BROADENING SMALLHOLDER FARMER OPTIONS THROUGH LEGUME ROTATIONAL AND INTERCROP DIVERSITY IN MAIZE-BASED CROPPING SYSTEMS OF MALAWI

By

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ABSTRACT

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Sustainability of rainfed cropping across southern Africa is undermined by maize (*Zea mays* L.) monocultures which are mostly cultivated on nitrogen (N) deficient soils. Smallholder farmers rarely achieve access to adequate quantities of inorganic fertilizers, and this limits crop productivity and negatively impacts food and nutritional security. Sustainable intensification with legumes has been proposed as a solution to address these challenges. Legumes such as groundnut (*Arachis hypogaea* L.) and pigeonpea (*Cajanus cajan* L.) potentially improve soil fertility and productivity of cereal crops grown in sequence through biological nitrogen fixation (BNF) and high-quality organic residues. However, successfully addressing smallholder farmer challenges requires understanding cropping system performance on-farm, in different environments. This is critical for site-specific agricultural technology recommendations that suit smallholder farmer goals.

This dissertation consists of three studies on sustainable intensification with legumes in maize-legume cropping systems in central and southern Malawi. A participatory research approach of researcher designed, and farmer-managed trials were used to evaluate legume and maize production, the economic feasibility of cropping systems, BNF contributions and effect of residue quality and quantity on soil N dynamics. In the first chapter, four cropping systems in on-farm experiments, in five locations from three agroecologies in central Malawi were used to compare

intercrop diversity and rotational diversity. The objective of the study was to determine suitable cropping systems for smallholder farmers in terms of grain production and economic viability. Above and belowground biomass was monitored to understand inter- and intra-specific competition of pigeonpea, and groundnut compared to the traditional maize/pigeonpea intercrop. Pigeonpea biomass was suppressed when intercropped with either groundnut or maize, whereas groundnut was not sensitive to interspecific competition. The second chapter is an evaluation of on-farm nitrogen dynamics, including a detailed assessment of BNF by plant tissue components of groundnut and pigeonpea within four legume-maize diversified cropping systems in central Malawi. The findings show that the net nitrogen balance with groundnut varied markedly, from deficit to a net benefit for subsequent crops, depending on growth and residue management. Another finding was that pigeonpea, especially when grown as part of a doubled-up legume system, provided substantial nitrogen inputs on rain-fed smallholder farms. The third chapter involved determining the effect of incorporating high- vs low-quality and quantity of crop residues on mineral N dynamics and subsequent maize yield in southern Malawi. Findings show the actual crop residue biomass quantity and quality that smallholder farmers are capable of producing depending on their biophysical environment. Each of the three studies highlights implications for on-farm sustainable intensification with legumes to address various farmer goals in different environmental context.

This dissertation is dedicated to my wonderful husband Villeneuve and our children Eliana and Elihai. Thank you for your unwavering support, love and patience throughout my PhD journey.

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1. Chapter One: Legume rotational and intercrop diversity in maize-based cropping systems of Malawi

Abstract

Sustainability of rainfed farming across east and southern Africa is undermined by the continuous presence of maize (*Zea mays* L.) across the vast majority of fields. Farmers have traditionally intercropped maize with food legumes, an important source of field and dietary diversity, but simplified cropping systems including sole cropped maize are common. An important agrodiversity question remains, is intercrop diversity sufficient for sustainability, or is rotational diversity more advantageous? A two-year, on-farm experiment was conducted in central Malawi at five sites along a marginal to a mesic gradient. Above and belowground biomass was monitored to understand inter- and intra-specific competition of pigeonpea (*Cajanus cajun* L.) and groundnut (*Arachis hypogaea* L.) compared to the traditional maize/pigeonpea intercrop (MZPP). Alternate systems studied included: pigeonpea rotated with maize (PP-MZ), groundnut rotated with maize (GN-MZ), and GNPP intercrop rotated with maize (GNPP-MZ). Across locations, PP-MZ produced the highest grain yield in the maize rotation phase at 5.51 Mg/ha. System performance in terms of gross margins ranged from $1407 to $1145/ha and in the order: GNPP-MZ=MZPP-MZPP>GN-MZ>PP-MZ. Pigeonpea biomass was suppressed when intercropped with either maize or groundnut, whereas groundnut was not sensitive to interspecific competition. The GNPP-MZ system met multiple goals including high amounts of biomass from pigeonpea for soil fertility replenishment, profitable groundnut grain, and high yields of maize

grown in sequence with minimal fertilizer application. The PP-MZ rotation was highly suitable for sites with infertile soils. However, pigeonpea grain alone might be insufficient to make the PP-MZ system attractive to farmers.

Keywords: Groundnut, Intercropping, Legumes, Maize, On-farm, Pigeonpea, Rotation

Introduction

Efficient use of limited land and nutrient resources is key to viable farming systems in some densely populated Sub-Sahara African (SSA) countries. Agroecology principles can be harnessed to improve the sustainability of food production on smallholder farms in SSA. This includes the careful selection of diverse species, and planned mixtures, to enhance facilitation and complementarity (Malézieux *et al*., 2009; Raseduzzaman and Jensen, 2017). Maize-dominated smallholder farming in SSA countries is becoming intensified through the adoption of fertilizer and other inputs yet crop diversification has been overlooked as a means to sustainably intensify, and in some cases intercrop diversification has been actively suppressed through agricultural policies that promote sole cropping, with inadvertent consequences (Isaacs *et al*., 2016). The complementarity of legumes associated with nitrogen fixation and other soil fertility enhancing traits can be used to reinforce sustainable production of maize. This is critical in SSA where N limited soils are limiting maize's genetic expression of yield potential (Giller and Cadisch, 1995). Legume food crops provide nutritious grain. The long-duration growth types, such as pigeonpea, provide forage in the form of copious vegetation and deep root systems for soil rehabilitation (Odeny, 2007; Snapp and Silim, 2002).

Farmers use both intercrops and rotational sequences to integrate legumes into their cropping systems. However, whether intercrops or rotations are more effective at supporting sustainable intensification on smallholder farms is debated. Intercropping of maize with grain legumes enhances land-use efficiency and productivity (Raseduzzaman and Jensen, 2017). About 50% of fields in Malawi are intercropped, which is consistent with farmers maximizing returns to land on smallholder farms of about 0.5 to 1.5 hectares (Silberg *et al*., 2017). There is conflicting evidence regarding the relative advantages of rotations vs. intercrops as a means to lower cost of production, improve soil fertility, increase total grain yield, and support yield stability (Bhuva *et al*., 2017; Malézieux *et al*., 2009; Raseduzzaman and Jensen, 2017). When inappropriate component plant densities or incompatible crop varieties are intercropped, there is often markedly reduced yields of one or both of the species (Dalal, 1974; Rusinamhodzi *et al*., 2012; Snapp and Silim, 2002).

According to Tully *et al*. (2015), integrating legumes in rotations is an effective strategy in terms of water-use efficiency, increased nutrient availability, increased soil biological activity and C sequestration. Chimonyo *et al*. (2019) reported that rotating maize with legumes such as pigeonpea and groundnut results in high and stable maize grain yield. At the same time, a meta-analysis by (Raseduzzaman and Jensen, 2017), concluded that intercropping cereals with grain legumes generally improved yield stability compared to sole cropping. The environmental context may influence the relative performance of rotational vs. intercrop diversity and needs to be considered.

To address the knowledge gaps, this research involved an analysis of crop diversification through rotations and intercrops in different environmental contexts. The focus of this study was on two grain legumes that are highly suited to maize-based rainfed smallholder farms in SSA: pigeonpea and groundnut. Pigeonpea is a long duration grain legume crop that accumulates large biomass over a six to eight-month growth period. Under favourable environmental conditions, pigeonpea can biologically fix up to 200 kg/ha N but in unfavourable conditions, it might be as low as 6 kg/ha N (Adu-Gyamfi *et al*., 2007; Kumar Rao and Dart, 1987). Initial pigeonpea growth is slow, making it an ideal crop for intercropping with competitive crops such as maize or short early maturing legumes such as groundnut (Snapp and Silim, 2002). Groundnut is widely grown in sub-humid and semi-arid SSA as a high oil content cash or food crop, where it is often cultivated with maize, cassava (*Manihot esculenta* L.), and plantain (*Musa paradisiaca* L.) (Wendt and Atemkeng, 2004).

Our study evaluated the performance of farmers' traditional maize/pigeonpea intercrop and that of alternative maize cropping sequence strategies through rotation with groundnut and pigeonpea cultivated as sole crops and as a doubled-up legume system (intercrop of two legumes). Specifically, objectives were: 1) to document legume above and belowground biomass in sole and mixed cropping system patterns, for a gradient of marginal to mesic on-farm sites in central Malawi; 2) to document biomass, yield and economic performance of maize, groundnut, and pigeonpea in sole, intercropped and doubled-up legume maize systems relative to a maize/pigeonpea intercrop farmer control; and 3) evaluate interspecific vs. intraspecific competition in sole and intercropped systems for pigeonpea and groundnut.

Materials and methods

Study sites and field sites characterization

A stratified random approach was used to select the research sites to represent marginal to mesic potential areas (Mungai *et al*., 2016) in central Malawi (13.2543° S, 34.3015° E). The locations were in the Linthipe, Golomoti and Kandeu Extension Planning Areas (EPA) (Figure 1.1). Linthipe is a high potential, sub-humid tropical agroecology with well-distributed rainfall in most years. Kandeu is a medium agricultural potential, sub-humid tropical agroecology with a rainfall distribution that is above average in most years. Golomoti is a low potential, semi-arid to sub-humid tropical agroecology, at low altitude and with erratic rainfall; high temperatures increase evapotranspiration at this site. Linthipe soils are ferric luvisols, the Kandeu study site has a mixture of chromic luvisols and orthic ferralsols, while Golomoti soils are a mixture of eutric cambisols and eutric fluvisols (Mungai *et al*., 2016). The field experiments were conducted at five field sites (Table 1.1). Soil sampling was conducted in late June and early July of 2016, at 0– 20 cm depth, three composite samples per plot using a dutch auger (5.5 cm diameter). Soils were air-dried, sieved (2 mm) and soil texture was determined using the hydrometer method (Kellogg Biological Station/ Long-Term Ecological Research, 2008). Soil pH was determined in a 1:2 soil to water suspension (Kellogg Biological Station/ Long-Term Ecological Research, 2016). Total soil carbon and total soil N were determined, after grinding to a fine powder with a shatter mill, by dry combustion with Costech ECS 4010 (Costech Analytical Technologies, Inc., Valencia, CA). To determine potential mineralizable NH4-N (PMN), soil samples were anaerobically incubated at 30 °C for seven days (Kane *et al.*, 2015). After incubation, NH4-N was extracted using 2.66 M KCl. KCl extracts were analysed for inorganic N concentrations on a Thermo MultiskanTM 96-well plate reader (Kane *et al.*, 2015). The cumulative rainfall from the two study years received in Linthipe, Kandeu and Golomoti during the 2015-2016 and 2016-2017 growing seasons is shown on Figure 1.2.

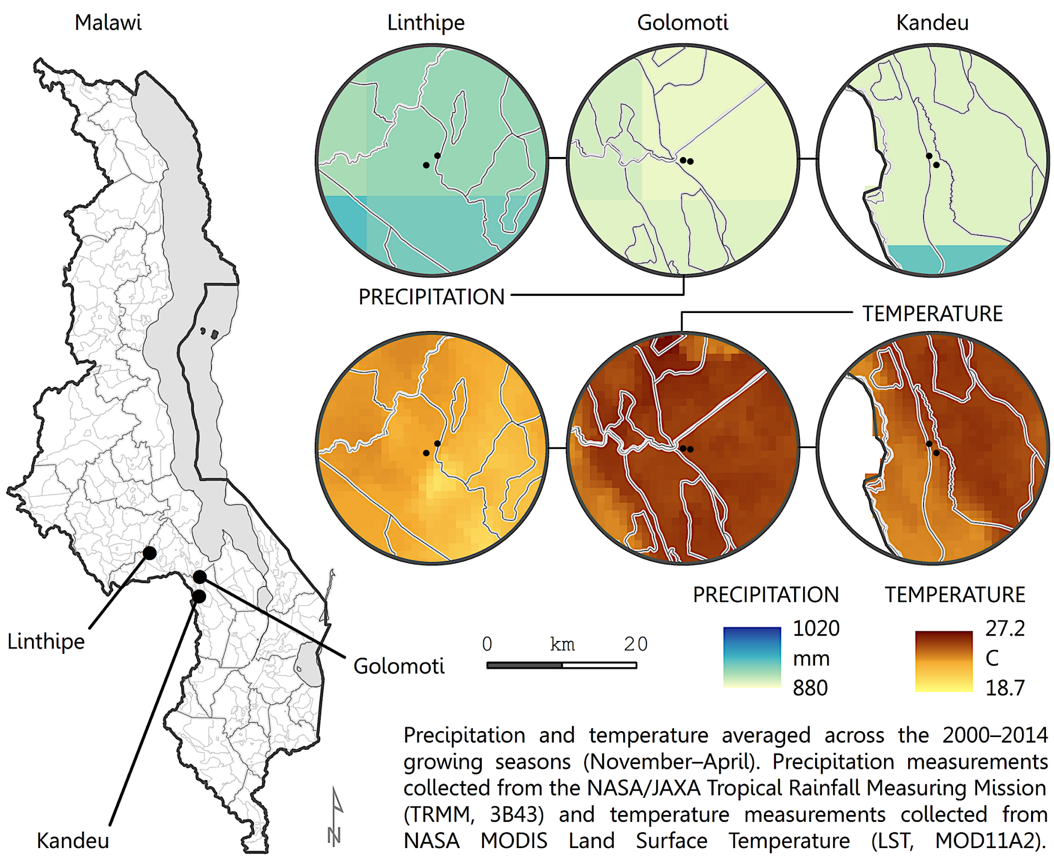

Figure 1.1. Map of Malawi showing the location of the three research agroecologies with precipitation and temperature averages. Map courtesy of Brad Peter, Department of Geography, Michigan State University (2016)

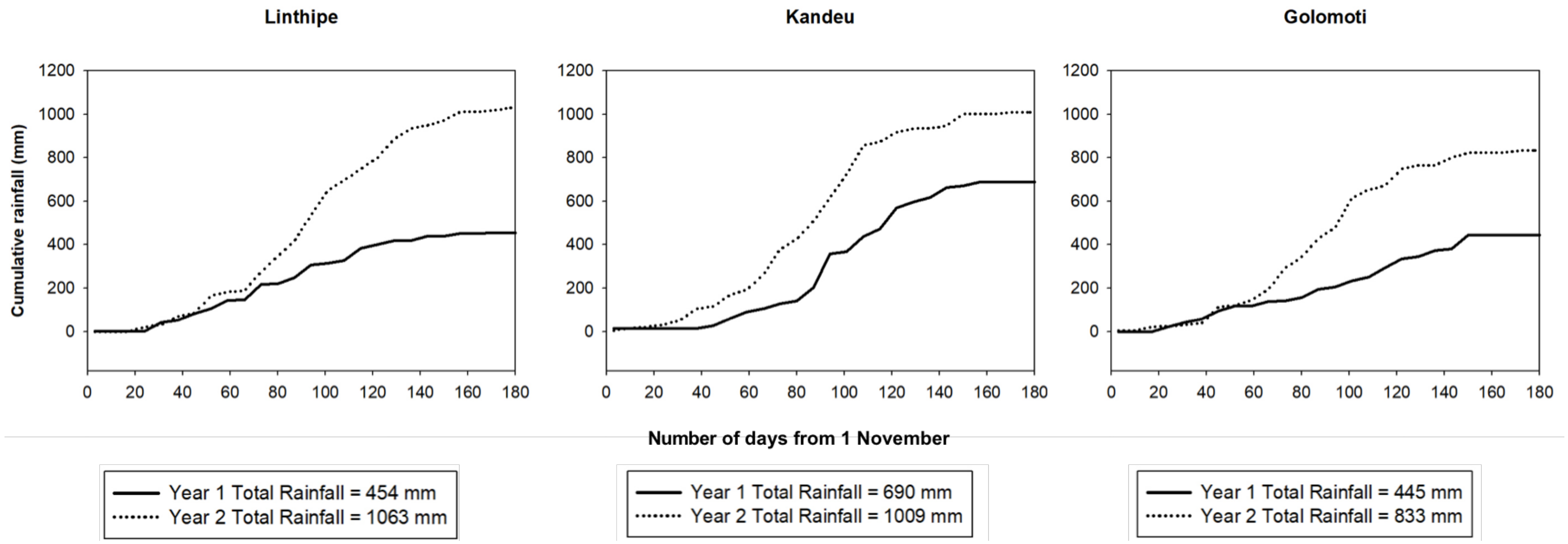

Figure 1.2. Cumulative rainfall received in Linthipe, Kandeu and Golomoti during the 2015-2016 (Year 1) and 2016-2017 (Year 2) growing seasons

Experimental design

Four cropping systems were tested and set up in a randomized complete block design with four replicates per location. The four cropping systems included in this study consisted of sole pigeonpea rotated with maize (PP-MZ), sole groundnut rotated with maize (GN-MZ), groundnut/pigeonpea doubled-up intercrop rotated with maize (GNPP-MZ), and the maize/pigeonpea intercrop system rotated with another maize/pigeonpea intercrop system in the second year (MZPP-MZPP). The traditional maize/pigeonpea intercrop (MZPP) system was included as the control.

Management of cropping systems

Field experiments were set up during the 2015/16 growing season. The productivity of legumes was assessed during year one with a rotational maize crop used to quantify the cropping system effect in year two. Crops were planted in December of 2015, harvested between May and July 2016, and a second year of the experiment was planted in 2016 and harvested in 2017. Hand hoes were used for land preparation and making ridges where crops are normally planted. Plot sizes were 5m x 5m and ridges were spaced at 75 cm apart. Fields were planted in December after the first effective rains. Planting at each of the sites was completed on each day. Sole pigeonpea was planted at a spacing of 0.9 m x 0.75 m, with three plants per planting station to achieve a plant population density of 44 000/ha. Sole groundnut within row spacing was 0.1 m to achieve a plant population density of 120 000 plants/ha. An additive intercropping design was used for the pigeonpea/groundnut intercrop to attain a total plant population density of about 164 000 plants/ha. In the pigeonpea/maize cropping system, both maize and pigeonpea were planted at a spacing of 0.9 m x 0.75 m in an additive intercropping design. There were three plants per planting station for both pigeonpea and maize. Crops in all intercrop systems were planted in the same row.

