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Roots, soil water and crop yield: tree crop interactions in a semi-arid agroforestry system in Kenya.

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Odhiambo[1], H.O., Ong[1], C.K., Deans[2], J.D., Wilson[2], J., Khan[1], A.A.H. and Sprent[3], J.I.

[1] International Centre for Research in Agroforestry, P. O. Box 30677, Nairobi, Kenya.

[2] Centre for Ecology and Hydrology, Bush Estate, Penicuik, Midlothian, EH26 0QB, Scotland, UK.

[3] Department of Biological Sciences, University of Dundee, Dundee DD1 4HN, Scotland UK.

Corresponding Author:-
Prof. C. K. Ong
International Centre for Research in Agroforestry,
P.O. Box 30677,
Nairobi,
Kenya

Telephone No.   (+254) 2 521 450
Fax No.   (+254) 2 521 001
Email   c.ong@cgiar.org

Abstract

Variations in soil water, crop yield and fine roots of 3 to 4 year-old *Grevillea robusta* Cunn. and *Gliricidia sepium* (Jacq.) Walp. growing in association with maize (Zea mays L.) were examined in semiarid Kenya during the long rains of 1996 and 1997. Even although tree roots penetrated more deeply than maize roots, maximum root length densities for both tree species and maize occurred in the top 200 mm of the soil profile where soil moisture was frequently recharged by rains. Populations of roots in plots containing trees were dominated by tree roots at the beginning of the growing season but because tree roots died and maize root length increased during the cropping season, amounts of tree and maize roots were similar at the end of the season. Thus, there was evidence of temporal separation of root activity between species, but there was no spatial separation of the rooting zones of the trees and crops within that part of the soil profile occupied by crop roots. Tree root length density declined with increasing distances from rows of trees and with depth in the soil profile. Although *Grevillea* trees were largest, plots containing *G. sepium* trees always contained more tree roots than plots containing *G. robusta* trees and *Gliricidia* was more competitive with maize than *Grevillea*. Overall, *Gliricidia* reduced crop yield by about 50% and *Grevillea* by about 40% relative to crop yield in control plots lacking trees and reductions of crop yield were greatest close to trees. There was less soil moisture in plots containing trees than in control plots. Such difference between control plots and plots containing trees were maximal at the end of the dry season and there was always less soil moisture close to trees than elsewhere in the plots. Plots containing *Gliricidia* trees contained less soil water than plots containing *Grevillea* trees.

Keywords: fine root dynamics, *Grevillea robusta, Gliricidia sepium*, *Zea mays*, soil moisture, crop yield.

Introduction

The most formidable problem in managing simultaneous agroforestry in drylands is how to retain the positive effects of tree canopies and roots on soil physical and chemical properties while reducing the negative effects of below-ground competition for limited resources (Schroth, 1995; Ong and Leakey, 1999). It is widely accepted that a better knowledge of below-ground interactions between trees and crops is needed before the real benefits of agroforestry associations can be fully exploited (Sanchez, 1995; Gregory, 1996; Rao, 1998). A key issue is the extent of complementarity, either spatial or temporal, in the location of tree and crop root systems. Huxley (1983) suggested that exploiting the different rooting depths of trees and crops could increase resource capture in agroforestry systems without introducing intense below-ground competition. Clumped distributions of tree roots within the soil, as seen in the proteoid roots of *Grevillea robusta*, might also reduce interspecific competition (Huxley et al., 1994). However, numerous studies have shown that most tree roots, especially those of fast-growing species, exploit the same soil depths as crop roots (Jonsson et al., 1988; Daniel et al., 1991; van Noordwijk et al., 1996), and the importance of root clumping remains uncertain.

Lack of information on below-ground dynamics occurs mainly because it is either too costly or too destructive for the conventional methods (soil cores, ingrowth cores and trench profiles) of fine root assessment to provide information on root production, mortality and longevity aspects at the necessary high frequency (Heereman and Juma, 1993; Gregory, 1996). The minirhizotron technique, where roots are studied through a transparent window or tube, is perceived as being cheaper, less destructive and more suitable for making repeated observations than root coring or root trenching and minirhizotrons have been used successfully in studying root growth and dynamics (Majdi, 1996).

