# BELOW- AND ABOVEGROUND PIGEONPEA PRODUCTIVITY IN ON-FARM SOLE AND INTERCROP SYSTEMS IN CENTRAL MALAWI

**By**

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# ABSTRACT

## BELOW- AND ABOVEGROUND PIGEONPEA PRODUCTIVITY IN ON-FARM SOLE AND INTERCROP SYSTEMS IN CENTRAL MALAWI

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Smallholder farmers in Malawi face many challenges which include a degrading soil resource base. Pigeonpea is one legume that has shown promise in Malawi in terms of improving soil fertility but its below and aboveground productivity is not fully understood. On-farm trials were set-up in 2013/14 across three agro-ecologies in central Malawi. Pigeonpea was planted as a sole crop or in an additive intercrop system with soyabean, groundnut or maize (the farmer check system). The objectives of this study were to (1) assess the effect of cropping system and soil texture on pigeonpea root and shoot biomass and (2) to evaluate variability of pigeonpea growth within a smallholder farm context. Destructive harvest was conducted six months after planting to evaluate shoot parameters, and roots of the same plants were excavated from 0– 60 cm. Cropping system and soil texture effected shoot and root biomass ($\alpha$=0.05). Sole pigeonpea had the highest shoot biomass at 11.83 Mg ha$^{-1}$, root at 1.56 Mg ha$^{-1}$ and pigeonpea/maize had the lowest shoot at 3.57 Mg ha$^{-1}$ root at 0.53 Mg ha$^{-1}$. Root biomass was largely confined to the topsoil, with trends similar to that for aboveground biomass. The results confirm that intra-specific competition in a pigeonpea/maize intercrop is large, while pigeonpea productivity in pigeonpea/groundnut intercrop is comparable to sole cropped pigeonpea, with additional groundnut grain benefits. Promoting the later cropping system can enhance land productivity on smallholder farms in Malawi.

To Melchisedec, the King Salem and all His loyal subjects, to my family and Dr. S.S Snapp

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## KEY TO ABBREVIATIONS

BNF: Biological nitrogen fixation

C: Carbon

C/N Ratio: Carbon-to-nitrogen ratio

EPA: Extension planning area

GPS: Global positioning system

N: Nitrogen

$NH_4^+$-N: Ammonium

$NO_3^-$ -N: Nitrate

PMN: Potentially mineralizable N

SOC: Soil organic carbon

SSA: Sub-Saharan Africa

# CHAPTER ONE: LITERATURE REVIEW

## *1.1.a Background*

The maize (*Zea mays* L.) based systems in Sub-Saharan Africa (SSA) are generally nutrient-depleted and farmers add nutrients that are inadequate for maintaining soil fertility (Vitousek, 2009). Legume rotations are used to maintain soil fertility in some cropping systems. However, synthetic nitrogen (N) fertilizers are an alternative to labor- and land- intensive legume rotations (Crews and Peoples, 2004) but, the economic challenges that small holder farmers face in the region lead to low inorganic fertilizer inputs. Small holder farmers in Malawi are no exception to this phenomenon. A large gap in the literature is the extent to which leguminous crops grown on smallholder farms can help address the need for N inputs through above and belowground biomass. To address this missing information, studying the productivity of long duration legume crops such as pigeonpea (*Cajanus cajan* L.) under on-farm environmental conditions in Southern Africa is vital.

## *1.1.b Malawi farming systems*

Malawi has high population densities and very small land holdings (Orr and Ritchie 2004; Doward, 1999). Agriculture is the main backbone of the country's economy as the sector contributes 35% of the gross domestic product (Ngwira *et al*., 2012). However, there is a high degree of seasonality due to the unimodal rainfall pattern and frequent dry spells (Doward, 1999). Maize-based farming systems dominate the agricultural sector, particularly over the last century as maize has become the staple crop. The crop occupies about two-thirds of the land area under cultivation and accounting for more than 60 to 80% of the population's caloric intake (Ngwira *et* *al*., 2012). Continuous maize cropping with limited fertilizers has led to poor soil health and low yields (Ngwira *et al*., 2012; Doward, 1999). Maize yields can be as low as 0.8 Mg ha$^{-1}$ and 1.8 Mg ha$^{-1}$ for local and hybrid varieties respectively (Orr and Ritchie, 2004).

Other challenges to improving soil quality and crop productivity include the hand-hoe agricultural system which involves forming ridges every year, incorporating all crop residues and leaving soil bare after harvest (Ngwira *et al*., 2012). Soil erosion is aggravated by this exposure of bare soil during the dry season and early rains, and a shortage of natural, organic sources of soil carbon (C) and N (Orr and Ritchie, 2004). Farm outputs are usually low for most smallholder farmers in Malawi, who have very limited access to both formal and informal credit sources (Doward, 1999). According to Ngwira *et al*. (2012), smallholders have limited access to adequate amounts of farm inputs such as fertilizer and improved seed due to low purchasing power and weak value chains. This holds true for many farmers even with the Farm Input Support Programme (FISP) being implemented in Malawi. However, according to Orr and Ritchie (2004), Malawian farmers still prioritize soil fertility.

Sustainable production practices that are resource-efficient are clearly needed in Malawi smallholder farming systems (Ngwira *et al*., 2012). Sustainable intensification applies agro-ecological principles which can be implemented in SSA so as to produce more food from less land. This involves more efficient use of natural resources with minimal impact on the environment in order to meet the growing population demands (Ngwira *et al*., 2012). The continuous monocropped maize systems in Malawi are not sustainable– they degrade the natural base, and are labor and time intensive. Therefore, soil health cannot be improved with the use of inorganic fertilizes only. Legumes such as pigeonpea that biologically fix N from the atmosphere have to be included in these cropping systems.

*1.1.c Legumes*

Legumes have been promoted as a means to harness biological processes for N inputs that are less costly and not dependent on finite fossil-fuel reserves. Indeed, technologies that enhance reliance on biological N fixation (BNF) and nutrient cycling by legumes are a key sustainable option for maize production in SSA (Snapp *et al.*, 1998). Grain legumes have been seen as less important and have received less emphasis than cereal grains, yet they are vital for food, feed and industrial purposes (Sinclair and Vadez, 2012). They have a high protein content compared to other crops and are a primary source of protein in human diets. Legumes are usually intercropped with cereal, tuber or root crops so that they are "hidden" and often not counted in government census data (Broughton, 2002). According to Mhango *et al*. (2012) smallholder farmers in Malawi prefer high-yielding legumes with edible seed. Some legumes such as pigeonpea and cowpea (*Vigna unguiculata* L.) are valuable because both their leaves and grain are be a source of protein for farmers (Broughton, 2002). At the same time, legumes are a major source of N through BNF in most developing countries where synthetic fertilizers are expensive and inaccessible to many (Giller and Cadisch, 1995). Pypers *et al*. (2007) reported that if legumes are included in rotations they have positive soil-microbiological effects that promote maize growth and production. However, a number of obstacles prevent small holder farmers from producing more legumes even when they are willing to do so.

*1.1.d Constraints to legume production*

Most legume seeds have a short storage life which is a challenge to most small holder farmers because they are resource constrained (Sinclair and Vadez, 2012). With the exception of soyabean (*Glycine max* L.), there is little demand for legumes in international trade (Broughton, 2002). Legume seeds are more expensive than cereal grains and some legumes such as groundnuts

(*Arachis hypogaea* L.) may have higher labor requirements (Snapp *et al*., 2002). Most legumes are vulnerable to diseases and drought and their high protein and oil content makes them susceptible to pests (Broughton, 2002; Sinclair and Vadez, 2012). For example, despite considerable effort to develop pest resistant pigeonpea, new cultivars can be highly susceptible to pests, as was observed in on-farm trials conducted in Malawi and in Kenya (Ritchie *et al*., 2000). Goat and cattle destruction of pigeonpea is another constraint to adoption of pigeonpea in central Malawi (Snapp *et al*., 2002). Pigeonpea is a valued fodder source in some locales, but grain production becomes problematic if livestock are not intensively supervised. Livestock control issues are frequently debated among communities that are experimenting with growing long-duration pigeonpea. Trade-offs can occur between use of pigeonpea as a fodder and a food source. In on-farm trials, in areas new to pigeonpea production, the crop frequently survives for a month or two after the rains, but goats or cattle graze it just before harvest. Therefore, small holder farmers allocate little or no resources to legumes and invest more in cereal crops (Zingore *et al*, 2007). Field survey data from northern Malawi indicate that farmers allocate only about 10 to 15% of cropland to food legumes, and almost none to agroforestry legumes (Mhango *et al*, 2012). This is due to the extreme land constraints, with typically one ha or less per farmer (FAO, 2012). There are also constraints in terms of legume species farmers can grow, both environmental resource constraints and market related barriers. Options for legumes suitable for the highly eroded sandy soils in SSA are limited (Chikowo *et al*., 2004). For example, groundnut is productive in sandy soils but not common bean (*Phaseolus vulgaris* L.). Access to the necessary infrastructure and markets limit small holder farmers, who specialize in producing traditional legume varieties (Broughton, 2002). However, there is growing evidence that long duration legumes such as pigeonpea have a lot to offer small holder farmers in SSA, even with the social and ecological constraints involved with legume production.

*1.1.e Long duration legumes*

Long duration legumes have the potential to improve both N and P sustainability in small holder farming systems in Africa (Snapp, 1998). Indeterminate, long duration legumes fix more N than early duration legumes and provide another option for small holder farmers to use for improving soil fertility (Snapp and Silim, 2002). Perennial legumes enhance uptake of soil N through extended growth at a time when annual crops are being re-established (Crews and Peoples, 2004). They have the potential to reduce soil erosion on marginal lands (Giller and Cadisch, 1995). According to Snapp and Silim (2002), long duration legumes may minimize erosion by the continuous soil cover they provide by their leaf biomass. Long duration legumes produce higher quality residues than short duration legumes which could be due to the crop's extended period in the field for BNF. They are tolerant to pests, drought stress and poor soil fertility but are usually associated with low to moderate yields, high labor demand and a longer waiting time for harvest (Snapp and Silim, 2002). There are tradeoffs, but perennial legumes have a unique role in terms of provision of ecosystem services to farmers compared to short duration annuals. This is especially true for agroforestry legume species.

Agroforestry species show considerable potential to address environmental services; however, they do not all provide food, fodder and fuel, and this makes them unattractive to farmers. Smallholder farmers that are often food insecure necessarily prioritize crops that produce food (Mhango *et al*., 2013). There are viney and shrubby long duration legume crops that show potential to be multi-purpose, producing food as well as leaf and root residue inputs that can ameliorate soils. Pigeonpea is one such crop.

*1.1.f Pigeonpea*

There is considerable evidence that peninsular India is the place where pigeonpea originated (Nene *et al*., 1990). This is highly likely due to the presence of several wild relatives, the large diversity of the crop genetic pool, ample linguistic evidence, some archaeological remains, and the wide usage in daily cuisine. The name "pigeonpea" probably originated in the Americas, where it reached sometime in the 15th Century, because the seeds were found to be favored by pigeons. Therefore, it may be satisfactorily concluded that pigeonpea originated in India and spread quite early. It is now widely grown in the Indian subcontinent. Other regions where pigeonpea is grown are Southeast Asia, Africa, and the Americas. There is a substantial area of pigeonpea in Kenya, Uganda, and Malawi in Africa, and in the Dominican Republic and Puerto Rico in Central America. In most other countries pigeonpea is grown in small areas and as a backyard crop. A secondary center of diversity of the species is found in eastern Africa and other authors contend that eastern Africa is the center of origin, since it occurs wild in Africa (Nene *et al*., 1990).

Pigeonpea is a multi-purpose, tropical grain legume crop grown under rain fed conditions in the semi-arid tropics (Snapp *et al*., 2003; Nam *et al*., 1993). The legume is a semi-perennial whose height can reach up to 4 m. (Snapp *et al*., 2003; Nene *et al*., 1990). There is potential for pigeonpea to be adopted in many areas of the semi-arid tropics because the crop contains a wide range of maturity groups suitable for various agro-ecologies and cropping systems (Kumar Rao and Dart, 1987). At ICRISAT, Patancheru, India, ten maturity groups ranging from 60 days to more than 160 days were identified, based on days to 50% flowering (Kumar Rao and Dart, 1987). According to Snapp *et al*. (2003), the four main genotype categories are: extra short duration (<105 d), short duration (105–145 d), medium (146–199 d), and long-duration (>200 d) cultivars. Pigeonpea is managed in agricultural systems as an annual or biannual because varieties can have either determinate or indeterminate growth habits but monoculture production of pigeonpea is rare. Pigeonpea grown on-farm, in poor soils and without inputs, produces highly variable yields—from 0.2 to 2.5 Mg $ha^{-1}$ grain and from 1.0 to 3.8 Mg $ha^{-1}$ of leaves and stems (Snapp *et al*., 2003).

Pigeonpea has extensive roots that reach to depths of 1– 2m, with multiple branches, which increases its drought tolerance (Nene *et al*., 1990). The vigorous root system explores a large soil volume and recycles nutrients below the soil profile. It can form nodules up to a depth of 90 cm (Kumar Rao and Dart, 1987). Further, pigeonpea root exudates have the ability to solubilize iron-bound phosphorus from some soil types (Snapp *et al*., 2003). The pigeonpea root system also improves the soil structure by breaking plough pans (Nene *et al*., 1990), making the legume suitable for production in diverse soil types (Snapp *et al*., 2003). That is why pigeonpea is also known as the "biological plough" (Nene *et al*., 1990).

Pigeonpea is highly adaptable to a wide range of environments, it thrives in diverse cropping systems and is tolerant to abiotic and biotic stresses (Mhango *et al*., 2012; Singh and Jauhar, 2005). What sets it apart is its ability to produce fuel, fodder, and food on rocky, barren and infertile sites. It can be productive in a wide range of soil types from gravelly stones to heavy clay loams with a high moisture content, if there is no standing water on the soil surface (Nene *et al*., 1990). Farmers in India often allocate pigeonpea to fields with poor soils where other crops are not productive. Pigeonpea can tolerate salinity and alkalinity, but not extremely acidic soils (below a pH of 5.0). It tends to have fewer pest problems in drier areas, but droughts reduce the grain yield. However, the crop has more drought tolerance than many other grain legumes and is able to maintain vegetative growth during consecutive dry months because of its vigorous taproot system and osmotic adjustment (Snapp *et al*., 2003). However, the food crop is underestimated in both research and agricultural statistics.

### *1.1.g Underestimation of pigeonpea*

Pigeonpea is one of the world's oldest food crops and ranks fifth among edible legumes such as beans, peas, and chickpeas in terms of area and production (Snapp *et al*., 2003; Nene *et al*., 1990). It is used in more diverse ways than other legumes. However, research attention to the semi-perennial legume remains limited and its prominence is underestimated due to a number of reasons. The production systems pigeonpea is usually grown in (intercrops, boundary markers, household vegetable and as a backyard crop) are often excluded in agricultural statistics. According to Nene *et al*. (1990), pigeonpea has been recorded as present in 40 African countries yet FAO reports production in five countries only (Snapp *et al*., 2003). Even though pigeonpea is understudied compared to cereals and other legumes, a handful of studies in both developed and developing countries has been done on the 'wonder shrub'. The legume's characteristics make it a perfect fit in diverse intercropping situations in SSA.

### *1.1.h Pigeonpea-based cropping systems*

Pigeonpea is used within complex farming systems around the world, involving intercropping, relay cropping and double cropping (Snapp *et al*., 2003). Long-duration pigeonpea cultivars are generally planted simultaneously as an intercrop with a cereal at the beginning of the rainy season. In a unimodal system, cereals are harvested toward the end of the rainy season, and pigeonpea develops rapidly on residual moisture after harvest of the companion crop. The growth habit facilitates soil protection, as the canopy continues to expand for four months in the dry season after other crops are harvested. The living and senescent pigeonpea leaves during that extended period may be the only source of cover in semi-arid agro-ecosystems (Odion *et al*., 2007; Snapp *et al*., 2003). The traditional pigeonpea mixed cropping systems used in the semi-arid to sub-humid tropics make efficient use of available natural resources. This addresses the needs of smallholder farmers to grow crops that provide stable returns while being ecologically sustainable (Nene *et al*., 1990).

Landraces, traditional cultivars, and other long-duration, indeterminate types of pigeonpea have an ideal phenotype for intercrop production— slow initial growth and a deep rooting habit (Snapp *et al*., 2003; Snapp, 1998). This limits competition within an intercrop system. Branching of the pigeonpea shoot occurs late in the season, after harvesting of the cereal crop (Nene *et al*., 1990). In dryer areas, and especially in coarser-textured, infertile soils, farmers use wide spacing between plants to limit competition for soil moisture and nutrients.

Studies by Snapp and Silim (2002) showed that smallholder farmers in SSA are interested in sustainable intensification systems involving pigeonpea. These systems have been reported to increase calorie production and yield of pigeonpea-based intercrops in on-farm trials in Malawi and Kenya. Pigeonpea significantly contributes to soil nutrient cycling— particularly N and phosphorous cycling. Sinclair and Vadez (2012) reported that pigeonpea thrived for a month after sowing while four other, shallow rooted crop species died from P deficiency. Earlier studies are also in agreement with those findings as Ae and others (1990) found that pigeonpea enhanced P uptake by sorghum in an intercropping system.