The doubled-up legume intercrops were fertilized just before planting with 23:21 N: P compound fertilizer at the rate of 11.5 kg ha-1 N and 10.5 kg ha-1 of P. The pigeonpea/maize intercrop was fertilized at the rate of 23 kg ha-1 N and 21 kg ha-1 P, with a side-dress application of urea at 100 kg ha-1 which provided 46 kg ha-1 N. The plots were weeded by hand hoes three times at each location. Plant population density assessment in all plots was done at harvesting to determine final plant population densities.

Aboveground and belowground biomass and yield

Destructive harvest timing varied with plant species and location to ensure sampling was done when plants were at physiological maturity. For maize and groundnut, it was from early-mid May 2016 and for pigeonpea, it was in July 2016. In 2017, maize was harvested in May and pigeonpea in July. Harvested net plots for groundnut destructive sampling were two ridges x 2m for a total area of 2.25 m^2. Groundnut biomass was separated into stems, leaves, pods, and roots. Maize plants were harvested from three middle rows x 5m long on the plot to determine total biomass and cob weights from the total harvested area of 11.25 m^2. For pigeonpea, four plants were randomly selected per plot, cut at ground level, chopped, and fresh biomass was determined for aboveground biomass separated into stems, twigs, leaves, and pods. The legume plant samples were oven-dried at 75 °C to constant weight, to determine dry weights.

All plants were cut at ground level and a soil volume was excavated by hand hoe to a depth of 0.60 m (0.405 m^3 soil volume) in three increments, 0– 0.20 m, 0.20– 0.40 m and 0.40– 0.60 m. Large roots were removed through dry sieving (2-mm). Fine roots were hand-picked using tweezers. In intercrops, legume roots were identified through their characteristic smell – ‘the Gwezu smell technique” (Mapfumo *et al*., 2005), a method which was found to be straight forward to distinguish pigeonpea in a previous study (Gwenambira, 2015). The roots were weighed fresh, oven-dried at 75 ^{o}C to constant weight and reweighed for dry weight determination.

Economic feasibility of cropping systems

Crop input and output prices were obtained from farmer-reported values from an Africa RISING Malawi panel household survey which was conducted in 2015 (n=324) (Mungai *et al*., 2016; Snapp *et al*., 2018). Market prices we collected at our trial site locations in the same year (Snapp *et al*., 2018). To consider the value of legumes as fuelwood and forage sources, we used a Kenya study (Rao and Mathuva, 2000) to set values at $0.03/kg (pigeonpea stems for fuelwood, and groundnut haulms) and $0.08/kg (pigeonpea leaves). It is challenging to assign a value to these products, but it was important to do so because previous research in southern Malawi shows that farmers value pigeonpea stems for fuelwood (Orr *et al*., 2015). To address this, we conducted a sensitivity analysis to consider 30% lower values for fuelwood and forage and found a modest difference in the economic ranking of cropping systems.

The formulas used for estimating cropping systems economic feasibility (per hectare) were as follows, based on gross margin performance as a widely used metric (Snapp *et al*., 2018).

Cost of production= Cost of fertilizer + Cost of seed

Total revenue= Yield in kg/ha x Price/kg

Gross margin= Total Revenue – Total cost of production

Statistical analysis

Data were analysed using the MIXED and GLIMMIX procedures in SAS 9.4 (SAS Institute, 2002) statistical package. A two-way analysis of variance (ANOVA) model of cropping system by location was used to evaluate the response of legume biomass and grain yield to sole crops vs. intercrops in 2016. The 2017 maize grain yield response to the different 2016 legume-based cropping systems was also determined using a two-way ANOVA of cropping system by location. The Least Significant Difference (LSD) at 5% level of significance was used to test mean differences.

Results

Environment

The soil properties at the five locations are shown in Table 1.1. Overall, soils at three of the on-farm sites were moderately acidic as indicated by values that ranged from 5.4 to 5.9. The drier sites in Golomoti were close to neutral pH with values almost all from 6.2-6.4. The topsoil organic matter content was low at all but one site, as indicated by soil organic C levels of 0.9 – 1.5 %C for four sites, and 3.2 %C at Linthipe A. Soil total N % was low with a range of 0.06 % in Golomoti A to 0.19 % in Linthipe A. Generally, the sites were sandy, with the highest clay content in the 0-20 cm soil depth being 30 % at the Linthipe A location and the lowest clay content 12 % at Golomoti B (Table 1.1).

Table 1.1. Soil chemical and physical properties at research locations (0-20 cm) from marginal (Golomoti A and B), moderate (Kandeu) and mesic (Linthipe A and B) sites in central Malawi from sampling conducted in June of 2016. Values are means followed by standard deviations.

Location	N (%)	C (%)	PMN (mg/kg soil)	pH	Clay (%)	Sand (%)
Linthipe A	0.19 ± 0.03	3.20 ± 0.61	0.67 ± 0.40	5.74 ± 0.17	30 ± 3.80	59 ± 5.84
Linthipe B	0.09 ± 0.01	1.46 ± 0.18	0.20 ± 0.16	5.41 ± 0.29	19 ± 7.35	73 ± 11.05
Kandeu	0.07 ± 0.01	0.85 ± 0.19	0.94 ± 0.25	5.88 ± 0.26	14 ± 3.07	81 ± 3.03
Golomoti A	0.06 ± 0.01	0.92 ± 0.21	0.22 ± 0.19	6.16 ± 0.19	17 ± 5.55	76 ± 6.04
Golomoti B	0.07 ± 0.02	0.87 ± 0.23	0.40 ± 0.31	6.38 ± 0.23	12 ± 1.60	83 ± 1.97

Legume biomass

Cropping system had a marked effect on pigeonpea biomass, along with the location (Table 1.2). For pigeonpea aboveground biomass, Linthipe A had the lowest amount of biomass at 3.70 Mg/ha and biomass at Golomoti A was more than threefold higher, at 12.33 Mg/ha. Sole pigeonpea had the largest biomass, whereas pigeonpea biomass was lower in intercrops, with equivalent amounts produced in the groundnut/pigeonpea and maize/pigeonpea intercrops. There was a location and cropping system interaction effect on pigeonpea biomass. As for groundnut biomass, there was a strong location effect but no cropping system effect on groundnut biomass. In contrast to pigeonpea, groundnut biomass in sole (GN) was equivalent to intercropped groundnut (GNPP) (Table 1.2).

Table 1.2. Analysis of variance for pigeonpea and groundnut shoot biomass in five locations across central Malawi during the 2016 growing season. Presented values are means followed by standard deviations. Cropping systems shown are sole pigeonpea (PP), groundnut/pigeonpea intercrop (GNPP), maize/pigeonpea intercrop (MZPP) and sole groundnut (GN).

Cropping system	Linthipe A	Linthipe B	Kandeu	Golomoti A	Golomoti B
			Mg/ha		
PP (PP)	3.70 ± 1.58	8.44 ± 2.13	9.43 ± 2.61	12.33 ± 2.50	7.36 ± 2.74
GNPP (PP)	2.91 ± 2.03	3.53 ± 1.04	10.55 ± 2.27	6.70 ± 3.03	4.86 ± 1.48
MZPP (PP)	2.87 ± 0.73	6.19 ± 1.77	8.63 ± 3.93	8.04 ± 4.73	8.09 ± 3.96
GN (GN)	2.29 ± 0.92	4.88 ± 0.75	3.77 ± 0.59	3.02 ± 0.66	1.86 ± 0.63
GNPP (GN)	2.22 ± 0.37	4.90 ± 0.61	3.63 ± 1.11	2.55 ± 0.58	2.09 ± 0.55

ANOVAS	Pigeonpea	Groundnut
Location	Pr > F = <.0001*	Pr > F = <.0001*
Cropping system	Pr > F = 0.0018*	Pr > F = 0.6493
Location x cropping system	Pr > F = 0.0341*	Pr > F = 0.8015

*Significant at P = 0.05

There was a strong location effect on both pigeonpea, and groundnut root biomass excavated from the 0-20 cm soil depth. Cropping system had a significant effect on pigeonpea root biomass but not on groundnut roots. Pigeonpea root biomass from the topsoil layer (0-20 cm) followed a trend similar to shoot biomass with the lowest root biomass in Linthipe A at 0.72 Mg/ha for sole pigeonpea and 0.47 Mg/ha and 0.40 Mg/ha for intercropped pigeonpea (Table 1.3). Pigeonpea root biomass in Kandeu was almost twofold as that of Linthipe A with 1.42 Mg/ha for sole pigeonpea and 1.27 and 0.81 Mg/ha for intercropped pigeonpea (Table 1.3). Even though Golomoti A had good pigeonpea shoot biomass, root biomass in the topsoil layer was relatively low. Groundnut root biomass ranged from 0.05 Mg/ha (Golomoti B) to 0.20 Mg/ha (Linthipe B).

There were no groundnut roots below the 20 cm depth at all locations. For pigeonpea, all locations had some roots in the 20-40 cm depth. However, some locations did not have pigeonpea roots in the 40-60 cm soil depth layer (Table 1.3).

Table 1.3. Analysis of variance for pigeonpea root biomass from the 0-60 cm soil depth, three intervals, from five locations across central Malawi in 2016. Presented values are means followed by standard deviations. Root biomass is shown in Mg/ha. Cropping systems shown are sole pigeonpea (PP), groundnut/pigeonpea intercrop (GNPP), maize/pigeonpea intercrop (MZPP) and sole groundnut (GN).

Cropping system	Soil Depth (cm)	Linthipe A	Linthipe B	Kandeu	Golomoti A	Golomoti B
				Mg/ha		
PP	0-20	0.72 ± 0.43	1.00 ± 0.30	1.42 ± 0.47	1.25 ± 0.55	1.02 ± 0.24
GNPP (PP)	0-20	0.47 ± 0.32	0.52 ± 0.22	1.27 ± 0.30	0.94 ± 0.44	0.68 ± 0.31
MZPP (PP)	0-20	0.40 ± 0.07	0.67 ± 0.19	0.81 ± 0.32	1.05 ± 0.65	1.12 ± 0.57
GN	0-20	0.14 ± 0.02	0.19 ± 0.03	0.10 ± 0.02	0.07 ± 0.02	0.05 ± 0.02
GNPP (GN)	0-20	0.13 ± 0.01	0.20 ± 0.02	0.12 ± 0.03	0.06 ± 0.02	0.06 ± 0.01
PP	20-40	0.05 ± 0.05	0.20 ± 0.14	0.33 ± 0.18	0.26 ± 0.15	0.19 ± 0.04
GNPP (PP)	20-40	0.05 ± 0.03	0.04 ± 0.06	0.26 ± 0.13	0.21 ± 0.09	0.13 ± 0.10
MZPP (PP)	20-40	0.04 ± 0.02	0.08 ± 0.04	0.20 ± 0.08	0.34 ± 0.21	0.30 ± 0.23
PP	40-60	_	0.06 ± 0.03	0.03 ± 0.02	0.02 ± 0.02	0.02 ± 0.01
GNPP (PP)	40-60	_	_	0.03 ± 0.01	_	0.02 ± 0.01
MZPP (PP)	40-60	_	0.02 ± 0.01	0.03 ± 0.01	0.02 ± 0.01	0.02 ± 0.01

ANOVAS

	Pigeonpea	Groundnut	Pigeonpea	Pigeonpea
Depth	0-20 cm	0-20 cm	20-40 cm	40-60 cm
Location	Pr >F = <.0001*	Pr >F =.0001*	Pr >F = <.0001*	Pr >F = 0.0048*
Cropping System	Pr >F = 0.0062	Pr >F = 0.5470	Pr >F = 0.0768	Pr >F = 0.4819
Location x C System	Pr >F = 0.2823	Pr >F = 0.4921	Pr >F = 0.1135	Pr >F = 0.0615

*Significant at P = 0.05

Legume and maize grain yield

Pigeonpea, groundnut and maize grain yields are reported in Table 1.4. Location had a strong influence on grain yield for both pigeonpea and groundnut. In contrast to the pattern observed for biomass, modest to nil grain yield was produced by pigeonpea (0.03 to 0.6 Mg/ha), and it was not influenced by cropping system. There was a large range of groundnut yields (0.5 to 1.8 Mg/ha) and biomass accumulation patterns. For example, aboveground biomass was markedly high at Linthipe B (4.9 Mg/ha), as was belowground biomass (0.2 Mg/ha). Linthipe B also produced high groundnut grain yield (1.7 to 1.8 Mg/ha). However, about one-half as much groundnut biomass was accumulated at Linthipe A and Golomoti B, which were also the low yielding sites at 0.5 to 0.9 Mg/ha (Table 1.4).

Both location and cropping system had a significant effect on maize grain but with no interaction effect. In a comparison of all systems that were fertilized (69kg N/ha for sole maize and 35 kg N/ha for the MZPP intercrop), the performance of maize yield across locations in 2017 varied. Maize yield after sole pigeonpea produced the highest maize grain (5.51 Mg/ha), maize after sole groundnut was 5.01 Mg/ha, maize after the GNPP intercrop was 4.06 Mg/ha, and maize yield was lowest in the MZPP intercrop system at 3.05 Mg/ha. These findings were consistent across four of the five locations, the one exception was the lowest yielding site (Golomoti B) (Table 1.4). During the 2016 agricultural season, the sole groundnut cropping system produced the lowest shoot biomass across all sites. However, the system produced high maize grain yield in 2017 (Table 1.4).

Table 1.4. Analysis of variance for pigeonpea, groundnut and maize grain yield in five locations across central Malawi during the 2016 (legume) and 2017 (maize) growing seasons. Presented values are means followed by standard deviations. Cropping systems shown are sole pigeonpea (PP), groundnut/pigeonpea intercrop (GNPP), maize/pigeonpea intercrop (MZPP) and sole groundnut (GN).

Cropping system	Linthipe A	Linthipe B	Kandeu	Golomoti A	Golomoti B
			Mg/ha		
PP (PP)	0.12 ± 0.12	0.58 ± 0.60	0.34 ± 0.45	0.38 ± 0.48	0.03 ± 0.02
GNPP (PP)	0.12 ± 0.12	0.32 ± 0.32	0.13 ± 0.19	0.31 ± 0.22	0.04 ± 0.04
MZPP (PP)	0.09 ± 0.05	0.56 ± 0.45	0.29 ± 0.36	0.22 ± 0.43	0.07 ± 0.06
GN (GN)	0.54 ± 0.36	1.72 ± 0.47	1.34 ± 0.32	1.60 ± 0.30	0.87 ± 0.19
GNPP (GN)	0.45 ± 0.21	1.80 ± 0.32	1.28 ± 0.80	1.44 ± 0.32	0.93 ± 0.18
PP-MZ (MZ)	7.78 ± 0.47	8.14 ± 0.82	5.25 ± 1.33	4.54 ± 0.58	1.85 ± 0.33
GN-MZ (MZ)	6.48 ± 0.92	6.58 ± 0.58	4.60 ± 1.38	4.35 ± 1.66	3.02 ± 0.99
GNPP-MZ (MZ)	4.68 ± 0.82	6.18 ± 1.50	4.70 ± 0.23	2.87 ± 1.24	1.87 ± 1.16
MZPP-MZPP (MZ)	4.22 ± 0.59	5.01 ± 1.01	2.60 ± 0.59	2.27 ± 1.47	1.18 ± 0.14

ANOVAS

	Pigeonpea	Groundnut	Maize
Location	Pr > F = <.0001*	Pr > F = <.0001*	Pr > F = <.0001*
Cropping system	Pr > F = 0.1631	Pr > F = 0.7605	Pr > F = <.0001*
Location x cropping system	Pr > F = 0.6991	Pr > F = 0.9323	Pr > F = 0.2677

*Significant at P = 0.05

Interspecific vs. intraspecific competition

Across locations, the PP-MZ rotation sequence produced the highest maize grain yield at 5.51 Mg/ha. The GN-MZ, GNPP-MZ and the MZPP-MZPP systems produced 9%, 26% and 45% less maize yield respectively than the PP-MZ system (p=<.0001, Table 1.4). Intercropping pigeonpea with maize and groundnut negatively impacted pigeonpea biomass (p=0.0018, Table 1.2). There was no cropping system on pigeonpea grain yield but there was a trend of lower grain yield in all intercrops. Compared to sole pigeonpea grain yield at 0.30 Mg/ha, there was a 16% drop in the

MZPP system and a 42% drop in grain yield in the GNPP system (Table 1.4). For shoots, with sole pigeonpea at 8.25 Mg/ha, there was an 18% drop in the MZPP system and a 31% drop in shoot biomass in the GNPP system. Compared to sole pigeonpea roots at 1.32 Mg/ha, there was a 23% drop in in the MZPP system and a 31% drop in roots in the GNPP system. For groundnut, there was no intercrop system effect; grain, shoot, and root biomass were not reduced relative to the sole crop (Tables 1.2-1.4).

Economic feasibility of cropping systems

Gross margins of the four cropping systems ranged from $1145 (PP-MZ) to $1407 (GNPP-MZ). The best two performing cropping systems in terms of monetary gain were the GNPP-MZ and the MZPP-MZPP systems with gross margins of $1404 and $1407, respectively. The cropping system with the highest cost of production was GNPP-MZ at $353 and the lowest was PP-MZ at $223 (Table 1.5). Overall, when legume stems and haulms are included with prices at $0.03 and $0.08, respectively, the order of technology system valuation is GNPP-MZ=MZPP-MZPP> GN-MZ> PP-MZ (Table 1.5). However, when the prices are 30% less, the order changes to GN-MZ> GNPP-MZ > MZPP-MZPP> PP-MZ.

Table 1.5. Economic feasibility of four cropping systems involving maize, pigeonpea, and groundnut across three agroecologies in central Malawi. Cropping systems shown are sole pigeonpea rotated with sole maize (PP-MZ), sole groundnut rotated with sole maize (GN-MZ), groundnut/pigeonpea intercrop rotated with sole maize (GNPP-MZ) and maize/pigeonpea intercrop rotated with maize/pigeonpea intercrop (MZPP-MZPP). Figures in italics show the total economic values of combined crops/ha for every cropping system assessed over two years.