Despite the above perceived advantages of the minirhizotron system, there are only a few reported instances of its application in agroforestry. Smucker et al. (1995) measured root distribution at Ibadan, Nigeria, throughout the growing season in a seven-year old *Leucaena leucocephala* / maize alley cropping system and observed maximum root growth two months after maize planting and least maize roots adjacent to the *Leucaena* hedgerows. Root numbers began to decline three months after maize planting and maize roots dominated the soil profile. About 50-65 % of the roots disappeared during the dry season.

Smucker et al. (1995) calculated that as much as 193 kg ha^{-1} of N was recycled from root turnover of both maize and *Leucaena* during each growing season. Akinnifesi et al. (1999) concluded that there was little root competition between trees and crops like maize and cowpea, even where 60 % of *Leucaena* root length occupied the crop- rooting zone of 0 - 600 mm depth. It seems possible that the overall benefit of nutrient cycling through root turnover and pruning may exceed the effects of below-ground competition in humid environments. However, there appears less opportunity for such benefits from root turnover in drylands. In semiarid Kenya, the contribution to soil nitrogen made from root turnover of *Leucaena* hedges was only 7 kg ha^{-1} compared to 40 kg N ha^{-1} available from shoot prunings (Govindarajan et al., 1996). Similarly, contributions to soil N via root turnover from two year-old *Gliricidia sepium* hedgerows in sub-humid Cote d'Ivoire were small (15 kg ha^{-1}) *i.e.* only a tenth of the above-ground contribution (Schroth and Zech, 1995).

The overall objective of this study was to determine whether competition with crops by *Grevillea robusta* Cunn. and *Gliricidia sepium* (Jacq.) Walp. in semi-arid Kenya, is associated with their fine root distribution and dynamics. These species differ in their leafing phenologies and their nutrient acquisition strategies. Whereas *Grevillea* maintains leaf cover throughout the year, *Gliricidia* leaf canopies are maximal in the long rains but become

leafless in the subsequent dry season. Leaf production begins again about the start of the short rains. *Grevillea* has proteoid or cluster roots that release exudates into the soil (Skene et al., 1996) and which may enhance uptake of nutrients with low solubility (Dinkelaker et al., 1995). *Gliricidia* is a well known N-fixing species. *Grevillea* is considered by farmers in the highlands of East Africa to be an outstanding agroforestry tree (Tyndall, 1996). It is believed to be deep rooting and to possess few superficial lateral roots (Laycock and Wood, 1963; Mwihomeke, 1993). Recent sap flow studies in roots have shown that its root system is capable of extracting 80% of its water from below the crop rooting zone which suggests good potential for below-ground complementarity (Howard et al., 1997; Lott et al., 1996). *Gliricidia* is commonly used in agroforestry in the tropics because of its highly valued fodder. It also provides good quality mulch which raises crop yield to amounts similar to that obtained from compound fertiliser (Kormawa et al., 1999). Studies on alley cropping in the tropics indicate that *Gliricidia* is relatively uncompetitive when pruned regularly (Rao et al., 1993; Schroth and Zech, 1995; De Costa and Chandrapala, 1999) but results from semi-arid Kenya showed that on a whole tree basis, unpruned *Gliricidia* diminished crop yield further than *Grevillea* (Rao et al., 1998). Because in previous (unpublished) studies at this site, *Gliricidia* and *Grevillea* of the same dbh appeared to transpire water at about the same rate but *Gliricidia* is more competitive (Rao et al., 1998), their differential competitiveness might be associated with differences in the manner in which their roots exploit the soil profile, hence their selection for this study.

Materials and methods

Study site

The study was conducted at ICRAF's field station at Machakos, Kenya (1° 33'S and 37° 8'E) at a mean elevation of 1660 m. The annual rainfall averages 740 mm and occurs bimodally.

The duration of the wet seasons differ; the long rains fall between March and July, and the short rains between October and February with total precipitation being approximately equal in both seasons. Traditionally, maize is grown in the long rains season and beans are grown in the short rains season.

