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Full Length Research Paper

Spatial rooting patterns of gliricidia, pigeon pea and maize intercrops and effect on profile soil N and P distribution in southern Malawi

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The concept of competition or complementarity between tree and crop roots for below ground resources have been a major debate in simultaneous systems. Root studies were conducted in three cropping systems, namely: sole maize, pigeon pea/maize intercropping and *Gliricidia sepium* (Gliricidia)/maize intercropping, with the objective of understanding the potential for competition or otherwise. Pigeon pea and maize root development was monitored at 21, 42 and 63 days after planting (DAP). Also soil mineral N and Olsen P were assessed along the soil profile up to 200 cm depth. Maize roots developed faster than those of pigeon pea during the first 42 days after planting and there was little overlapping of maize and pigeon pea roots. However, the roots of both pigeon pea and maize had its peaks at 63 DAP, suggesting potential competition during reproductive growth stage of maize. In Gliricidia/maize intercropping, maize had the highest root density averaging 1.02 cm cm^{-3} in the top 0 -4 0 cm soil layer, whereas gliricidia had lower root length density (0.38 cm cm^{-3}) in the top 0 - 40 cm soil layer compared to 0.65 cm cm^{-3} in the subsoil (40 - 100 cm). In Gliricidia/maize intercropping, mineral N was increased by 34 - 44 kg ha^{-1} in the 0 - 100 cm soil layer, whereas Olsen P decreased by 32 kg ha^{-1} in the entire 0-200 cm soil profile compared to the sole maize plot. Pigeon pea may be the "loser" in an association that involved both maize and Gliricidia. Because maize had more roots growing within 0 - 40 cm soil layer than Gliricidia it is able to take advantage of the nutrients from the applied Gliricidia prunings in the ridges. The study confirmed root compatibility between Gliricidia and maize and nutrient pumping from deep soil layers.

Key words: Fertilizer trees, roots, nutrient distribution, Makoka.

INTRODUCTION

Competition for both the above- and below-ground resources may arise between trees and crops growing in the same space and soil mass, especially when the trees have more competitive advantage than the crops (Schroth, 1999). In simultaneous systems interactions between component species are essentially a response of one species to the environment as modified by the presence of the other (Akinnifesi et al., 1999a, 2004). Depending on the management, and or environmental and and physiological factors controlling plant growth and functioning, one species may gain at the expense of the other, causing one species to be a winner (strong competitor) and the other a loser (weak competitor) (van Noordwijk et al., 1996). These interactions may have competitive (deleterious), complementary (beneficial) or balanced-off (neutral) overall effects. Competition occurs when species have to share the resources from a limited pool. Understanding and managing competitions is crucial for the success and sustainability of any simultaneous agroforestry systems (Akinnifesi et al., 2004; Schroth, 1999).

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Table 1. Initial topsoil (0-20 cm) characteristics at MZ12 and MZ21, Makoka Agricultural Research Station, Zomba.

Soil parameter	MZ12	MZ21
Physical characteristics		
Clay (%)	42	38
Sand (%)	46	54
Silt (%)	12	8
Bulk density (g/cm^3)	1.42	1.55
Chemical characteristics		
pH in water (1:2.5)	5.9	5.6
Organic carbon (g/kg of soil)	8.8	9.3
P-Olsen (mg/kg of soil)	26.0	10.3
Exchangeable K (mmol (+)/kg of soil)	3.0	3.7
Exchangeable Ca (mmol (+)/kg of soil)	44.0	17.3
Exchangeable Mg (mmol (+)/kg of soil)	16.0	4.2

Knowledge of root stratification of the trees/shrubs and the associated crops in an agroforestry system is needed in order to ascertain the extent of competition or complementarity or otherwise between the trees and the crops. Previous root studies have revealed that trees having large and extensive roots will interfere with seedbed preparation or tillage operations (Akinnifesi et al., 2004). Tree species with lateral roots confined to less than 1 m distance from the tree trunk, are more desirable in simultaneous agroforestry systems that require tillage of the inter-row spaces (Akinnifesi et al., 1999a, b; Ruhigwa et al., 1992). Shallow rooted tree species that exhibit rapid decline in root mass, length or density with increasing soil depth may compete highly with crops on soil nutrient resources, whereas trees with high concentration of their fine roots in the topsoil but at the same time with a substantial proportion of their fine roots in the deeper soil layers may compete less (Akinnifesi et al., 2004; Schroth, 1999; Schroth and Zech, 1995;) because they explore a large volume of soil. Tree roots at soil depths below the feeding zone of most annual crops may capture nutrients from deeper resources and transfer them to the surface (Van Noordwijk et al., 1996).

The success of the simultaneous intercropping of trees with crops in agroforestry system is dependent on the temporal and spatial complementarity of resource capture by trees and crops (Akinnifesi et al., 2004; Cannell et al., 1996). In simultaneous agroforestry systems, pruning management of the aboveground part of the trees reduces both the aboveground as well as below ground competition (Akinnifesi et al., 1995).

Competition for belowground resources is high when the agroforestry trees have most of the fine roots confined in the same strata as the associated food crop (Akinnifesi et al., 1999a; Ruhigwa et al., 1992; Schroth, 1995, 1999), and low when the trees have few roots growing in the rooting horizon of the crops and more of their roots growing in the deeper soil layers. It has been suggested that competition between the trees and crops for belowground resources could be minimized by (1) deep ploughing so that the tree roots growing in the top soil layer are sloughed off (Kowar and Radder, 1994), (2) root pruning along the tree hedges (Fernandes et al., 1993), (3) selecting trees that have most of their roots growing below the crops rooting horizon (Akinnifesi et al., 1999a), (4) shoot pruning to reduce competition for water and nutrients (Miller and Pallardy, 2001), and (5) by growing crops in ridges and trees in furrows (Akinnifesi et al, 2004).

Smallholder farmers in southern Malawi intercrop pigeon pea in Gliricidia-maize intercropping system. Trees are grown in furrows and maize and pigeon pea on ridges. This practice further increases the harmony of intercropping tree and crops in a small piece of land. The information previously obtained from wider alleys (4 - 5 m) (Akinnifesi et al., 1995, 1999 b, c; Itimu et al., 1997) may not easily be extrapolated to Gliricidia intercropping system in Malawi with 1.5 m between rows. Since root characteristics of trees change with crop husbandry, tree management and site conditions (Akinnifesi et al., 1995, 1999b, 2004; Schroth, 1999; van Noordwijk et al., 1991, 1996), it is essential to understand the rooting patterns of trees and crops in a simultaneous intercropping of Gliricidia with maize and pigeon pea.

The premise of the study was that the simultaneous intercropping agroforestry systems as practiced in Malawi will face competition for belowground resources, but that the practice of growing trees in furrows and crops on ridges minimizes such competition. We further hypothesize that rooting systems of Gliricidia are compatible with maize and pigeon pea in the intercropping system. This study was undertaken to (1) understand the vertical and horizontal root distribution of Gliricidia, pigeon pea and maize in a simultaneous system, (2) increase our understanding of pigeon pea and maize root development during the growing period in an intercropping system, and (3) understand the effect of Gliricidia and pigeon pea on mineral N and Olsen P down the soil profile.