Cropping system	Crop or crops	Year Harvested	Cost of production US $*	Total revenue US $#	Gross margins US $
PP-MZ	Pigeonpea	2016	47	252	205
PP-MZ	Maize	2017	176	1116	940
PP-MZ	*Pigeonpea and maize*	*2016-2017*	*223*	*1368*	*1145*
GN-MZ	Groundnut	2016	130	699	569
GN-MZ	Maize	2017	176	986	810
GN-MZ	*Groundnut and maize*	*2016-2017*	*306*	*1685*	*1379*
GNPP-MZ	Groundnut	2016	130	684	554
GNPP-MZ	Pigeonpea	2016	47	212	165
GNPP-MZ	Maize	2017	176	864	688
GNPP-MZ	*Groundnut, pigeonpea and maize*	*2016-2017*	*353*	*1760*	*1407*
MZPP-MZPP	Maize	2016	96	574	478
MZPP-MZPP	Pigeonpea	2016	47	237	190
MZPP-MZPP	Maize	2017	96	642	546
MZPP-MZPP	Pigeonpea	2017	47	237	190
MZPP-MZPP	*Maize and pigeonpea*	*2016-2017*	*286*	*1690*	*1404*

* Seed and fertilizer cost over two years
# Economic returns included forage, fuelwood, and grain

Discussion

Legume biomass by cropping system and environment

The choice of sites was strategic, in that it allowed evaluation of cropping system performance along a gradient from marginal to mesic. A strong location effect was observed on legume shoots, roots and grain, with Kandeu providing conditions that supported high legume biomass above and belowground in 2016, whereas the Linthipe A site supported surprisingly modest pigeonpea biomass, presumably due to dry spells in this drought year (Figure 1.2). The drought is likely to have affected the overall performance and economic feasibility of the various intercrops and rotations. The cumulative rainfall in the 2015-16 agricultural season was 55% lower than in the 2016-17 season (Figure 1.2). A combination of drought and infertile sandy soils at Golomoti B could have contributed to the modest yields of pigeonpea and groundnut at this site. The susceptibility of pigeonpea to early cessation of rains has been observed previously (Wendt and Atemkeng, 2004).

To the best of our knowledge, this is the first report of on-farm pigeonpea root, shoot biomass and grain yields in traditional and alternate legume diversified maize systems that include a doubled-up legume system. Pigeonpea roots in doubled-up legume intercrop were comparable to sole pigeonpea at 0.8 vs. 1.1 Mg/ha. Pigeonpea belowground biomass across all systems was about 15% of total biomass while groundnut was about 3%. These are conservative estimates given the challenges of recovering root systems in the field. This additional biomass has rarely been considered in previous studies and is important in terms of soil carbon accrual potential of cropping systems (Kell, 2012). Overall, pigeonpea dry matter (6.95 Mg/ha) including shoot, root, and grain is similar to that observed by Kumar Rao and Dart (1987) where 11 pigeonpea cultivars averaged 6.86 Mg/ha. Pigeonpea grain yields were frequently under 0.4 Mg/ha, similar to on-farm values reported by Chirwa *et al*. (2003), Myaka *et al*. (2006) and Høgh-Jensen *et al*. (2007). Previous research from central Malawi indicates that livestock damage is contributing to these low yields, with about 44% of farmers reporting substantial goat damage (Waldman *et al*., 2017).

Cropping system had no effect on groundnut shoots, roots and grain (Tables 1.2 and 1.3). This is important as farmers value groundnut. The presence of pigeonpea in an intercrop did not reduce groundnut biomass and yields, even at the site with substantial dry spells (Tables 1.2, 1.3 and 1.5). This is suggestive that the root system of pigeonpea exerts minimal competition for water in a groundnut system. Previous studies are consistent with this, as pigeonpea may enhance soil moisture in the topsoil through a hydraulic lift mechanism (Sekiya and Yano, 2004).

Maize yield response to legume rotation

Maize yield response to sole pigeonpea was positive across sites (Table 1.4). This might have been due to improved nutrient and water uptake from pigeonpea's deep root system since there was no relationship of maize yield to vegetative legume biomass (r=0.2015). Based on model simulations, Ollenburger and Snapp (2014) indicate seasonal water recharge in pigeonpea-maize rotation sequences for a wide range of rainfall scenarios and soil types in Malawi. In Kenya, Tully *et al.* (2015) report on a multi-site study where maize grain yields were positively related to legume biomass N only under sufficient rainfall conditions, and dry spells may have contributed to inconsistent maize response in our study.

Even though groundnut biomass was lower than pigeonpea at all locations with a range from 1.86 to 4.9 Mg/ha (Table 1.2), this modest amount of biomass generally supported good maize growth in the subsequent year (Table 1.4). This could be due to a rotation effect that is independent of residue nutrient inputs (Tully *et al.*, 2015). In an 11-yr experiment in northern Ghana, Agyare *et al*. (2006) reported that over the long term, maize rotations with crops including groundnut and soybean (*Glycine max* L.) were superior in terms of household food security potential than maize intercrops with the same crops, and a maize-groundnut rotation was the best performing combination with a 3 Mg/ha maize yield response that was comparable to our study.

Interspecific vs. intraspecific competition in intercrops

Pigeonpea biomass and grain yield in intercrops was much lower than sole pigeonpea, consistent with high sensitivity of this crop to interspecific competition. The drought could have exacerbated the competition. A field study of a pigeonpea-soybean intercrop system found similar results, and attributed pigeonpea biomass suppression to nutrient limitations (Ghosh *et al.*, 2006). This sensitivity to competition within an intercrop indicates that if farmers are interested in the rehabilitation of degraded soils, or have livestock forage requirements, then sole pigeonpea is a high performer and should be considered as a substitute for current systems such as the maize-pigeonpea intercrop. According to a choice experiment conducted in Malawi, Waldman *et al*.,

(2017) found that farmers value maize yield twice as much as pigeonpea yield, yet a substantial minority of farmers recognize pigeonpea's ability to provide some grain combined with high biomass for soil fertility and grow pigeonpea primarily for its copious biomass. Groundnut root, shoot, and grain yields were not suppressed by the presence of pigeonpea in the doubled-up legume intercrop, thus this crop was not sensitive to interspecific competition in this mixed planting system. The slow growth of pigeonpea early in the growing season may minimize the competitive effects of this species on groundnut (Snapp and Silim, 2002).

Economic feasibility and overall performance

Considering economic feasibility is critical because farmers usually have multi-faceted goals and have to consider costs and returns associated with a cropping system before they adopt. The initial cost of production with all systems involving groundnut was high because groundnut seed is significantly more expensive than maize and pigeonpea. In India, Bhuva *et al.* (2017) reported similar results to ours, in that high groundnut seed expense did not reduce the attractiveness of groundnut-based systems as gross returns were high relative to other systems. A crop modeling study conducted in Central Malawi (Smith *et al*., 2016) combined with an economic analysis found 75% higher profits associated with a groundnut rotation compared to maize monocultures; due in large part to 50% reduced requirements for nitrogen fertilizer in the maize phase of the rotation (Komarek *et al*., 2018). The high gross margin associated with the traditional farmer MZ/PP intercrop system was not surprising as this shows farmer wisdom in preferring a system that is economically robust and which provides maize grain for subsistence. Of the alternatives tested here, the novel doubled-up GNPP intercrop rotated with maize was the only one to perform as well economically as the farmer check. This is consistent with earlier findings of farmer preference for a highly diverse doubled-up rotational system (Snapp *et al*., 2018). A breadth of environmental and economic returns is required to compensate for opportunity costs associated with maize production limitations due to small farm sizes.

Previous research has shown that the choices smallholder farmers in Malawi make are mostly due to a combination of factors (Hockett and Richardson, 2018) such as socio-economic status, environment, access to inputs and credit. In our study, environmental context and farmer goals both influence which system can be the overall 'best bet'. At the mesic sites where groundnut grew well, sole groundnut or doubled-up groundnut/pigeonpea rotation systems were a good choice, in terms of highly nutritious food produced, high maize yield response, and economic profitability. At marginal sites, particularly where soil organic matter was low, the additional soil fertility benefits from pigeonpea systems could lead to these being the top choice. The value farmers place on vegetation (for fuelwood, fodder or soil fertility), matters in terms of system performance ranking. Rusinamhodzi *et al*. (2012) found that farmers prioritize cropping systems with multiple benefits such as food security, combined with cash income that can be generated with low input costs. This may be uniquely addressed by the doubled-up legume system where half-rates of fertilizer supported high maize grain in our study.

What is the 'best bet' may change in the near future as a result of climate change. An adaptability study conducted in central Malawi on over a dozen maize-based systems provided evidence of superior maize yield stability in grain legume rotations relative to both continuous maize and intercrops (Chimonyo et al., 2019a). This suggests there may be a resilience value associated with rotational systems that require attention as climatic risk increases.

Conclusions

This research is an important contribution to the scarce knowledge on the performance of legume-based intercrops vs. legume-maize rotations in rain-fed, on-farm trials from different environmental contexts. This study provides evidence that in a drought, pigeonpea is highly sensitive to interspecific competition. Therefore, maximizing growth for the production of pigeonpea grain, fuelwood, forage, and soil fertility benefits would require sole pigeonpea which could then be rotated with maize. At the same time which systems farmers prefer will depend on their goals, resources and the environment. If a farmer’s goal is to obtain maize and some legume grain every year, the ‘best bet’ system might be the currently popular maize/pigeonpea intercrop. Groundnut was not sensitive to interspecific competition. Therefore, if farmers have sufficient land for sole legumes, the novel doubled-up groundnut/pigeonpea system could help farmers meet multiple goals. Farmers would get nutritiously enriched groundnut grain along with environmental benefits of pigeonpea for a subsequent maize crop. The relative advantage of each component would depend on the site. This research guides recommendations for context-specific cropping systems which enhance farm productivity and food security in Malawi.

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2. Chapter Two: Pigeonpea and groundnut productivity, biological nitrogen fixation, and residual benefits to maize on smallholder farms in central Malawi

Abstract

Smallholder farmers rarely achieve access to adequate quantities of inorganic fertilizers when nitrogen (N) is often the most limiting element for cereal grain production. Legumes such as groundnut (*Arachis hypogaea* L.) and pigeonpea (*Cajanus cajan* L.) fix N through biological nitrogen fixation (BNF) and potentially improve soil fertility and productivity of cereal crops grown in sequence. However, legume BNF benefits under smallholder, on-farm conditions are understudied. The objective of this study was to determine the effect of location and cropping system on yield and BNF of sole legumes, doubled-up legumes and cereal-legume cropping systems on rain-fed smallholder farms. On-farm experiments were conducted at six locations in in high, low and medium agro-ecological potential zones in central Malawi. The study evaluated four cropping systems: 1) sole groundnut 2) sole pigeonpea 3) groundnut/pigeonpea intercrop (referred to as a doubled-up legume system) and 4) maize/pigeonpea intercrop which is the farmer check system. All the systems were rotated with maize in the second year. Overall, total N input by cropping system was in the order groundnut/pigeonpea> sole pigeonpea> maize/pigeonpea> sole groundnut at 180, 130, 103 and 87 kg N/ha respectively. The mean proportion of BNF was 66% for groundnut and 52% for pigeonpea. Our study highlights that in maize-based systems, there is need for integrated soil fertility approaches that include legume intercrops, rotations, residue incorporation, and modest inorganic N inputs for sustainable maize

production.

Keywords: Biological nitrogen fixation, Cropping system, Groundnut, Intercrop, On-farm, Pigeonpea, ^{15}N natural abundance.

Introduction

Sustainable agriculture through BNF

BNF is an important and significant part of the global N cycle. Annually, BNF is estimated to be around 175 million tones N, of which close to 79% is from terrestrial fixation. Sustainable agriculture depends on renewable resources like BNF which plays an important role in maintaining soil fertility through economically and ecologically sound means of reducing external N inputs and improving the quality and quantity of internal resources (Wani *et al*., 1995). BNF is dependent upon environmental, physical and biological factors. Inclusion of N fixing plants in agricultural systems does not automatically result in increased contributions to the soil N pool (Wani *et al*., 1995). However, in developing countries where fertilizers are expensive and inaccessible to many, legumes are the main source of N, through BNF (Giller and Cadisch, 1995).

Malawi legume crops and nitrogen balance on-farm

Smallholder farm sustainability is challenged in Malawi, as it is across much of sub-Saharan Africa, by the overwhelming presence of maize, a highly N-demanding cereal crop. Legume diversification has been studied in some detail as a means to improve sustainability of smallholder maize-based farming. Although long-duration agroforestry and green manure systems show sustainable potential to redress the nitrogen deficit imposed by maize production, smallholder farm adoption of such systems has been almost nil (Sirrine *et al*., 2010), presumably due to associated risks and labor requirements. Farmer interest in short duration grain legume species such as common bean and groundnut is often much higher than long-duration indeterminant species, although medium to long duration cultivars of pigeonpea are in some cases a notable exception (Waldman *et al*., 2017). A number of grain legumes are grown in Malawi either as sole crops or in intercrops with cereals, particularly maize. The most commonly cultivated legumes in Malawi are common bean (*Phaseolus vulgaris* L.) and groundnut *(Snapp et al*., 2002). Pigeonpea is mostly grown in southern Malawi where it is traditionally intercropped with maize (Orr *et al*., 2015). A doubled-up legume system of complementary growth habits has been introduced in Malawi, whereby a short duration groundnut is grown as an under species to a shrubby, long duration pigeonpea species (Snapp *et al*., 2010). What is not well known is the extent to which this legume diversified system can address the N balance deficit on smallholder farms, within maize-based farming systems, and the interaction with environmental context.

Pigeonpea and groundnut BNF

Pigeonpea can fix substantial amounts of N that can reach up to 235 kg N/ha (Peoples *et al*., 1995). According to Kumar Rao and Dart (1987), pigeonpea has excellent nodulation and fixes most of its N from the atmosphere. Late maturing pigeonpea varieties have much to offer since they produce more biomass and fix more N. Pigeonpea sheds its leaves throughout the growing season and senesced pigeonpea leaves from late maturing varieties can contribute substantial amounts of about 28–40 kg N (Kumar Rao and Dart, 1987). Kumar Rao & Dart (1987) reported that in India, pigeonpea fixed about 58 to 88 kg N/ha when grown as a sole crop and may provide 30 to 50 kg/ha of residual N in crop rotations with maize, wheat and sorghum. In a multi-country, on-farm study, Adu-Gyamfi *et al*. (2007) reported that in Malawi, pigeonpea contributed about 38 -117 kg/ha of N through BNF while in Tanzania it was about 6 -72 kg/ha.

Groundnut has been shown to fix substantial quantities of N from the atmosphere under favorable conditions in the tropics ranging between 41 and 150kg N/ha (Giller *et al*. 1987; Toomsan *et al*., 1995; Okito *et al*., 2004). From a study in northeast Thailand, Toomsan *et al*. (1995) reported that groundnut fixed 72-77% of its N amounting to 150-200 kg N/ha. Giller *et al*. (1987) also reported that for groundnut, 86% to 92% of its plant nitrogen was derived from BNF. However, the net N balance associated with growing groundnut in a rotation sequence is often low as whole plants are often uprooted during harvesting, a practice that can remove roots and nodules from the field.

The quantity of N that is contributed from groundnut BNF is variable in the literature. It can be as high as 86-99% N fixation as shown in a field study in India (Giller *et al*., 1987), an outdoor basin study in Sri Lanka (Senaratne *et al*., 1995) and an on-farm study in northern Malawi (Mhango *et al*., 2017). Other studies such as a field study from Thailand suggest modest rates ranging from 59-64% (Mcdonagh *et al*., 1993). This may well be a result of BNF being a function of local agro-ecological conditions and varieties (Giller *et al*., 1987).

Additionally, in most previous field experiments, for both pigeonpea and groundnut, belowground legume N fixation is not measured. To address these research gaps, detailed below and aboveground assessments of BNF in mixed cropping systems on smallholder farms were conducted. Overall, the objectives of this study were 1) To quantify the N fixation associated with sole pigeonpea, sole groundnut, pigeonpea/groundnut and pigeonpea/maize cropping systems 2) To determine if N fixation rate in pigeonpea and groundnut are reduced when grown in higher fertility soil or increased when grown in a maize intercrop due to competition for N by the maize which stimulates BNF in pigeonpea. The hypotheses of this study were 1) Cropping system will have an effect on total N and will be in the order: groundnut/pigeonpea> sole pigeonpea> sole groundnut> maize/pigeonpea cropping systems and 2) Groundnut and pigeonpea BNF will decrease with increasing agro-ecology crop production potential and soil fertility.

Materials and methods

Study sites and field sites characterization

A stratified random approach was used to select the research sites to represent marginal to mesic potential areas (Mungai *et al*., 2016) in central Malawi (13.2543° S, 34.3015° E). The locations were in the Linthipe, Golomoti and Kandeu Extension Planning Areas (EPA). Linthipe is a high potential, sub-humid tropical agroecology with well-distributed rainfall in most years. Kandeu is a medium agricultural potential, sub-humid tropical agroecology with decent rainfall distribution in most years. Golomoti is a low potential, semi-arid to sub-humid tropical agroecology, at low altitude and with erratic rainfall; high temperatures increase evapotranspiration at this site.

Linthipe soils are ferric luvisols, the Kandeu study site has a mixture of chromic luvisols and orthic ferralsols while Golomoti soils are a mixture of eutric cambisols and eutric fluvisols (Mungai *et al*., 2016). The field experiments were conducted at six locations (Table 2.1). Soil sampling was conducted in late June and early July of 2016, at 0– 20 cm depth, three composite samples per plot using a dutch auger (5.5 cm diameter). Soils were air-dried, sieved (2 mm) and soil texture was determined using the hydrometer method (Kellogg Biological Station/ Long-Term Ecological Research, 2008). Soil pH was determined in a 1:2 soil to water suspension (Kellogg Biological Station/ Long-Term Ecological Research, 2016). Total soil carbon and total soil N were determined after grinding to a fine powder with a shatter mill, by dry combustion with Costech ECS 4010 (Costech Analytical Technologies, Inc., Valencia, CA). To determine potential mineralizable NH4-N (PMN), soil samples were anaerobically incubated at 30 °C for seven days (Kane *et al*., 2015). After incubation, NH4-N was extracted using 2.66 M KCl. KCl extracts were analysed for inorganic N concentrations on a Thermo MultiskanTM 96-well plate reader (Kane *et al*., 2015).

Experimental design

Four cropping system treatments were set up in a randomized complete block design with four replicates per location. The four cropping systems included in this study consisted of sole pigeonpea (PP), sole groundnut (GN), groundnut/pigeonpea doubled-up intercrop (GNPP), and the maize/pigeonpea intercrop system (MZPP). The traditional maize/pigeonpea intercrop (MZPP) system was included as the control.