A relatively new technology in Malawi is a legume/legume intercrop, which is known as the ‘doubled-up’ system. Pigeonpea intercrops with groundnut are traditional in some regions of India but are relatively new in SSA. Farmers in Malawi are experimenting with pigeonpea/soyabean or pigeonpea/groundnut intercrops. Combining a short and long-season legume increases yields, woody stems for fuel wood and produces more high quality residues for soil fertility enhancement (Snapp *et al*., 2003). Intercropping pigeonpea with cereals in semiarid regions with weathered soils has been proven to decrease soil erosion while increasing available N and P (Vance, 2001). Most small holder farmers prefer intercrops because they produce higher yields per unit area, minimize pests, improve the N economy (in legume associations), reduce risks and equally spread the farm resources (Nene *et al*., 1990).

There is great potential for pigeonpea production to be economically beneficial to smallholders in Malawi as the crop’s export market continues to develop (Snapp *et al*., 2003). Pigeonpea is endowed with several, unique characteristics, giving it an important place in the farming systems adopted by smallholder farmers in developing countries. The pigeonpea crop does not require special land preparation or harvesting. Deep ploughing to a depth of 15 cm is sufficient to obtain a good crop and farmers commonly hand harvest the grain (Nene *et al*., 1990). Pigeonpea is grown as an intercrop with maize in southern Malawi, where it accounts for 20% of household income among poor farmers (Orr *et al*., 2000). It is also a constituent of boundary plantings and vegetable gardens in northern Malawi. However, pigeonpea is rarely seen in central Malawi, even though the crop can be used in various ways in the small holder farming context.

*1.1.i Importance and uses of pigeonpea*

Pigeonpea is important for both human and soil nutrition. According to Snapp and others (2003), it has a high protein content (20 to 32%). More than 80 percent of the world's pigeonpea is produced and consumed in India where it is widely grown for dal (processed, dehulled, split seed) and immature, green pods are a vegetable source. Crushed grain is used for animal feed (Nene *et al*., 1990) and leaves for fodder and soil improvement (Snapp *et al*., 2003). Pigeonpea leaves are an excellent source of fodder due to the high N content and low lignin levels. On smallholder farms in Malawi, goats and cattle preferentially feed on pigeonpea residues (Snapp *et al*., 2003). Ten tonnes of dry pigeonpea sticks per hectare can be obtained. The stems are a source of fuel wood and are used to make huts, fences and baskets. Around small farms the shrubby legume is often used as a live fence. In India, pigeonpea plants are also used to culture the lac-producing insect. On mountain slopes, pigeonpea is cultivated to reduce soil erosion. It is used as a green manure in some countries, as windbreak hedge, and shade for tree crops like vanilla (Nene *et al*., 1990). Farmers in eastern and southern Africa produce pigeonpea as a vegetable or export grain crop, which is intercropped with maize and other cereals or high value crops, such as tomatoes (Snapp *et al*., 2003).

*1.1.j Nutrient budgets*

To understand the impact of legumes on nutrient status of smallholder farms in Africa, nutrient budgets could provide important information. Nutrient budgets with cropping systems that involve pigeonpea in some studies. An experiment in India, where maize followed pigeonpea, residual N was estimated to be approximately 40 kg ha$^{-1}$ (Kumar Rao *et al.*, 1981). Kumar Rao and Dart (1987) conducted a comparative study on nodulation, N fixation and N uptake by pigeonpea from different maturity groups. They reported that long duration varieties produced up to 11 Mg ha$^{-1}$, while the early duration varieties produced as little as 4 Mg ha$^{-1}$ .The study gave further insight on the importance of deep-rooted legumes in nutrient cycling. The researchers concluded that among all the pigeonpea maturity groups the total N uptake from the system varied from 69 to 134 kg ha$^{-1}$, which may otherwise have leached from the system. The long duration varieties fixed more N than the early duration varieties (Kuma Rao and Dart, 1987). In another study, Kuma Rao and others (1994), reported that pigeonpea fixed between 58 to 88 N kg ha$^{-1}$ when grown as a sole crop and from 30 to 50 N kg ha$^{-1}$ of residual N in crop rotations with maize, wheat and sorghum. Khan *et al.* (2002) found that pigeonpea had a higher belowground N value than fababean and mungbean, in yet another study in India. Over the years, farmers in India have adopted pigeonpea for various reasons. Bantilan and Darthasarathy (1999) reported that the majority of farmers who quickly adopted pigeonpea in northern India did so mainly to improve soil fertility. The farmers reported a number of benefits that resulted from pigeonpea cultivation. The amount of inorganic fertilizer required for subsequent crops declined, soil structure improved, land preparation was easier, and other crops germinated well.

According to Myaka *et al*. (2006), pigeonpea increased the recirculation of dry matter, N and P on on-farm trials at multiple sites in Malawi and Tanzania. Total soil C, total N and inorganic N were not affected by two seasons of pigeonpea/maize but were negatively affected by sole maize systems. They found the pigeonpea/maize intercrops to be sustainable, low risk and they mitigated topsoil nutrient leaching (Myaka et al, 2006). Adu-Gyamfi *et al*. (2007) conducted 2-yr, farmer-managed trials in Malawi and Tanzania, where they calculated N and P budgets of sole maize and maize-pigeonpea intercrops. The study consisted of two sites in each country and 20 farmers per site. They discovered that in Malawi, pigeonpea contributed about 38– 117 kg ha$^{-1}$ of N through

BNF while in Tanzania it was about 6– 72 kg ha$^{-1}$. The authors provided evidence that incorporating pigeon pea into the soil improves N budgets. In Malawi the N budgets of sole maize were negative and about five times lower than those of the maize/pigeonpea intercrops which were positive (30.5 kg ha$^{-1}$). This was achieved by incorporating the whole aboveground pigeonpea biomass (excluding grain) into the soil. However, in Tanzania, N budgets in both intercrop and sole maize fields were negative but sole maize systems were six times more negative than the intercrops (Adu-Gyamfi et al., 2007). Based on these studies in Malawi, soil N and P budgets improved when maize was intercropped with long duration pigeonpea.

Snapp and Silim (2001), reported that pigeonpea residues provided 30 to 70 N kg ha$^{-1}$ and were particularly suited to the resource base of smallholders in a 3-yr study at 40 farm sites in Malawi. After two years of intercropping or rotations with pigeonpea, maize yields increased by 0.3–1.6 Mg ha$^{-1}$ compared with sole-cropped maize (Snapp and Silim, 2001). Other studies in Malawi and Benin have shown that after a pigeonpea fallow, maize grain yields reflect an N fertilizer equivalency of 50 kg ha$^{-1}$ (McCall, 1989). Yield enhancement of cereals after a pigeonpea fallow has also been observed in Kenya and Cameroon (Degrande, 2001; Onim *et al*., 1990).

### *1.1.k Research gaps*

Legumes are widely grown and their importance is known but they are still understudied compared to cereals. A substantial number of studies on N contributions by legumes are available but most of them were carried out on research stations, where soil conditions are often more favorable for growth than on farmers' fields. Long duration pigeonpea, a multi-purpose legume that is indeterminate in growth habit (8 or more months) is also understudied compared to rapid cycling legumes (3 to 4 months), or agroforestry species (multiple years). Vitousek *et al*. (2009), carried out farm budgets in Kenyan and Chinese farming systems with zero contribution from legumes, an unrealistic approach showing that the role of legumes in nutrient cycling is often underestimated. The contribution of belowground legume biomass and its role in nutrient cycling is another key unknown factor. The 'hidden half' of plant biomass is mostly understudied because roots are very difficult to measure. The methods used to excavate roots are often time consuming, expensive and laborious. Taken together, there is urgent need to conduct participatory on-farm research with smallholder farmers to investigate the overall productivity of aboveground and belowground biomass of pigeonpea.

# CHAPTER TWO: BELOW AND ABOVEGROUND PIGEONPEA PRODUCTIVITY IN ON-FARM SOLE AND INTERCROP SYSTEMS IN CENTRAL MALAWI.

## 2.1 INTRODUCTION

Agro-ecological intensification improves the performance of agriculture through integration of ecological principles into farm and cropping system management. Examples of agro-ecological principles include the biological conservation of resources such as soil, nutrients and water. Increased use efficiency of limited nutrient and land resources is key to viable farming systems in densely populated African countries. Smallholder farmers face a rapidly changing physical environment in SSA. A degraded soil resource base, climate change and a variable market environment are some of the challenges, and opportunities, faced by farmers (Mhango *et al*, 2012).

The use of legumes such as pigeonpea, which biologically fix N and provide high protein grain while recycling nutrients, is one approach that has shown promise in Malawi. Pigeonpea is used within mixed cropping systems around the world, such as intercropping, relay cropping and double cropping (Snapp *et al*., 2003). Living and senescent pigeonpea dry matter minimizes soil erosion and may be the only source of cover in semi-arid agro-ecosystems (Odion *et al*., 2007; Snapp et al., 2003; Snapp and Silim (2002); Giller and Cadisch, 1995). However, pigeonpea is not widely cultivated in central Malawi. Small holder farmers' constraints to pigeonpea adoption in central Malawi include lack of intensive community management of animal grazing (Snapp *et al*., 2002), access to affordable seed and high susceptibility to pests for some cultivars (Ritchie *et al*., 2000). Animal grazing is a major constraint in pigeonpea production as maize, the main crop is harvested months before pigeonpea matures. Community management of animal grazing is only effected till maize harvest.

Legumes are widely grown worldwide and their importance on biological nitrogen fixation is known but are still understudied compared to cereals. Many legume studies are done on research stations and in greenhouses and very few on farmers' fields. Knowledge of small holder farming systems is limited, and few studies take into account farmer decision making (Mhango *et al.*, 2012). Long duration pigeonpea, a potential multi-purpose legume is understudied compared to other short duration legumes such as soyabean. Empirical data on legume root and shoot biomass additions to the systems have also remained scarce (Myaka *et al.*, 2006). Additionally, roots are understudied because the methods used to quantify them are time consuming and very laborious.

A handful of studies on contribution of pigeonpea shoot biomass to N cycling have been done in Malawi, Tanzania and India. Adu-Gyamfi *et al*. (2007) quantified N exports from aboveground biomass of pigeonpea from farmer-managed pigeonpea/maize intercrops in Malawi. However, the authors did not have any sole pigeonpea or doubled-up legume cropping systems involving pigeonpea. The authors also did not quantify root biomass as well. Myaka *et al*. (2006) quantified only the shoot biomass of pigeonpea in a pigeonpea/maize intercrop in on-farm trials in Malawi and Tanzania. Kumar Rao and Dart (1987) quantified both shoot and root biomass of pigeonpea but only from sole pigeonpea of different maturity groups and no intercrops.

The benefits of legumes on soil N and organic matter depend on the quality and quantity of both below and aboveground biomass that is returned to the soil. The quality of crop residues vary with legume species, soil nutrient levels, plant density, planting type and field management practices (Reddy *et al*., 2003). Quantifying the root and shoot biomass of pigeonpea in on-farm trials with various intercrops will help farmers in choosing the best cropping system especially if their goal is to improve soil fertility, particularly soil N.

This chapter seeks to fill these research gaps by quantifying aboveground and belowground biomass of pigeonpea in on-farm trials in central Malawi. Our findings are from research that was conducted on farmers' fields in a rain-fed system. The aim of this study is to improve the understanding of pigeonpea productivity in different cropping systems, to help farmers design more resource efficient cropping systems that suit farmers' needs. Identifying combinations of crops that can efficiently cycle or increase the availability of soil nutrients is relevant in the small holder farming context.

On-farm, participatory research trials were set-up across three agro-ecologies in central Malawi, during the 2013/14 cropping season. Pigeonpea was planted as a sole crop or in an additive intercrop system with soyabean or groundnut. A pigeonpea/maize intercrop was also included.

The objectives of this study were to:

- Assess the effect of the type of cropping system on pigeonpea root and shoot biomass and other soil properties— total soil N %, SOC %, inorganic N and PMN
- Determine the effect of soil texture on pigeonpea root and shoot biomass
- Evaluate variability (shoot and root biomass) of pigeonpea growth in different cropping systems within a smallholder farm context

We hypothesized that:

- Cropping system would have a significant effect on both root and shoot biomass of pigeonpea and that biomass would be highest in the sole pigeonpea cropping system and lowest in the pigeonpea/maize intercrop

- Heavy textured soils would have higher root and shoot biomass than light textured soils
- The pigeonpea/maize intercrop would have the highest variability compared to other cropping systems.

## 2.2 MATERIALS AND METHODS

### *2.2.1 Site description*

This study was conducted as part of the Africa Research in Sustainable Intensification for the Next Generation (Africa RISING), Malawi project. The participatory, research-for-development project's aim is to transform maize-based agricultural systems in SSA through sustainable technologies. There were four research sites from three different agro-ecological zones in central Malawi. The locations were Linthipe and Golomoti Extension Planning Areas (EPA) in the Dedza District and the Kandeu EPA in Ntcheu District. Dedza and Ntcheu districts are in the Lilongwe Agricultural Development Division (LADD). Linthipe is a high potential, sub-humid tropical site with well distributed rainfall in most years (Tables 1 and 2). Kandeu is a medium potential, sub-humid tropical site. Golomoti is a low potential, semi-arid to sub-humid tropical site located at low altitude and with erratic rainfall. Soils at Linthipe are ferric luvisols, the Kandeu study site has a mix of chromic luvisols and orthic ferralsols while Golomoti soils are a mix of eutric cambisols and eutric fluvisols (Lowole, 1984). The GPS locations for each site are shown in Figures 1, 2 and 3. The 2013/14 growing season precipitation and temperatures, as well as historical 15-yr monthly precipitation and temperature averages for three sites are presented in Tables 1 and 2. The edaphic properties of the three sites are shown in Tables 3 and 4.

### *2.2.2 Experimental Design*

A participatory 'mother' and 'baby' trial design as described by (Snapp *et al.*, 2002) was used. It involved trials that test a full complement of technologies that are located on-farm at central locations, with three replicates per trial, in a randomized complete block design— the mother trials. The mother trials at each site were linked systematically with a cluster of 20–30 baby trials. These are a type of on-farm trials where farmers choose a subset of technologies from the mother trial to test, where replication occurs across sites. In this study we focus on both mother and baby trials.

*2.2.2.a Mother trials*

Four cropping systems were tested. They consisted of pigeonpea grown as sole crops, and three intercrop systems involving pigeonpea grown in an additive intercrop system with maize, groundnut and soyabean. Intercropping two compatible grain legumes is known as the doubled-up legume technology. Many doubled-up legume cropping systems in Malawi involve pigeonpea, because the success of the approach hinges on the initially slow growth of pigeonpea, facilitating the growth of companion crops as if sole-cropped. The plot sizes were 5 m x 5 m and ridges were spaced at 0.75 m.

*2.2.2.b Africa RISING Baby Trials*

The cropping systems from the Africa RISING baby trials and the number of farmers that adapted or adopted a particular system differed. A total of 30 farmers adopted similar cropping systems from the mother trials while 10 cultivated pigeonpea around the borders of their fields—a treatment referred to as pigeonpea/borders. Eleven farmers had pigeonpea/groundnut, ten had pigeonpea/borders, eight had pigeonpea/maize, seven had sole pigeonpea and only four had pigeonpea/soyabean. The management of baby trials varied with each farmer. Therefore, short interviews on nutrient management were conducted with each of the 40 farmers (data not shown). Aboveground biomass, belowground biomass and soils samples were collected from all the 40 baby trials.

*2.2.3. Agronomy*

The variety of pigeonpea that was planted at the three sites is locally known as Mwaiwathu alimi (pedigree ICEAP 00557). It is a medium maturing (180 d) variety with a yield potential of about 2.5 Mg $ha^{-1}$. According to Tropical Legumes II (2013), the variety is adapted to low to medium altitude areas. The varieties for the other crops pigeonpea was intercropped with are shown in Table 5.

Field experiments were set up in the 2013/14 growing season, with crops planted during December of 2013 (Table 5). 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 per ha. In all the 'doubled-up' legume intercrops, the pigeonpea planting population was managed as a sole crop and groundnut or soya bean were planted in the space between the pigeonpea plants, using an additive intercropping design. The plant population density of soya beans and groundnuts in the intercrops were 160 000 and 120 000 plants $ha^{-1}$, respectively. The ratio of pigeonpea to groundnut plants was about 1:3 and that of pigeonpea to soya beans was about 1:4. 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 design so pigeonpea population density was the same as sole pigeonpea at 44 000 plants $ha^{-1}$. The combined pigeonpea and maize plant population density was 88 000 plants $ha^{-1}$ (Table 6). All the intercrops were planted in the same row. Seeds were planted after the first effective rains, and all plots were planted on the same day at each site. Planting dates for all mother trials were recorded (Table 7).

Weed and fertility management followed the Malawi agricultural recommendations (Malawi Guide to Agriculture, Government of Malawi, 2010). The plots were weeded by hand hoe three times at each site. The doubled-up legume intercrops (pigeonpea/groundnut and pigeonpea/soybean) 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.

*2.2.4 Rainfall and temperature*

The sources for the rainfall data for all sites were the Tropical Rainfall Measurement Mission Project (TRMM) (2015) and the Earth Observing System Data and Information System (EOSDIS) (2009). Temperature data was sourced from NASA Land Processes Distributed Active Archive Center (LP DAAC) (2010).

*2.2.5 Aboveground biomass assessment*

Wooden litter traps of 30 x 30 cm were placed in all treatments at the onset of pigeonpea flowering on 13 May 2014. The litter biomass was collected and weighed every fortnight, until senescence in mid-August. The leaves from the litter traps from each treatment were combined and ground using a Wiley laboratory mill (Thomas® Model 4 Wiley Mill, Swedesboro, NJ).