MATERIALS AND METHODS

The studies were conducted in two separate fields of about 300 meters apart, that is, the MZ 12 and MZ 21, both at Makoka Agricultural Research Station during 2000-01 and 2001-02 seasons. The at MZ12 trial was established in December 1991 for studying long-term biophysical performance of Gliricidia intercropping system including nitrogen dynamics (Ikerra et al., 1999), P dynamics (Mweta et al., 2007), maize yield and tree biomass production trends (Akinnifesi et al., 2006), and C sequestration (Makumba et al., 2007). The MZ21 was established in December 1995 for understanding the intercropping of Gliricidia intercropping and *Cajanus cajan* (pigeon pea) (Chirwa et al., 2006). The profile soil characteristics of both sites are presented in Table 1. The experiment is a randomized complete block design with three blocks. Each treatment was replicated thrice. For the purpose of this study, the following six treatments were selected: (1) Monoculture maize without N-fertilizer (Control), (2) Monoculture maize with 50% of the recom-



Figure 1. a) Spatial arrangement of trees and crops in the Gliricidia/maize intercropping system at Makoka;
b) Mapping of roots at MZ21 in a Gliricidia-maize-pigeon pea intercropping system (Root trenches were dug parallel to the ridges and tree rows in each plot).

mended N dose (46 kg N ha^{-1}), (3) Monoculture maize with 25% of the recommended N dose (23 kg N ha^{-1}), (4) Maize-Gliricidia intercropping without fertilizer, (5) Maize-Gliricidia intercropping amended with 50% of the recommended N dose (46 kg N ha-1), and (6) Maize-Gliricidia intercropping amended with 25% of the recommended N dose (23 kg N ha^{-1}).

For both trials, Gliricidia (*Gliricidia sepium* (Jacq.) Walp (ex Retalhaleu, Guatemala prov.) was established from seedling stock in December 1991 in MZ12 and 1995 for MZ21, without cropping in the first year. Maize and pigeon pea were planted on the same dates in 16 November in 2000 and 20th November in 2000, and the yield has been reported by Makumba (2003). Pigeon pea was intercropped each year in MZ21. Gliricidia plots consisted of four rows of trees planted in every other furrow at 90 cm within tree rows and 150 cm between tree rows (7400 trees ha^{-1}s). Plot size was 6.75 x 5.1 m, separated by 1-m wide path. Tree management has been described in detail in Akinnifesi et al. (2006, 2007) and Makumba et al. (2006). Figure 1 (a) shows the spatial arrangement of tree and crop at MZ 12. Maize hybrid NSCM 41 was planted on ridges at a spacing of 30 cm within rows and 75 cm between rows (44,000 plants ha^{-1}), in both the monoculture maize as well as intercropping. Maize was weeded twice by hand during the cropping season typical of the traditional farming practice. Maize grain and dry matter yields, and tree biomass for Gliricidia were measured every season have been reported elsewhere (Akinnifesi et al., 2006; Makumba et al., 2006; Chirwa et al., 2003, 2006).

Root sampling and determination of root length of maize and pigeon pea

Three methods were deployed to assess the rooting patterns of the trees and crops including (1) root core sampling at various growth stages of maize, (2) root mapping on the profile wall following the procedures extensively described elsewhere (Akinnifesi et al., 1999a, 2004; Vanlauwe et al., 2001) and (3) excavation of structural roots (that is, large roots more than 5 mm) and tap roots of the central and border trees. The 'central trees' were those inner rows of trees at the middle of the plot, and at the center, while 'border trees' were those at the edge of the plot. Three replicates were used for three methods.

Maize and pigeon pea root development was monitored in the maize-pigeon pea intercropping during the maize growing period at 21, 42 and 63 days after planting (DAP), corresponding to the periods of vegetative growth and the start of anthesis, respectively. Root samples were taken by driving a core sampler (100 cm^3

volume) into the soil on the ridge at lateral distances of 10, 20, 30 and 40 cm from the maize plant and at 10 cm intervals to 60 cm depth at 21 DAP, and to 70 cm depth at 42 DAP. At 63 DAP, soil cores were collected from the soil profile wall.

The soil cores were washed through a set of sieves (2 mm, 1 mm and 300 µm). The fine roots (<2 mm) collected were treated with 17% acetic acid and kept in a refrigerator at 4°C while awaiting sorting and measurement.

The fine roots (< 2 mm) were sorted under a 10 times magnifying glass. The roots of different species were differentiated based on their color, pliability and branching characteristics, as done by Akinnifesi et al. (1999) and Vanlauwe et al. (2002). The dead roots were distinguished by their darkish-gray coloration of the cortex. The method described by Tenant (1975) was followed to determine the root lengths. A 0.5 x 0.5 cm grid paper was placed beneath a one-liter beaker filled with about 2 cm film of water on which the roots were floated. The set up was illuminated with a table reading light. Counts of the intercepts of the roots with the vertical and horizontal grid lines were made with the aid of the magnifying glass and a hand tally counter. Complete counts were converted to length measurements using the Tennant (1975) modified formula:

Root length (R) (cm) = $^{11}/_{14}$ * number of intercepts (N) * grid unit (cm)……....Eq. 1

The root length estimates were then divided by the volume of the core to obtain the root length density (cm dm^{-3}).

Root quantification of maize and Gliricidia on the soil profile wall

In MZ12, at eight weeks after maize planting in 2001 trenches measuring 2.5 m length x 1.0 m width x 3.0 m depth were dug perpendicular to the tree and maize rows in sole maize (Sole-Maize) and Gliricidia-maize intercropping (Gs-Maize) plots. The trenches were dug perpendicular to the tree rows and grid frame was inserted on the profile wall covering at least four maize rows and two tree rows (Figure 1 b). Detail of this method has been described earlier (Akinnifesi et al., 1999; Vanlauwe et al., 2002).

At the MZ21 field, trenches were excavated in the following cropping systems (1) Sole-Maize, (2) maize intercropping with pigeon pea (Pea-Maize), (3) Gliricidia - maize simultaneous intercropping (Gs-Maize) and (4) Gliricidia - pigeon pea - maize (Gs-Pea-Maize) simultaneous intercropping. The trenches were dug in March 2002, each measuring 2.5 m length x 1.0 m width x 3.0 m depth. The trenches were dug parallel to the ridges, 40 cm away from the tree row and 5 cm from the maize/pigeon pea row. A grid frame was fixed on the profile wall covering three maize rows on the ridges and two pigeon pea rows in between the maize rows (Gliricidia trees were in a furrow behind pigeon pea plants, Figure 1b). At both sites three replications were used.