Management of cropping systems

Field experiments were set up during the 2015/16 growing season. Crops were planted in December of 2015, and the productivity of the legumes was assessed between May and July 2016. During the following cropping season 2016/17, the residual effects of the systems was assessed by planting maize in all plots. Hand hoes were used for land preparation and making ridges because the local practice in this farming system is to make ridges on which rows of crops are planted. Plot sizes were 5m x 5m and ridges were spaced at 75 cm apart. Fields were planted in December after the first effective rains. Planting at each of the sites was completed on each day. Sole pigeonpea was planted at a spacing of 0.9 m x 0.75 m, with three plants per planting station to achieve a plant population density of 44 000/ha. Sole groundnut within row spacing was 0.1 m to achieve a plant population density of 120 000 plants/ha. An additive intercropping design was used for the pigeonpea/groundnut intercrop to attain a total plant population density of about 164 000 plants/ha. In the pigeonpea/maize cropping system, both maize and pigeonpea were planted at a spacing of 0.9 m x 0.75 m in an additive intercropping design. There were three plants per planting station for both pigeonpea and maize. In intercrop systems, the associated crops were planted on the same ridge.

The doubled-up legume intercrops were fertilized just before planting with 23:21 N: P compound fertilizer at the rate of 11.5 kg/ha N and 10.5 kg/ha of P. The pigeonpea/maize intercrop was fertilized at the rate of 23 kg ha-1 N and 21 kg/ha, with a side-dress application of urea at 100 kg/ha which provided 46 kg/ha N. The plots were weeded by hand hoes three times at each location. Plant population density assessment in all plots was done at harvesting to determine final plant population densities.

Aboveground and belowground biomass and yield

Destructive harvest timing varied with plant species and location to ensure sampling was done when plants were at physiological maturity. For groundnut, it was from early-mid May 2016 and for pigeonpea, it was in July 2016. Harvested net plots for groundnut destructive sampling were two ridges x 2m for a total area of 2.25 m^2. Groundnut biomass was separated into stems, leaves, pods, and roots. For pigeonpea, four plants were randomly selected per plot, cut at ground level, chopped, and fresh biomass was determined for aboveground biomass separated into stems, twigs, leaves, and pods. The legume plant samples were oven-dried at 75 °C to constant weight, to determine dry weights.

For belowground biomass determinations, destructive root sampling was conducted during harvesting. Pigeonpea plants were cut at ground level and roots were excavated using hand hoes. Soil pits were dug to a depth of 60 cm and roots were collected in three increments from the 0-20 cm, 20-40 cm and 40-60 cm soil layers. Roots from each layer were collected by first completing excavating the 20 cm (depth) x 90 cm (intrarow spacing) x 75 cm (interrow spacing) layer (Figure 2.1). When all roots were collected from the three layers from the 0-60 cm soil depths, the total soil volume was 0.405 m^3. Large roots were removed through dry sieving (2 mm sieve). Fine roots were hand-picked using tweezers. In intercrops, legume roots were identified through their characteristic smell – 'the Gwezu smell technique" (Mapfumo *et al.*, 2005), a method which was found to be straight forward to distinguish pigeonpea in a previous study

(Gwenambira, 2015). The roots were weighed fresh, oven-dried at 75 ^{o}C to constant weight and reweighed for dry weight determination.

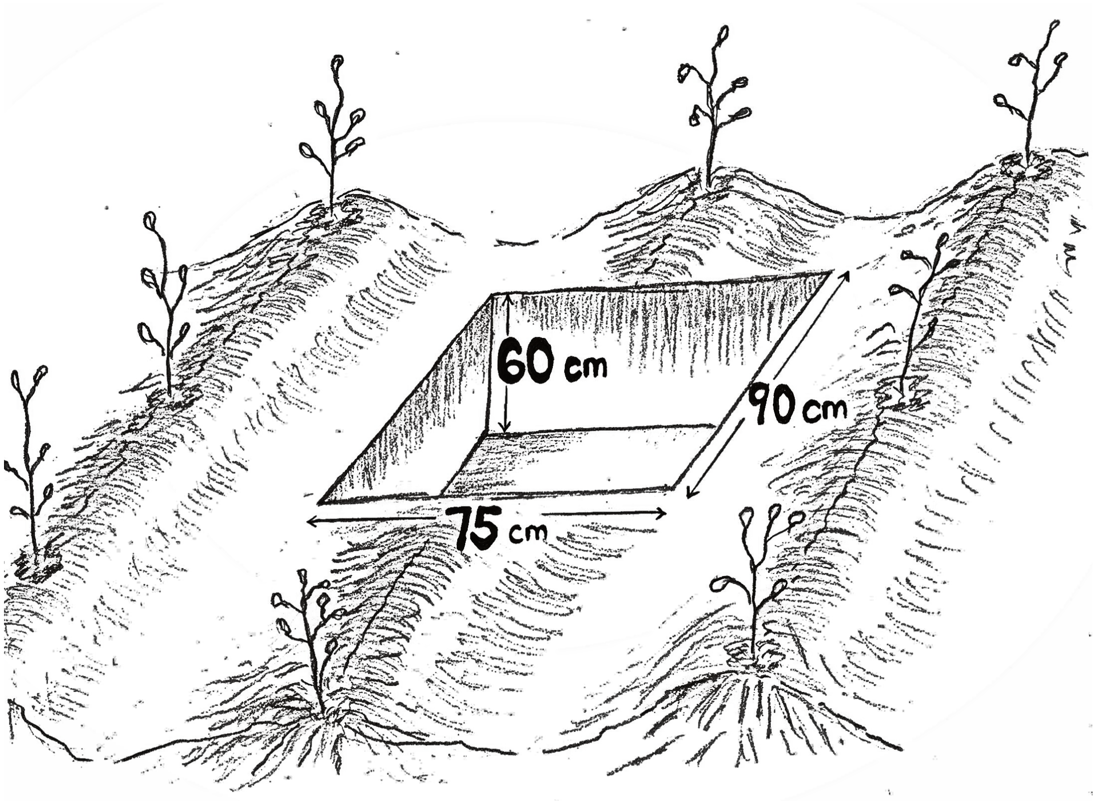

Figure 2.1. Belowground biomass destructive sampling pit measuring 90 cm x 75 cm x 60 cm. Hand hoes were used to excavate roots from the pit. Roots were collected in increments from the 0-20, 20-40 and 40-60 cm soil depths. Sketch prepared by Kibale V. Mwika.

Biological nitrogen fixation

Shoot, root and plant residue components were ground to pass through a 1mm sieve, and the amount of nitrogen biologically fixed by pigeonpea was determined using the ^{15}N natural abundance method. The stable isotope analysis was conducted at the UC Davis stable isotope facility. Maize was used as the non-fixing reference crop. The calculation that was used for BNF is:

% N2-fixation = 100 x δ15N (reference crop: maize) - δ15N (legume N)/ (δ15N (reference crop) – B) (Hogberg, 1997)

Statistical analysis

Data were analyzed using the MIXED procedure in SAS 9.4 (SAS Institute, 2002) statistical package. Two-way analysis of variance (ANOVA) tests were used to determine the combined effect of cropping system and location on the percent N, total N and BNF-N percent of groundnut and pigeonpea shoot and root biomass, where sole-cropped and intercropped groundnut and pigeonpea cropping systems were compared. The Least Significant Difference (LSD) at 5% level of significance was used to test mean differences.

Results

Environment

The soil properties at the six locations are shown in Table 2.1. Overall, soils at four of the sites were moderately acidic as indicated by values that ranged from 5.4 to 5.9. The drier sites in Golomoti were close to neutral pH with values all from 6.2-6.4. The topsoil organic matter content was low at all but one site, as indicated by soil organic C levels of 0.43 – 1.5 %C for five sites, and 3.2 %C at Linthipe A. Soil total N % was low with a range of 0.04 % in Kandeu B to 0.19 % in Linthipe A. Potential mineralized nitrogen was low at all six locations and ranged from 0.22 at Golomoti A to 0.94 mg/kg soil at Kandeu A. Generally, the sites were sandy, with the highest clay content in the 0-20 cm soil depth being 30 % at the Linthipe A location and the lowest clay content 12 % at Golomoti B and Kandeu B (Table 2.1).

Table 2.1. Soil chemical and physical properties at research locations (0-20 cm) from mesic (Linthipe A and B), marginal (Golomoti A and B) and moderate (Kandeu A and B) sites in central Malawi from sampling conducted in June of 2016. Values are means followed by standard deviations.

Location	N (%)	C (%)	PMN (mg/kg soil)	pH	Clay (%)	Sand (%)
Linthipe A	0.19 ± 0.03	3.20 ± 0.61	0.67 ± 0.40	5.74 ± 0.17	30 ± 3.80	59 ± 5.84
Linthipe B	0.09 ± 0.01	1.46 ± 0.18	0.20 ± 0.16	5.41 ± 0.29	19 ± 7.35	73 ± 11.05
Golomoti A	0.06 ± 0.01	0.92 ± 0.21	0.22 ± 0.19	6.16 ± 0.19	17 ± 5.55	76 ± 6.04
Golomoti B	0.07 ± 0.02	0.87 ± 0.23	0.40 ± 0.31	6.38 ± 0.23	12 ± 1.60	83 ± 1.97
Kandeu A	0.07 ± 0.01	0.85 ± 0.19	0.94 ± 0.25	5.88 ± 0.26	14 ± 3.07	81 ± 3.03
Kandeu B	0.04 ± 0.01	0.43 ± 0.08	0.38 ± 0.22	5.54 ± 0.31	12 ± 4.12	83 ± 4.84

Crop biomass production

Total groundnut and pigeonpea biomass is presented in Table 2.2. For groundnut, total biomass is defined as the total sum of stem, leaf, grain and root biomass. For pigeonpea, total biomass is defined as the total sum of stem, twig, leaf and pod biomass.

Groundnut total biomass in the sole groundnut cropping system ranged from 1.86 Mg/ha in Golomoti B to 4.88 Mg/ha in Linthipe B. For the groundnut/pigeonpea intercrop, groundnut produced biomass which ranged from 2.09 Mg/ha in Golomoti B to 4.91Mg/ha in Linthipe B. Location had a significant effect on groundnut biomass production (Pr>F = <.0001) but cropping system did not. Pigeonpea total biomass including grain ranged from 4.11 Mg/ha to 12.33 Mg/ha in the sole pigeonpea cropping system, 2.91 Mg/ha to 10.55 Mg/ha for groundnut/pigeonpea, and from 2.85 Mg/ha to 8.63 Mg/ha for the maize/pigeonpea intercrop. Location and cropping system had significant effects on pigeonpea total shoot biomass but there was no location x cropping system interaction. Sole cropped pigeonpea biomass was greater than pigeonpea grown in an intercrop (Table 2.2).

Table 2.2. Analysis of variance for groundnut$^{\phi}$ and pigeonpea total biomass including grain in six locations across central Malawi during the 2016 growing season. Presented values are means followed by standard deviations. Cropping systems shown are sole groundnut (GN), sole pigeonpea (PP), groundnut/pigeonpea intercrop (GNPP), and maize/pigeonpea intercrop (MZPP)

Cropping System	Linthipe A	Linthipe B	Golomoti A	Golomoti B	Kandeu A	Kandeu B
			Mg/ha			
GN	2.65 ± 0.55	4.88 ± 0.53	3.02 ± 0.65	1.86 ± 0.65	3.77 ± 0.41	3.24 ± 0.38
GNPP (GN)	2.22 ± 0.30	4.91 ± 0.55	2.55 ± 0.13	2.09 ± 0.53	3.63 ± 0.80	2.93 ± 0.75
PP	4.11 ± 1.57	8.44 ± 2.15	12.33 ± 1.88	7.37 ± 1.74	9.43 ± 1.02	4.14 ± 1.06
GNPP (PP)	2.91 ± 1.60	3.53 ± 1.08	6.69 ± 3.24	4.85 ± 1.23	10.55 ± 2.09	3.64 ± 1.05
MZPP (PP)	2.87 ± 0.65	6.19 ± 0.98	8.05 ± 5.01	8.09 ± 3.20	8.63 ± 2.14	2.85 ± 0.50

ANOVAS

	Groundnut	Pigeonpea
Location	Pr>F = <.0001*	Pr>F = <.0001*
Cropping System	Pr>F = 0.3341	Pr>F = 0.0080*
Location x Cropping System	Pr>F = 0.8626	Pr>F = 0.1573

$^{\phi}$groundnut biomass includes roots; * Significant at P=0.05

Percent N of groundnut and pigeonpea

Tissue N concentration is presented in Table 2.3. Percent N of groundnut stems ranged from 1.26% (Golomoti A) to 2.38% (Linthipe A), groundnut leaves from 2.63% (Kandeu A) to 3.31 % (Linthipe A), groundnut grain from 3.78% (Kandeu A) to 5.02% (Linthipe A) and roots from 1.76% (Golomoti A) to 2.96% at the Linthipe A location (Table 2.3). Location had an effect on the percent N of groundnut stems, leaves and roots but not on grain. Linthipe A was consistently associated with high %N. Cropping system had an effect on groundnut leaves. The concentration in leaves from sole cropped groundnut was significantly higher than intercropped groundnut (Table 2.4). There was no location x cropping system interaction on any groundnut plant parts (Table 2.3).

Pigeonpea stems percent N ranged from 1.03% (Golomoti) to 1.16% (Kandeu), leaves from 2.82% (Linthipe A) to 3.43% (Kandeu A), pods from 2.43% (Kandeu B) to 3.11% (Kandeu A), and roots from 0.89% (Linthipe B) to 1.40% (Golomoti B). Location had an effect on the percent N of pigeonpea leaves, pods and roots but not stems. The medium potential, Kandeu A location was consistently associated with high %N. Cropping system had an effect on stems N concentration which was in the order maize/pigeonpea>groundnut/pigeonpea>sole pigeonpea at 1.19, 1.16 and 0.93% respectively. In addition, there was a location x cropping system effect on pigeonpea stems, leaves, and roots (Table 2.3).

Table 2.3. Analysis of variance for groundnut and pigeonpea percent N at six locations in Malawi during the 2016 growing season. Presented values are means followed by standard deviations.

Location	Crop	Stems	Leaves	Pods	Roots
			% N		
Linthipe A	Groundnut	2.38 ± 0.28	3.31 ± 0.14	5.02 ± 0.26	2.96 ± 0.16
	Pigeonpea	1.08 ± 0.26	2.82 ± 0.15	3.09 ± 0.34	1.34 ± 0.18
Linthipe B	Groundnut	1.71 ± 0.25	2.77 ± 0.28	4.60 ± 0.13	2.28 ± 0.35
	Pigeonpea	1.08 ± 0.26	3.19 ± 0.13	3.02 ± 0.32	0.89 ± 0.14
Golomoti A	Groundnut	1.26 ± 0.18	2.77 ± 0.21	4.63 ± 0.35	1.76 ± 0.24
	Pigeonpea	1.03 ± 0.29	2.94 ± 0.12	2.81 ± 0.44	1.04 ± 0.18
Golomoti B	Groundnut	1.45 ± 0.16	2.73 ± 0.44	4.37 ± 0.19	1.95 ± 0.32
	Pigeonpea	1.03 ± 0.29	3.13 ± 0.28	2.75 ± 0.27	1.40 ± 0.35
Kandeu A	Groundnut	1.68 ± 0.10	3.16 ± 0.24	3.78 ± 0.17	2.33 ± 0.19
	Pigeonpea	1.16 ± 0.12	3.43 ± 0.32	3.11 ± 0.31	1.29 ± 0.24
Kandeu B	Groundnut	1.45 ± 0.13	2.63 ± 0.21	3.93 ± 0.24	1.84 ± 0.14
	Pigeonpea	1.16 ± 0.12	2.97 ± 0.18	2.43 ± 0.34	0.94 ± 0.18
			ANOVAS		
			Groundnut		
Location		Pr>F = <.0001*	Pr>F = 0.0012*	Pr>F = 0.3702	Pr>F = <.0001*
Cropping System		Pr>F = 0.3920	Pr>F = 0.0318*	Pr>F = 0.1158	Pr>F = 0.3963
Location*Cropping System		Pr>F = 0.7659	Pr>F = 0.6668	Pr>F = 0.5610	Pr>F = 0.2422
			Pigeonpea		
Location		Pr>F = 0.2669	Pr>F = <.0001*	Pr>F = 0.0041*	Pr>F = <.0001*
Cropping System		Pr>F = 0.0041*	Pr>F = 0.9954	Pr>F = 0.9922	Pr>F = 0.1674
Location x Cropping System		Pr>F = 0.0062*	Pr>F = 0.0062*	Pr>F = 0.3063	Pr>F = 0.0709**

*Significant at P=0.05; **Significant at P=0.10

Table 2.4. Percent N and total N means and standards deviations of groundnut and pigeonpea in four cropping systems in central Malawi. Cropping systems are sole groundnut (GN), sole pigeonpea (PP), doubled-up groundnut/pigeonpea intercrop (GNPP), and maize/pigeonpea intercrop (MZPP)

Cropping system	Leaves % N	Leaves Total N kg/ha	Pods % N	Pods Total N kg/ha	Roots % N	Roots Total N kg/ha
GN	2.99 ± 0.35	8.86 ± 6.82	4.10 ± 1.46	48.96 ± 27.71	2.21 ± 0.50	2.41 ± 1.26
PP	3.08 ± 0.24	23.94 ± 13.71	2.87 ± 0.39	9.47 ± 9.18	1.21 ± 0.30	1.21 ± 0.30
MZPP (PP)	3.09 ± 0.24	21.31 ± 12.43	2.86 ± 0.55	8.73 ± 8.85	1.14 ± 0.31	1.14 ± 0.31
GNPP (GN)	2.78 ± 0.33	5.95 ± 5.08	4.68 ± 0.37	55.29 ± 27.75	2.19 ± 0.51	2.41 ± 1.10
GNPP (PP)	3.05 ± 0.29	17.19 ± 8.84	2.87 ± 0.37	7.49 ± 7.52	1.09 ± 0.28	1.09 ± 0.28
GNPP (GN+PP)		*23.14*		*62.78*		*3.50*

Total nitrogen fixed by groundnut and pigeonpea

The total N that was contained in groundnut stems ranged from 11.65 kg/ha (Golomoti A) to 38.74 kg/ha (Linthipe B), leaves from 2.85 kg/ha (Linthipe A) to 15.57 kg/ha (Golomoti B), and roots from 0.91 kg/ha (Kandeu B) to 3.82 kg/ha (Golomoti B). The protein contribution of the groundnut cropping systems in terms of total N contained in the grain ranged from 22.34 kg/ha (Golomoti A) to 78.73 kg/ha (Golomoti B). Location had an effect on all groundnut plant parts while cropping system had an effect on groundnut leaves only. The low potential, hot and dry Golomoti B location was consistently associated with high total N. Total N contained in groundnut leaves was higher in sole groundnut compared to intercropped groundnut (Table 2.4). There was no location x cropping system effect on any groundnut plant parts (Table 2.5).