Six months after planting, destructive sampling of three randomly selected plants per plot was conducted at peak flowering. The plants were cut at ground level, chopped, and fresh biomass was determined. The plant samples were oven-dried at 75 °C to constant weight, and dry weighs recorded. The dry aboveground biomass was separated into stems, twigs, leaves, and pods. The biomass was reported as Mg $ha^{-1}$, for fresh and dry weights. The separate biomass components were ground to pass a 1-mm sieve with a Wiley laboratory mill and samples sent to the University of California Davis Stable Isotope Facility for natural abundance isotopic N analysis (data not shown).

*2.2.6 Belowground biomass assessment*

The method used for destructive root sampling was similar to that of Taylor (1986). Pigeonpea plants were cut at ground level and an area measuring 45 cm x 37.5 cm was marked at the base of the plant to hand-dig a pit to a depth of 60 cm. Soil and roots were removed in three increments (0– 20 cm, 20– 40 cm and 40– 60 cm). Large roots were removed from soils while dry sieving with a 2-mm sieve. Fine roots were hand-picked using tweezers. The belowground biomass was separated into surface and deep roots. The roots were weighed fresh, oven-dried at 75 $^{o}C$ to constant weight and reweighed. They were ground with a 1-mm sieve Wiley laboratory mill and analyzed for total N concentration (data not shown).

*2.2.7 Soil Sampling and analyses*

Soil samples were collected from each plot at all sites in increments of 0– 20 cm, 20– 40 cm and 40– 60 cm. During root excavations, all the soil from a volume of 0.135 $m^3$ per layer was spread on plastic sheets. After all the roots were removed, the soil was mixed thoroughly and composite samples of about 2 kg were collected. The samples were air-dried for 48 h and sieved through a 2-mm sieve at the Lilongwe University of Agriculture and Natural Resources

(LUANAR) soil science laboratory. After sieving, rocks and large pieces of organic matter were discarded.

*2.2.7.a Soil texture*

Soil texture was determined using the hydrometer method (Kellogg Biological Station LTER, 2008) at LUANAR. Soil subsamples were shipped to Michigan State University (MSU) for further physical and chemical analysis.

*2.2.7.b Soil pH*

The 1:5 soil: water suspension method (Department of Sustainable Natural Resources, 2013) was used to determine soil pH, and a Metler Toledo SevenEasy S20 pH meter was used.

*2.2.7.c Inorganic N*

Sub-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 extractant was analyzed for inorganic N ($NO_3^-$ -N and $NH_4^+$-N) concentrations using the colormetric method described in Doane and Horwath (2003), and a Thermo Multiskan$^{TM}$ 96-well plate reader (Kane *et al*., 2015).

*2.2.7.d Potentially mineralizable N (PMN)*

Sub-samples of 10 g were weighed into a 100 mL plastic centrifuge cups and 10mL of distilled water was added. Anaerobic conditions were created by adding N2 gas and the samples were incubated at 30 °C for seven days. After incubation, $NH_4^+$-N was extracted from samples by adding 30 mL of 2.66 M KCl to each sample, effectively bringing the molarity of the sample solution to 2M KCl. Extracts were then analyzed for $NH_4^+$-N only since the anaerobic condition created during the incubation inhibits nitrification. The initial $NH_4^+$-N concentration of each sample was then subtracted from the concentration of the corresponding incubated sample to determine the amount mineralized during incubation. The samples were frozen until they were analyzed as described above.

*2.2.7.e Total soil N and Soil Organic Carbon (SOC) percent*

Soil subsamples were ground to pass a 1-mm sieve in a shatter mill. The dried, ground soils were weighed on a microbalance into tin capsules for analysis and total C/N content was determined by combustion. A Carlo Erba NA1500 SeriesII Combustion Analyzer (Kellogg Biological Station LTER, 2003) was used.

*2.2.7 Biological N fixation*

The amount of N biologically fixed by pigeonpea was determined using the natural abundance method. The samples were sub sampled and weighed into capsules before the stable isotope analysis was conducted at the UC Davis stable isotope facility. Maize and a local non-N-fixing grass known as ‘tsangwi’ were collected from all plots and were used as reference crops (data not shown).

*2.2.8 Statistical analysis*

Data were analyzed using the MIXED and CORR procedure in SAS 9.4 (SAS Institute, 2002) statistical package. A one-way analysis of variance was carried out to assess effect of cropping system on pigeonpea shoot and root biomass, where sole-cropped and intercropped pigeonpea was compared. Soil texture effects on pigeonpea root and shoot biomass were also tested using the same procedures. In addition to aboveground and belowground biomass, the amount of senescence biomass, soil N and C content from different cropping systems and soil textures were analyzed by ANOVA. The Least Significant Difference (LSD) at 5% and 10 % level of significance was used to test mean differences. Graphs were created using R version 3.2.1 (Team R, 2015) and SigmaPlot version 13.0 (SigmaPlot, 2015). Maps for the global positioning system coordinates (GPS) and for temperature gradients across Malawi were created using ArcMap (2010).

## 2.3 RESULTS

### *2.3.1 Study locations and soil characteristics*

The Linthipe mother trial was located at 14° 12′ S latitude and 34° 5′ E longitude. The location of baby trials from Linthipe ranged from 14° 11′ to 14° 12′ S latitude and from 34° 5′ to 34° 6′ E longitude. The GPS coordinates for the Linthipe mother and baby trials are shown on a map in Figure 1. Golomoti mother trials were both at 14° 26′ S latitude and 34° 36′ and 34° 55′ E longitude. Baby trials from Golomoti were between 14° 26′ S latitude and 34° 34′ and 34° 36′ E longitude. The locations of the Golomoti mother and baby trials are presented in Figure 2. The Kandeu mother trial was located at 14° 37′ S latitude and 34° 35′ E longitude. The Kandeu baby trials in this study were located between 14° 35′ and 14° 37′ S latitude and 34° 34′ and 34° 36′ E longitude (Figure 3). All the mother trials are located in the Dedza and Ntcheu districts of central Malawi. The soil characteristics for all mother trials are shown in Table 3 and for baby trials they are presented in Table 4.

#### *2.3.1.a Rainfall and temperature*

Average monthly precipitation and temperature for a 15-yr period for all study locations are shown in Tables 1 and 2 respectively. The rainfall was unevenly distributed with the total rainy days for Linthipe being 59 and 49 for both Golomoti and Kandeu. Total rainfall for the 2013/2014 growing season for Linthipe was 979 mm (higher than the 15-yr average), 848 mm for Golomoti (lower than the 15 yr average) and 909 mm for Kandeu, which was well in its historical precipitation range. Averages and ranges for monthly precipitation and temperature for the 2013/2014 growing season are shown in Tables 1 and 2.

### *2.3.2 Pigeonpea total shoot biomass*

The mother trial data was used to investigate the effect of cropping system and of soil properties on pigeonpea biomass (Tables 8, 10 and 12). Response of pigeonpea biomass could only be assessed for soil texture in baby trials due to no replication within a site, and not all cropping systems being represented at each baby trial site. Therefore, the statistical analysis of data from baby trials focused on effects of soil texture (an important determinant of plant growth) on pigeonpea biomass. Cropping system had the following effect on shoot biomass: the largest amount was accumulated in sole pigeonpea (11.83 Mg $ha^{-1}$ ± 1.2), and doubled up pigeonpea/groundnut intercrop (6.99 Mg $ha^{-1}$ ± 1.24) had comparable amounts of biomass to sole and to pigeonpea/soyabean intercrop (5.08 Mg $ha^{-1}$ ± 0.77). Pigeonpea/soyabean biomass was comparable to pigeonpea/maize (3.57 Mg $ha^{-1}$ ± 0.33), which saw the smallest accumulation overall (Table 12).

Soil texture was also evaluated for effects on shoot biomass using data from the four mother trials, where response in light-textured soils (mother trial sites Kandeu and Golomoti-E) was compared to heavy-textured soils (mother trial sites Linthipe and Golomoti-B). Total shoot biomass was (4.75 Mg $ha^{-1}$ ± 0.61) in light textured soils and (8.17 Mg $ha^{-1}$ ± 1.48) in heavy textured soils ($p = 0.05$).

#### *2.3.2.a Pigeonpea litter*

Overall, response in the mother trials shows that initial litter biomass averaged 0.28 Mg $ha^{-1}$ and accumulated litter biomass was 0.7 Mg $ha^{-1}$ (Table 8). Cropping system had a significant effect on initial litter and on litter biomass from litter traps, and followed the same pattern (highest in sole pigeonpea, intermediate in doubled-up legumes and lowest in the pigeonpea/maize cropping system) observed for total shoot biomass (*P* = 0.0005, Table 12). Initial litter ranged from 0.002 Mg ha$^{-1}$ in a pigeonpea/soyabean intercrop to 0.866 Mg ha$^{-1}$ in a sole pigeonpea cropping system. The lowest pigeonpea litter biomass of 0.01 Mg ha$^{-1}$ was from the pigeonpea/soyabean intercrop and the highest litter biomass of 2.16 Mg ha$^{-1}$ was from the sole pigeonpea cropping system (Table 8).

The initial leaf fall average for baby trials was 0.34 Mg ha$^{-1}$ and values ranged from 0.001 to 1.55 Mg ha$^{-1}$ (Table 9). Soil texture did not have any effect on initial leaf fall in baby trials (*P* = 0.3716, Table 13).

*2.3.2.b Stems*

Overall, the average stem biomass in mother trials was 3.27 Mg ha$^{-1}$ and it ranged from 0.45 Mg ha$^{-1}$ in a pigeonpea/soyabean intercrop to 7.4 Mg ha$^{-1}$ in a sole pigeonpea cropping system (Table 8). Pigeonpea stem biomass from mother trials was affected by the type of cropping system, in a similar manner to the response of total shoot (*P*=0.0059, Table 12).

The overall average stem biomass for baby trials was 3.86 Mg ha$^{-1}$ and the lowest stem biomass was at 0.53 Mg ha$^{-1}$, while the highest was 12.32 Mg ha$^{-1}$ (Table 9). For baby trials, soil texture did not have any significant effect on stem biomass (*P*= 0.1119, Table 13).

*2.3.2.c Twigs*

The average twig biomass from mother trials was 1.07 Mg ha$^{-1}$and the lowest was 0.05 Mg ha$^{-1}$ in a pigeonpea/soyabean intercrop while the highest was 4.37 Mg ha$^{-1}$ in a sole pigeonpea cropping system (Table 8). There was a significant effect of cropping system on twig biomass in mother trials (*P*= 0.0025, Table 12).

Soil texture had a significant effect on twig biomass in baby trials (*P*=0.0799, Table 13). The overall mean for twig biomass from baby trials was 1.03 Mg/ ha$^{-1}$, the minimum was 0.12 Mg ha$^{-1}$ and the maximum was 3.62 Mg ha$^{-1}$ (Table 9).

*2.3.2.d Leaves*

There was a significant effect of cropping system on leaf biomass in mother trials (*P*= 0.0387, Table 12). Average leaf biomass from mother trials was 0.73 Mg ha$^{-1}$, minimum was 0.02 Mg ha$^{-1}$ in a pigeonpea/maize intercrop and the maximum of 2.76 Mg ha$^{-1}$ was from a sole pigeonpea cropping system (Table 8).

Soil texture did not have a significant effect on leaf biomass in baby trials (*P*=0.1546, Table 13). The overall average leaf biomass from baby trials was 0.97 Mg ha$^{-1}$ and the biomass ranged from 0.002 to 4.87 Mg ha$^{-1}$ (Table 9).

*2.3.2.e Pods*

The average pod biomass from mother trials was 1.33 Mg ha$^{-1}$, and cropping system had a marked effect, where pod biomass was highly suppressed in a pigeonpea/maize intercrop (0.02

Mg ha$^{-1}$), compared to 3.98 Mg ha$^{-1}$ in a sole pigeonpea cropping system (Table 8, Figure 6). This suppression effect in the pigeonpea/maize systems was greater than that observed for overall shoot biomass (Figure 6). In contrast to the dramatic effect of cropping system, soil texture did not have an effect on pod biomass in any trial (*P*=0.9655, Table 13). The overall pod biomass from baby trials was 0.57 Mg ha$^{-1}$, the lowest biomass was 0.02 Mg ha$^{-1}$ and the highest was 2.02 Mg ha$^{-1}$ (Table 9).

*2.3.2.f Root biomass*

Root biomass was largely present in the 0– 20 cm depth, as observed for both mother and baby trials across all soil textures present. In mother trials, cropping system had a significant effect on root biomass, which was primarily due to response at the 0– 20 cm depth (*P*= 0.0052, Table 12). For mother trials, average root biomass from the 0– 20 cm depth was 882.17 kg ha$^{-1}$, with ranges from 56.00 kg ha$^{-1}$ (pigeonpea/soyabean) to 2877.78 kg ha$^{-1}$ (sole pigeonpea). Root biomass from the 20– 40 cm depth ranged from 0.44 kg ha$^{-1}$ to 241.93 kg ha$^{-1}$ (both pigeonpea/soyabean), and the average was 45.28 kg ha$^{-1}$ (Table 8). The 40– 60 cm depth had very little biomass with ranges from 0.15 kg ha$^{-1}$ in a pigeonpea/soyabean intercrop to 43.26 kg ha$^{-1}$ in a sole pigeonpea cropping system. Figures 9 and 10 show effect of cropping system and soil texture on root biomass by depth for mother trials.

In baby trials, soil texture had a significant effect on root biomass from the 0– 20 cm depth (*P*= 0.0429, Table 13) but not on the root biomass from the 20– 40 cm depth (*P*=0.9398, Table 13) or the 40– 60 cm depth (*P*= 0.7696, Table 13). Soil texture had a significant effect on total root biomass of pigeonpea from baby trials (*P*=0.0407, Table 13). The overall average for root biomass from the 0– 20 cm depth was 927.52 kg $ha^{-1}$, and the biomass ranged from 31.54 to 3331.11 kg $ha^{-1}$. Root biomass from the 20– 40 cm depth ranged from 1.62 to 302.70 kg $ha^{-1}$ and the average was 80.99 kg $ha^{-1}$. The 40– 60 cm depth had very little biomass compared to the other two depths, with ranges from 0.86 to 147.41 kg $ha^{-1}$ and the average was 24.77 kg $ha^{-1}$ (Table 9). Overall, total root biomass from baby trials had ranges from 0.03 to 3.78 Mg $ha^{-1}$ and an average of 1.03 Mg $ha^{-1}$. Figures 11 shows effect of soil texture on root biomass by depth for baby trials.

### *2.3.2.g Root shoot ratio*

There was no significant effect of cropping system on root shoot ratios from the mother trials (*P*=0.1728, Table 12). Overall, the average root shoot ratio from mother trials was 0.14 and the ranges were from 0.05 (pigeon/maize intercrop) to 0.26 (pigeonpea/groundnut and pigeonpea/maize intercrop). Root shoot ratios for each cropping system from mother trials are shown in Table 12.

Soil texture did not have any significant effect on root shoot ratios of pigeonpea from baby trials (*P*=0.9663, Table 13). The average root shoot ratio from baby trials was 0.17 with ranges from 0.12 to 0.35 (Table 9).

### *2.3.2.h Soil pH*

Soil pH was slightly acidic for both mother and baby trials. The overall soil pH average for mother trials was 5.20 and it had ranges from 4.51 to 6.35 (Tables 3).

In baby trials, soil texture did not have any significant effect on pH (*P*= 0.6907, Table 13). The overall soil pH average for baby trials was 5.37 and the pH had ranges from 4.36 to 7.63 (Table 4).

*2.3.2.i Soil texture*

Clay content increased down the soil profile for both mother and baby trials. A threshold of clay content which was equal to, or greater than 20% was set as the heavy textured soils. Soils with a clay content lower than 20% were classified as light textured soils. From the 0– 20 cm depth in mother trials, 38% were light textured soils while 62 % were heavy textured. The 20– 40 cm depth had 18 % of light textured soils and 82% heavy textured soils. Only 3% were light textured soils in mother trials from the 40– 60 cm depth, while 97% were heavy textured soils. Averages of percent silt, percent clay and percent sand by depth for each mother trial are presented in Table 3.

Soil texture from baby trials varied (Figure 5). From the 0– 20 cm depth, 52.5 % of baby trials were light textured while 47.5 % were heavy textured. For the 20– 40 cm depth 35 % of the baby trials were light textured while 65 % were heavy textured. For the 40– 60 cm depth, only 27.5 % of baby trials were light textured while were 72.5 % heavy textured. Averages of percent clay and percent sand by depth for baby trials from each location are presented in Table 4.

*2.3.2.j Total soil N and SOC*

As expected, for recently established trials (November, 2012), the cropping system did not have an effect on either soil N percent (*P*=0.8235) or SOC (*P*=0.9112). Total soil N ranged from

0.01% in a pigeonpea/groundnut intercrop to 0.16 % in a pigeonpea/maize intercrop, and the average was 0.07 %. Overall, SOC average for mother trials was 1.01% with a range of 0.05 to 2.93% (Table 3).

Soil texture was associated with soil organic matter in baby trials. Clay % was positively correlated with soil N ($P$=0.0287) and SOC ($P$=0.001), while sand % was negatively correlated to both (Table 15). The average percent N for baby trials was 0.05 with ranges from 0.004 to 0.17. SOC in baby trials had ranges from 0.007 to 2.52 and an average of 0.8 (Table 4). Correlations between variables from both mother and baby trials are shown in Tables 14 and 15 respectively.