Excavating lateral structural roots of Gliricidia

More detailed 'destructive' root studies were conducted at MZ21 because the aboveground biophysical studies at this site were phased out in following this study. From the *net* plot (central trees) of MZ21 the roots of five trees were excavated to 200 cm depth exposing the taproot and all the primary or structural roots (>5 mm). Diameter of taproot was measured before each branching point and primary roots branching from the taproot were counted. In a separate excavation, the spread and form of the lateral structural roots (>5 mm) were investigated. To determine the potential root vigour in the sites, five trees were randomly selected from the *border* of the plots (exterior) and the roots growing in the surface 0-40 cm were excavated, exposing them to their full length and then the taproot was followed to 200 cm depth. The diameter of the primary roots was measured from the tree trunk or taproot to the tip at 10 cm intervals. The number of secondary roots growing from the primary roots was also recorded and the measurements were repeated for the taproot. The branching angle of the primary roots for the interior and border trees were measured.

Assessment of mineral N and Olsen P along the soil profile

After root mapping described above, soil samples for determination of mineral N, were collected along the profile wall at 20 cm depth intervals to 300 cm at MZ 12 and at 10 cm depth intervals to 200 cm at MZ 21. The grid frame was used to demarcate the sampling points just as it was done in roots studies. The profile wall was divided just as in root mapping. Samples were taken at intervals of 20 cm to a depth of 300 cm at MZ12, and at intervals of 10 cm to a depth of 200 cm at MZ21. The samples were subdivided into two; one sub-sample was dried and analyzed for Olsen P and the other was placed in a fridge at 4°C prior to mineral N analysis. The analysis of P was done using Olsen method, and N was determined using calorimetric method. Both methods were described in detail by Makumba et al. (2007).

Statistical analysis

Data was analyzed using GENSTAT version 5. Means were separated using the least significant difference (LSD) at 0.05 probability level.

RESULTS

Maize grain yield and stover yields

The grain and stover yields of maize have been reported elsewhere (Akinnifesi et al., 2006; Makumba et al., 2006; Chirwa et al., 2003, 2004). Maize grain yields and stover biomass were significantly higher in Gliricidia intercropping than the sole maize plots, generally more than triple to five times higher in both sites. In MZ21, the trend is generally in the order of Gliricidia + pigeon pea +maize > gliricidia + maize >sole maize. Intercropping reduced the grain yield of pigeon pea by 11 and 18% during 2000-01 and 2001-02 respectively (Makumba, 2003). Gliricidia biomass was one ton higher in Gliricidia + pigeon pea +maize plot than gliricidia + maize plot.

Maize and pigeon pea root distribution

At 21 days after planting (DAP) maize root length density (RLD) was highest (0.22 cm cm^{-3}) in the upper 10 cm, close to the maize hill (10 cm away) and decreased with distance away from the maize plant and also with soil depth (Figure 2). A similar trend was obtained for pigeon pea roots. Pigeon pea had most of its roots growing close to the pigeon pea stump; root length density sharply declined with distance away from the plant. No maize roots were found close to the pigeon pea plant at lateral distance of 40 cm and soil depth of 0-20 cm and vice versa. A few maize roots occurred at the soil depth 30 - 60 cm at lateral distance of 40 cm close to pigeon pea row.

At 42 DAP maize root length density had increased to

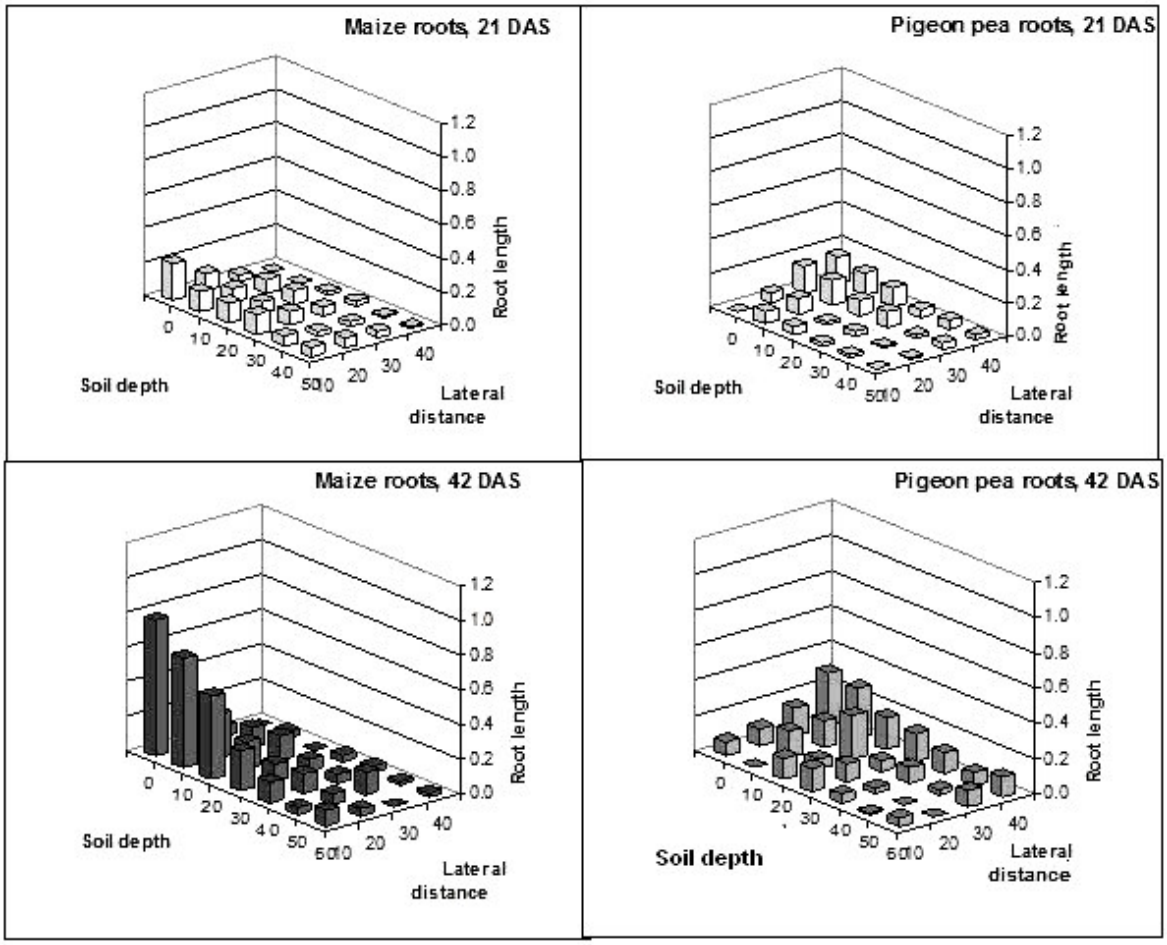


Figure 2. Variation in fine root (≤ 2mm diameter) densities (cm cm^{-3}) of maize and pigeon pea with soil depth (cm) and lateral distance (cm) maize and pigeon pea in intercropping systems in MZ21 at 21 and 42 DAP.

0.78 cm cm^{-3} in the soil surface (10, 10 cm) and to 0.09 cm cm^{-3} at a depth of 70 cm (Figure 2). Maize root length density was still low in the surface soil close to the pigeon pea plant. Pigeon pea root length density was 0.08 cm cm^{-3} in the surface soil close to the maize plant, and increased to 0.12 cm cm^{-3} at a depth of 30 - 40 cm just below the maize plants. Maize and pigeon pea roots substantially coincided between 20 and 30 cm lateral distance.