Soils are well-drained dark brown sandy clays, derived from basement complex gneiss. They are classified as haplic lixisols (FAO-UNESCO) or kandic rhodulstalfs (USDA soil taxonomy). These soils are weakly to moderately leached with a pH of 6 to 6.5 and possess medium base saturation (50 to 80 %) in the topsoil. Nitrogen and phosphorus contents are less than optimal but like other nutrients, are considered adequate for growth (Mathuva et al., 1998).

Plant material and experimental design

Measurements were made in the Roots and Competition (RAC) trial established in April 1993 by ICRAF which contained eight different tree species. For reasons given above, *Grevillea robusta,* and *Gliricidia sepium* were selected for study. The trees were pruned to leave branch free stems to a height of about 2.5m which mimics current farmer practice for pole production. All plots were planted with maize (*Zea mays* L.) in the long rains and with beans (*Phaseolus vulgaris L.*) during the short rains. In addition, there was a crop only treatment that lacked trees (control) but which was also planted with maize in the long rains and with beans during the short rains. The study site comprised a randomized complete block design with 4 replicate blocks. Each block had one plot containing a single row of trees for each tree species, as well as a single plot containing the control treatment. The experimental trees (21 per plot) were planted at 1 m inter-tree spacing in a single line across the centre of each 20m by 18 m plot. The lines of trees were oriented east/west to minimise

shading of the crop plants. Neutron probe access tubes were installed in each plot (including controls) in three of the four replicate blocks.

At the beginning of each wet season, 1 to 2m deep trenches (depending on depth to bedrock) were dug at the margins of each plot to stop roots from one plot penetrating into and exploiting adjacent plots. The current study lasted from the long rains in 1996 to the long rains of 1997 inclusive. However, the intervening short rains bean crop failed because of drought. Consequently, studies focused on the two seasons of maize growth. A local short duration variety, 'Katumani composite' that can be harvested in advance of the dry period that occurs in Machakos towards the end of each long rains season was used. Maize seeds were planted, 2 per hole at 250 mm spacing within rows which were parallel to the lines of trees and at 1 m spacing between rows on 13 March 1996 and 2 April 1997. The first row of maize was located 1 m from tree stems and the last one 9 m from trees. Four weeks after planting, maize seedlings were thinned to leave only one plant per planting hole. All cultivations were by hand tools which mimics farmer practise and caused minimal disturbance to tree roots. Similarly, each season, weeds were controlled by cutting/uprooting them with hand tools on 2 occasions after crop germination.

Tree and crop growth

Tree stem height and diameter at breast height (dbh) were measured at intervals of 8 weeks from planting in December 1993 until August 1997. In plots containing trees, crop emergence (germination) was monitored by counting the number of emerged seedlings in the central 6 m section of each of rows 1 to 6 on both sides of the trees 2 weeks after sowing. In control plots, the number of emerged seedlings was counted on 6 m lengths of the 12 central rows. In each plot containing trees, and at equivalent locations in control plots, two maize plants were harvested from each side of the trees in each of rows 1, 2, 4, 6 and 8 on 16 April,

15 May, 22 May, 15 June and 20 July 1996, and on 15 May, 15 June, 24 June and 28 July 1997. Maize plants were separated into components (leaves stems etc) before drying at 75°C to constant weight. To prevent plant removal from the trial influencing growth of the remaining plants while at the same time minimising edge effects, on each sampling occasion, the two harvested crop plants were successively removed from the western end of each row.

Soil moisture

Soil moisture was measured between 350 mm and 1800 mm depth by a neutron probe (Didcot Instrument Co Ltd, Abingdon, UK). The neutron probe access tubes were installed on the southern side of the tree rows in 1994 at distances of 1.5, 2.5, 3.5, 4.5, 5.5 and 6.5 m perpendicular to each row of trees. Access tube insertion depth varied between 1400 and 1800 mm and was determined by depth to impenetrable bedrock. Measurements were taken at intervals of approximately two weeks in all treatments. In control plots, measurements were made at 3 positions near the plot centre. Details of the configuration of access tubes and calibration of the neutron probe are given in Odhiambo et al. (1999). In one block of the trial, soil moisture in the top 400 mm of the profile was also recorded by time domain reflectometry equipment, (TDR probes and Tektronix cable tester, Campbell Scientific Ltd, Shepshed, UK). Readings were taken every 20 minutes from sensors located 3, 4.5 and 6 m from rows of trees at depths of 200, 300 and 400 mm below ground. TDR sensors were also located at the same depths near the centre of a control plot. Data were averaged every 6 hours and stored in a Campbell Scientific Ltd. 21X data logger.