### *2.3.2.k $NH_4^+$-N, Soil $NO_3^-$ -N and PMN*

Ammonium response is shown in Figure 12, where the average level was quite low at 2.05 mg/kg soil with ranges from 0.41 to 9.38 mg/kg soil in mother trials. The soil $NO_3^-$ -N levels followed ammonium levels closely, with the lowest value being undetectable and the highest at 6.69 mg/kg soil. The overall $NO_3^-$ -N average was 0.9 mg/kg soil. Potential mineralized soil N from mother trials had an average of 0.45 mg/kg/day soil, with ranges from -0.19 mg/kg soil/day indicating immobilization, to a high value of 1.96 mg/kg soil/day.

Figure 13 shows the soil $NH_4^+$-N for light and heavy textured soils from baby trials by soil depth. The soil $NH_4^+$-N had ranges from 0.18– 4.14 mg/kg soil, with an average of 1.73 mg/kg soil. Baby trials had a soil nitrate average of 0.77 mg/kg soil, with ranges from 0.00– 8.55 mg/kg soil. Mineralized N from baby trials had an average of 0.47 mg/kg soil with ranges from -0.09– 1.71 mg/kg soil/day. The results also indicate N immobilization in baby trials.

## 2.4 DISCUSSION

### *2.4.1 Precipitation*

Precipitation was variable and unevenly distributed (Table 1, Figure 4). This is expected based on the highly variable weather patterns experienced in this region, which have been exacerbated in recent years by global climate change as indicated by global climate models which all predict gains in rainfall variability in the coming decades (Burke *et al.*, 2009. Climate variability has a negative effect on crop productivity. Root and shoot biomass variability from our mother and baby trials may have been as a result of rainfall patterns, and heterogeneity in soil as well as farm management decisions. Other studies have highlighted the variability of the maize-based farming systems in SSA, and vulnerability to rainfall patterns (Funk *et al.*, 2008).

### *2.4.2 Pigeonpea shoot biomass*

Total shoot biomass of pigeonpea from both baby and mother trials was quite high, in the range of 3.57 to 11.83 Mg $ha^{-1}$ (Tables 12 and 13), and highest for sole pigeonpea as hypothesized. Pigeonpea in the intercrop systems produced aboveground biomass similar to previous reports from a maize-pigeonpea intercrop field study conducted in Tanzania and Malawi (Myaka *et al.*, 2006), and higher than the biomass accumulation observed in on-farm trials in northern Malawi (Mhango, 2012). The high biomass observed may be due in part to our collection of litter over ten weeks, as pigeonpea growth pattern includes leaf senescence during the growing season which can complicate measurement of primary productivity and lead to under-estimation. According to our knowledge, this is the first study that monitored both on-farm root and shoot biomass, and included collection of leaf litter over the growing season. Kumar Rao and Dart (1987) measured root, shoot biomass and litter of pigeonpea but this was conducted on a research station. Overall the highest levels of biomass we observed were in the sole pigeonpea (11.83 Mg ha$^{-1}$) and pigeonpea-groundnut intercrop (6.99 Mg ha$^{-1}$). The total shoot biomass from sole pigeonpea is within the range reported for a long duration cultivar of pigeonpea (220 days) conducted on a research station in India (Kumar Rao and Dart, 1987). Research stations might have high soil fertility status compared to farmers' fields, thus it is interesting that we observed high biomass accumulation potential in this 180 days pigeonpea genotype grown on Malawi smallholder farms. Others have reported highly variable pigeonpea biomass from 1.5 Mg ha$^{-1}$ to greater than 7 Mg ha$^{-1}$ (Giller *et al.*, 1997). In our study we quantified shoot and root biomass from high plant population density field stands, showing the high growth and yield potential that is possible on-farm but may not be achieved by farmers constrained in access to seed. The negative effect of low plant population density on pigeonpea shoot biomass and N fixation estimates have been observed previously in on-farm studies in Malawi (Mhango, 2012).

Overall, findings are consistent with the ability of pigeonpea to perform well on smallholder fields in central Malawi and suggest the need for in-depth monitoring to fully document the growth of indeterminate plant life forms. This is notably true for sole pigeonpea stands which were highly productive. However, pigeonpea is widely grown in mixed intercrop systems due to the complementarity of its slow initial growth pattern with the rapid early growth of short-season annual crops such as maize and grain legumes. Crop species effect on pigeonpea and inter vs intra competition is an important aspect to understand in pigeonpea production. Although pigeonpea/maize is the most widely used pigeonpea production approach in Malawi, we noted very low pod biomass in this system relative to all others and relative to stem or leaf biomass (Figure 6). Competition from maize appears to differentially impact pod production which we expect to have negative implications for pigeonpea grain production (this was not measured here due to livestock pressure). Overall, pigeonpea biomass (particularly root biomass) in the pigeonpea/groundnut system was quite similar to sole cropped pigeonpea. In addition to the forage and pigeonpea grain associated with sole pigeonpea, a pigeonpea/groundnut intercrop produces additional groundnut grain that can be sold or consumed (Snapp *et al*., 2010). Our findings are thus consistent with the pigeonpea/groundnut intercrop as a 'best bet' option for small holder farmers whose goal is to improve soil fertility (Gilbert, 2004). From a study that compared pigeonpea with three other shrubby legumes ([*Sesbania sesban* L)], [*Crotalaria grahamiana*], and [*Tephrosia vogelii*], Gathumbi *et al*. (2002) also concluded that groundnut yields were substantially better when intercropped with species with an open canopy structure, such as pigeonpea.

In addition to mean response we examined variability of shoot growth. The pigeonpea/soyabean intercrop was the most variable cropping system (Table 8). In terms of total shoot biomass, sole pigeonpea had a 30% coefficient of variation while the pigeonpea/soyabean intercrop had 52%. On-farm experiments have been shown to exhibit high variability, usually in the range of 15 to 40% (Snapp *et al*., 2010), similar to our field results. We observed very high pigeonpea growth variability in the pigeonpea/soyabean system, which is a novel finding and requires further research to determine if this is related to variability in soybean growth under different environmental conditions or some other factor.

These results confirm previous research on pigeonpea as a crop that can thrive in unfavorable environmental conditions (Singh and Jauhar, 2005), such as poor fertile soils typical of smallholder farms (soil $NH_4^+$-N data, Figures 12 and 13). At the same time, aboveground biomass of pigeonpea on heavy textured soils from baby trials produced more shoot biomass than on light textured soils. Higher aboveground biomass from heavy textured soils may have been due to the high soil nutrient status associated with heavier soils, which has previously been shown to enhance growth of legumes such as pigeonpea on smallholder farms in northern Malawi (Mhango *et al*., 2012). No difference in shoot biomass was observed relative to soil texture from pigeonpea cropping systems evaluated in mother trials. These trials were also conducted on-farm, however in researcher-designed systems that included fertilizer application which may have mitigated any difference due to soil texture on plant growth.

*2.4.3 Root biomass*

Root biomass findings are consistent with studies in India by Kumar Rao and Dart (1987). Overall mean total root biomass was highest in sole pigeonpea and lowest in the pigeonpea/maize intercrop. Root biomass from both mother and baby trials was largely confined to the 0– 20 cm soil layer. The pigeonpea/maize and pigeonpea/soyabean intercrops performed the same way as short duration cultivars from the Kumar Rao and Dart (1987) study. The same authors had the same range of root biomass for long duration cultivars as we had in sole pigeonpea and the pigeonpea/groundnut intercrop. In all the cropping systems from mother trials, overall root growth followed shoot growth in our study (Figures 6 and 9). Previous research has also found high correlations between aboveground biomass and belowground biomass, with root to shoot ratios that vary within a narrow range (Ravindranath and Ostwald, 2007).

Soil texture had a significant influence on total root biomass. Heavy textured soils were associated with higher amounts of root biomass than light textured soils in the topsoil of all trials. However, at lower depths in light textured soils there was evidence from the mother trials of the opposite response: higher amounts of roots were observed compared to heavy textured soils. The topsoil response overall was consistent with shoot and root growth being in synchrony. However, there was modest evidence – from the mother trial sites but not the baby trials – that a deep rooting pattern was preferentially observed for low fertility, light soils. This is consistent with the foraging theory which suggests that allocation of a large proportion of the root biomass and root surface area occurs relative to shoots, specifically in low-nutrient soils. In the literature support for this hypothesis is mixed, with either a positive or no correlation found between foraging precision and plant growth rate (de Kroon and Mommer, 2005).

Overall, our total shoot and root biomass findings provide evidence that pigeonpea may be a highly effective agroforestry crop compared to many other widely promoted agroforestry shrub species. For instance, we found shoot biomass from pigeonpea to be in the range of 3 to 12 Mg $ha^{-1}$, which is substantially more than the biomass reported by Schroth and Zech (1995) who conducted an above and belowground biomass study on gliricidia (*Gliricidia sepium*) in West Africa. A research station study conducted in Zimbabwe found that pigeonpea consistently produced more aboveground biomass than either *Acacia angustissima* or *Sesbania sesban* agroforestry species in an improved fallow evaluation (Mafangoya and Dzowela, 1999). This is also consistent with Gathumbi *et al*. (2002) who concluded pigeonpea performed better in intercrop systems than three other agroforestry species. Our findings of high biomass on on-farm trials are also consistent with another study in Malawi (Chirwa *et al*., 2003). Chirwa and others (2003) found pigeonpea biomass production to be higher on-farm than on-station and also higher than gliricidia biomass.

*2.4.4 Root shoot ratio*

According to Cairns *et al*. (1997) root shoot ratios are the relative biomass allocation between roots and shoots and the ratios are derived from dividing the total root biomass by the shoot biomass (Mokany *et al*., 2006). Root shoot ratios are important as they are the evidence of plant partitioning of photosynthates between roots and shoots. There is a relationship between root shoot ratio and the factors that affect partitioning of aboveground and belowground biomass. Some of the factors include soil texture and plant species (Kuyah *et al*., 2012). We hypothesized higher root shoot ratios from the pigeonpea/maize intercrop (high competition and plant stress) in mother trials and from light textured soils in baby trials. However, contrary to our hypothesis, there were no significant effects of cropping systems in mother trials or soil texture in baby trials on root shoot ratios of pigeonpea. Our findings did not show a trend of decreasing root shoot ratios with increasing shoot biomass in mother trials. The root shoot ratio of sole pigeonpea was equal to that of the pigeonpea/maize intercrop in mother trials (Table 12). Root shoot ratios from baby trials in light and heavy textured soils were also equal. These results conflict with previous meta-analysis reviews by Mokany *et al*. (2006), who concluded that fertile and productive soils enhance aboveground biomass while sacrificing belowground biomass and that limiting water and nutrients in light textured soils result in larger root shoot ratios than those in heavy textured soils. These results could also suggest that there might have been underestimations of root biomass such as from C losses (root exudation and respiration or root sloughing). Soil physical factors can modify the quantity, density, branching patterns and depth of roots and this indirectly affects sampling methods (Vogt *et al*., 1998). This may explain the lack of significant difference of root biomass from the different soil textures and cropping systems. However, our findings are consistent with Cairns *et al*. (1997). In a comparative review with more than 160 studies, the authors concluded that root shoot ratios did not vary significantly with latitude (tropical, temperate or boreal), soil texture (fine, medium or coarse) or tree type (angiosperms or gymnosperms).

*2.4.5.a Soil pH*

In agreement with previous authors (Kamanga *et al*., 2014; Mhango *et al*., 2012; Adu-Gyamfi *et al*., 2007; Snapp, 1998), soil pH from all the mother and baby trials was moderately acidic. The overall pH values for mother and baby trials were 5.20 and 5.37 respectively (Tables 3 and 4). According to Snapp (1998), moderate soil acidity is not a major edaphic problem for small holder farmers in Malawi. Poor soil fertility is one of the major challenges the farmers in Malawi face instead.

*2.4.5.b Soil texture*

Soil texture varies vastly throughout the landscape and changes in soil quality are heavily influenced by soil texture. Like other studies from Malawi (Mhango *et al*., 2012; Snapp, 1998), our findings show that soils on smallholder farms include a wide range of textures. Our silt, clay, and sand content from both mother and baby trials were consistent with findings from Kamanga *et al*. (2014). As with the former authors, clay content from both mother and baby trials increased down the soil profile as sand content decreased.

*2.4.5.c Total N and SOC*

In agreement with Myaka *et al*., (2006), we also found more N and C in the upper soil layer and the two decreased with increasing soil depth (Tables 3 and 4 ). SOC ranges from both mother and baby trials were consistent with those of Snapp (1998). SOC and N were both significantly affected by soil texture in baby trials. Both parameters were higher in heavy textured soils than in light textured soil as hypothesized. Our soil N percentages were in the same range as in previous studies from Malawi (Kamanga *et al*., 2014; Myaka *et al*., 2006, Sakala *et al*., 2000). As expected, cropping system had no effect on SOC or N in this study. Previous on-farm studies in Malawi also did not observe significant differences in total N and C content from plots planted with maize and with pigeonpea/maize intercrops after only two cropping seasons (Myaka *et al*., 2006; Adu-Gyamfi *et al*., 2007). This suggests that it takes time for soil properties to change in highly eroded SSA soils.

*2.4.5.d Soil $NO_3^-$ -N, $NH_4^+$-N and PMN*

There were no significant effects of cropping system on soil $NO_3^-$ -N, $NH_4^+$-N or PMN. However, $NH_4^+$-N and PMN were higher in the topsoil and in heavier soils (Figure 12). Harawa *et al*. (2006) also observed similar trends for inorganic N in southern Malawi under agroforestry cropping systems. Our results from mother trials are in agreement with Myaka *et al*. (2006), who did not find any effect of cropping systems (sole maize and pigeonpea/maize intercrops) on soil inorganic N in Malawi on-farm studies. However, long-term studies have shown that agroforestry intercrop systems with pigeonpea produce higher soil inorganic N levels than sole maize (Beedy *et al*., 2014).

*2.4.6 Conclusions and future directions*

The type of cropping system had a significant effect on the total shoot and root biomass. Pigeonpea productivity in terms of root and shoot biomass was highest in the sole pigeonpea cropping system, it was intermediate in the doubled-up legume intercrops and lowest in the pigeonpea/maize intercrop. Soil texture also had a significant effect on total shoot and root biomass in baby trials. The pigeonpea/soyabean intercrop was the most variable cropping system. There is need to explore more on the causes of variability of the pigeonpea/soyabean intercrop. Further research is needed to evaluate combined shoot and root biomass of all crops involved in the pigeonpea-based intercrops. Of the four cropping systems, there was no significant effect on soil N and this suggests that small holder farmers can adopt or adapt any of the cropping systems depending on farmers' economic and social needs. Overall, pigeonpea productivity in the pigeonpea/groundnut system was comparable to sole cropped pigeonpea, and a bonus crop of groundnut grain was produced as well.

# APPENDIX

**Table 1**. Monthly precipitation in mm during the 2013/2014 growing season for the three sites. A historical 15-yr monthly average precipitation is presented. Source: TRMM (2015).

| Location | Oct 2013 | Nov 2013 | Dec 2013 | Jan 2014 | Feb 2014 | Mar 2014 | Apr 2014 | May 2014 | Total (mm) | 15-yr Average (2000– 2014) |
|---|---|---|---|---|---|---|---|---|---|---|
| Linthipe | 4.97 | 55.15 | 146.43 | 289.08 | 307.87 | 76.79 | 96.49 | 1.72 | 978.50 | 933.26 |
| Golomoti | 8.66 | 45.62 | 181.19 | 224.61 | 250.09 | 77.20 | 57.40 | 3.66 | 848.43 | 902.59 |
| Kandeu | 13.04 | 38.45 | 188.91 | 261.79 | 290.85 | 68.75 | 40.55 | 6.39 | 908.72 | 911.08 |

**Table 2.** Monthly average temperatures and ranges in o C during the 2013/2014 growing season for the three sites. A historical 15-yr monthly average temperature is presented. Source: NASA (2010).

| **Year** | **Month** | **Location** | **Mean °C** | **Min °C** | **Max °C** |
|---|---|---|---|---|---|
| 2013 | Oct | Linthipe | 30.05 (1.57) | 24.83 | 31.79 |
| | | Golomoti | 35.32 (0.40) | 34.13 | 36.22 |
| | | Kandeu | 33.68 (1.01) | 31.76 | 35.10 |
| 2013 | Nov | Linthipe | 29.82 (1.70) | 24.70 | 31.76 |
| | | Golomoti | 36.85 (0.71) | 35.11 | 38.40 |
| | | Kandeu | 35.51 (1.16) | 32.76 | 37.70 |
| 2013 | Dec | Linthipe | 26.06 (1.20) | 22.35 | 27.42 |
| | | Golomoti | 31.42 (0.37) | 30.52 | 32.57 |
| | | Kandeu | 30.74 (1.20) | 28.29 | 32.86 |
| 2014 | Jan | Linthipe | 20.81(0.92) | 17.76 | 22.35 |
| | | Golomoti | 19.64 (0.65) | 18.35 | 21.83 |
| | | Kandeu | 19.53 (0.67) | 18.30 | 21.17 |
| 2014 | Feb | Linthipe | 20.54 (0.59) | 18.80 | 21.43 |
| | | Golomoti | 22.97 (0.69) | 21.95 | 24.89 |
| | | Kandeu | 23.00 (0.86) | 20.80 | 24.78 |
| 2014 | Mar | Linthipe | 21.30 (0.77) | 18.73 | 22.27 |
| | | Golomoti | 23.56 (0.34) | 22.89 | 24.35 |
| | | Kandeu | 23.70 (0.42) | 22.76 | 24.53 |
| 2014 | Apr | Linthipe | 20.76 (0.77) | 18.27 | 21.92 |
| | | Golomoti | 23.00 (0.54) | 21.43 | 24.71 |
| | | Kandeu | 23.44 (0.49) | 22.57 | 24.49 |
| 2014 | May | Linthipe | 21.30 (0.81) | 18.08 | 22.58 |
| | | Golomoti | 23.93 (0.51) | 23.18 | 25.49 |
| | | Kandeu | 24.08 (0.50) | 22.97 | 25.10 |
| 2000-2014 | Oct- May | Linthipe | 22.97 (0.89) | 20.31 | 23.77 |
| | | Golomoti | 26.34 (0.11) | 26.11 | 26.70 |
| | | Kandeu | 26.00 (0.51) | 24.76 | 26.57 |