At 63 DAP the maize root length density had increased to 1.08 cm cm^{-3} and pigeon pea root length density to 0.89 cm cm^{-3} in the soil surface close to each plant (Figure 3). Pigeon pea roots grew up to 200 cm deep whereas no maize roots grew deeper than 130 cm soil depth. In the subsoil between 30 and 80 cm and at a distance of just 10 cm from the maize plant, pigeon pea root length density ranged between 0.27 and 0.36 cm cm^{-3}.

Maize and Gliricidia roots

Maize root length density was significantly (P = 0.05) higher in the topsoil between 0 and 40 cm than at greater depths at both sites, MZ12 and MZ 21 (Figure 4). The maize root length density declined with increasing depth up to 120 cm soil profile. The root length density of sole maize was higher than that of maize intercropped with Gliricidia and the decline of root length density with depth was less in sole maize than in maize intercropped with Gliricidia. Gliricidia had significantly (P = 0.05) lower root length density between 0 and 20 cm depth (ranging between 0.03 and 0.46 cm cm^{-3}) than between 20 and 90 cm at MZ12 and than between 20 and 170 cm depth at MZ21. Gliricidia root length density remained high up to 120 cm, but decreased below that depth.

Effect of N fertilizer the root distribution of Gliricidia and maize

Figure 5 showed the effects of N application rates on *G. sepium* and maize root abundance at Makoka (MZ12). The root abundance showed % root distribution for each treatment along the soil strata based on root counts on the profile wall, also know as root stratification. Differential root stratification was observed between maize

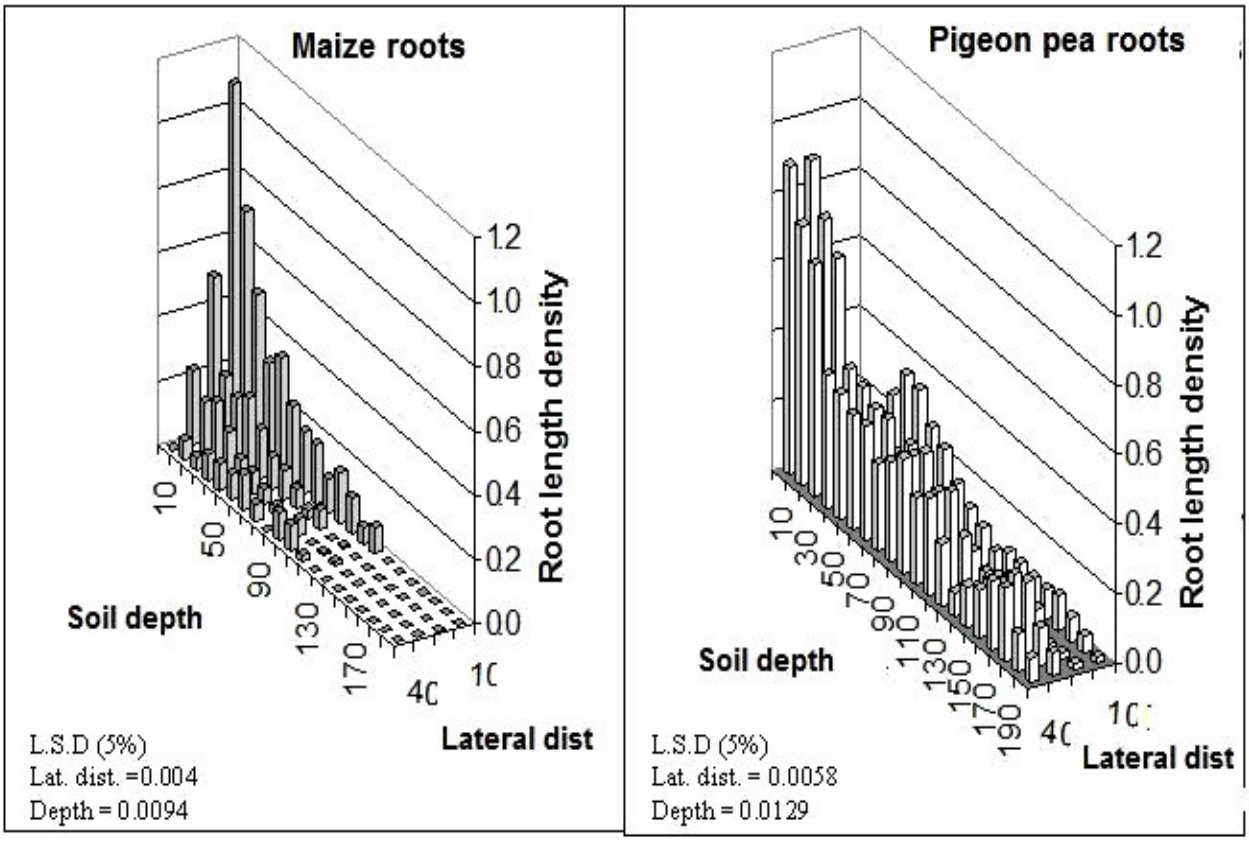


Figure 3. Variation in root length density (cm cm^{-3}) with soil depth (cm) and lateral distance (cm) from maize and pigeon pea plants in a maize-pigeon pea intercropping system (MZ12) at 63 days after planting.

and tree in the site and may explain the non-competitive association of *G. sepium* in Malawi. Gliricidia root counts were less than 10% at the top 20 cm compared to 32-53% for maize. The peak of Gliricidia roots occurred at 30 - 60 cm soil layer (Figure 5). Both roots of tree and maize were enhanced by N application.

Lateral spread of structural roots of Gliricidia

Structural root (>5 mm) diameters differed considerably between the central trees (net plot) and the boundary trees (Figure 6). The roots spreading outside the tree plot from the boundary trees were bigger (35.2 mm diameter) than the central trees (26.9 mm diameter). The roots of the central trees tapered from 26.9 cm to 6.6 cm within an average distance of 80 cm from the tree trunk whereas the average diameter of roots from the boundary trees at the same root length was 21.4 mm. The boundary trees spread as far as 400 cm away from the tree trunk whereas the central trees had a maximum spread of 110 cm (Figures 3). The angle between the primary root and taproot show whether the roots spread outwards or go deep into the soil. The smaller the angle the more the roots go deep into the soil. The angle between taproot and the primary roots of the central trees (49^o) was smaller than the roots spreading outside the tree plot (89^o).

Mineral N and P distribution

Figure 7 depicts soil mineral N (a) and Olsen P (b) distribution down the soil profile in the two cropping systems of MZ12 and MZ21 respectively. In Sole-Maize, less mineral N was found in 0 - 100 cm than in the subsoil (100 - 200 cm) of MZ12; the difference in soil mineral N between Sole-Maize and Gs-Maize was big in the layers between 0 and 100 cm, but not in the deeper soil from 100 - 200 cm. In almost all soil layers to 200 cm, mineral N was higher in Gs-Maize than in Sole-Maize. At MZ21, amounts of soil mineral N in the upper 50 cm were significantly (P = 0.05) larger in Pea-Maize, Gs-Maize, Gs-Pea-Maize than in Sole-Maize.