Root Cores

At monthly intervals during the 1996 cropping season, soil/root cores were extracted to depths of 1250 mm at distances of 1.5, 3 and 4.5 m from tree rows on four occasions using a sharpened steel corer of 100 mm internal diameter (2 replicates for each position in each plot). After extraction, the 0 to 500 mm section of the core was separated into 100 mm depth sub-samples and the remainder of the core was allocated to 250 mm depth sub-samples. All core sub-samples were then carefully washed out over a 0.5 mm sieve. For further details of root storage, processing, quantification and discrimination between species, see Smith et al. (1999).

Treatment of data

To satisfy the requirement of homogeneity of variances for analysis of variance (ANOVA), data from root cores were log_{10} transformed prior to ANOVA. However, data presented in Figures are untransformed values. In all analyses, results were accepted as significantly different when $p \leq 0.05$.

Results

Tree size

At planting in 1993, mean tree sizes, *c* 1 m tall and *c* 20 mm diameter at breast height (dbh) were similar for both tree species. However, by the start of the long rains in 1996, *Grevillea* was about 6m in height with mean dbh of 140 mm, both of which were significantly (p#0.05) larger than the 4.6 m height and 100 mm dbh of *Gliricidia*.

Rainfall and crop growth

Rainfall at the site was below average (235 mm and 320 mm) in the two rainy seasons studied and the second study season followed a crop failure in the intervening short rains when only 168 mm of rain fell at the site (Figure 1).

In general, crop plants situated close to trees were smaller than those located further from trees and such differences were apparent very early in the growing season. At the onset of the long rains in 1996, a period of 2 weeks without rain followed sowing of the crop. Lack of rainfall significantly (p#0.001) slowed germination of maize seeds (Figure 2) that had been planted close to the trees. Subsequent rainfall permitted full germination and emergence of the crop, but growth and development of maize plants close to trees was retarded relative to that of plants located further from trees and in control plots.

Overall, above-ground biomass of crop plants increased as distance from rows of trees increased (p#0.001) and crop plants were larger in control plots than in plots containing trees. Figure 3 illustrates maize dry biomass at two plant growth stages during the 1997 season. The majority of the maize plants in the row closest to trees had either become moribund, or had died by the "anthesis" stage of growth and these plants were excluded from the sampling.

There was a trend for maize grain yield per unit area to be smaller in plots containing trees than in control plots, but differences were not statistically significant (p= 0.10 and 0.086 in 1996 and 1997 respectively). Although average maize grain yield in the plots containing *Gliricidia* trees was consistently smaller (49 and 47% of control) than yield in plots containing *Grevillea* trees (58 and 56% of control), differences in grain yield obtained from plots containing differing tree species were not significantly different from each other. Within 3 m of trees, grain yield was severely depressed (p#0.02) relative to yield at plot edges and to yield obtained in control plots (Figure 4). As distance from the tree rows increased, grain yield increased faster in plots containing *Grevillea* trees than in plots

containing *Gliricidia* trees, but with both species and in both years, at a distance of 8 m from trees, yields were similar to those obtained in control plots.