**Table 3**. Soil properties measured in mother trials. Soil texture is indicated by silt, sand and clay percent. Total soil N and SOC are indicated by N % and C %, pH is the measure of the acidity or basicity of soil. Overall averages across mother trials are followed by standard deviations in parentheses.

| Depth (cm) | Silt % | Clay % | Sand % | pH | N % | SOC % | C/N Ratio |
|---|---|---|---|---|---|---|---|
| Linthipe mother trial | | | | | | | |
| 0– 20 | 13 | 33 | 55 | 5.3 | 0.14 | 2.49 | 18 |
| 20– 40 | 14 | 47 | 39 | 5.3 | 0.13 | 2.30 | 18 |
| 40– 60 | 13 | 49 | 38 | 5.4 | 0.10 | 1.65 | 17 |
| Golomoti mother trial 1 (E) | | | | | | | |
| 0– 20 | 9 | 22 | 69 | 5.6 | 0.06 | 0.84 | 14 |
| 20– 40 | 11 | 22 | 67 | 5.3 | 0.01 | 0.13 | 13 |
| 40– 60 | 10 | 28 | 62 | 5.2 | 0.01 | 0.09 | 9 |
| Golomoti mother trial 2 (B) | | | | | | | |
| 0– 20 | 12 | 31 | 58 | 5.4 | 0.08 | 1.03 | 13 |
| 20– 40 | 12 | 41 | 47 | 5.4 | 0.01 | 0.1 | 10 |
| 40– 60 | 12 | 42 | 46 | 5.4 | 0.01 | 0.09 | 9 |
| Kandeu mother trial | | | | | | | |
| 0– 20 | 6 | 10 | 83 | 5.0 | 0.03 | 0.33 | 11 |
| 20–40 | 8 | 23 | 69 | 4.7 | 0.02 | 0.24 | 12 |
| 40– 60 | 8 | 36 | 55 | 4.9 | 0.02 | 0.16 | 8 |
| Average | 10 (3.96) | 23.69 (10.01) | 66.36 (13.91) | 5.2 (0.38) | 0.08 (0.05) | 1.23 (0.94) | 14 (2.49) |
| Average | 10 (3.96) | 23.69 (10.01) | 66.36 (13.91) | 5.2 (0.38) | 0.08 (0.05) | 1.23 (0.94) | 14 (2.49) |

**Table 4**. Soil properties measured in baby trials. Soil texture is indicated by silt, sand and clay percent. Total soil N and SOC are indicated by N % and C %, pH is the measure of the acidity or basicity of soil. Overall averages across baby trials are followed by standard deviations in parentheses.

| Depth (cm) | Silt % | Clay % | Sand % | pH | N % | SOC % | C/N Ratio |
|---|---|---|---|---|---|---|---|
| 0– 20 | 8 | 20 | 72 | 5.4 | 0.06 | 0.99 | 17 |
| 20– 40 | 9 | 23 | 68 | 5.3 | 0.05 | 0.82 | 16 |
| 40– 60 | 10 | 27 | 63 | 5.4 | 0.03 | 0.59 | 20 |
| Average | 8 (3.11) | 23 (10.81) | 67.58 (0.05) | 5.4 (0.66) | 0.05 (0.03) | 0.80 (0.50) | 17 (2.26) |

**Table 5**. Cultivars of crops planted in the mother trials.

| District | EPA | Pigeonpea | Groundnut | Soyabean | Maize |
|---|---|---|---|---|---|
| Dedza | Linthipe | Mwaiwathu alimi | Nsinjiro | Nasoko | PAN 53 |
| Dedza | Golomoti | Mwaiwathu alimi | JL24 | Nasoko | DKC 8033 |
| Ntcheu | Kandeu | Mwaiwathu alimi | JL24 | Nasoko | DKC 8033 |

**Table 6**. Plant population densities in four pigeonpea-based cropping systems in mother trials.

| Crop | Cropping system | Plant population density | Total |
|---|---|---|---|
| Pigeonpea | Sole pigeonpea | 44 000 | 44 000 |
| Groundnut | Pigeonpea/Gnut | 120 000 | 164 000 |
| Soyabean | Pigeonpea/Soya | 160 000 | 204 000 |
| Maize | Pigeonpea/Maize | 15 200 | 59 200 |

**Table 7**. Planting dates across sites in mother trials.

| District | EPA | Planting date |
|---|---|---|
| Dedza | Linthipe | 6 December 2013 |
| Dedza | Golomoti-B | 19 December 2013 |
| Dedza | Golomoti-E | 20 December 2013 |
| Ntcheu | Kandeu | 17 December 2013 |

**Table 8**. Averages and ranges of shoot and root biomass across mother trials. Means are followed by standard deviations in parentheses.

| Variable | Mean | Min | Max |
|---|---|---|---|
| Litter (Mg $ha^{-1}$) | 0.70 (0.64) | 0.01 | 2.16 |
| Stems (Mg $ha^{-1}$) | 3.27 (1.55) | 0.45 | 7.40 |
| Twigs (Mg $ha^{-1}$) | 1.07 (0.91) | 0.05 | 4.37 |
| Leaves (Mg $ha^{-1}$) | 0.73 (0.60) | 0.02 | 2.76 |
| Pods (Mg $ha^{-1}$) | 1.33 (1.17) | 0.02 | 3.98 |
| Initial leaf fall (Mg $ha^{-1}$) | 0.28 (0.26) | 0.002 | 0.86 |
| Total shoot biomass (Mg $ha^{-1}$) | 6.73 (4.16) | 0.48 | 19.44 |
| Root biomass kg $ha^{-1}$ (0– 20 cm) | 882.17 (604.76) | 56.00 | 2877.78 |
| Root biomass kg $ha^{-1}$ (20– 40 cm) | 45.28 (57.89) | 0.44 | 241.93 |
| Root biomass kg $ha^{-1}$ (40– 60 cm) | 11.41(12.57) | 0.15 | 43.26 |
| Total root biomass (Mg $ha^{-1}$) | 0.94 (0.65) | 0.06 | 3.11 |
| Root shoot ratio | 0.14 (0.05) | 0.05 | 0.26 |

**Table 9**. Averages and ranges of shoot and root biomass in baby trials. Means are followed by standard deviations in parentheses.

| Variable | Mean | Min | Max |
|---|---|---|---|
| Stems (Mg $ha^{-1}$) | 3.86 (2.64) | 0.53 | 12.32 |
| Twigs (Mg $ha^{-1}$) | 1.03 (0.79) | 0.12 | 3.62 |
| Leaves (Mg $ha^{-1}$) | 0.97 (0.93) | 0.002 | 4.87 |
| Pods (Mg $ha^{-1}$) | 0.57(0.61) | 0.02 | 2.02 |
| Initial leaf fall (Mg $ha^{-1}$) | 0.34 (0.39) | 0.001 | 1.55 |
| Total shoot biomass (Mg $ha^{-1}$) | 6.37 (5.04) | 0.10 | 21.55 |
| Root biomass kg $ha^{-1}$ (0– 20 cm) | 927.52 (770.83) | 31.54 | 3331.11 |
| Root biomass kg $ha^{-1}$ (20– 40 cm) | 80.99 (76.09) | 1.62 | 302.70 |
| Root biomass kg $ha^{-1}$ (40– 60 cm) | 24.77 (30.57) | 0.86 | 147.41 |
| Total root biomass (Mg $ha^{-1}$) | 1.03 (0.82) | 0.03 | 3.78 |
| Root shoot ratio | 0.17 (0.04) | 0.12 | 0.35 |

**Table 10**. Soil $NO_3^-$-N (mg/kg soil) and potential mineralizable N (PMN) (mg/kg soil/day) means by cropping system and soil depth in mother trials. Means are followed by standard deviations in parentheses.

| Cropping system | Variable | Depth | Mean | Min | Max |
|---|---|---|---|---|---|
| Sole Pigeonpea | Soil $NO_3^-$-N | 0– 20 cm | 0.94 (0.49) | 0.17 | 1.57 |
| | | 20– 40 cm | 0.42 (0.53) | 0.00 | 1.31 |
| | | 40– 60 cm | 0.13 (0.18) | 0.00 | 0.47 |
| Pigeonpea/Gnut | | 0– 20 cm | 2.07 (2.74) | 0.03 | 6.69 |
| | | 20– 40 cm | 0.76 (1.23) | 0.00 | 3.71 |
| | | 40– 60 cm | 0.44 (0.69) | 0.00 | 2.13 |
| Pigeonpea/Soya | | 0– 20 cm | 3.00 (2.18) | 0.23 | 5.51 |
| | | 20– 40 cm | 0.86 (1.32) | 0.00 | 4.45 |
| | | 40– 60 cm | 0.25 (0.38) | 0.00 | 1.05 |
| Pigeonpea/Maize | | 0– 20 cm | 1.32 (1.00) | 0.17 | 2.79 |
| | | 20– 40 cm | 0.11 (0.15) | 0.00 | 0.25 |
| | | 40– 60 cm | 0.002 (0.01) | 0.00 | 0.02 |
| Sole Pigeonpea | PMN | 0– 20 cm | 0.52 (0.34) | 0.13 | 1.08 |
| | | 20– 40 cm | 0.34 (0.24) | 0.05 | 1.60 |
| | | 40– 60 cm | 0.19 (0.14) | 0.04 | 0.41 |
| Pigeonpea/Gnut | | 0– 20 cm | 0.75 (0.44) | 0.09 | 1.46 |
| | | 20– 40 cm | 0.54 (0.45) | 0.05 | 1.60 |
| | | 40– 60 cm | 0.31 (0.33) | 0.02 | 1.13 |
| Pigeonpea/Soya | | 0– 20 cm | 0.88 (0.49) | 0.35 | 1.96 |
| | | 20– 40 cm | 0.46 (0.42) | 0.18 | 1.52 |
| | | 40– 60 cm | 0.09 (0.15) | -0.19 | 0.32 |
| Pigeonpea/Maize | | 0– 20 cm | 0.73 (0.33) | 0.29 | 1.21 |
| | | 20– 40 cm | 0.36 (0.16) | 0.00 | 1.21 |
| | | 40– 60 cm | 0.24 (0.20) | -0.03 | 0.59 |

**Table 11**. Soil $NO3^-$ -N (mg/kg soil) and potential mineralizable N (PMN) (mg/kg soil/day) means by soil texture and soil depth in baby trials. Means are followed by standard deviations in parentheses.

| **Soil texture** | **Variable** | **Depth** | **Mean** | **Min** | **Max** |
|---|---|---|---|---|---|
| Light | Soil $NO_3^-$ -N | 0– 20 cm | 1.22 (1.52) | 0.00 | 5.96 |
| | | 20– 40 cm | 0.48 (1.12) | 0.00 | 4.30 |
| | | 40– 60 cm | 0.21 (0.32) | 0.00 | 1.29 |
| Heavy | | 0– 20 cm | 2.20 (1.97) | 0.27 | 8.55 |
| | | 20– 40 cm | 0.41 (0.86) | 0.00 | 3.98 |
| | | 40– 60 cm | 0.18 (0.34) | 0.00 | 1.29 |
| Light | PMN | 0– 20 cm | 0.62 (0.34) | 0.27 | 1.71 |
| | | 20– 40 cm | 0.32 (0.29) | 0.01 | 1.09 |
| | | 40– 60 cm | 0.24 (0.41) | -0.09 | 1.31 |
| Heavy | | 0– 20 cm | 0.83 (0.46) | 0.27 | 1.71 |
| | | 20– 40 cm | 0.52 (0.34) | 0.08 | 1.51 |
| | | 40– 60 cm | 0.26 (0.21) | 0.00 | 0.80 |

**Table 12**. One-way ANOVA and mean response of pigeonpea litter, stems, twigs, leaves, pods, initial leaf fall, total shoot biomass, root biomass and root shoot ratio to cropping system. This data is from mother trials (n=39). Means are followed by standard errors.

| Variable | Cropping System | Mean | Pr > F |
|---|---|---|---|
| Litter (Mg $ha^{-1}$) | Sole Pigeonpea | 1.37 ± 0.19 | 0.0005*** |
| | Pigeonpea/Gnut | 0.64 ± 0.19 | |
| | Pigeonpea/Soya | 0.60 ± 0.17 | |
| | Pigeonpea/Maize | 0.22 ± 0.07 | |
| Stems (Mg $ha^{-1}$) | Sole Pigeonpea | 4.84 ± 0.57 | 0.0059*** |
| | Pigeonpea/Gnut | 3.46 ± 0.40 | |
| | Pigeonpea/Soya | 2.56 ± 0.38 | |
| | Pigeonpea/Maize | 2.44 ± 0.18 | |
| Twigs (Mg $ha^{-1}$) | Sole Pigeonpea | 2.01 ± 0.35 | 0.0025*** |
| | Pigeonpea/Gnut | 1.31 ± 0.29 | |
| | Pigeonpea/Soya | 0.62 ± 0.14 | |
| | Pigeonpea/Maize | 0.50 ± 0.06 | |
| Leaves (Mg $ha^{-1}$) | Sole Pigeonpea | 1.07 ± 0.23 | 0.0387** |
| | Pigeonpea/Gnut | 0.80 ± 0.24 | |
| | Pigeonpea/Soya | 0.69 ± 0.14 | |
| | Pigeonpea/Maize | 0.33 ± 0.11 | |
| Pods (Mg $ha^{-1}$) | Sole Pigeonpea | 2.66 ± 0.29 | 0.0036*** |
| | Pigeonpea/Gnut | 1.39 ± 0.69 | |
| | Pigeonpea/Soya | 0.88 ± 0.25 | |
| | Pigeonpea/Maize | 0.09 ± 0.03 | |
| Initial leaf fall (Mg $ha^{-1}$) | Sole Pigeonpea | 0.55 ± 0.08 | 0.0005*** |
| | Pigeonpea/Gnut | 0.26 ± 0.07 | |
| | Pigeonpea/Soya | 0.24 ± 0.07 | |
| | Pigeonpea/Maize | 0.09 ± 0.03 | |
| Total shoot biomass (Mg $ha^{-1}$) | Sole Pigeonpea | 11.83 ± 1.20 | <0.001*** |
| | Pigeonpea/Gnut | 6.99 ± 1.24 | |
| | Pigeonpea/Soya | 5.08 ± 0.77 | |
| | Pigeonpea/Maize | 3.57 ± 0.33 | |
| Root biomass kg $ha^{-1}$(0– 20 cm) | Sole Pigeonpea | 1436.12 ± 225.44 | 0.0052*** |
| | Pigeonpea/Gnut | 1087.88 ± 201.96 | |
| | Pigeonpea/Soya | 589.70 ± 104.53 | |
| | Pigeonpea/Maize | 512.48 ± 79.98 | |

**Table 12.** Cont'd

| Variable | Cropping System | Mean | Pr > F |
|---|---|---|---|
| Root biomass kg ha$^{-1}$(20– 40 cm) | Sole Pigeonpea | 96.99 ± 22.24 | 0.0139** |
| | Pigeonpea/Gnut | 36.08 ± 10.13 | |
| | Pigeonpea/Soya | 36.12 ± 19.18 | |
| | Pigeonpea/Maize | 15.00 ± 4.94 | |
| Root biomass kg ha$^{-1}$(40– 60 cm) | Sole Pigeonpea | 25.43 ± 5.07 | 0.0269* |
| | Pigeonpea/Gnut | 8.10 ± 2.03 | |
| | Pigeonpea/Soya | 7.72 ± 2.87 | |
| | Pigeonpea/Maize | 5.63 ± 2.45 | |
| Total root biomass (Mg ha$^{-1}$) | Sole Pigeonpea | 1.56 ± 0.24 | 0.0043*** |
| | Pigeonpea/Gnut | 1.13 ± 0.21 | |
| | Pigeonpea/Soya | 0.63 ± 0.12 | |
| | Pigeonpea/Maize | 0.53 ± 0.08 | |
| Root shoot ratio | Sole Pigeonpea | 0.13 ± 0.02 | 0.1728 |
| | Pigeonpea/Gnut | 0.17 ± 0.02 | |
| | Pigeonpea/Soya | 0.13 ± 0.01 | |
| | Pigeonpea/Maize | 0.15 ± 0.02 | |

* Significant at α = 0.1
**Significant at α = 0.05
***Significant at α = 0.01

**Table 13**. One-way ANOVA and mean response of pigeonpea stems, twigs, leaves, pods, initial leaf fall, total shoot biomass, root biomass and root shoot ratio to soil texture. This data is from baby trials (n=40). Means are followed by standard errors.