At MZ12 Olsen P was higher than at MZ21. At MZ12 Olsen P was higher in Gs-Maize than in Sole-Maize in the 0 - 40 cm soil layer, but lower at depths below 80 cm (Figure 7b). Olsen P was 9 kg ha^{-1} higher in Gs-Maize than in Sole-Maize in the upper 0 - 100 cm, but was 53 kg ha^{-1} lower in the subsoil (100 - 200 cm). At MZ21, Olsen P was lower in Gs-Maize than that in Sole-Maize and Pea-Maize. At both sites, Olsen P level decreased

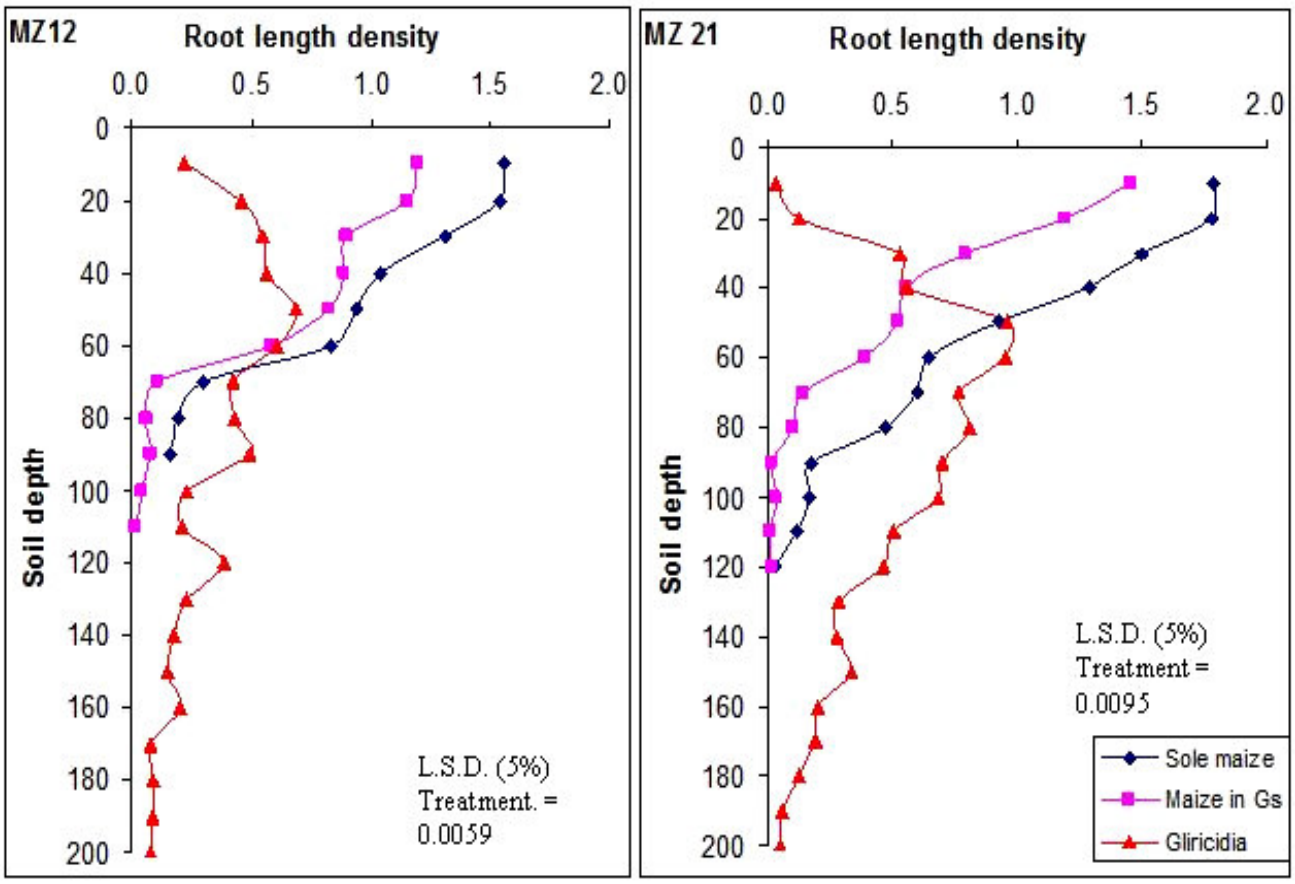


Figure 4. Variation in fine root length density (cm cm^{-3}) of maize and Gliricidia with soil depth (cm) at MZ 12 and MZ 21. L.S.D (5%) is for the log10 (n+1) transformed root length density. 'Maize in Gs' is root length density of maize intercropped with Gliricidia.

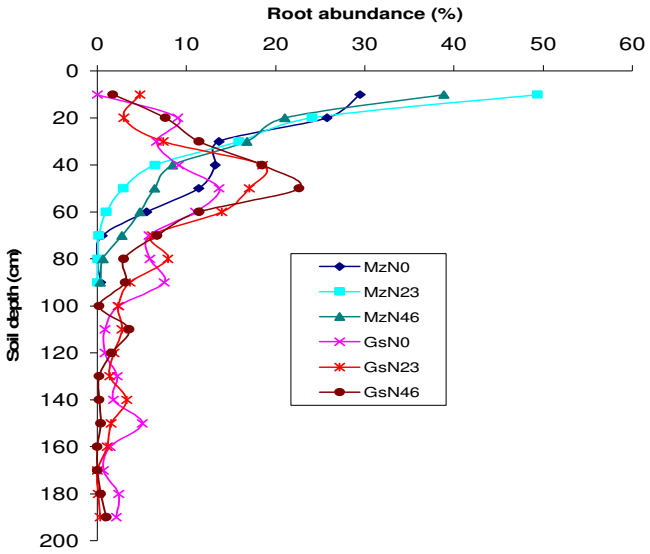


Figure 5. Effect of N application on root abundance of *Gliricidia sepium* and maize in simultaneous fallow intercropping system in MZ12 field plot at Makoka, Malawi (G = Gliricidia; M = maize; N = nitrogen fertilizer at 0, 23 and 46 kg N ha^{-1}).