Soil water

Figure 5 illustrates volumetric soil moisture content variation with depth in soil and distance from trees averaged over the period from crop sowing to crop harvest for the 1996 maize season. Patterns for 1997 were similar and are not presented. Proximity of bedrock reduced apparent soil moisture content at depth in one of the blocks. This effect can be seen in the relatively sudden reduction of volumetric soil water content at depths exceeding 1350 mm in Figure 5. To aid interpretation of Figure 5, a simplified form of presentation is given in Figure 6 which illustrates average values for soil moisture in all blocks to a depth of 1350 mm in control plots and at differing distances from trees. Control plots always contained more soil water than plots containing trees (7% more and 4% more for *Gliricidia* and *Grevillea* respectively), and plots containing *Gliricidia* trees always contained less water than plots containing *Grevillea* trees. These differences between control plots and plots containing trees occurred throughout the soil profile (Figure 5). Even in the dynamic surface horizons, there was always more water in control plots than in plots containing trees (Figure 5). Although there was a trend of increasing soil moisture as distance from trees increased, the significance of differences between treatments depended on the particular sampling occasion and the intensity and timing of rainfall. Where soils had been recently wetted by rain, differences were minimized. There was significantly ($p\#0.01$) less water in soil profiles close to trees than at plot edges soon after sowing in 1996 and also when crop plants were at the flag leaf stage of growth. During grain filling, the probability of there being no effect of distance from trees on soil moisture content was 0.070. There was no significant depth by treatment interaction which indicates that patterns of soil wetting and drying were similar on

tree and control plots but close to *Gliricidia* trees, soil was frequently significantly (p#0.001) dryer than soil in control plots.

Averaged over all sampling dates and seasons, volumetric soil moisture content increased with increasing distances from trees (p#0.001) and was significantly less (p#0.001) in plots containing *Gliricidia* trees than it was in plots containing *Grevillea* trees. There was no significant species x distance from trees interaction and no significant difference in mean soil moisture between years (Figure 6).

Root distribution in soil/root cores

Irrespective of species, tree root length density declined with increasing distances from rows of trees (p#0.02, Figure 7, Table 1). Fine root concentrations for both trees and maize were maximal in the top 200 mm of the soil profile and declined as depth in soil increased (p#0.05 to p#0.001; Figures 7 and 8). Patterns of growth and mortality of fine tree and maize roots differed during the season (Figures 7 and 8). Whereas maize root length density initially increased as the plants developed in the field during 1996 (Figure 8), concurrently, mortality was the dominant process for tree roots. Tree fine root length declined by 71% and 54% for *Gliricidia* and *Grevillea* respectively between April and July 1996. However, by 26 April, maize stem diameter and leaf number were maximal and height growth had almost stopped, (data not presented). Therefore most vegetative crop growth took place when tree root length densities were close to maximal. Nevertheless, even although tree roots dominated total root length during the early phases of maize development, by the end of the season, there were approximately equal amounts of tree and crop roots in the plots and there was no significant difference in amounts of maize roots colonising control or agroforestry plots (Figure 9). At the beginning of the season, there were significantly more *Gliricidia* roots than *Grevillea* roots and differences in root length density between tree species were greatest close to trees

(p#0.001). However, because mortality of *Gliricidia* roots was greatest, by May, there was no significant difference in tree root length density in plots occupied by the two tree species (Table 1). Nevertheless, during 1996, tree root length density in plots containing *Grevillea* was on average 30% less than in plots containing *Gliricidia*.

Discussion

Crop growth

The presence of trees significantly inhibited germination of maize seeds that had been planted in close proximity to them. Although rainfall interception by tree canopies would reduce moisture input to soil in the vicinity of trees, rapid water uptake by the dense canopy of pre-existing tree roots which shallowly colonised soil near to the tree rows would exacerbate soil moisture shortages and thus contribute to the delay in germination, see below, as well as Ong et al. (1999). Thus, irrespective of any further competitive effect of trees on crops, delayed germination dictated that maize plants close to trees were almost always smaller and at an earlier stage of development than those growing at greater distances from trees and in plots lacking trees. Delayed germination probably contributed to depressed grain yield close to trees. Yamoah (1991) found that in narrow cropped alleys (4m wide) situated between *Sesbania* hedgerows, germination of maize was reduced by about 50% and even when replanted, subsequent growth of maize was extremely poor. Yamoah (1991) felt that shading and damage by birds were largely responsible for the poor performance of the maize. However, shading *per se* is unlikely to have delayed germination at Machakos. Germination occurred in two phases, seeds located at distances in excess of 4m from trees germinated quickly, but germination of seeds planted close to trees did not occur until rainfall resumed after two weeks without rain. Delayed plant development can be crucial for grain crops like maize when rainy seasons are short. Where soils dry toward the end of the growing season as here, there may be insufficient water available to permit grain maturation