| **Variable** | **Cropping System** | **Mean** | **Pr > F** |
|---|---|---|---|
| Stems (Mg ha$^{-1}$) | Light | 3.22 ± 0.57 | 0.1119 |
| | Heavy | 4.57 ± 0.60 | |
| Twigs (Mg ha$^{-1}$) | Light | 0.82 ± 0.17 | 0.0799* |
| | Heavy | 1.26 ± 0.18 | |
| Leaves (Mg ha$^{-1}$) | Light | 0.76 ± 0.20 | 0.1546 |
| | Heavy | 1.19 ± 0.21 | |
| Pods (Mg ha$^{-1}$) | Light | 0.56 ± 0.16 | 0.9655 |
| | Heavy | 0.57 ± 0.16 | |
| Initial leaf fall (Mg ha$^{-1}$) | Light | 0.40 ± 0.09 | 0.3716 |
| | Heavy | 0.28 ± 0.09 | |
| Total shoot biomass (Mg ha$^{-1}$) | Light | 4.75 ± 0.61 | 0.0420** |
| | Heavy | 8.17 ± 1.48 | |
| Root biomass kg ha$^{-1}$ (0– 20 cm) | Light | 677.19 ± 76.32 | 0.0429** |
| | Heavy | 1204.19 ± 232.90 | |
| Root biomass kg ha$^{-1}$ (20– 40 cm) | Light | 79.71 ± 20.86 | 0.9398 |
| | Heavy | 81.66 ± 15.31 | |
| Root biomass kg ha$^{-1}$ (40– 60 cm) | Light | 26.64 ± 9.45 | 0.7696 |
| | Heavy | 23.37 ± 5.82 | |
| Total root biomass (Mg ha$^{-1}$) | Light | 0.77 ± 0.09 | 0.0407** |
| | Heavy | 1.33 ± 0.24 | |
| Root shoot ratio | Light | 0.18 ± 0.02 | 0.9663 |
| | Heavy | 0.18 ± 0.02 | |

* Significant at $\alpha = 0.1$
**Significant at $\alpha = 0.05$

**Table 14**. Correlation matrix of explanatory variables in mother trials.

| Pearson Correlation Coefficients, N = 39 | | | | | | | |
|---|---|---|---|---|---|---|---|
| Prob > \|r\| under H0: Rho=0 | | | | | | | |
| | Total shoot biomass | Total root biomass | pH | Clay % | Sand % | N % | SOC % |
| Total shoot biomass | 1 | 0.88724 | 0.25039 | -0.0426 | -0.0195 | 0.25993 | 0.31107 |
| | | <.0001 | 0.1242 | 0.7967 | 0.9061 | 0.11 | 0.0539 |
| Total root biomass | 0.88724 | 1 | 0.18352 | 0.21851 | -0.2648 | 0.49623 | 0.53236 |
| | <.0001 | | 0.2634 | 0.1814 | 0.1033 | 0.0013 | 0.0005 |
| pH | 0.25039 | 0.18352 | 1 | 0.37946 | -0.3863 | 0.28903 | 0.22382 |
| | 0.1242 | 0.2634 | | 0.0172 | 0.0151 | 0.0743 | 0.1708 |
| Clay % | -0.0426 | 0.21851 | 0.37946 | 1 | -0.9789 | 0.79979 | 0.74488 |
| | 0.7967 | 0.1814 | 0.0172 | | <.0001 | <.0001 | <.0001 |
| Sand % | -0.0195 | -0.2648 | -0.3863 | -0.9789 | 1 | -0.8161 | -0.7706 |
| | 0.9061 | 0.1033 | 0.0151 | <.0001 | | <.0001 | <.0001 |
| N % | 0.25993 | 0.49623 | 0.28903 | 0.79979 | -0.8161 | 1 | 0.98834 |
| | 0.11 | 0.0013 | 0.0743 | <.0001 | <.0001 | | <.0001 |
| SOC % | 0.31107 | 0.53236 | 0.22382 | 0.74488 | -0.7706 | 0.98834 | 1 |
| | 0.0539 | 0.0005 | 0.1708 | <.0001 | <.0001 | <.0001 | |

**Table 15**. Correlation matrix of explanatory variables in baby trials.

| Pearson Correlation Coefficients, N = 40 | | | | | | | |
|---|---|---|---|---|---|---|---|
| Prob > \|r\| under H0: Rho=0 | | | | | | | |
| | Total shoot biomass | Total root biomass | pH | Clay % | Sand % | N % | SOC % |
| Total shoot biomass | 1 | 0.88724 | 0.25039 | -0.0426 | -0.0195 | 0.25993 | 0.31107 |
| | | <.0001 | 0.1242 | 0.7967 | 0.9061 | 0.11 | 0.0539 |
| Total root biomass | 0.88724 | 1 | 0.18352 | 0.21851 | -0.2648 | 0.49623 | 0.53236 |
| | <.0001 | | 0.2634 | 0.1814 | 0.1033 | 0.0013 | 0.0005 |
| pH | 0.25039 | 0.18352 | 1 | 0.37946 | -0.3863 | 0.28903 | 0.22382 |
| | 0.1242 | 0.2634 | | 0.0172 | 0.0151 | 0.0743 | 0.1708 |
| Clay % | -0.0426 | 0.21851 | 0.37946 | 1 | -0.9789 | 0.79979 | 0.74488 |
| | 0.7967 | 0.1814 | 0.0172 | | <.0001 | <.0001 | <.0001 |
| Sand % | -0.0195 | -0.2648 | -0.3863 | -0.9789 | 1 | -0.8161 | -0.7706 |
| | 0.9061 | 0.1033 | 0.0151 | <.0001 | | <.0001 | <.0001 |
| N % | 0.25993 | 0.49623 | 0.28903 | 0.79979 | -0.8161 | 1 | 0.98834 |
| | 0.11 | 0.0013 | 0.0743 | <.0001 | <.0001 | | <.0001 |
| SOC % | 0.31107 | 0.53236 | 0.22382 | 0.74488 | -0.7706 | 0.98834 | 1 |
| | 0.0539 | 0.0005 | 0.1708 | <.0001 | <.0001 | <.0001 | |

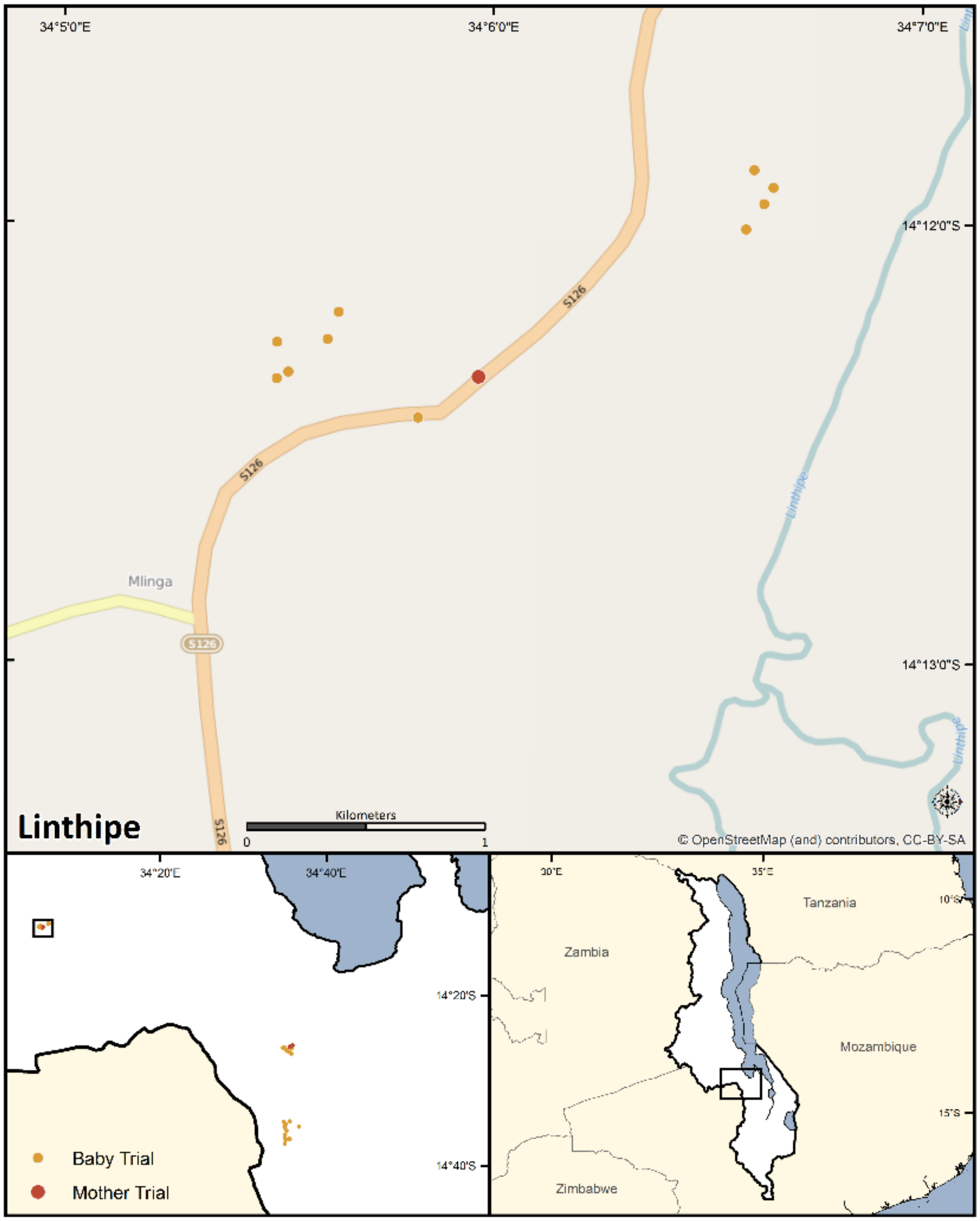


**Figure 1**. Map of Malawi showing the central region and the specific locations of mother and baby trials from the Linthipe site.

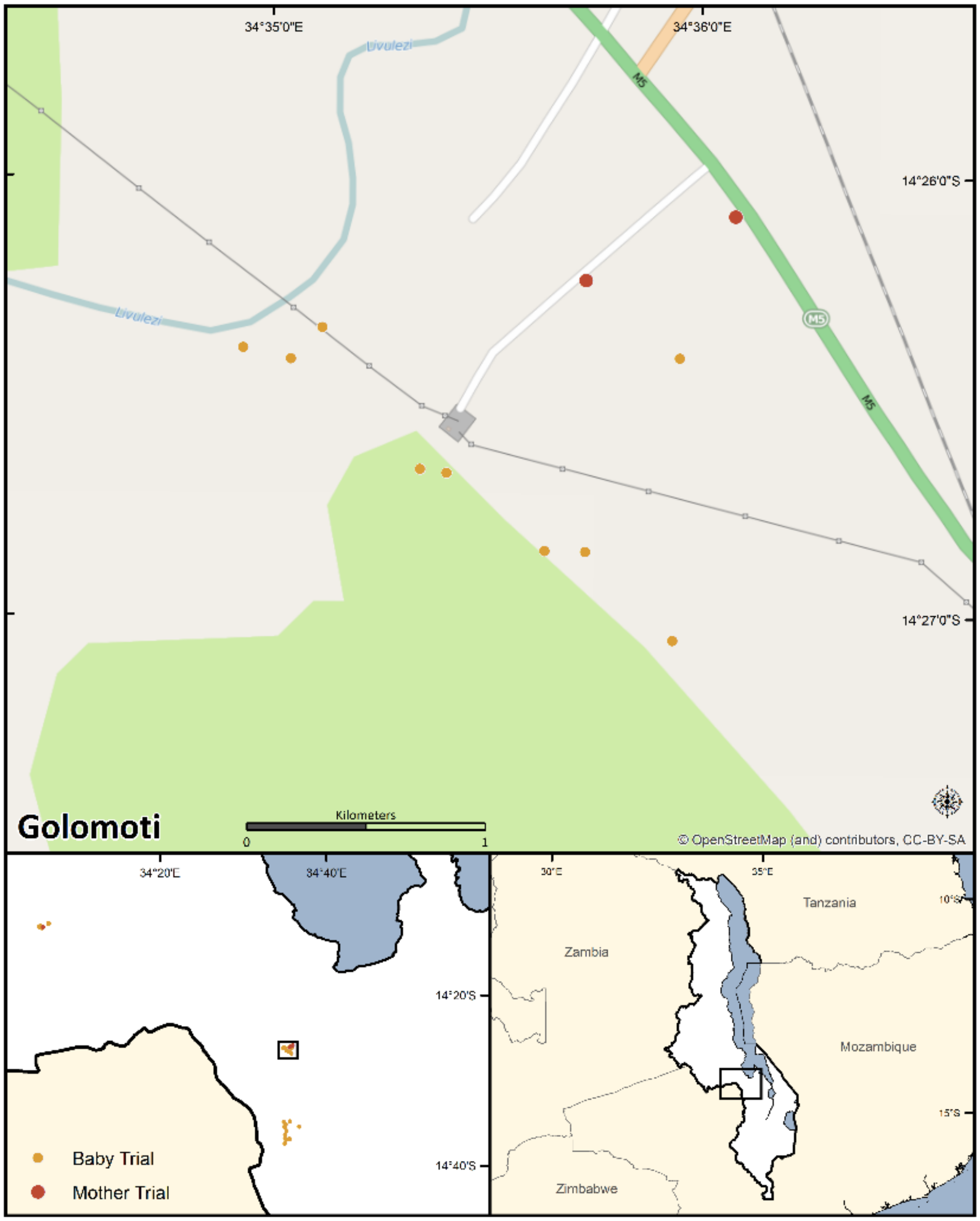


**Figure 2**. Map of Malawi showing the central region and specific locations of mother and baby trials for the Golomoti site.

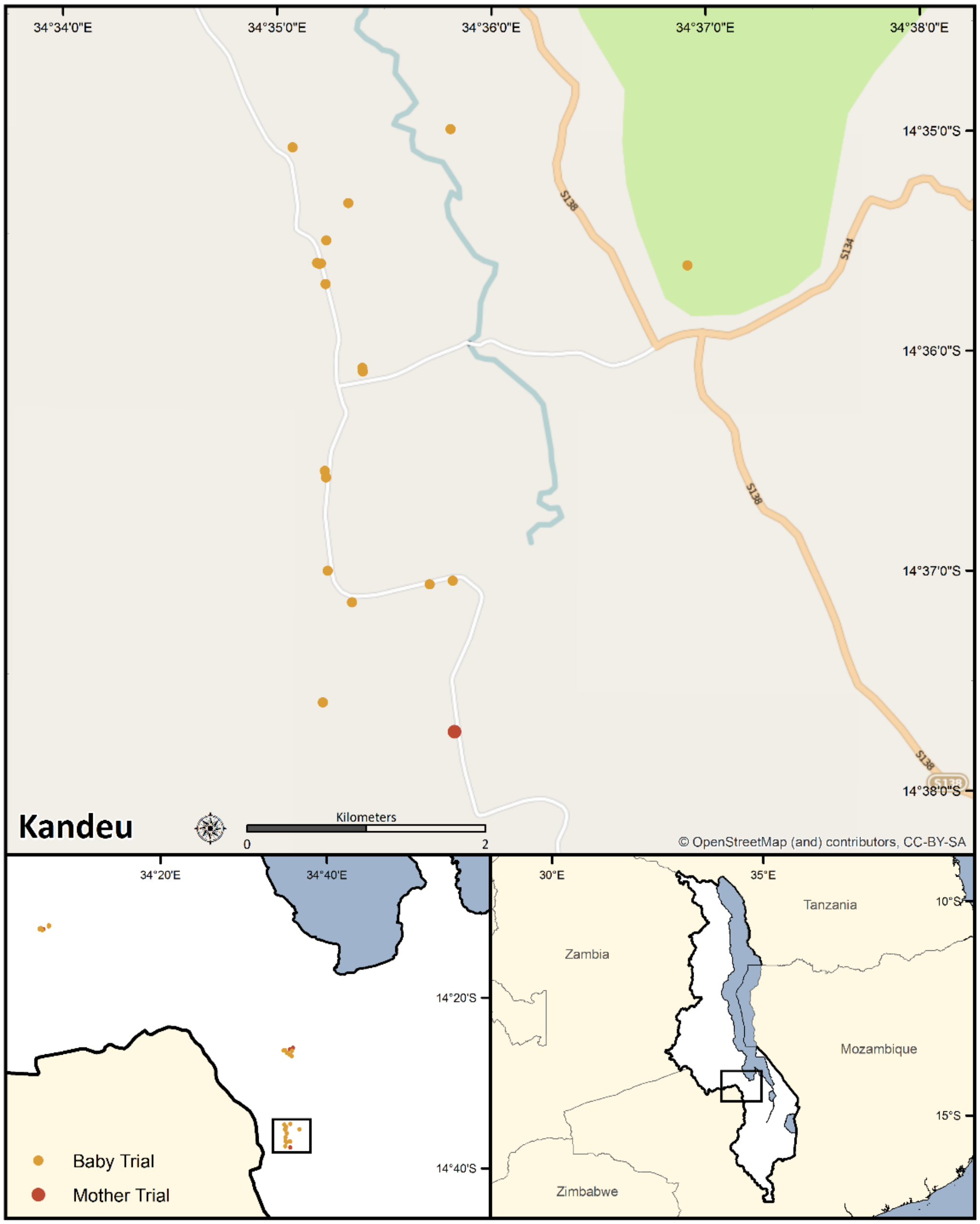


**Figure 3**. Map of Malawi showing the central region and specific locations of mother and baby trials for the Kandeu site.