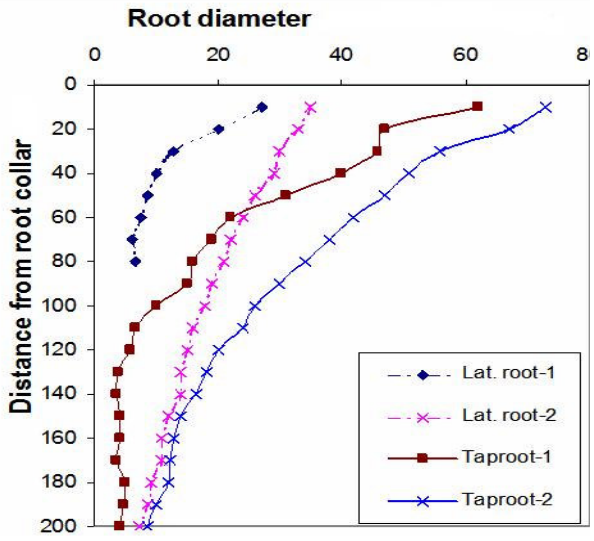
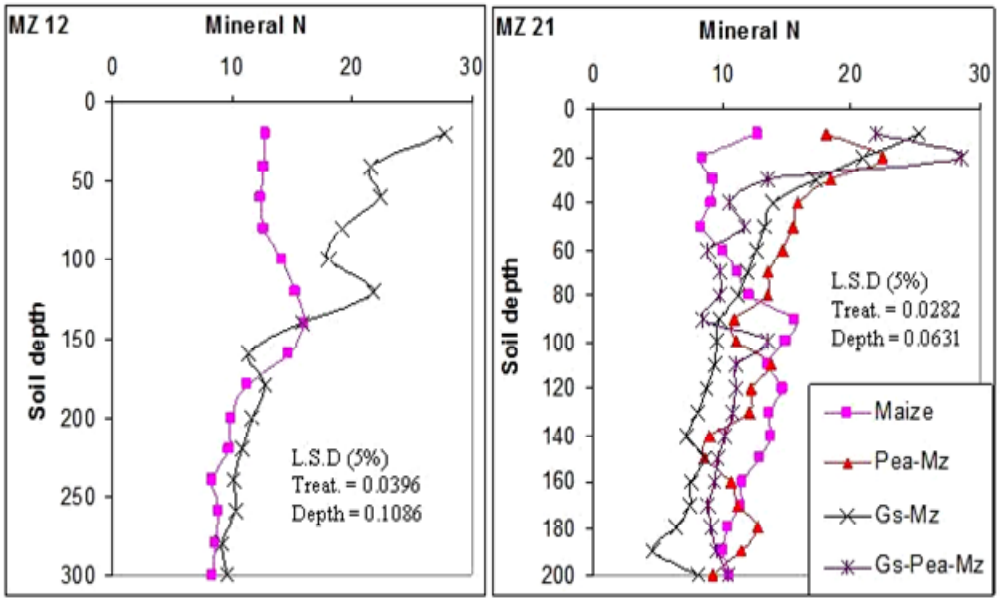
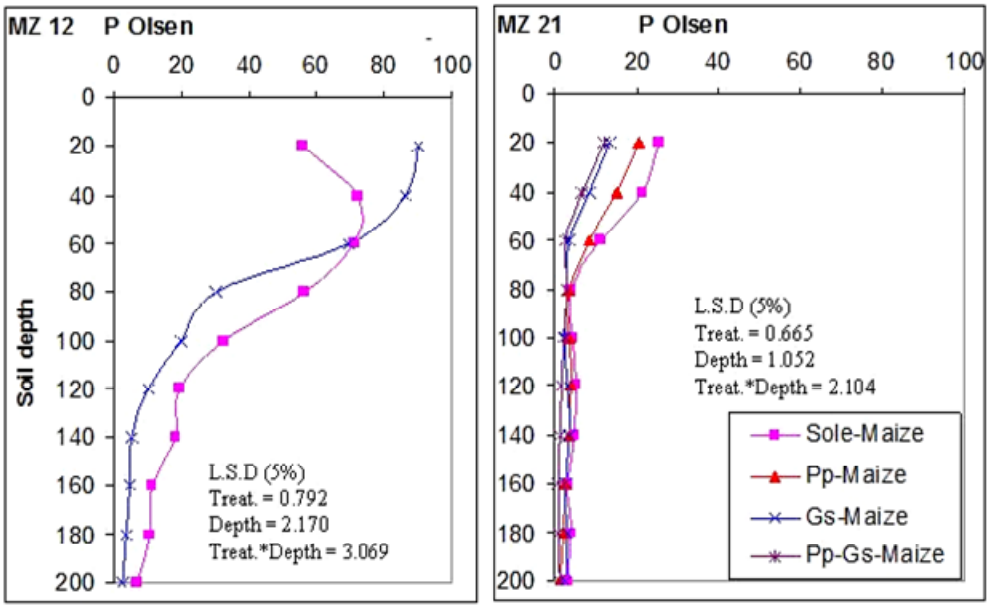


Figure 6. Variation in taproot diameter (mm per 10 cm length) and structural root diameter (cm per 10 cm) with distance from root collar for the border row and interior trees in a Gs-Maize intercropping system. Lat. root-1 and Taproot-1 are lateral and tap roots for the central trees and Lat. root-2 and Taproot-2 are for the border trees.



(a)



(b)

Figure 7. Variation in (a) Mineral N (kg ha^{-1}), and (b) Olsen P (kg ha^{-1}) with soil depth at MZ12 and MZ21 sites. At MZ12, sole-maize and Gliricidia-maize were compared, and at MZ21 sole-maize, Gliricidia-maize, pigeon pea-maize and pigeon pea-maize-Gliricidia. The L.S.D. (5%) is for log10 (n+1) transformed mineral N or Olsen P.

with depth but more in the Gs-Maize than in Sole-Maize.

DISCUSSION

Both Gliricidia and pigeon pea had deep rooting systems at the study site (Figures 2 - 4), and this explains why both legumes remained green during the dry seasons when most annual crops are dried. Although the maximum sampling depth in the study was 2.5 m, earlier excavation depth done in a nearby plot to the study site showed that *G. sepium* attained 5.6 m depth at Makoka, Malawi (Akinnifesi et al., 2004). Trees adapted to semi-arid conditions are well known for having deep root systems (Akinnifesi et al., 2004; Schroth, 1999). In general,

shallow rooted trees are a common place in strongly acidic soils and rooting depth is often dictated by mechanical soil impedance in drier soils (Akinnifesi et al., 2004). The abundance of tree roots at soil depths below the feeding zone of most annual crops may transfer more deep resources to the surface. This may also explain why Gliricidia often grows well and coppices during dry seasons or prolonged drought periods without signs of water stress in the sites.

The root length densities of maize in our study are comparable to the root length densities reported by other authors (van Noordwijk and Brouwer, 1991; Scroth and Zech, 1995) in simultaneous systems.

