeonpea could be related effects of P on nodulation, biomass production and N fixation process.

Biomass production of sole and intercropped legumes

Early growth was not altered by crop system, indicating that competition was minimal early in the growing season. This is not surprising as pigeonpea has a slow growth pattern, and had 50% of groundnut dry matter accumulation during early vegetative growth.

This may have also been due to relatively low plant population densities, which follows farmer practice. Surprisingly, groundnut biomass was not affected in late growth stages and this could be due to differences in growth rates relative to semi- perennial pigeonpea. A follow up study in 2012 showed that different densities of pigeonpea, from 12350 to 37000 plants per hectare did not alter the growth and grain yield of CG7 groundnut. In contrast, the late season growth competition demonstrated by low pigeonpea biomass could be related to inadequate soil moisture due to early cessation of rain in 2008 which inhibited vegetative biomass production.

The grain yield of groundnut reported in this study is lower than the potential yield but is within the average yields (500 kg ha$^{-1}$) obtained on smallholder farms in Malawi (Kamanga 2002; Malawi Government, MoAIFS, 2005). Pigeonpea grain yield on smallholder farms are generally low and one of the major constraints are pests such as blister beetles (*Mylabris* species) that feed on flowers (Boehringer and Caldwell, 1989). Other on-farm studies in central Malawi have reported pigeonpea grain yield of 155-348 kg ha$^{-1}$ (Twomlow et al., 2004; Chamango, 2004). The findings from this study also illustrate that there was efficient utilization of growth resources under groundnut-pigeonpea intercropping than sole stands, LER=1.52.

Biological nitrogen fixation of sole and intercropped groundnut and pigeonpea, and sustainability of cropping systems

Effective nodulation is important for maximizing N fixation by legumes. In this study, the reduction in nodule weight in a drier year can be attributed to drought. The number of nodules per plant in both legumes is comparable to previous work by Giri and De (1980) and Kumar Rao et al. (1996).

Interspecific competition is one of the determinants of intercrop productivity. It is an important finding that the proportion of Ndfa was not affected by cropping system. This is consistent with Katayama et al. (1995) but differ in that they reported higher %Ndfa in pigeonpea intercropped with cereals (84%) than sole or doubled up legumes (52 to 70%).

Groundnut met 78% of its N requirement from BNF. This was higher than 22 to 67% as reported by Katayama et al. (1995) and Phoomthaisong et al. (2003), and this could be due to low soil N (Table 1). The total amount of N fixed per area were lower than those reported by Ojiem et al (2007) for CG7 groundnut probably due to low inorganic soil P (Table 3), plant density and biomass production.

Ojiem et al. (2007) reported 115 to 124 kg ha$^{-1}$ as N fixed with application of inorganic P fertilizer and higher plant densities of approximately 1.5 times than the density in this study. Since crop N was positively correlated with amount of N fixed by legume, inadequate soil moisture during reproductive growth stage of groundnut may have limited pod formation and grain filling consequently reducing total plant biomass.

The positive correlation between inorganic P and total N fixed by intercropped pigeonpea may suggest that the two crops were accessing the same P pools (Makumba et al., 2009). However, in a short rainfall season (2007/08), the lack of a correlation between inorganic P and N fixed by PPGN is probably due to poor growth of pigeonpea with inadequate soil moisture and hence less competition for nutrients.

Long duration legumes such as pigeonpea are expected to fix more N, and produce higher biomass than the early maturing varieties. In this study, pigeonpea fixed less N than groundnut in a short rainfall season probably because of inadequate soil moisture. The average total N fixed by pigeonpea is lower compared to 46-118 kg ha$^{-1}$ as reported in earlier studies for ICEAP00040 variety in Malawi (Adu-Gyamfi et al., 2007). Sole pigeonpea fixed 30 and 53 kg ha$^{-1}$ in a dry and wet season respectively and this is within 20-60 kg N ha$^{-1}$, values reported for the same variety on selected sites in Tanzania. These findings can be attributed to low inorganic P (Table 1) and inadequate soil moisture to support biomass production following a dry spell that occurred when pigeonpea was still at early vegetative stage in 2007/08 season.

Legumes have been promoted in farming systems as an alternative strategy to improving soil N and productivity of cereals. In Malawi, the recommended N rate for maize on most smallholder farms is 92 kg N ha$^{-1}$. The proportion of N requirement met by sole and intercropped legume systems is 12-50%. This implies that on low fertility soils (<15 g kg$^{-1}$ OM), legume based cropping systems alone cannot sustain maize productivity and hence the need for integrated soil fertility management (ISFM) approaches.

CONCLUSION

This study evaluated biological nitrogen fixation and yield of sole, and intercropped groundnut and pigeonpea on smallholder farms. Soil P availability was not related to
general soil properties such as soil organic carbon and texture, yet it was an important determinant of nitrogen fixation in these legume diversified cropping systems. This indicates that it may be possible to support greater legume growth without building soil organic carbon to higher levels, rather the emphasis should be on judicious use of P-fertilizer and other P amendments such as compost.

Intercropping pigeonpea with groundnut or maize can help to improve crop productivity, maximize use of limited land and labor. The results have demonstrated that the drivers of biological N fixation are inorganic P, plant density and interspecific competition.

In a short rainfall season, interspecific competition may limit vegetative growth of semi-perennial pigeonpea, and this has negative implications for BNF. The findings from this study also suggest that different legume cropping systems should be recommended for farmers, sole cropping for grain maximization; and intercropping for smallholder farmers interested in multiple benefits.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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