Total N contained in pigeonpea stems ranged from 31.48 kg/ha (Kandeu B) to 109.42 kg/ha (Kandeu A), 13.00 kg/ha (Linthipe A) to 35.82 kg/ha (Linthipe B) for leaves, 1.38 kg/ha (GB) to 15.54 (Kandeu B) for pods, and 3.61 kg/ha (Golomoti B) to 14.86 kg/ha (Kandeu A) for roots. Location had an effect on all pigeonpea plant parts and cropping system had an effect on stems, leaves, and roots but not pods. Total N contained in pigeonpea leaves, pods and roots was in the order sole pigeonpea>maize/pigeonpea>groundnut/pigeonpea (Table 2.4) There was a location x cropping system interaction on leaves and roots (Table 2.5).

The total N contained in different groundnut and pigeonpea plant parts in four cropping systems is shown on Figure 2.2. Overall, groundnut total fixed N was 87.01 kg/ha in the sole groundnut cropping system. Pigeonpea total fixed N was 129.54 kg/ha in the sole pigeonpea cropping system and 102.69 kg/ha in the maize/pigeonpea cropping system. When combined, groundnut and pigeonpea total fixed N was a 179.64 kg/ha in the groundnut/pigeonpea cropping system. Therefore, total N by cropping system was in the order groundnut/pigeonpea>sole pigeonpea>maize/pigeonpea>sole groundnut (Figure 2.2).

Table 2.5. Analysis of variance for groundnut and pigeonpea total N at six locations in Malawi during the 2016 growing season. Presented values are means followed by standard deviations.

Location	Crop	Stems$^{\phi}$	Leaves	Pods	Roots
			Kg/ha		
Linthipe A	Groundnut	32.22 ± 3.77	2.85 ± 1.35	65.85 ± 24.02	3.32 ± 0.75
	Pigeonpea	36.41 ± 14.68	13.00 ± 6.83	3.57 ± 1.93	6.81 ± 2.90
Linthipe B	Groundnut	38.74 ± 6.79	5.05 ± 1.98	55.57 ± 12.90	2.27 ± 0.67
	Pigeonpea	61.62 ± 32.51	35.82 ± 10.57	15.45 ± 11.79	6.34 ± 2.07
Golomoti A	Groundnut	11.65 ± 2.83	11.12 ± 2.51	22.34 ± 10.24	2.29 ± 0.35
	Pigeonpea	97.99 ± 43.29	20.96 ± 11.19	7.71 ± 4.25	11.07 ± 4.96
Golomoti B	Groundnut	13.13 ± 5.37	15.57 ± 8.70	78.73 ± 36.27	3.82 ± 0.73
	Pigeonpea	74.09 ± 27.32	17.50 ± 10.19	1.38 ± 0.87	3.61 ± 6.66
Kandeu A	Groundnut	36.72 ± 6.48	6.32 ± 3.84	54.83 ± 24.40	1.59 ± 0.36
	Pigeonpea	109.42 ± 21.63	25.41 ± 10.46	7.77 ± 5.93	14.86 ± 5.93
Kandeu B	Groundnut	23.05 ± 3.10	3.60 ± 3.00	35.41 ± 6.61	0.91 ± 0.28
	Pigeonpea	31.48 ± 10.54	13.10 ± 5.34	15.54 ± 8.53	5.03 ± 2.42
			ANOVAS		
			Groundnut		
Location		Pr>F = <.0001*	Pr>F = <.0001*	Pr>F = 0.0025*	Pr>F = <.0001*
Cropping System		Pr>F = 0.9941	Pr>F = 0.0395*	Pr>F = 0.3997	Pr>F = 0.3487
Location x Cropping System		Pr>F = 0.8983	Pr>F = 0.4272	Pr>F = 0.5849	Pr>F = 0.5851
			Pigeonpea		
Location		Pr>F = <.0001*	Pr>F = <.0001*	Pr>F = 0.0005*	Pr>F = <.0001*
Cropping System		Pr>F = 0.0047*	Pr>F = 0.0988**	Pr>F = 0.7460	Pr>F = 0.0030*
Location x Cropping System		Pr>F = 0.1569	Pr>F = 0.0362*	Pr>F = 0.9356	Pr>F = 0.0655**

$^{\phi}$ Pigeonpea stems include twigs; *Significant at P=0.05; **Significant at P=0.10

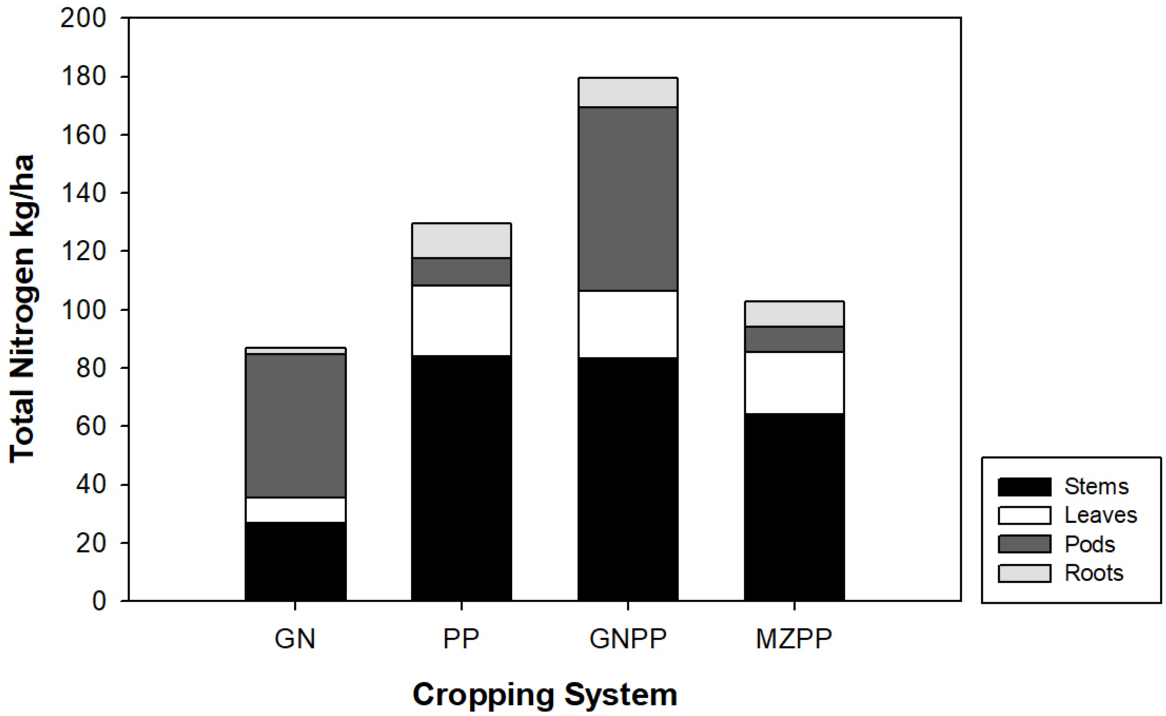

Figure 2.2. Total nitrogen in kg/ha by plant parts in four cropping systems in central Malawi. Cropping systems include are groundnut (GN), sole pigeonpea (PP), doubled-up groundnut/pigeonpea intercrop (GNPP), and maize/pigeonpea intercrop (MZPP).

Groundnut and pigeonpea BNF-N %

The proportion of fixed N that was located in groundnut stems ranged from 48.65% (Linthipe A) to 89.24% (Kandeu B), leaves from 39.99% (Kandeu A) to 83.42% (Linthipe B), grain from 39.52% (Kandeu B) to 79.37% (Linthipe B), and roots from 25.72% (Kandeu B) to 97.86% at the Linthipe B location (Table 2.6). Location had an effect on the BNF-N % of all groundnut plant parts. The high potential Linthipe B location was consistently associated with high BNF-N %. Cropping system had an effect on leaves at P=0.10 and there was a location x cropping system interaction on leaves (Table 2.6). Intercropped groundnut had higher BNF-N% than sole cropped groundnut. Overall, the mean proportion of groundnut BNF was 65.83% (± 21.99).

For pigeonpea stems, BNF-N % ranged from 75.74% (Golomoti) to 78.99% (Linthipe), leaves from 33.21% (Linthipe A) to 91.81% (Kandeu A), pods from 31.35% (Kandeu A) to 60.48% (Golomoti A), and roots from 13.13% (Kandeu A) to 51.81% at the Linthipe B location (Table 2.6). Location had an effect on the BNF-N % in pigeonpea leaves, pods and roots but not stems. Cropping system had an effect on pigeonpea leaves and pods. For pigeonpea leaves, BNF-N% was in the order groundnut/pigeonpea>sole pigeonpea=maize/pigeonpea and for pods it was maize/pigeonpea =groundnut/pigeonpea>sole pigeonpea. There was a location x cropping system interaction on pigeonpea leaves and pods as well (Table 2.6). Overall, the mean proportion of pigeonpea BNF was 52.01% (± 29.03) for pigeonpea.

Table 2.6. Analysis of variance for groundnut and pigeonpea BNF-N % at six locations in Malawi during the 2016 growing season. Presented values are means followed by standard deviations.

Location	Crop	Stems	Leaves	Grain	Roots
			%		
Linthipe A	Groundnut	48.65 ± 9.99	63.82 ± 5.51	62.58 ± 14.67	89.40 ± 9.04
	Pigeonpea	78.99 ± 25.03	33.21 ± 7.51	34.99 ± 25.62	26.79 ± 11.41
Linthipe B	Groundnut	73.16 ± 15.14	83.42 ± 7.55	79.37 ± 8.23	97.86 ± 1.53
	Pigeonpea	78.99 ± 25.03	79.35 ± 22.59	46.13 ± 25.52	51.81 ± 15.16
Golomoti A	Groundnut	75.85 ± 20.71	72.99 ± 11.57	66.88 ± 8.59	86.88 ± 7.83
	Pigeonpea	75.74 ± 10.40	87.85 ± 8.69	60.48 ± 21.23	23.00 ± 22.15
Golomoti B	Groundnut	-	-	-	60.86 ± 38.00
	Pigeonpea	75.74 ± 10.40	38.82 ± 44.98	-	-
Kandeu A	Groundnut	79.07 ± 17.62	39.99 ± 17.19	57.22 ± 35.50	72.77 ± 9.64
	Pigeonpea	78.32 ± 8.26	91.81 ± 13.29	31.35 ± 13.75	13.13 ± 17.37
Kandeu B	Groundnut	89.24 ± 9.73	46.14 ± 16.28	39.52 ± 8.68	25.72 ± 14.09
	Pigeonpea	78.32 ± 8.26	81.42 ± 16.51	36.32 ± 25.40	18.29 ± 15.16
ANOVAS					
Groundnut					
Location		Pr>F = <.0001*	Pr>F = <.0001*	Pr>F = <.0001*	Pr>F = 0.0003*
Cropping System		Pr>F = 0.6300	Pr>F = 0.0681**	Pr>F = 0.5720	Pr>F = 0.6265
Location x Cropping System		Pr>F = 0.4688	Pr>F = 0.0344*	Pr>F = 0.9659	Pr>F = 0.2667
Pigeonpea					
Location		Pr>F = 0.8900	Pr>F = <.0001*	Pr>F = <.0001*	Pr>F = <.0001*
Cropping System		Pr>F = 0.0826	Pr>F = 0.0031*	Pr>F = 0.0213*	Pr>F = 0.1703
Location x Cropping System		Pr>F = 0.3648	Pr>F = <.0001*	Pr>F = 0.0747**	Pr>F = 0.7982

-Data not available; *Significant at P=0.05; **Significant at P=0.10

Discussion

N dynamics by species

This is one of the first detailed reports of N allocation to legume plant tissues within intercropped and sole cropped systems on smallholder farms. This study is unique as it documented BNF contributions from not only aboveground biomass of groundnut and pigeonpea but belowground biomass as well. Additionally, the study assesses nitrogen allocation of groundnut and pigeonpea within maize-legume cropping systems at multiple locations which ranged from high to low agricultural potential.

We hypothesized that cropping system would have an effect on total N, it would be in the order: groundnut/pigeonpea> sole pigeonpea> sole groundnut> maize/ pigeonpea cropping systems and that BNF would decrease with agro-ecology crop production potential. Cropping system had a significant effect on total N (Figure 2.2) but was in the order: groundnut/pigeonpea> sole pigeonpea> maize/pigeonpea> sole groundnut. However, BNF did not follow a particular trend in terms of agro-ecology potential. This might have been due to the effect of the 2016 drought on plant biomass production and ultimately BNF. The 2016 cumulative rainfall across locations was 55% less than the norm.

Overall, the nitrogen accumulated by groundnut and pigeonpea in our study (87 to 180 kg/ha) was in a range similar to that of previous studies (Giller *et al*., 1987; Mcdonagh *et al*., 1993; Mhango *et al*., 2017; Okito *et al*., 2004; Senaratne *et al*., 1995; Toomsan *et al*., 1995). Using the ^{15}N isotope dilution method in a field study in India, Giller *et al*. (1987) reported 86 to 92% of groundnut N fixation rates amounting to 100 to 153 kg N/ha. Senaratne *et al*., (1995) also reported high groundnut N fixation of 85% from an outdoor basin study using the isotope dilution method in Sri Lanka. The groundnut BNF-N% mean of 66% in our study was much closer to the 59-64% range reported by Mcdonagh *et al*., (1993) from a field study in Thailand where the ^{15}N isotope dilution method was used. From researcher managed field trials on farmers' fields in Thailand, Toomsan *et al*. (1995) reported 72-77% of fixed N amounting to 150-200 kg N/ha in groundnut using the ^{15}N isotope dilution method. We used the ^{15}N natural abundance method and the sole groundnut cropping system in our study produced much less total N at 87 kg/ha compared to (Toomsan *et al*., 1995). Mhango *et al*. (2017) also used the ^{15}N natural abundance method in an on-farm study in northern Malawi and reported total N fixed means of 75% for groundnut and 76% for pigeonpea. However, the authors reported a very wide range of 22-99% N fixation from BNF for pigeonpea and very low total N (below 35 kg N/ha). In a field study on a research station in Brazil using the ^{15}N natural abundance method, Okito *et al*. (2004) also reported low groundnut contribution from BNF at 40.9 kg N/ha.

A unique finding in our study was that groundnut roots had higher %N, %BNF and total N than pigeonpea roots by about 50% or more. This may be related to groundnut roots being located near pods, so N that is assimilated up to the leaves is cycled back down to the pods near the roots when the growing season is ending. In pigeonpea, when N is cycled from leaves to pods, they are not near roots so N might be expected to be lower in pigeonpea roots. Species performance varied by site, in that groundnut grew notably well at the high potential site (Linthipe B), and pigeonpea was more resilient in that it grew well and accumulated N at marginal sites such as

Golomoti A. Similarly, in an earlier report on legume-based cropping systems in on-farm trials in central Malawi, it was observed that pigeonpea based systems perform well in marginal environments (Chimonyo et al., 2019b). Crop modeling results support these findings as well, where simulation scenarios conducted at these sites in central Malawi predicted that groundnut responds to adequate moisture with high growth and grain yield, whereas pigeonpea performs well over a wide range of environments including marginal sites such as Golomoti (Snapp *et al*., 2018)

Cropping systems effect

There was very limited cropping system effect overall. Groundnut leaf BNF-N% was higher within the doubled-up groundnut/pigeonpea intercrop compared to sole groundnut and there was a significant effect of cropping system (Table 2.6). This was not due to %N or total N being higher in leaves of groundnut in the groundnut/pigeonpea intercrop as actually the opposite was observed. Groundnut leaf %N and total amount of N was higher in sole cropped groundnut than in the groundnut/pigeonpea intercrop. Shading in the doubled-up groundnut/pigeonpea intercrop might have led to a reduction in groundnut N uptake. However, since N fixation was not suppressed, the shaded groundnut plants growing under pigeonpea might rely more on BNF.

In an alfalfa/walnut agroforestry study in France, Querné *et al.* (2017) reported that shading reduced alfalfa yield but significantly increased BNF which they attributed to probable N competition and mineralization inhibition under walnut trees. However, from a review on BNF in cereal-legume intercrops, Fujita *et al*. (1992) reported that mutual shading of component crops by tall cereals reduces both legume yield and BNF.

Cropping system effect on pigeonpea stem N concentration might have been due to higher stem biomass in the sole crop compared to intercropped pigeonpea. The total N contained in pigeonpea stems was high because of high stem biomass compared to leaves, pods and roots. Our findings are similar to Maskey *et al*. (2001) who reported that total N fixed in various legume crops was primarily influenced by crop growth, crop duration and rainfall. However, N contained in the stems could be discounted in systems N inputs as many smallholder farmers use pigeonpea stems as firewood (Orr *et al*., 2015). BNF-N% was surprisingly low in the sole pigeonpea cropping system. This could be due to the 2016 drought in Malawi which might have impacted BNF, although the multiple sites reported on this study did vary in terms of rainfall. Previous studies have reported the effect of drought on BNF. From a Thailand research station field study, using the N-difference method, Pimratch *et al*. (2008) reported reductions in both groundnut biomass production and BNF with increasing levels of drought stress. Mhango *et al*. (2017) reported that total N differed with cropping system in a drought where intercropped pigeonpea produced lower total N compared to sole pigeonpea. According to Mhango *et al*. (2017), interspecific competition is one of the drivers of BNF in a pigeonpea-based intercrop especially in a drought.

Similar to Katayama *et al*. (1995), our study shows overall higher BNF-N% in leaves of intercropped pigeonpea (78.37 ± 27.12 in groundnut/pigeonpea) compared to sole pigeonpea (64.47 ± 31.15). Katayama *et al*. (1995) attributed that to pigeonpea's increased dependency on

BNF when intercropped with cereals in soils with low soil N. However, in our study, this was true when pigeonpea was intercropped with both maize and groundnut.

Sustainability implications

The proportion of BNF by cropping system is important to consider in terms of sustainability as this indicates reduced reliance on N fertilizer, an external input. Our results showed that sole groundnut produced the least amount of total N fixed compared to sole pigeonpea, maize/pigeonpea, and the groundnut/pigeonpea intercrops. Similar to Njira *et al*.(2012), the doubled-up groundnut/pigeonpea intercrop was effective at enhancing most nitrogen per unit area (Figure 2.2) compared to sole pigeonpea and sole groundnut.