The patterns of tree root length density and root abundance were similar (Figures 4 and 5). Tree root length density typically shows an exponential decline with soil depth (Akinnifesi et al., 1999; Ruhigwa et al., 1992; Schroth and Zech, 1995). In general, Gliricidia had relatively low root length density at the top 0 - 30 cm, with root density averaging 0.5 cm cm^{-3} at both sites (Figures 4) and root abundance of less than 10% for Gliricidia (Figure 5), indicate relatively low potential competitiveness with maize. In a similar study, the root length density of 1.45 cm cm^{-3} at 0 - 20 cm depth reported for *Senna siamea* in Glidji, southern Togo (Vanlauwe et al., 2002), was much higher than Gliricidia in our study. This low root density of Gliricidia at the surface soil may be due to the possibility that (1) roots were unconsciously sloughed off when during tilling with hand-hoeing, (2) planting of maize on ridges and the trees in the furrows already brought tree roots to start growing at 30 cm below the ridge top, and (3) low spread of structural roots of the central trees in the surface (0 - 40 cm) due to suppression by intercropped maize which is a more aggressive N user. Similar result was reported by Schroth and Zech (1995) in which maize had higher root density in the surface soil than the Gliricidia trees. By contrast, Gliricidia had many roots distributed at deeper soil layers that were not explored by maize roots (Figures 4, 5 and 6). The trees that have their roots growing below the crop rooting horizon are beneficial in the sense that they can intercept leached nutrients that is, act as a "safety-net" (Akinnifesi et al., 2004; Rowe et al., 1999) and also capture nutrients from deep layers. In Gliricidia-maize alley cropping at Chitedze, Malawi, Itimu (1997) found root length density of maize of 0.94 cm cm^{-3} in the top 0 - 20 cm and of 0.13 cm cm^{-3} at 70 - 80 cm depth, whereas Gliricidia had between 400 and 0.50 cm cm^{-3} in the top 0 - 20 cm and more than 0.50 cm cm^{-3} below 40 cm. In alley cropping of *Grevillea robusta* and maize, Livesley et al. (2000) found that maize had 60% of its roots in the upper 0-30 cm and as little as 20% below 90 cm depth. In the current study, it is suggested that maize being a more aggressive N user may have forced Gliricidia roots downwards. Gliricidia may have altered its roots (plasticity) in order to explore available nutrients below root zone of maize. Such phenomenon is also noted for *Sesbania sesban* by Cadisch et al. (2002).

The structural roots from the border trees extended to 4 m into the neighboring plots without trees, whereas in cultivated plot Gliricidia roots are less vigorous (Figure 6). This suggests that Gliricidia can also obtain nutrients from the neighboring plots, but the root penetration to neighbouring plot is not as vigorous as that reported for *S. siamea* having lateral roots growing horizontally to feed in the neighboring plots as far as 9 m away (Rao et al., 1993). Because of the possible competition between the neighboring trees and also with the crop, the central trees develop fewer structural roots in the upper 0 - 40 cm and increase down the profile. It implies that cultivation and pruning management are sufficient to keep structural root development in check, but these roots can develop if plots are unpruned and are left to fallows, as observed for *Leucaena leucocephala* subjected to different management in Ibadan (Akinnifesi et al., 1995).

Growth rate of pigeon pea roots was lower than that of maize roots during the early growing stages (Figures 2 and 3). The fast root and shoot development of maize during the early growing stages (up to 42 DAP) gave maize a competitive advantage over pigeon pea for below ground and aboveground resources. After 63 DAP, pigeon pea roots and maize roots simultaneously occurred within the 0 - 60 cm soil layer. This root overlap suggests competition for soil resources between maize and pigeon pea during the second half of the maize growing period. In a Brazilian Podzol, Akinnifesi et al. (1999c) also found that 93% of the pigeon pea roots occurred between 0 - 60 cm soil layer where most of maize roots occurred. However, the data of maize yield (Makumba, 2003) indicate that maize was a stronger competitor than pigeon pea, as maize yields were higher in Pea-Maize than in Sole-Maize.

The decomposing pigeon pea roots apparently also contributed substantially to the amount of mineral N in the soil as reflected by high subsoil mineral N in Pea-Maize in February 2002 (Figure 7a). Our results suggest that competition by Gliricidia was stronger on the pigeon pea (secondary crop), than on the primary crop (maize) when the three are combined in the same system. This is because pigeon pea and Gliricidia have both spatial and temporal overlap in their rooting system. A short duration pigeon pea might more desirable.

The distribution pattern of soil mineral N with depth reflects in part the distribution of roots in the various systems, and the application of Gliricidia prunings and pigeon pea crop residues. The lower subsoil N in Gliricidia + Maize compared to sole maize plot indicates that Gliricidia recycles N leached N from the surface soil. Hartemink et al. (2000) found that after 10 months of establishment of Sesbania in an improved fallow, the trees decreased subsoil N (100 - 200 cm depth) by 45 kg ha^{-1} in an Oxisol and 52 kg ha^{-1} in Alfisol in Kenya. In another study Jama et al. (1998) reported a reduction of 150 to 200 kg NO_3 ha^{-1} in the top 0-200 cm soil in *Callian-*

dra callothyrsus and Sesbania planted fallows. These results confirm that Gliricidia trees recycle mineral N leached to soil depth beyond the maize rooting horizon. The increase in subsoil mineral N in Gliricidia-maize + Pigeon pea compared to Gliricidia-maize might be due to N mineralized from the decomposing pigeon pea roots. Pigeon pea had up to 0.33 cm cm^{-3} root length density at the top 0-200 cm depth, which upon decomposition might have contributed to increased amounts of mineral N in the soil. In this system pigeon pea is grown as an annual crop and each year a new crop is replanted. This implies that the roots of the previous crop decompose and release nutrients within the soil profile every year. Gathumbi et al. (2002) also found larger amounts of mineral N in the subsoil in a Pigeon pea fallow than in a Sesbania fallow.

At MZ12, the increase of Olsen P between 0 - 100 cm and decrease in the subsoil (100-200 cm) in Gs-Maize compared to Sole-Maize (Figure 7 b) suggests that the trees 'pumped' P from the deeper soils layers through their roots and 'deposited' it in the surface soil via the prunings and root turnover. Increases in Olsen P in 0 - 100 cm soil layer are smaller than the decreases in 100 – 200 cm soil layer probably because of the P removal via maize harvesting and some removal via the tree wood. The occurrence of pigeon pea and Gliricidia roots below the maize rooting zone at 0 - 200 cm depth, and the decrease of N and P in the deeper soil layer further confirm the idea of capturing and pumping leached nutrients from the deeper soils to the topsoil.

Conclusions

The study confirmed that Gliricidia is a suitable ideotype species for simultaneous tree-crop intercropping system in Malawi because of its low surface rooting, as well as its deeper and stratified roots in the study site. This low root density and the high maize yield potential under Gliricidia-maize intercropping system indicate that Gliricidia did not compete much with maize for underground resources. Furthermore, the increase of Gliricidia root density below the maize rooting zone enabled the trees (1) to intercept the nutrients leached beyond the rooting zone and (2) to explore 'native' soil nutrients from greater soil depth and to pump these nutrients to the surface.

In pigeon pea/maize intercropping system, maize was initially a stronger competitor for nutrients in the surface soil than pigeon pea because maize had a faster root development and a higher rate of above ground biomass growth rate than pigeon pea. After maize harvest competition is reduced and pigeon pea is more prone to the above ground competition with Gliricidia because Gliricidia is already well-established. Although the yield of pigeon pea is slightly reduced by intercropping with maize and Gliricidia, the overall benefit will continue to be attractive to farmers. In addition to increased maize yield farmers also value the edible seed from pigeon peas, which are an important source of protein and income.

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REFERENCES

Akinnifesi FK, Makumba W, Kwesiga FR (2006). Sustainable Maize Production using Gliricidia/maize Intercropping in Southern Malawi. Exp. Agr. 42:441-457.

Akinnifesi FK, Rowe EC, Livesley SJ, Kwesiga F, Vanlauwe B, Alegre J (2004). Tree Root Architecture. In: Ong C., van Noordwijk M, Cadisch G. (eds). Belowground Interactions in Tropical Agroecosystems: Concepts and models with Multiple Plant Components. Wallingford, UK: CAB Publishing, pp. 61-81.