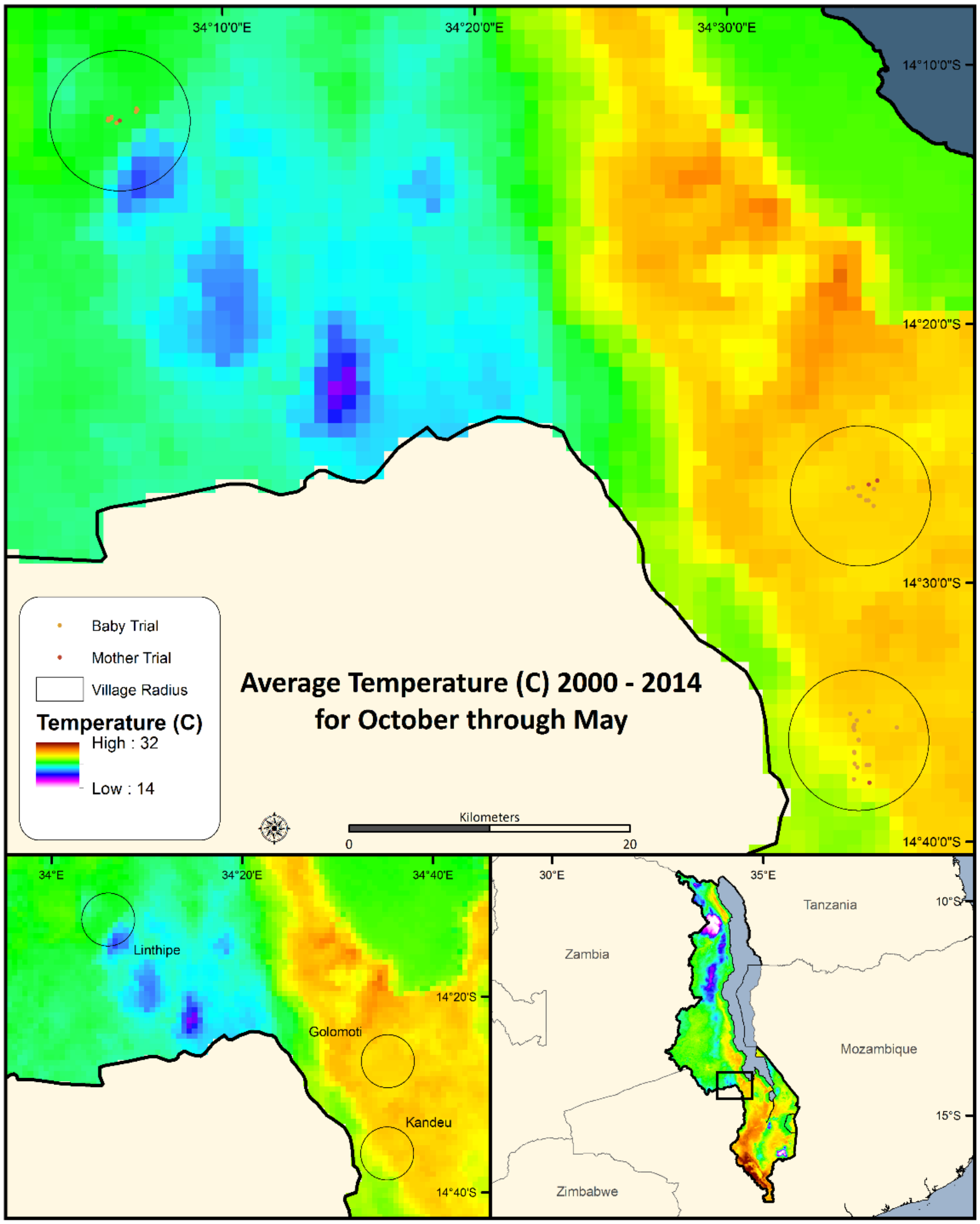


**Figure 4**. Map of Malawi showing temperature ranges across the country and the specific locations for which monthly temperature is presented for the three agro-ecologies.

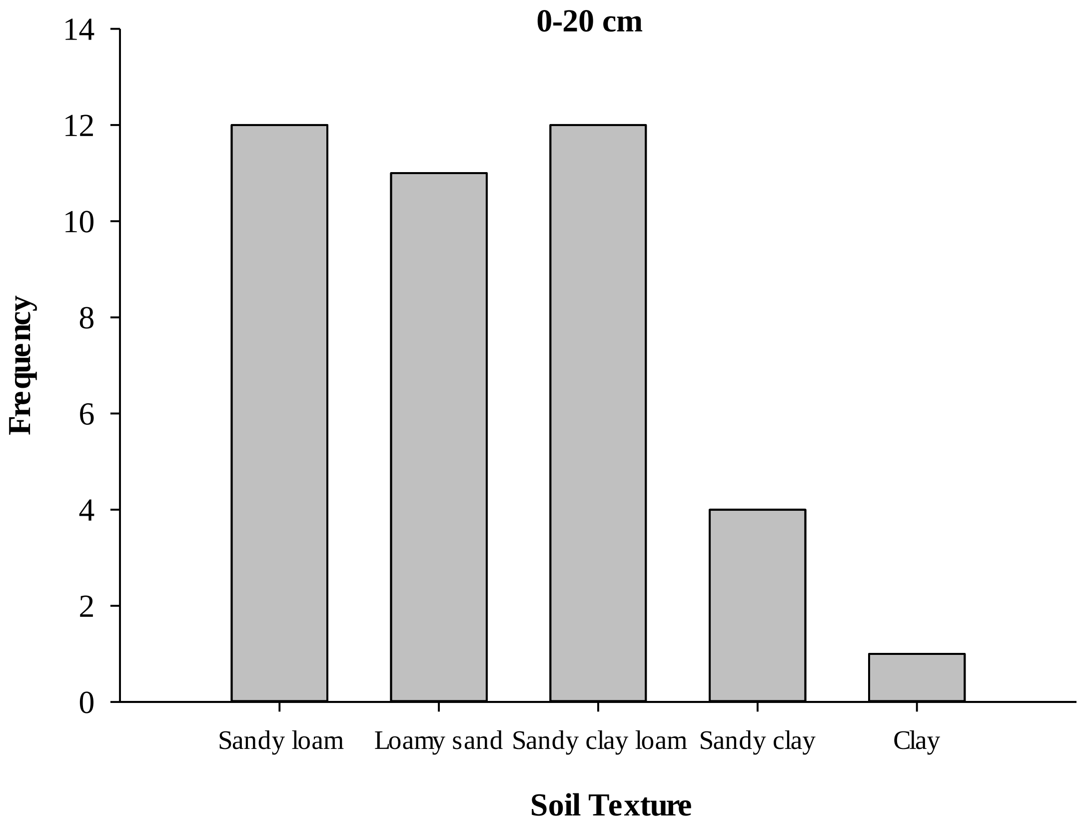


**Figure 5**. Frequencies of soil types in baby trials for the 0– 20 cm depth.

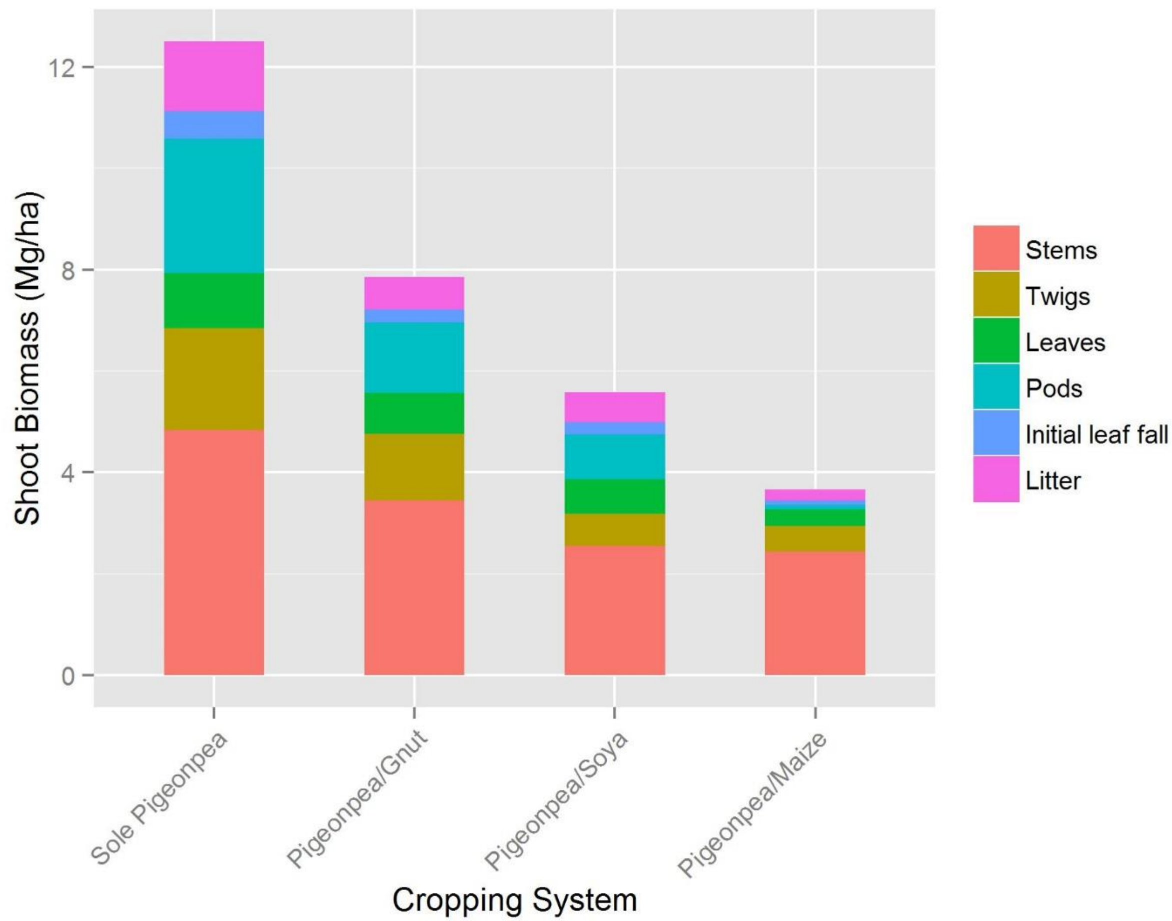


**Figure 6**. Shoot biomass in four cropping systems from mother trials. Total shoot biomass was separated into stems, twigs, leaves and pods initial leaf fall. Total litter that was collected over ten weeks from litter traps is also included in shoot biomass.

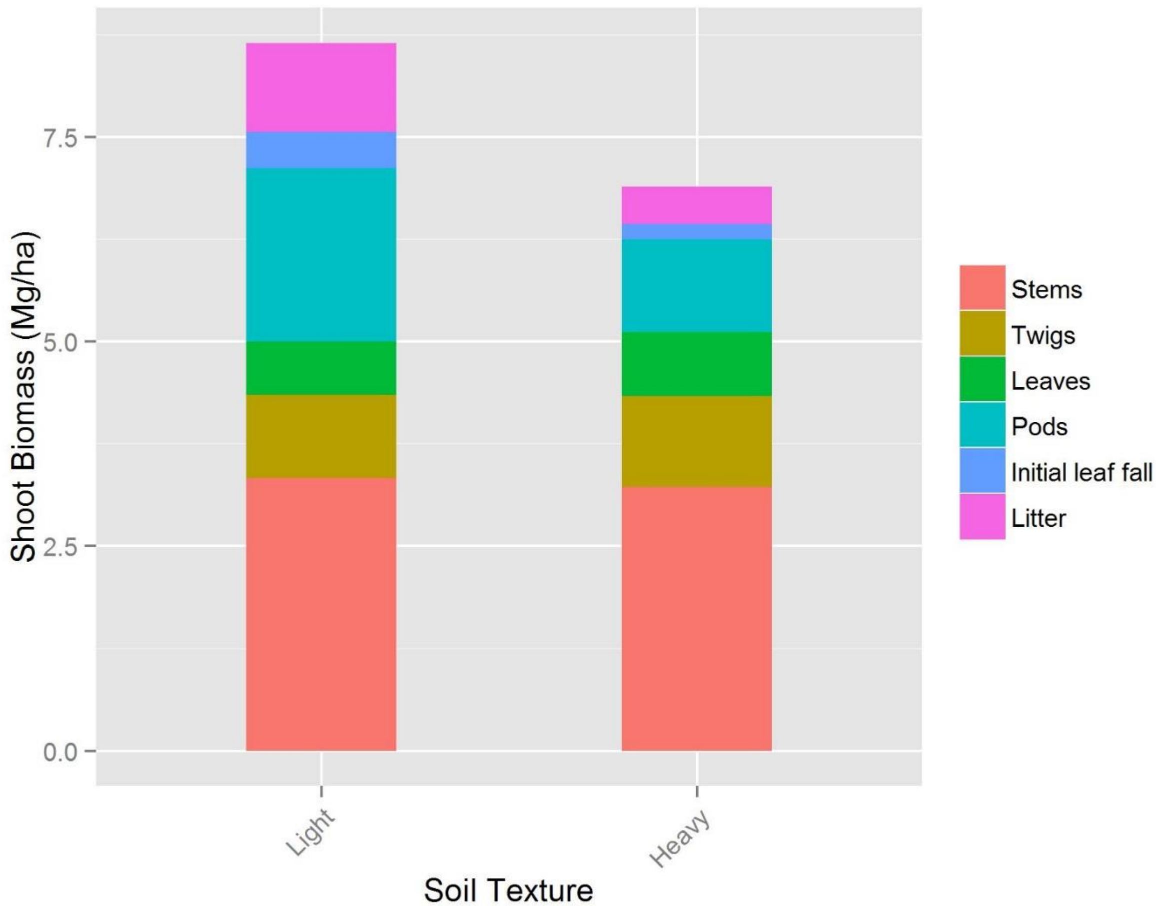


**Figure 7**. Shoot biomass from light and heavy textured soils from the 0– 20 cm depth in mother trials. Total shoot biomass was separated into stems, twigs, leaves and pods. Initial leaf fall is also included in shoot biomass.

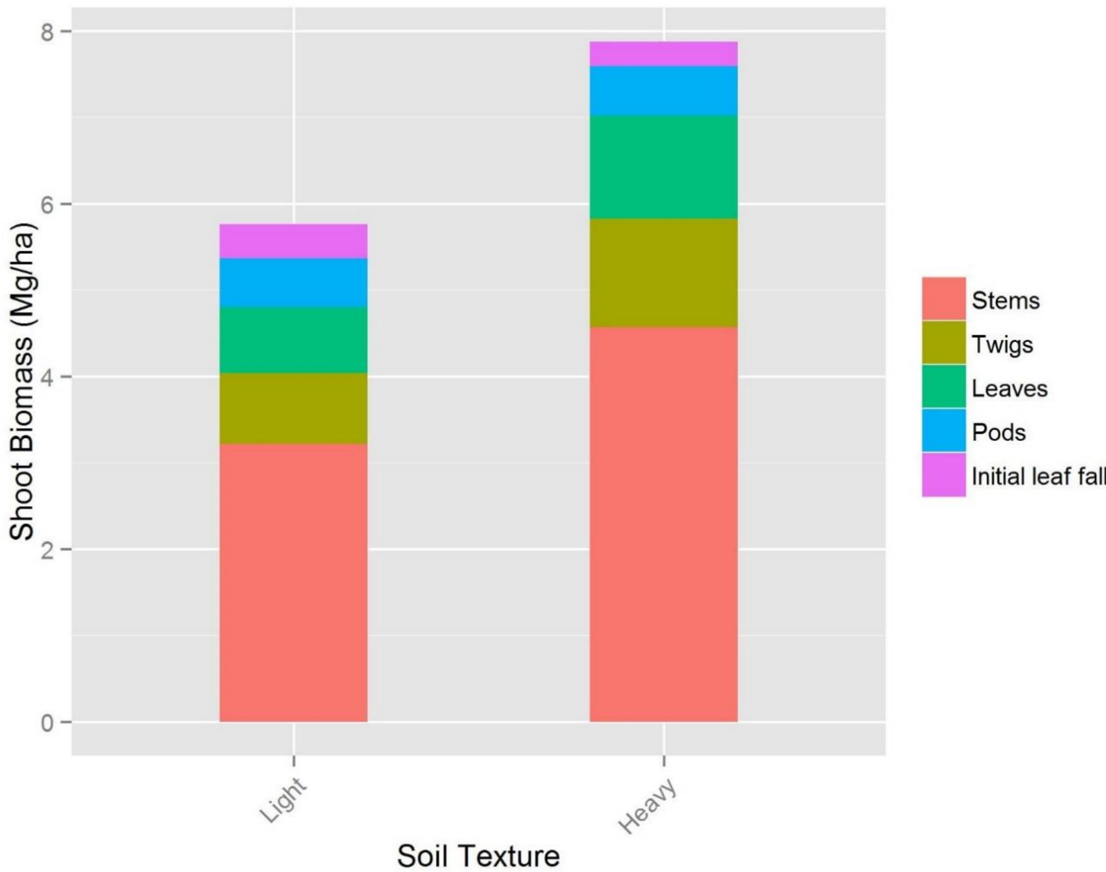


**Figure 8.** Shoot biomass averaged by sites with light and heavy textured soils, from baby trials. Total shoot biomass was separated into stems, twigs, leaves and pods. Initial leaf fall is also included in shoot biomass.