On the one hand, groundnut is highly preferred by many smallholder farmers who rotate it with a maize crop because of the possibility of both groundnut and maize grain (Okito *et al*., 2004). However, from a simple N balance calculation, Okito *et al*. (2004) indicated that the groundnut-maize sequence would, in the long term, deplete soil N reserves. In Ghana, a comparison of N fixation and growth of legume rotation and intercrop systems in Northern and Southern Guinea savanna illustrated that groundnut was associated with a net negative N balance at one site but not the other (Kermah *et al*., 2018). Our results are similar, consistent with groundnut rotation as a potentially N depleting system yet showing potential to contribute N fertility under some conditions. One sustainability challenge highlighted here with groundnut is that roots and nodules are often removed during harvest when plants are pulled out and removed from the field with the shoots, impacting total N and soil fertility (Toomsan *et al*., 1995). Our finding that root N concentration was high in groundnut further highlights the potential for a nitrogen deficit with this crop. In our study, this could also be the reason why subsequent maize yield after sole groundnut was the lowest (4.06 Mg/ha) compared to maize after groundnut/pigeonpea intercrop (5.00 Mg/ha) and sole pigeonpea (5.51 Mg/ha).

The doubled-up legume system which provided farmer-preferred crop of groundnut grain with combination of high total N from both pigeonpea and groundnut. Mcdonagh *et al*. (1993) demonstrated that positive N balances in groundnut-based systems can be attained if farmers return and incorporate legume residues to the soil. Further in an on-farm Ghana study, only longer duration varieties of groundnut provided a net positive N balance (Kermah *et al*., 2018).Taken together with our study, these findings highlight that appropriate residue management and incorporation of longer-duration legume species are both key if N sustainability is to be pursued in maize-legume diversified cropping systems without much access to external N inputs.

This study demonstrates a clear advantage in terms of soil fertility of the doubled-up groundnut/pigeonpea system is the N accumulation in plant parts, especially stems and leaves and roots (Figure 2.2). Leaf total N was significantly higher in both groundnut and pigeonpea in the doubled-up legume system compared to other cropping systems thereby reinforcing that there is more plant N accumulated in the doubled-up system. Considering that grain and stems harvested for firewood (pigeonpea) are included, the total amount of N fixed in this study, conducted in a relatively dry year, was modest (ranged from 87 to 180 kg/ha). This means that after crop harvesting, the remaining soil N is insufficient to support high productivity in subsequent maize rotation sequences without additional N sources (Njira *et al*., 2012). Legume rotational systems when integrated with modest doses of fertilizer have been shown to enhance N fertilizer efficiency and stability of maize rotation response on smallholder farms (Snapp *et al*., 2010). This study extends the earlier investigations of single and double legume technologies within smallholder maize-based systems, through detailed assessment of nitrogen fixation and allocation by plant tissue type as well as species.

Conclusions

Interspecific legume-based cropping systems alone might not sustain maize productivity and hence the need for integrated soil fertility approaches. Modest amounts of inorganic N combined with legume residue incorporation have the potential to maintain positive N balances. Therefore, there is need for extension messages to reinforce this and educate farmers on long-term sustainability aspects. Additionally, N contributions from belowground biomass have been under appreciated, and the potential negative impacts of groundnut root removal during harvest is highlighted in this study and should be reflected in extension education. The doubled-up legume cropping system shows potential as a means to consistently obtain a positive N balance when grown in rotation with maize based systems.

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3. Chapter Three: Short-term interactions between legume and maize residues and mineral N fertilizer on nitrate-N dynamics and maize productivity in Malawi

Abstract

Smallholder farmers in Sub-Saharan Africa (SSA) produce food crops for subsistence on nitrogen-deficient soils. This limits crop productivity and negatively impacts food and nutritional security. The use of inorganic fertilizers and organic resources from high quality crop residues have been proposed as a solution to the dilemma. However, not much is known about how different on-farm crop residues interact with inorganic N fertilizer in different agro-ecologies. To address these research gaps, two-year on-farm trials were implemented in three locations in southern Malawi that are typical of low, medium and high agro-ecological potential. During Year 1, maize and doubled-up legume rotation (groundnut/pigeonpea) plots were optimally managed to generate both grain and biomass. At harvest, 0X, 1X and 2X residues were incorporated and maize was planted in these plots in Year 2 to test the effect of residue quality and quantity.

From the three locations, on-farm biomass in year one from maize (low quality residues) ranged from 1.67 to 10.42 Mg/ha and groundnut/pigeonpea (high quality residues) ranged from 2.39 to 11.96 Mg/ha. In year two, location and treatment effect on maize grain yield ranged from 1.06 to 8.27 Mg/ha. However, treatment effects were only due to fertilizer and not residue quality or quantity. Residue % N content was in the order: green pigeonpea leaves > senesced groundnut leaves > senesced groundnut stover > green pigeonpea twigs > senesced pigeonpea leaves >

maize stover. Residue quality and quantity did not have an effect on inorganic soil N from the 0-80 cm soil depth. Our study shows the actual crop residue biomass quantity and quality that smallholder farmers are capable of producing depending on their biophysical environment. As no residue quality or quantity effects were detected on maize yield or soil N this shows the importance of integrated nutrient management over a long term for soil health and crop production. Agricultural development policies focus on access to inorganic fertilizer sources, and indeed nitrogen fertilizer has clear benefits as shown here.

Keywords: Inorganic nitrogen, Legumes, Maize, Residues

Introduction

Crop residues

Crop residues are often the only available source of organic amendments used by smallholder farmers to improve and conserve soils, given the limited access to livestock and green manures. Many soils on smallholder farms in Sub-Saharan Africa (SSA) have low soil organic matter (SOM) content (Smaling *et al*., 1997), which results in poor crop productivity. Building SOM requires improving both cereal and legume crops primary productivity through mineral fertilizers and retaining the associated crop residues on the cropped lands. These residues decompose to provide mineral N to crops grown in sequence, as well as being an important source for SOM capitalization (Beedy *et al*., 2010). Residues of legume crops have a narrow C/N ratio which supports N availability to the rotational crop, whereas residues of maize, which have a wide C/N ratio, promote N immobilization. Therefore, high quality legume residues are important for integrated nutrient management in SSA smallholder farming systems (Snapp *et al*., 1998). Soil C inputs from crop residues play a key role in soil organic carbon (SOC) sequestration and stabilization (Kong *et al*., 2005). Studies have shown that increases in SOC are often related to the incorporation of fresh organic materials to the soil such as from legumes, cover crops, and manure, if biochemical residue quality is sufficient to support soil C accrual,. Six *et al*. (2002) found that the light fraction and particulate organic matter pools are mainly made up of recently derived, partially decomposed plant residues.

Effect of crop residues on soil C and N

According to Chikowo *et al*. (2003), the chemical composition or quality of residues determines the release of mineral-N in soil from plant residues. Under leaching conditions, Chikowo *et al*. (2003) conducted an incubation study of different types of litter for 120 days and found that sesbania litter released more mineral N than acacia litter. Sakala *et al*. (2000) conducted a leaching tube incubation study with different textured soils and investigated the interactions of pigeonpea and maize residues during decomposition and N mineralization. The authors reported that the C:N ratio of senesced pigeonpea leaves was 24, while maize residues were at 75. Even though there eventually was N mineralization in the senesced pigeonpea treatment, there was an initial immobilization period that ranged from two to four weeks in all soil types. The authors also observed that the N immobilization period in the maize residue and in the mixed (maize and pigeonpea residues) treatments were longer but similar, lasting 18 weeks. Sakala *et al*. (2000) concluded that mixing pigeonpea and maize residues did not significantly reduce N immobilization. However, in intercropping systems, residues of varying quality are mixed and decompose concurrently, resulting in N mineralization processes which differ from those of residues in sole cropping systems (Sakala *et al*., 2000).

McDaniel *et al*. (2014) conducted a meta-analysis of 122 studies to examine crop rotation, crop types and management practices effects on total soil C and N in different soil types and climates. The authors found that increasing crop diversity by adding one or more crops in a rotation to a monoculture increased total N by 5.3% and total soil C by 3.6% and when rotations included a cover crop total N increased by 12.8% and total C by 8.5%. In a different study by Tiemann *et al*. (2015), increasing the quantity, quality and chemical diversity of residues through high diversity rotations sustained soil microbes, soil organic matter and soil fertility. Additionally, incorporating residues of mixed qualities in diverse cropping systems resulted in soil organic nitrogen mineralization.

The quality of residues determines their rate of decomposition, N release and eventually how much subsequent crops benefit (Sakala *et al*., 2000). Therefore, research on residue quality and management of organic inputs is of paramount importance. Sustainability is difficult to assess in cropping systems where residue inputs from above and belowground biomass remain uncharacterized, leaving uncertain this important determinant of soil C and N trends over time.

Malawi farming systems and farmer nutrient management

Farmland cultivation in Malawi is labor intensive as manual labor is used for land preparation and hand hoe weeding. The most common cropping systems include continuous maize, maize-groundnut rotations and maize/pigeonpea intercrops (Mungai *et al*., 2016). Mungai *et al*. (2016) established that more than 80% of farmers applied mineral fertilizer in one or more of their fields. Many farmers combine residue incorporation, or compost application, with fertilizer use in almost half of their fields. Farmers were also reported to remove or burn legume residues from their fields. Mungai *et al*. (2016) also found that timing of residue incorporation varied within and across locations where some farmers incorporated residues soon after crop harvesting while others incorporated residues during land preparation.

Malawi smallholder farming systems provide an important opportunity to evaluate agricultural practices for performance under variable and degraded soil conditions (Li *et al*., 2017). Mineral fertilizer use has grown markedly in recent years in Malawi due to policies that improve farmer access, yet maize yields are not always following the expected upward trend (Messina *et al*., 2017). Therefore, there is need to determine the practices under which crop and soil management practices support sustainable intensification (Snapp *et al*., 2018). This study investigated the effect of incorporating high- and low-quality crop residues on soil inorganic N status and maize yield on different soils and across a climate gradient in southern Malawi.

Our specific objectives were 1) To determine the effect of incorporating high- and low-quality crop residues on the effect of incorporated residue quality and quantity on mineral N dynamics during different times in the cropping season and 2) To determine the effect of inorganic fertilizer combined with high- and low-quality residues on subsequent on-farm maize yield. The hypotheses were 1) High residue quality will enhance soil inorganic N pools whereas high residue quantity will be associated with temporary immobilization of inorganic N and 2) Organic and inorganic N sources (high N-content residues + fertilizer) will act as additive sources of N, both being associated with high maize yields.

Materials and methods

Study locations

This study is part of the Africa RISING project, which was conducted between 2016-2018 in Machinga, in the southern region of Malawi, at three locations representing low yield production potential associated with hot and dry conditions (Mtubwi), moderate yield production potential with decent rainfall distribution in most years (Nsanama) and high yield production potential associated with the warm, mesic rainfall site of Nyambi (Figure 3.1). These sites were chosen based on net primary productivity potential through remote sensing data to obtain a range of yield production potential sites and validated through local agricultural land use systems. Mtubwi is in the Shire Valley, a low elevation zone that historically receives about 600 mm of rainfall annually and is the hottest site. Nsanama and Nyambi are at medium-high elevation and historically receive about 800-1200 mm of rainfall per year. The total annual rainfall and day temperature averages for the three locations are shown in Table 3.1.

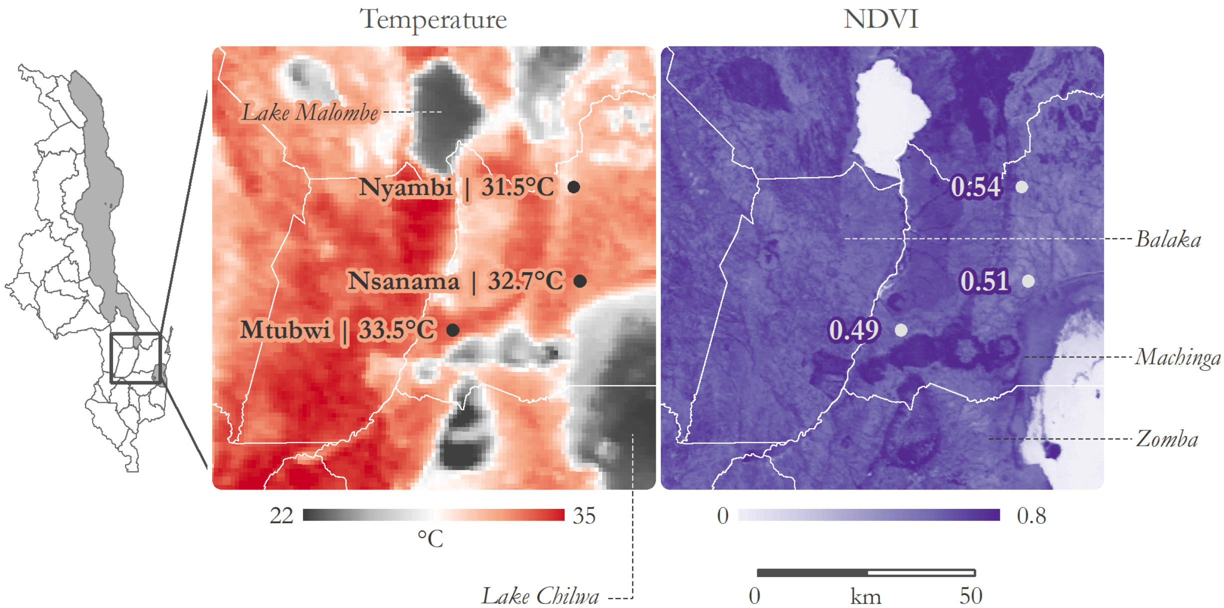

Figure 3.1. Map of Malawi showing the location of the three research agroecologies with 15-year temperature and normalized difference vegetation index (NDVI) averages. Temperature and NDVI are averaged across 2001-2015 growing seasons. Temperature measurements were sourced from the MODIS Land Surface Temperature. Map was prepared by Dr. Brad Peter, University of Alabama (2019).

Table 3.1. Total annual precipitation in mm and day temperature means during the 2016, 2017, and 2018 growing seasons for the three locations. Precipitation based on CHIRPS and temperature is from NASA MODIS Land Surface Temperature.

Location	2016	2017	2018
Mtubwi (Low potential)			
Cumulative precipitation (mm)	704	839	775
Day temperature mean (°C)	35.8	33.9	35.6
Nsanama (medium potential)			
Cumulative precipitation (mm)	678	811	770
Day temperature mean (°C)	35.3	33.6	34.1
Nyambi (high potential)			
Cumulative precipitation (mm)	735	897	904
Day temperature mean (°C)	34.4	32.6	33.4

During the 2016-17 agricultural season, there were three dry spells at each of the three locations and four in 2017-18. There were two flooding events at the Mtubwi site in 2017-18.

Experimental design

This study investigated maize productivity and soil mineral/inorganic N dynamics associated with inorganic and organic nutrient sources, comparing fertilizer effects, and quality and quantity of residues associated with continuous maize (ContMz) versus a doubled-up legume rotation (DLR) with maize.

Two year on-farm trials were implemented in three sites in southern Malawi that are typical of low, medium and high agro-ecological potential. During Year 1, maize and doubled-up legume rotation (groundnut/pigeonpea) plots were optimally managed to generate both grain and biomass. There were six 'treatments' that were essentially similar in Year 1 to generate maize biomass and three other doubled-up legume treatments (Table 3.2). At harvest, three levels of quantity of residues was achieved through a design that included 0X (shoot residues removed), 1X (shoot residues retained in situ) and 2X (doubled shoot residues through addition of residues from the 0X plot) (Table 3.2). Quality of residues were at two levels, based on the two cropping systems studied (continuous maize and doubled-up legume). Nitrogen fertilizer was applied in treatments 4-9 to assess inorganic N response in combination with quality and quantity of residues, relative to maize residues only (Treatments 1-3). The experiment was repeated in time, as a legume phase was established in 2018/19 and maize yield benefits were assessed during 2019/20, however only the initial study with years 1 and 2 are reported here. The research was carried out at three locations, using a randomized complete block design (RCBD) with three replications at all locations. As described in Table 3.2, the farming systems rationale for these systems include testing various scenarios. In addition, this incomplete factorial allowed testing of the effect of quality, quantity and fertilizer.

Treatments MZ-0N-0R, MZ-0N-2R and MZ-0N-1R received no fertilizer in year two while the other six treatments received 35 kg/ha N (23 kg NP-N and 12 kg Urea-N). To avoid P being limiting, 9 kg P was applied to all treatments as single super phosphate. All plots in all locations were under sole maize in the second year of the experiment, where intensive soil monitoring was carried out over 2017/18 in six of the treatments (MZ-0N-0R, MZ-0N-2R, MZ-35N-0R, MZ-35N-2R, GNPP-35N-0R and GNPP-35N-2R) at the three sites.

Table 3.2. Treatments structure and fertilization in the residue generation phases and, in the residue, quality and quantity assessment phases. Rationale for the treatment choices is also included.

Treatment number	Treatment code	Residue generation phase (Year 1)	Assessing residue quality and quantity (Year 2)	Rationale
1	MZ-0N-0R	Maize + 70 kg/ha N	Maize + no residues	Simulates grazing in mixed cropping and livestock systems, with no fertilizer access
2	MZ-0N-2R	Maize + 70 kg/ha N	Maize + 2X residues (from treatments MZ0N0R and MZ0N2R)	Systems that promote biomass transfer (e.g. conservation agriculture), with no fertilizer access
3	MZ-0N-1R	Maize + 70 kg/ha N	Maize + 1X residues	Fields that are protected from grazing, with no fertilizer access
4	MZ-35N-0R	Maize + 70 kg/ha N	Maize + no residues+ 35 kg/ha N	Simulates grazing in mixed cropping and livestock systems, with access to fertilizer
5	MZ-35N-2R	Maize + 70 kg/ha N	Maize + 2X residues (from treatments MZ35N0R and MZ35N2R) + 35 kg/ha N	Systems that promote biomass transfer, with access to fertilizer
6	MZ-35N-1R	Maize + 70 kg/ha N	Maize + 1X residues + 35 kg/ha N	Fields that are protected from grazing, with access to fertilizer
7	GNPP-35N-0R	Groundnut/Pigeonpea + 35 kg/ha N	Maize + no residues + 35 kg/ha N	Residue quality contrast with MZ-35N-0R
8	GNPP-35N-2R	Groundnut/Pigeonpea + 35 kg/ha N	Maize + 2X residues (from treatments GNPP35N0R and GNPP35N2R) + 35 kg/ha N	Residue quality contrast with MZ-35N-2R
9	GNPP-35N-1R	Groundnut/Pigeonpea + 35 kg/ha N	Maize + 1X residues + 35 kg/ha N	Residue quality contrast with MZ-35N-1R

Crop management

Crops were planted in late November or early December, after the first effective rains. Maize was planted at 75 cm spacing between ridges and 25 cm within ridge spacing to target a plant population of 53,000 plants/ha (Chimonyo et al., 2019a). The DLR with maize system had a population density 174,000 plants/ha for groundnut and 44,000 plants/ha for pigeonpea in the doubled-up legume phase of the rotation, and 53,000 plants/ha in the maize rotation phase. This followed Malawi government recommendation for DLR, which is an additive design, combining the recommended sole crop population density for groundnut and pigeonpea (Mungai *et al*., 2016). The planting system arrangement was that groundnut is spaced at 10 cm along a row, and pigeonpea planted at 4 seeds at planting stations every 90 cm along the row, thinned to 3 plants at 3 weeks after germination. All fields were kept weed free through hand-hoe cultivation.