Akinnifesi FK, Kang BT, Ladipo DO (1999a). Structural root form and fine root distribution of some woody species evaluated for agroforestry systems. Agroforest. Syst. 42:121-138

Akinnifesi FK, Smucker AJM, Kang BT (1999b). Below ground dynamics in agroforestry systems. Annals Arid Zone 38: 239-273.

Akinnifesi FK, de Araujo MA, Moura EG (1999c). Root distribution of *Cajanus cajan* and alley-cropped maize in response to inter-hedgerow spacing. Forest, Farm and Community Tree Res. Reports 4: 64-67.

Akinnifesi FK, Kang BT, Tijani-Eniola H (1995). Root size distribution of a *Leucaena leucocephala* hedgerows as affected by pruning and alley cropping. Nitrogen Fixing Tree Res. Reports 13: 65-69.

Akinnifesi FK, Makumba W, Sileshi G, Ajayi OC, Mweta D (2007). Synergistic effect of inorganic N and P fertilizers and organic inputs from *Gliricidia sepium* on productivity of intercropped maize in southern Malawi. Plant Soil 294: 203-217.

Cadisch G, Gathumbi SM, Ndufa JK, Giller KE (2002). Resource acquisition of mixed species fallows – competition or complementarity? In: Vanlauwe, B., Diels, J., Sanginga, N. and Merckx, R. (eds). Balanced Nutrient Management Systems for the Moist Savanna and Humid Forest Zones of Africa. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 143-154.

Cannell MGR, van Noordwijk M, Ong CK (1996). The central agroforestry hypothesis: the tree must acquire resources that the crop would not otherwise acquire. Agroforest. Syst. 34: 27-31.

Chirwa PW, Black CR, Ong CK and Maghembe JA (2003). Tree and crop productivity in gliricidia/maize/pigeon pea cropping systems in southern Malawi. Agroforestry Systems 59:265-277.

Chirwa PW, Black CR, Ong CK and Maghembe JA (2003). Nitrogen dynamics in cropping systems in southern Malawi containing *Gliricidia sepium*, pigeon pea and maize. Agroforestry Systems 67:93-106.

Fernandes ECM, Davey CB, Nelson LA (1993). Alley cropping on an acid soil in the upper Amozon: Mulch, fertilizer and hedgerow root prunings effects. Am. Soc. Agron. Spec. Publ. 56: 77-96

Gathumbi SM, Ndufa J, Giller KE, Cadisch G (2002). Do species mixtures increase above- and belowground resource capture in woody and herbaceous tropical legumes? Agron. J. 94: 518-526.

Hartemink AE, Buresh RJ, van Bodegom PM, Braun AR, Jama B, Janssen BH (2000). Inorganic nitrogen dynamics in fallows and maize on an Oxisol and Alfisol in the highlands of Kenya. Geoderma 98:11-33.

Ikerra ST, Maghembe JA, Smithson PC, Buresh RJ (1999). Soil nitrogen dynamics and relationships with maize yields in a Gliricidia-maize intercrop in Malawi. Plant Soil 211: 155-164.

Itimu OA (1997). Nitrogen dynamics and root distribution of Gliricidia

sepium and Senna spectabilis in maize (*Zea mays*)-based alley cropping systems in Malawi. Ph.D. Thesis. Department of Biological Sciences, Wye College, University of London, UK.
Jama B, Buresh RJ, Ndufa JK, Shepherd KD (1998). Vertical distribution of roots and soil nitrate: Tree species and phosphorus effects. Soil Sci. Soc. Am. J. 62:280-286.
Kowar GR, Radder GD (1994). Influence of root pruning and cutting interval of *Leucaena* hedgerows on performance of alley cropped *rabi* sorghum. Agroforest. Syst. 25:95-109
Livesley SJ, Gregory PJ, Buresh RJ (2000). Competition in tree row agroforestry systems. 1. Distribution and dynamics of fine root length and biomass. Plant Soil 227:149-161
Makumba WIH (2003). Nitrogen use efficiency and carbon sequestration in legume tree-based systems. A case study in Malawi. PhD Thesis. Wageningen University and Research Centre, Wageningen, The Netherlands.
Makumba W, Akinnifesi FK, Janssen B, Oonema O (2007). Long-term impact of gliricidia-maize simultaneous intercropping systems on carbon sequestration and soil properties. Agr. Ecosyst. Environ. 118:237-243.
Makumba W, Janssen B, Oenema O, Akinnifesi FK (2006). World Agroforestry Centre (ICRAF), Lilongwe (Malawi). Chitedze Agricultural Research Station. Influence of time of application on the performance of Gliricidia prunings as a source of N for maize. Exp. Agr. 42:51-63.
Miller AW, Pallardy SG (2001). Resource competition across the crop-tree interface in a maize-silver maple temperate alley cropping stand in Missouri. Agroforest. Syst. 53:247-259.
Mweta DE, Akinnifesi FK, Saka JDK, Makumba W, Chokotho N (2007). Green manure from prunings and mineral fertilizer affect phosphorus adsorption and uptake by maize crop in a Gliricidia-maize intercropping. J. Scientific Res. Essays 2(10): 446-453.
Rao MR, Muraya P, Huxley, PA (1993). Observations of some tree root systems in agroforestry intercrop situations, and their graphical representation. Exp. Agr. 29:183-194.
Rowe EC, van Noordwijk M, Cadisch G (1999). Testing the safety-net role of hedgerow tree roots by 15N placement at different soil depths. Agroforest. Syst. 43:81-93.
Ruhigwa BA, Gichuru MP, Mambani B, Tariah NM (1992). Root distribution of *Acioa bater, Alchonea cordifolia, Cassia siamea and Gmelina arborea* in acid Ultisol. Agroforest. Syst.19:67-78.
Schroth G, Zech W (1995). Above- and below-ground biomass dynamics in a sole cropping and alley cropping system with *Gliricidia sepium* in the semi-deciduous rainforest zone of West Africa. Agroforest. Syst. 31:181-198.
Schroth G (1995). Tree root characteristics as criteria for species selection and systems design in Agroforestry. Agroforest. Syst. 30:125-143.
Schroth G (1999). A review of belowground interactions in Agroforestry, focusing on mechanism and management options. Agroforest. Syst. 43:5-34.
van Noordwijk M, Brouwer G (1991). Review of quantitative root length data in agriculture.. In: McMicheal, B.L. and H. Persson (eds.). Plant roots and their environment. Elsevier publishers, Armsterdam, The Netherlands. pp.515-525
van Noordwijk M, Lawson G, Soumare A, Groot JJR, Hairiah K (1996). Root distribution of trees and crops: competition or complementary. In: Ong, C.K. and P. Huxley (eds.). Tree-crop interactions: A physiological approach. CAB international. Wallingford, UK, pp.319-364.
Vanlauwe B, Akinnifesi FK, Tossah TK, Lyasse O, Sanginga N, Merckx R (2002). Root distribution of *Senna siamea* grown on a series of derived-savanna-zone soils in Togo, West Africa. Agroforest. Syst. 54: 1-12.