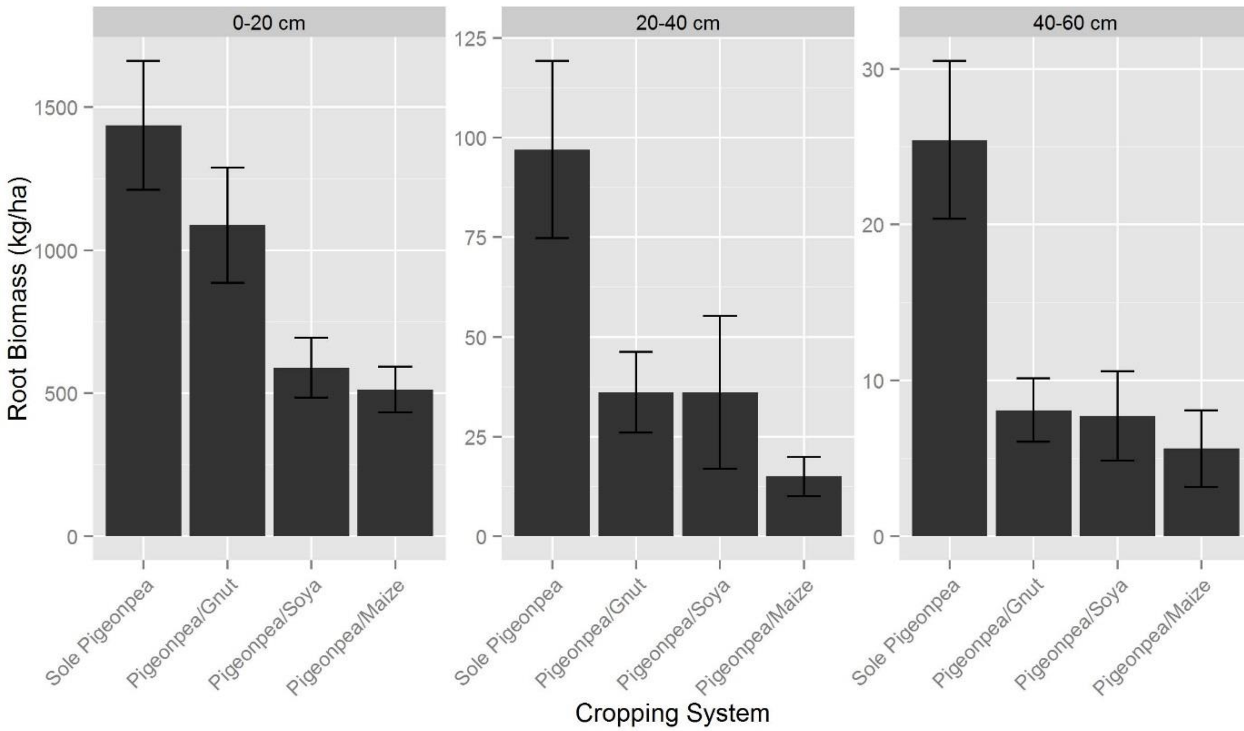


**Figure 9**. Root biomass from the 0– 20, 20– 40 and 40– 60 cm depths in four cropping systems from mother trials. Error bars represent ± standard errors of treatment means. Note: the scale across soil depths is different.

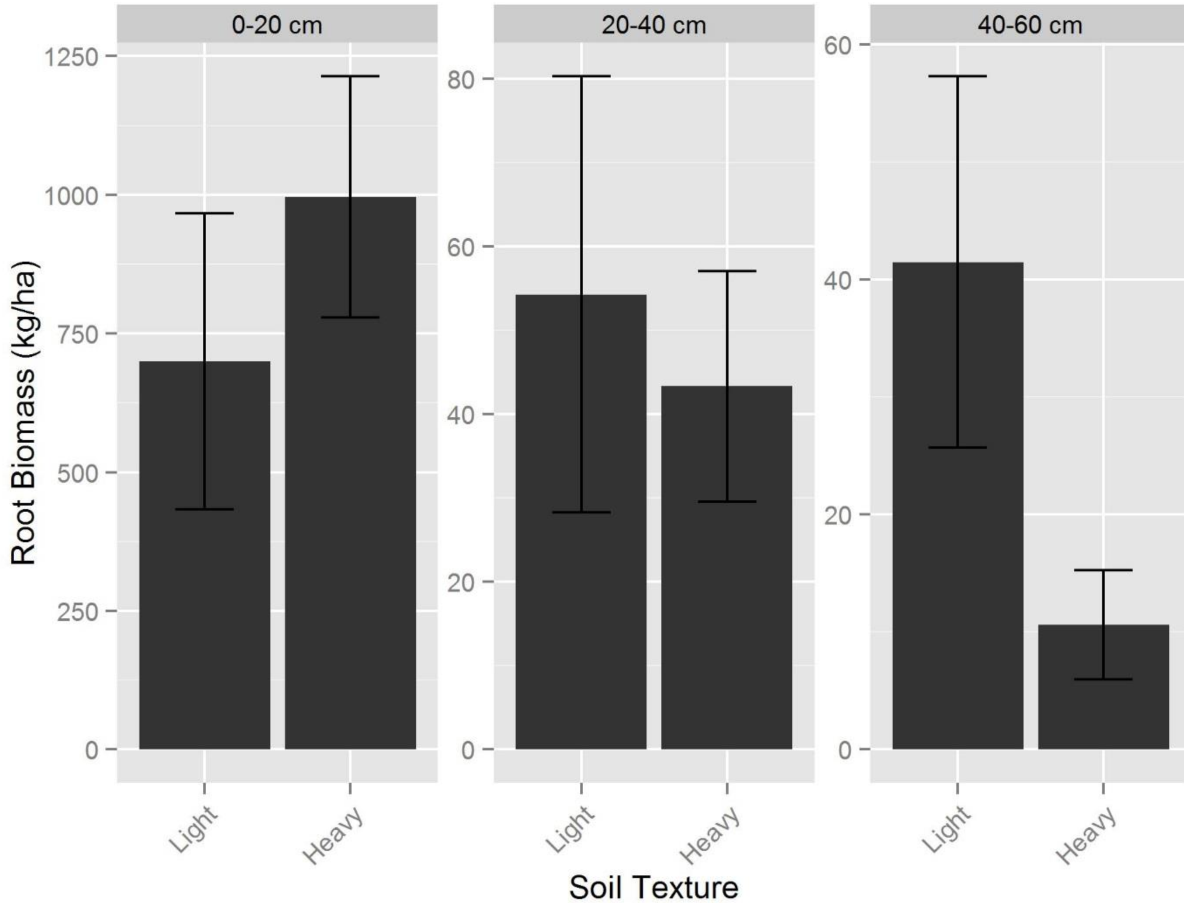


**Figure 10**. Root biomass from the 0– 20, 20– 40 and 40– 60 cm depths, grouped by light and heavy textured soils from mother trials. Error bars represent ± standard errors of treatment means. Note: the scale across soil depths is different.

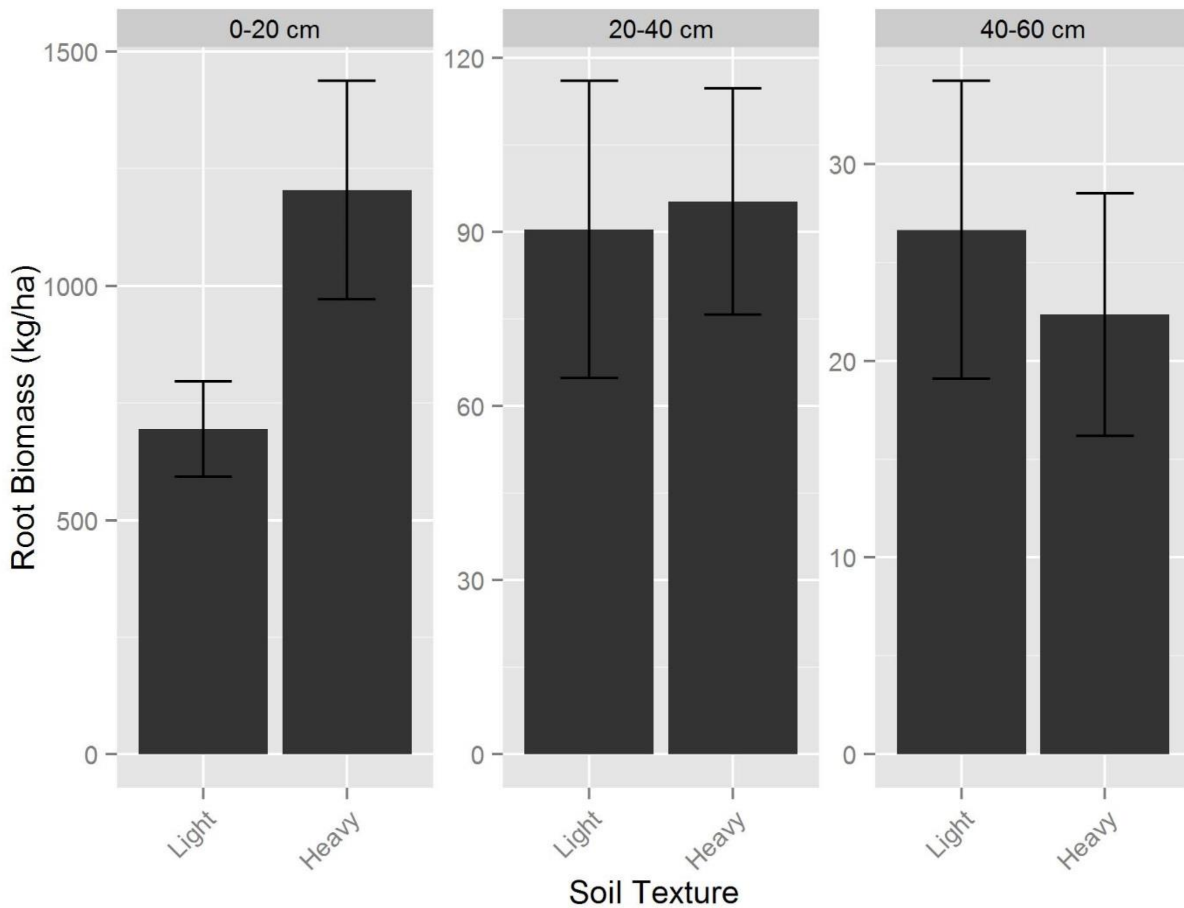


**Figure 11**. Root biomass from the 0– 20, 20– 40 and 40– 60 cm depths in light and heavy textured soils from baby trials. Error bars represent ± standard errors of treatment means. Note: the scale across soil depths is different.

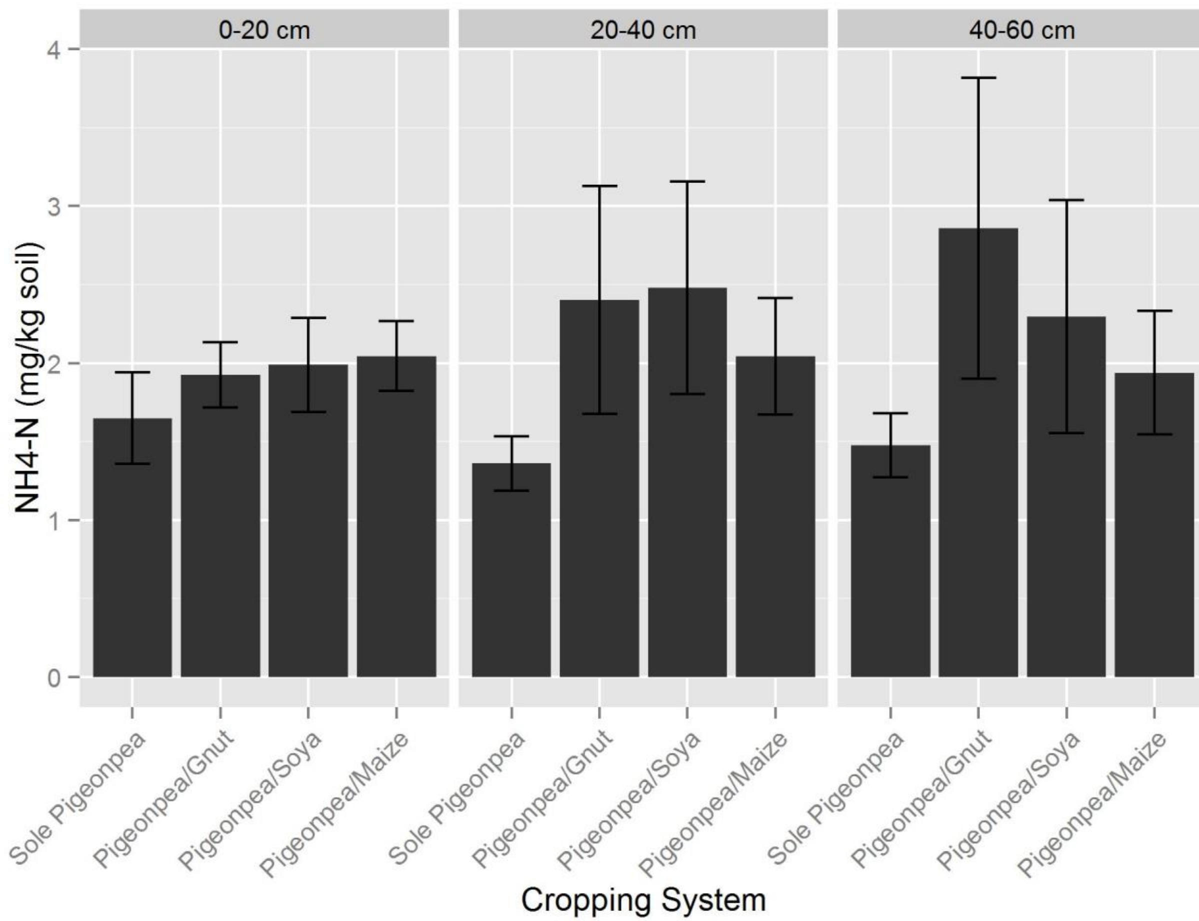


**Figure 12**. Soil $NH_4^+$-N by cropping systems from the 0– 60 cm depths in mother trials. Error bars represent ± standard errors of treatment means.

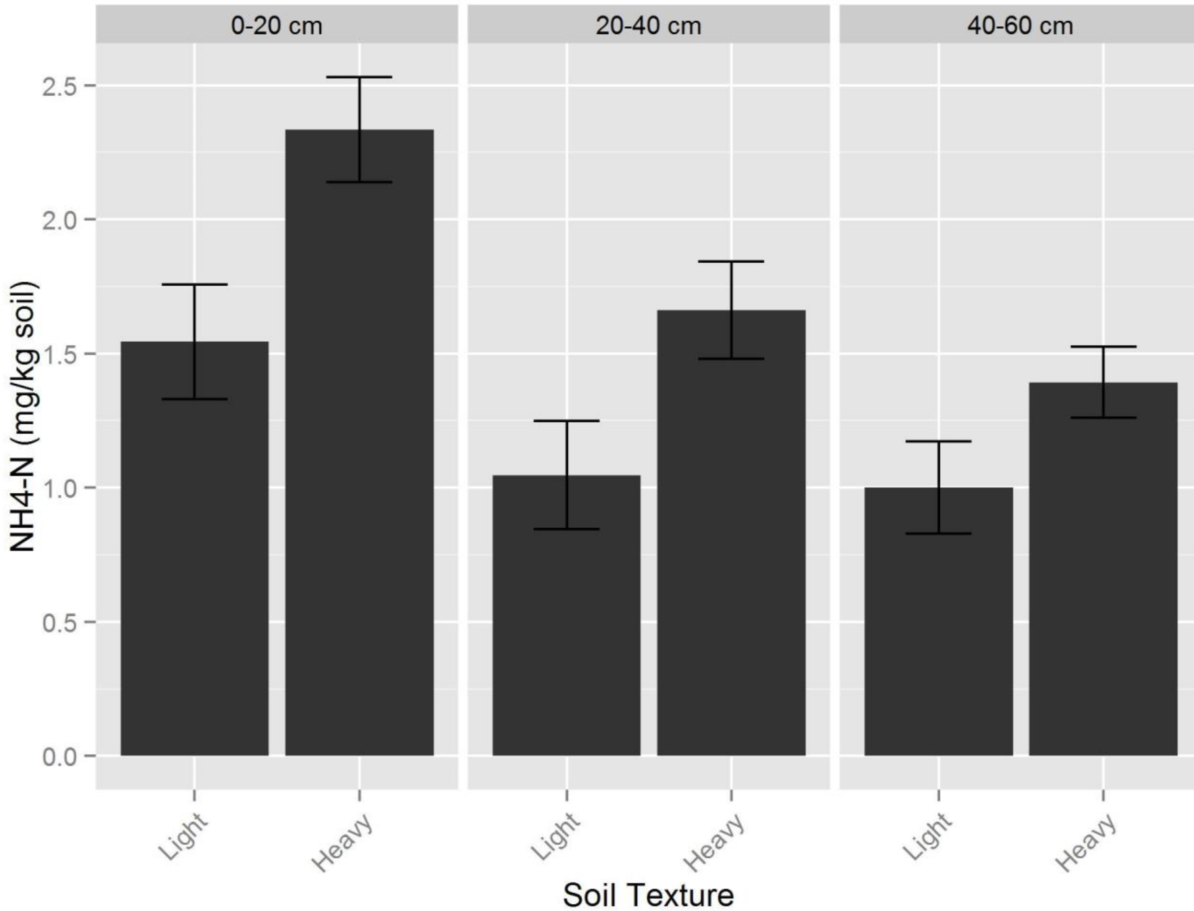


**Figure 13**. Soil $NH_4^+$-N by soil texture in baby trials from the 0– 60 cm depths. Error bars represent ± standard errors of treatment means.

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