Plant biomass assessments

In May of 2017, maize and groundnut crops from a whole plot of 26.25 m^2 per plot (7 ridges x 5 m x 0.75 m) were harvested and weighed. A randomly selected sample of approximately 3 kg of maize residues was collected by compositing multiple subsamples from a well-mixed, chopped up sample (approximately 8 cm) using a machete in the field. In July of 2017 after weighing pigeonpea biomass, stems were separated by hand from the leaves, pods, and twigs. All the dry and senesced pigeonpea and groundnut leaf mixtures were collected from the groundnut/pigeonpea plots and weighed. A random hand sampling technique was used to obtain representative fresh pigeonpea, senesced pigeonpea and groundnut residues, which were chopped and dried to constant weight in an oven.

Yield assessment and residue management

Maize and groundnut crops were harvested at physiological maturity in April-May 2017, and pigeonpea in July 2017. In groundnut/pigeonpea plots, pigeonpea pods were harvested by hand and weighed. Crop residues from year 1 were incorporated as described in Table 3.2. For maize systems, MZ-0N-2R, MZ-0N-1R, MZ-35N-2R and MZ-35N-1R (Table 3.2), maize residues were sun-dried in the field, placed in furrows, and ridges were made to incorporate these residues into the soil in June 2017. Groundnut residues were sun-dried in the field until pigeonpea physiological maturity. After pigeonpea was harvested in July 2017, mixtures of fresh pigeonpea leaves, twigs and flowers, senesced pigeonpea and groundnut leaves and groundnut stover were laid out in the furrows and ridges were made to incorporate the residues in the soil. The ridges were made following Malawi farmer practice using the hand hoe, to about 25 cm in height, and spaced at 75 cm. All plots were cropped with maize during the next cropping season that commenced in November 2017, to determine the effect of residue quality and quantity on maize productivity at maize physiological maturity in April-May 2018. In both years, crops were harvested on a whole plot basis.

Tissue quality analysis

Sub-samples of legume mixtures were ground using a laboratory mill (1 mm). Ground tissue samples were packed in tins, and C and N content was determined at the University of California Davis Stable Isotope Facility, by an elemental analyzer and isotope ratio mass spectrometer (https://stableisotopefacility.ucdavis.edu/13cand15n.html). For lignin and acid detergent fiber (ADF) %, crop residue samples were sent to the Dairyland Laboratories for analysis, where a modified AOAC Official Method 973.18 was used (https://www.dairylandlabs.com/feed-and-forage/methods).

Soil sampling and analyses

Soil samples were collected from the ridges before incorporation of residues in June of 2017. Randomly collected soil samples were composited (three per plot) to represent the 0-20 and 20-40 cm soil depths, using a dutch auger (5.5 cm diameter). Soils were air-dried, sieved (2 mm) and soil texture was determined using the hydrometer method (Kellogg Biological Station/ Long-Term Ecological Research, 2008). Total soil C and N % were determined after grinding to a fine powder with a shatter mill, by dry combustion with Costech ECS 4010 (Costech Analytical Technologies, Inc., Valencia, CA). Soil samples were sent to the A and L Great Lakes laboratory for pH (1:1 soil to water ratio), phosphorous (P), and potassium (K) analyses (Mehlich-3 ICP method). A subset of six treatments (MZ-0N-0R, MZ-0N-2R, MZ-35N-0R, MZ-35N-2R, GNPP-35N-0R, and GNPP-35N-2R) were used for detailed soil inorganic N monitoring. Soil samples were collected from the 0-20, 20-40, 40-60 and 60-80 cm soil depths at three times over the 2017-18 season. The first soil sampling for inorganic N determination was carried out at maize planting (December 2017), thirty days after planting (January 2018), and at maize harvest (May 2018).

Inorganic N was extracted using 2M KCl. Soil samples of 10 g were weighed into a 100 ml plastic centrifuge cups and 40 ml of 2M KCl was added. The cups were shaken for one hour on a reciprocal shaker at approx. 180 strokes per minute. After shaking, cups were allowed to settle for 15 mins. The supernatant was filtered through a Whatman No. 1 filter paper (GE Healthcare

Bio-Sciences, Pittsburg, PA) and poured into small plastic vials. The samples were frozen until they were analyzed. KCl extractants were analyzed for inorganic N (NO_3-N and NH_4-N) on a Thermo MultiskanTM 96-well plate reader (Kane *et al*., 2015). Gravimetric soil moisture content was determined by weighing approximately 10 g of soil into tins or bags, and oven-drying the soil at 105 °C for 48 hours or until constant weight. The soil moisture content was then determined by the formula:

% soil moisture = ((wet soil wt) – (dry soil wt – tin/bag wt.) / (dry soil wt. – tin/bag wt.)) * 100 (KBS LTER, 2019)

Statistical analysis

In 2017, the research design was an RCBD with fertilized sole maize or groundnut/pigeonpea intercrops as treatment factors. In 2018, the maize response year, the research design was an RCBD with residue quality (maize stover or groundnut/pigeonpea residues), residue quantity (0x, 1x and 2x) and inorganic fertilizer N levels (0 and 35 kg/ha N) as treatment factors. Maize grain yield response to treatment (residue quality and quantity) and location (low, medium and high yield potential gradient) effects were analyzed by a two-way analysis of variance (ANOVA) in SAS 9.4 (SAS Institute, 2002) using PROC MIXED to compare differences across treatments and locations. The ANOVA model that was used to test for maize yield response was (Maizegrainyield= Location|Treatment). Nitrate dynamics over the three sampling times were analyzed using the repeated measures ANOVA in SAS with the model (N=treatment time/ddfm=kr). Planned contrasts were used to determine residue quality and quantity effects on inorganic N and maize grain yield. The planned contrast models included block nested within location and treatment by block as random effects.

Results

Environment

The soil properties at the three locations are shown in Table 3.2. Overall, soils at all locations were close to neutral or slightly alkaline, with pH values of 6.8-7.1. The topsoil content of organic matter was low at all sites as indicated by soil organic C levels of 0.36 %C at Mtubwi, 0.47 %C at Nsanama and 1.23 %C at Nyambi. Soil total N % did not vary and was about 0.06 % at all three sites. Total inorganic N in the 0-20 cm soil depth ranged from 1.95 mg/kg soil (Nyambi) to 2.16 mg/kg soil (Nsanama). Soil P ranged from 36 ppm (Mtubwi) to 113 ppm (Nsanama) while soil K ranged from 67 ppm to 186 ppm (Nyambi). Generally, the sites were sandy, with the clay content in the 0-20 cm soil depth varying from 13% (Nsanama) to 19 % (Nyambi) (Table 3.3).

Table 3.3. Soil chemical and physical properties at research locations (0-20 cm) from marginal (Mtubwi), moderate (Nsanama) and mesic (Nyambi) sites in southern Malawi. Values are means followed by standard deviations.

Location	N (%)	C (%)	Inorganic N (mg/kg soil)	P-M3 (ppm)	K-M3 (ppm)	pH	Clay (%)	Sand (%)
Mtubwi	0.06 ± 0.05	0.36 ± 0.06	2.11 ± 1.05	35.65 ± 19.46	66.59 ± 28.62	6.99 ± 0.13	16.72 ± 3.18	75.95 ± 3.46
Nsanama	0.06 ± 0.05	0.47 ± 0.15	2.16 ± 0.82	113.06 ± 43.26	118.22 ± 75.21	7.09 ± 0.17	13.39 ± 3.50	81.17 ± 3.40
Nyambi	0.07 ± 0.04	1.23 ± 0.20	1.95 ± 0.37	69.63 ± 24.94	185.63 ± 73.08	6.80 ± 0.16	19.49 ± 3.33	73.22 ± 3.54

Aboveground biomass

Across treatments and locations, maize biomass production in 2017 ranged from 1.67 Mg/ha in Mtubwi to 10.42 Mg/ha in Nsanama (Table 3.4). Maize biomass in 2018 was lower at all sites than in 2017. Total aboveground biomass from groundnut and pigeonpea ranged from 2.39 Mg/ha in Mtubwi to 11.96 Mg/ha in Nsanama (Table 3.4). Legume biomass included senesced groundnut leaves, groundnut stover, senesced pigeonpea leaves, fresh pigeonpea leaves, and twigs.

Table 3.4. Crop residue biomass produced from nine treatments at three locations in 2017. For the species column, maize represents maize stover, GNPP-Senesced is a mixture of senesced groundnut and pigeonpea leaves, GNPP-Groundnut represents groundnut stover and GNPP-Pigeonpea is pigeonpea leaves and twigs. The incorporated columns show the total amount of incorporated crop residues, where treatments with 0R had no residues, 1R is 1x residues and 2R is 2x residues. Presented values are means, followed by standard deviations.

Treatment	Species	Mtubwi		Nsanama		Nyambi	
		Produced	Incorporated	Produced	Incorporated	Produced	Incorporated
MZ-0N-0R	Maize	2.43 ± 1.47	0	8.57 ± 1.82	0	3.95 ± 0.74	0
MZ-0N-1R	Maize	1.84 ± 1.05	1.84	7.73 ± 2.88	7.73	2.99 ± 0.83	2.99
MZ-0N-2R	Maize	3.17 ± 0.62	5.60	8.42 ± 1.22	16.99	2.47 ± 0.24	6.42
MZ-35N-0R	Maize	1.76 ± 1.28	0	8.00 ± 0.26	0	3.51 ± 0.14	0
MZ-35N-1R	Maize	1.67 ± 1.20	1.67	7.16 ± 1.82	7.16	3.68 ± 0.61	3.68
MZ-35N-2R	Maize	3.31 ± 2.02	5.07	10.42 ± 3.01	18.42	2.65 ± 0.88	6.16
GNPP-35N-0R	GNPP-Senesced	0.47 ± 0.34		3.24 ± 0.90		2.27 ± 0.76	
GNPP-35N-0R	GNPP-Groundnut	0.70 ± 0.06		4.07 ± 0.16		1.54 ± 0.27	
GNPP-35N-0R	GNPP-Pigeonpea	1.22 ± 0.36	0	3.89 ± 0.22	0	2.12 ± 1.07	0
GNPP-35N-1R	GNPP-Senesced	0.95 ± 0.72		2.33 ± 0.26		1.88 ± 0.42	
GNPP-35N-1R	GNPP-Groundnut	1.22 ± 0.59		4.03 ± 1.31		1.60 ± 0.44	
GNPP-35N-1R	GNPP-Pigeonpea	1.80 ± 0.79	3.97	4.87 ± 0.83	11.23	1.97 ± 0.09	5.45
GNPP-35N-2R	GNPP-Senesced	0.56 ± 0.06		3.78 ± 0.90		2.12 ± 0.68	
GNPP-35N-2R	GNPP-Groundnut	1.40 ± 0.17		3.08 ± 0.77		2.34 ± 1.40	
GNPP-35N-2R	GNPP-Pigeonpea	1.78 ± 0.62	6.13	5.10 ± 0.73	23.14	2.36 ± 0.73	12.75

Tissue quality

The chemical composition of incorporated maize, groundnut and pigeonpea residues are shown in Table 3.5. As expected, maize stover had the lowest N content of 0.87 % and green pigeonpea leaves had the highest N content of 3.06 %. The lignin content of senesced pigeonpea leaves (24.35 %) was much higher than that of maize stover (5.82 %) and senesced groundnut leaves (3.44 %). Senesced groundnut leaves had the lowest ADF % (19.30) whereas senesced pigeonpea leaves had the highest (56.17).

Table 3.5. Chemical composition of on-farm crop residues from Malawi which were incorporated

Residue type	N %	Lignin %	ADF %	Lignin:N
Maize stover	0.87	5.82	51.28	12.38
Senesced groundnut leaves	2.97	3.44	19.30	1.16
Senesced groundnut stover	1.62	9.07	44.51	5.60
Senesced pigeonpea leaves	1.50	24.35	56.17	16.23
Green pigeonpea leaves	3.06	15.84	29.14	5.18
Green pigeonpea twigs	1.59	11.27	42.59	7.09

Maize grain yield following incorporation of crop residues

There was a location and treatment effect on maize grain yield but no interaction (Table 3.6). Across locations and treatments, maize grain yield ranged from 1.06 Mg/ha in Mtubwi to 8.27 Mg/ha in Nyambi. From all treatments, the average maize grain yield at the Mtubwi location was 1.96 Mg/ha, 5.20 Mg/ha at Nsanama, and 7.20 Mg/ha at Nyambi. The treatment effect was due to fertilizer, as residue quality or quantity had no effect on maize grain yield as shown by planned contrasts (Table 3.6). The fertilizer effect (P=0.0634) was found at all locations, as shown by planned contrasts of fertilized vs. unfertilized treatments (Table 3.6). Across locations, unfertilized treatments had lower maize grain yield on average (4.00 Mg/ha) compared to fertilized treatments (5.18 Mg/ha). When ANOVAs were done separately by location, the fertilizer effect was even greater at the Nyambi location (P= 0.0034) and the Mtubwi location (P= 0.0215). Figure 3.2 shows maize grain yield from unfertilized and fertilized treatments from the six treatments which were studied in detail.

Table 3.6. The effect of residue quantity, residue quality and N fertilizer on maize yield in 2018. Means are followed by standard deviations for nine treatments at three locations in southern Malawi. Planned contrasts of six treatments across three locations are shown as well as the overall ANOVAS.

Treatment	Mtubwi	Nsanama	Nyambi
		Mg/ha	
MZ-0N-0R	1.54 ± 0.83	4.85 ± 1.04	5.97 ± 1.53
MZ-0N-2R	1.06 ± 0.41	4.52 ± 0.48	5.53 ± 1.04
MZ-0N-1R	1.52 ± 0.80	4.04 ± 1.69	6.95 ± 1.24
MZ-35N-0R	2.54 ± 0.88	5.57 ± 1.38	8.07 ± 1.52
MZ-35N-2R	2.31 ± 1.09	5.92 ± 1.68	6.84 ± 0.64
MZ-35N-1R	2.12 ± 1.43	5.52 ± 0.30	6.96 ± 1.49
GNPP-35N-0R	1.97 ± 0.34	5.53 ± 1.06	8.03 ± 0.51
GNPP-35N-2R	2.23 ± 0.22	5.91 ± 0.60	8.27 ± 0.76
GNPP-35N-1R	2.38 ± 0.71	4.94 ± 2.39	8.16 ± 0.88

Planned Contrasts

No residue vs. low quality residue treatments	Pr > F = 0.7956
No residue vs. high quality residue treatments	Pr > F = 0.8537
Low vs. high quantity residue treatments	Pr > F = 0.9635
Fertilized vs. unfertilized treatments	Pr > F = 0.0634**

ANOVAS

Location	Pr > F = <.0001*
Treatment	Pr > F = 0.0195*
Location x Treatment	Pr > F = 0.9647

*Significant at P = 0.05
**Significant at P = 0.10

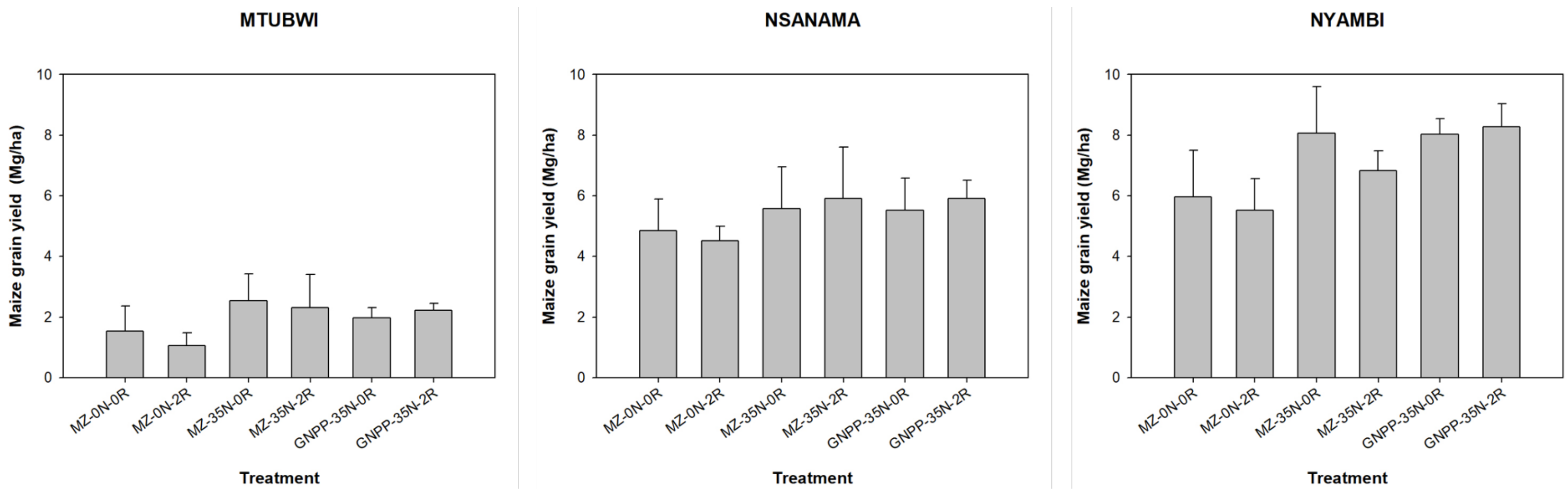

Figure 3.2. Maize grain yield from six treatments across three locations in southern Malawi. At all locations, treatments MZ-0N-0R and MZ-0N-2R were unfertilized while the rest were fertilized.

Soil NO_3-N

Soil NO_3-N was at moderate levels at all sampling times and was analyzed over time using a repeated measures model (NO_3-N=treatment time/ddfm=kr). Treatment had no effect on cumulative soil NO_3-N from the 0-80 cm depth (P=0.9266). Sampling time influenced soil NO_3-N (P=0.0103), as NO_3-N was low during the 2018 harvest (Figure 3.3). From a two-way ANOVA (model NO_3-N= location|time), cumulative soil NO_3-N was also influenced by location (P=<.0001), time (P= 0.0035) and by location x time (P= 0.0506) (Figure 3.3). At two locations (Nsanama and Nyambi), soil NO_3-N followed the same trend where the highest soil NO_3-N level was in December of 2017 at crop planting time and was lower over time. However, at the Mtubwi location, soil NO_3-N levels were highest in January 2018 and lowest in June 2018 (Figure 3.3).

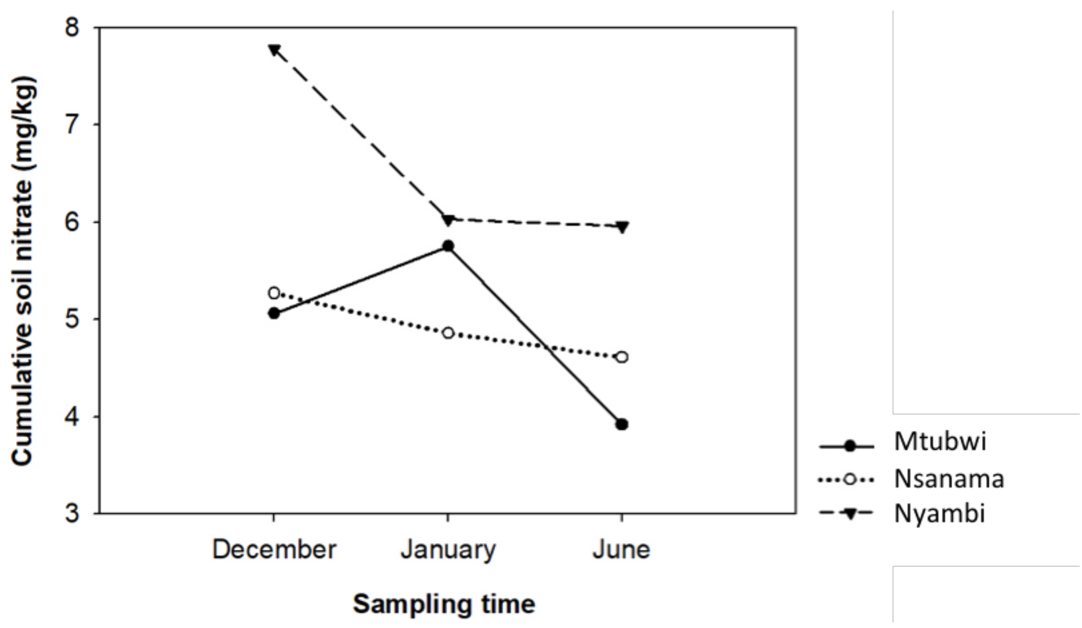

Figure 3.3. Cumulative soil NO3-N from the 0-80 cm soil depth during three sampling times at three locations in southern Malawi. From a two-way ANOVA, (model NO3-N= location|time), location (P=<.0001) and time (P= 0.0035) had an effect on soil NO3-N in 2017-2018.

Location had an effect on NO_3-N (P= 0.0006) so the average topsoil (0-20 cm) NO_3-N is shown by location, and sampling time in Table 3.7. Treatment residue quantity or quality had no effect on topsoil soil NO_3-N (Table 3.7). Across locations and treatments, soil NO_3-N ranged from 1.17 mg/kg soil to 2.20 mg/kg soil (Table 3.7). For the Mtubwi location, at the 0-20 cm soil depth only, time had an effect on soil nitrate N (P=<.0001, Table 3.7).

Table 3.7. Soil NO3-N in the 0-20 cm soil depth by treatment and three sampling times at three locations in southern Malawi.

	Mtubwi	Nsanama	Nyambi
	Soil NO_3-N (mg/kg soil)		
MZ-0N-0R	1.23	1.22	1.87
MZ-0N-2R	1.26	1.23	1.51
MZ-35N-0R	1.20	1.32	1.91
MZ-35N-2R	1.27	1.18	1.57
GNPP-35N-0R	1.17	1.54	1.50
GNPP-35N-2R	1.17	1.04	2.20
Time - Dec	1.29	1.48	2.30
Time - Jan	1.38	1.15	1.51
Time - Jun	0.98	1.13	1.47
ANOVAS			
Treatment	0.5682	0.4301	0.8137
Time	<.0001*	0.1949	0.2693
Treatment x Time	0.7982	0.5051	0.7672

*Significant at P = 0.05

Soil NH_4-N

Cumulative soil NH_4-N was analyzed using a repeated measures model (NH_4-N =treatment|time/ddfm=kr). Both treatment (P=0.0185) and sampling time (P=<.0001) had an effect on cumulative soil NH_4-N from the 0-80 cm depth but there was no interaction effect (P=0.8886). At two locations (Mtubwi and Nsanama), cumulative inorganic soil NH_4-N from the

0-80 cm soil depths followed the same trend, where the highest soil NH_4-N level was in January of 2018 at 30 days after planting, lower in December of 2017 at crop planting time, and much lower at crop maturity in June of 2018. However, at the Mtubwi location, soil NH_4-N levels were highest in December 2017 and lowest in June 2018 (Figure 3.4).

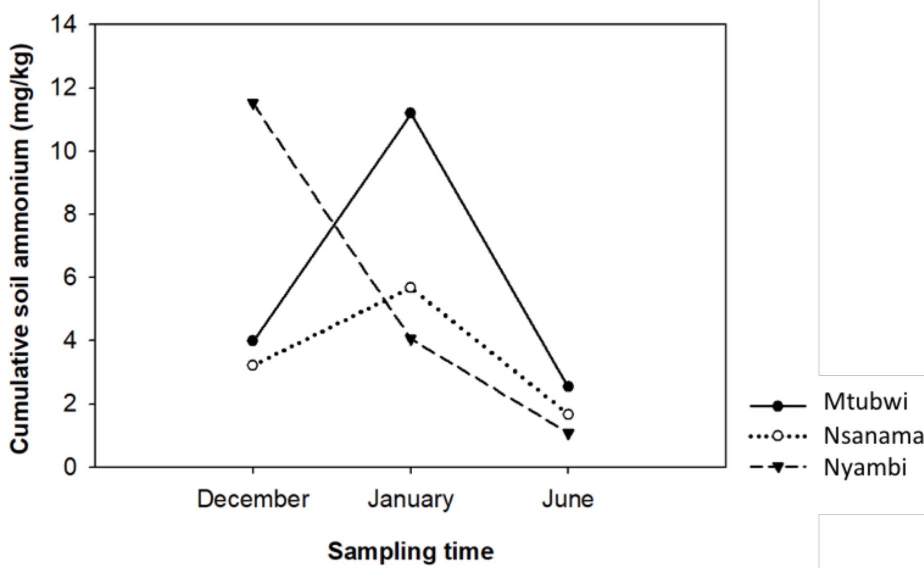

Figure 3.4. Cumulative soil NH4-N from the 0-80 cm soil depth during three sampling times at three locations in southern Malawi. From a two-way ANOVA, (model NH4-N = location|time), location (P<.0001) and time (P<.0001) had an effect on soil NH4-N.

The average 0-20 cm NH_4-N is shown by location, and sampling time in Table 3.8. Treatment had an effect on soil NH_4-N at the Mtubwi location only (P=0.0031, Table 3.8). Soil NH_4-N ranged from 0.91 mg/kg soil in the MZ-0N-0R treatment to 3.76 mg/kg soil in the GNPP-35N-2R treatment (Table 3.8). Planned contrasts in Table 3.8 show that treatment effects on NH_4-N were due to fertilizer and not residue quality or quantity. Sampling time had a significant effect on soil NH_4-N at the Mtubwi (1.13 to 4.91 mg/kg soil range) and Nyambi (0.44 to 3.90 mg/kg soil range) locations (Table 3.8).

Table 3.8. Soil NH4-N in the 0-20 cm soil depth by treatment and three sampling times at three locations in southern Malawi.

	Mtubwi	Nsanama	Nyambi
	Soil NH_4-N (mg/kg soil)		
MZ-0N-0R	0.91	0.99	1.01
MZ-0N-2R	1.10	0.38	1.01
MZ-35N-0R	3.54	2.21	2.18
MZ-35N-2R	3.14	1.01	2.11
GNPP-35N-0R	2.46	1.35	2.38
GNPP-35N-2R	3.76	1.71	2.23
Time - Dec	1.41	1.40	3.90
Time - Jan	4.91	1.39	1.12
Time - Jun	1.13	1.04	0.44
ANOVAS			
Treatment	0.0031*	0.1612	0.2236
Time	<.0001*	0.7057	<.0001*
Treatment x Time	0.1584	0.8820	0.4070
PLANNED CONTRASTS			
No residue vs. low quality residue treatments	0.9738	0.1453	0.8499
No residue vs. high quality residue treatments	0.5340	0.8918	0.9542
Low vs. high quantity residue treatments	0.6897	0.3269	0.8799
Fertilized vs. unfertilized treatments	0.0033*	0.0206*	0.0639**

*Significant at P = 0.05

*Significant at P = 0.10

Discussion

Biomass production and maize grain yield

This study shows on-farm biomass production quantities ranging from 1.67 to 10.42 Mg/ha for maize and 2.39 to 11.96 Mg/ha for the groundnut/pigeonpea intercrop. Similar to our study, Makumba *et al.* (2006) reported maize stover biomass amounts ranging from 1.7 Mg/ha (unfertilized sole maize) to 8.2 Mg/ha in a fertilized gliricidia/maize intercrop from an 11-year gliricidia/maize intercrop study in southern Malawi. For high quality legume biomass in SSA, different studies have reported incorporated gliricidia prunings amounting to 4.6 Mg/ha in Malawi (Makumba *et al*., 2006), 2.5-5.5 Mg/ha in Togo (Vanlauwe *et al*., 2005) and 5.7 Mg/ha in Nigeria (Kang *et al*., 1999). According to Snapp *et al*. (1998) about 7 Mg/ha to 10 Mg/ha of crop residues are needed to support soil organic matter gains in tropical sub-humid conditions, depending with the quality of residues. This suggests that in some cases, sufficient biomass can be produced to ameliorate soil organic matter and help maintain soil health on smallholder farms.

In 2017, biomass production of crops did not quite follow the anticipated pattern for the productivity gradient the experiment was established along, from low potential (Mtubwi) to high potential (Nyambi). The low potential Mtubwi location did have the lowest biomass, however the medium potential Nsanama location had twice the biomass of the high potential Nyambi site (Table 3.4). There is clearly high year to year variation in tropical rain-fed agricultural systems, particularly in Sub-Saharan Africa (Rockström *et al*., 2003)

The average maize grain yield from all treatments in 2018 followed the expected pattern along the productivity gradient, from low potential Mtubwi to high potential Nyambi (Figure 3.1). Mtubwi had the lowest maize grain yield (1.96 Mg/ha), followed by Nsanama (5.20 Mg/ha) and finally high potential Nyambi (7.20 Mg/ha). The low biomass and yield at the Mtubwi location (Tables 3.4 and 3.6), that remote sensing NDVI indicated was low potential, we expect is related to high evapotranspiration and soil properties, including sandy soil texture and low soil organic matter status (Figure 3.1, Tables 3.1 and 3.3). Further, Mtubwi was also water-logged in 2018 (personal observations). Low maize grain yield in 2018 at the Mtubwi and Nsanama locations could also have been due to some army worm damage (personal observations). Higher maize grain yield in 2018 at the Nsanama and Nyambi locations compared to the Mtubwi location could be attributed to lower evapotranspiration, higher NDVI and higher SOC. The soils at the Nsanama and Nyambi locations could have also responded better to inorganic nitrogen fertilizer than the Mtubwi soils. Similar to our results, Kafesu *et al*. (2018) reported that response to mineral N increased with increasing SOC from a maize productivity study on sandy soils in Zimbabwe.

According to Rusinamhodzi *et al*. (2011), when adequate fertilizer is available, rainfall is an important determinant of yield in southern Africa in rain-fed systems. However, these observations show that other determinants need to be considered, as total rainfall was similar at all sites. It should be kept in mind that soil quality, rainfall distribution, and temperature may all play a role (Smaling *et al*., 1997; Rockström *et al*., 2003) .

Crop response to nitrogen

Neither high quality residues nor large amounts of residues influenced maize yield. This result is somewhat surprising. Other studies have reported a positive impact of high-quality residues on maize yield. For instance, Makumba *et al*. (2006) reported that maize yields were roughly doubled with incorporating gliricidia prunings in an 11-year study. However, Makumba *et al*. (2006) might have been able to detect gliricidia residue quality effects on maize yield because it was a long-term study and the residues were highly N-enriched. In fact, in the first season of their study, Makumba *et al*. (2006) did not find any difference between maize yield from gliricidia/maize and sole maize cropping systems. However, cultivating gliricidia trees for 10 or more years involves considerable land and labor investment, which might not be feasible for most SSA smallholder farmers. Our study highlights that residues produced on-farm may not be as high quality as would be ideal for an integrated organic matter technology (Table 3.5).

Maize grain yield response was influenced by inorganic nitrogen fertilizer only and not residue quality or quantity (Table 3.6). The short two-year duration of this study could be the main reason why no residue quality and quantity effects were found on maize grain yield. Similarly, Nziguheba *et al*. (2005) did not detect a maize yield response to organic treatments in a 2.5 year study in western Kenya as there was no significant difference in cumulative maize yield from five seasons between organic residues and fertilizers. From a Zimbabwe study, Mtambanengwe and Mapfumo (2006) also reported no significant differences in maize grain yield among high quality, organic N sources from legumes (*C. juncea* and *C. calothyrsus*), manure and mineral N fertilizer at low application rate.

Nitrogen fertilizer and its appropriate use has been proposed as the fourth principle for conservation agriculture on smallholder farms, due to the widespread requirement in cereal based farming on N-deficient soils (Vanlauwe *et al*., 2014). Fertilizer use can substantially increase crop productivity and thus organic residue availability in smallholder farms in SSA where farmers lack adequate organic resources for nutrient management (Vanlauwe *et al*., 2014). Other studies have shown the importance of integrated nutrient management on degraded soils. A two-year study on degraded alfisols in Pakistan showed that having 50% N from organic and 50% from inorganic sources is the best management practice for sustainable production on (Ahmad *et al*., 2017). From a study in Malawi, Kalasa *et al*. (2018) also reported that maize grain yield can be improved by adding legume organic residues supplemented with low N inputs from mineral fertilizer. Kafesu *et al*.(2018) reported consistently higher maize grain yields when integrated nutrient management was practised by combining organic and inorganic N sources compared to either just organic or inorganic N sources. From a 14-year study in Malawi, Beedy *et al*. (2010) also confirmed the importance of combining organic N sources (gliricidia residues) and N fertilizers for soil recapitalization and maize production. At the same time, our study shows that producing sufficient organic high-quality residues on-farm is a challenge and short-term positive impacts from these may not be feasible.

Tissue quality

The N content of pigeonpea residues (Table 3.5) was similar to that reported by Thippayarugs *et al*. (2008) and Sakala *et al*. (2000). Sakala *et al*. (2000) reported an N content of 1.9% for senesced pigeonpea leaves and 3.2% for green pigeonpea leaves. The maize stover N content, lignin and ADF % were also similar to those reported by Sakala *et al*. (2000). However, the lack of treatment differences between maize grain yield from high- and low-quality residue could be attributed to other aspects of residue quality other than N and C % which impact N release. From an 8-week laboratory experiment, Palm and Sanchez (1991) concluded that some leguminous plant materials (including pigeonpea leaves) may not be readily available sources of N due to high polyphenolic contents despite their high % N values. However Sakala *et al*. (2000) reported that high amounts of lignin and not polyphenols in pigeonpea leaves could have contributed to less N mineralization than expected. This might be the case in our study as high-quality pigeonpea residues had higher N content and also much higher lignin content than maize.

Soil inorganic N

Inorganic N status (Figures 3.3 and 3.4) varied over time and sampling time had an effect on soil inorganic N. Similar to our results, Mtambanengwe and Mapfumo (2006) conducted soil sampling for inorganic N seven different times and managed to pick some differences in soil N status throughout the season. The differences in soil inorganic N over time may well be attributed to plant N use and precipitation patterns over time.

No response of cumulative NO_3-N was observed to treatment. However, treatment influenced NH_4-N. Similar to maize grain yield, NH_4-N response to treatment was due to the fertilizer effect as planned contrasts (Table 3.8) showed that for NH_4-N, only fertilized and unfertilized were significantly different. Therefore, over the two seasons of this study, organic residue quantity and quality did not influence soil inorganic N. Nziguheba *et al*. (2005) found similar results with potentially mineralizable N (PMN), where PMN did not corelate with any residue quality value. Nziguheba *et al*. (2005) also reported that even though high quality organic residues from calliandra, senna and tithonia improved some soil parameters, their effect were rarely greater than that of inorganic fertilizers. Contrary to our results, a research station study from Zimbabwe depicted that soil NH4-N was significantly influenced by residue quality (Mtambanengwe and Mapfumo, 2006). In our study, the extreme heat in Machinga and the long dry season between harvest/incorporation of residues and the rotational crop could degrade the quality of doubled-up legume residues and be the overriding factor.

Mtambanengwe and Mapfumo (2006) noted that most of the organic resources used by smallholder farmers are usually of lower quality than the *C. juncea* and *C. calothyrsus* they used at the research station. Additionally, Snapp and colleagues (1998) reported that research stations in Malawi and surrounding areas usually have 50% more soil carbon and about 30% more soil N than smallholder farms have.

Additionally, in the short term, under field conditions, it is common to get a lot of noise in responses. However, in the medium to long term, the systems tested will not be overly driven by N fertilizer effects alone, rather, over time it might be possible to detect the effect of accumulated residues on both the soil chemical and physical properties. Therefore, for on-farm soil N differences to be detected from organic residues, our study highlights that multiple rotation cycles are needed.

Conclusions

Nitrogen fertilizer benefits to maize yield were clear in our study, consistent with previous studies, and why farmers and governments invest in inorganic fertilizer. After one rotation cycle, we did not detect any residue quality or quantity effect on soil inorganic N or maize grain yield. Therefore, more rotation cycles are required for further studies on residue quality and quantity effects on soil N and crop yields in smallholder farming systems. Additionally, farmers may well need to be supported through policies that provide support for sustainable intensification practices such as high-quality residue retention. This is because it often takes multiple years to see an appreciable effect when such practices are implemented. This stands in contrast to current policies that often focus on access to inorganic fertilizer sources, with almost no attention to complementary investments in farmer access to organic, high quality amendments from legume residues.

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