and ripening in plants that germinated slowly, even where vegetative growth was satisfactory. Yamoah (1991) reported grain yield reductions in excess of 80% in his trial where initial germination and subsequent growth were poor. Surprisingly, in the current study, there was no significant difference in overall grain yield between control plots and plots containing trees when the land planted with trees was excluded. The absence of significant differences in grain yield between treatments reflects the substantial variability in yields from the different plots, rather than absence of effects of trees on crop growth, because maize above ground biomass was significantly greater in control plots than elsewhere. Crop growth in plots containing *Grevillea* trees was almost always better than in plots containing *Gliricidia* trees, but despite the consistency of differences, crop yields in plots containing differing tree species did not differ significantly ($p>0.1$). However, Huxley (1999) cautions that in agroforestry, the rigorous application of statistical acceptance levels ($p=0.05$ or less) may be inappropriate, because in comparison with simpler crop trials, conditions are inevitably more variable in agroforestry. Nevertheless, had there been a larger number of replicates, or smaller plots, it seems likely that it would have been possible to conclude that *Gliricidia* was more competitive than *Grevillea*. This opinion is supported by the contention of Rao et al. (1993), Schroth and Zech (1995) and De Costa and Chandrapala (1999) that unless pruned, *Gliricidia* can be competitive when grown with crops. Even though the *Grevillea* trees grew fastest and were much larger than the *Gliricidia* trees, the production of maize above ground dry biomass was significantly larger in plots containing the former. This more general result supports the view of farmers that *Grevillea* competes less with crops than some other tree species do (Tyndall, 1996), and demonstrates the potential for the selection of trees for simultaneous agroforestry on the basis of their competition with crops. This result is extremely important for farmers cultivating small plots of land where high tree spacing density prevails. It also confirms work in semi-arid Nigeria

(Jones et al., 1998) and interestingly, in that study too, the least competitive tree species (*Prosopis juliflora*) grew fastest.

Soil water

Amounts of soil water were usually smaller close to trees than in control plots or at greater distances from trees. However, it was not surprising that such differences were not always statistically significant. Where large amounts of rain occurred immediately prior to recording, differences were minimised and sometimes insignificant. Even so, differences regained significance as plant water uptake dried soils and they were most evident in close proximity of trees at the time of crop seed sowing. Similar effects of proximity to trees on soil moisture content have been found previously (Malik and Sharma, 1990; Onyewotu et al., 1995). Livesley et al. (2000a) working in linear agroforestry systems at a wetter site in western Kenya reported that *Grevillea robusta* maintained as upperstorey poles used more soil water than *Senna spectabilis* trees which were maintained as severely pruned hedges. In their plots containing *Grevillea* trees, there was less water close to trees than at greater distances from them. Surprisingly, at 750 mm from *Senna* hedges, there was as much soil water as elsewhere in the plots, but soil moisture decreased between 750 and 3000 mm from *Senna*. Increases in soil moisture close to managed hedges relative to elsewhere seem quite common (Lal, 1989; Mazzarino et al., 1993; Chirwa et al., 1994; Govindarajan et al., 1996), and have been variously ascribed to reduced evaporation, improved moisture penetration and increased presence of organic matter which improved soil water holding capacity. However, intuitively, where soil moisture removal by plants rather than by evaporation, surface runoff or drainage is the main source of soil moisture removal, a trend of decreased soil moisture content in proximity of trees will develop. The effect will be most evident during dry seasons when rainfall does not influence patterns and where trees/hedges retain some of their

leaves (Namirembe, 1999). Thus it seems inevitable that at the onset of the rains, stored water will be at a minimum close to trees whether they are hedged or not, and there can be immediate consequential effects for crops grown simultaneously with them as evidenced from the delayed germination of maize.

Overall, there was significantly less water in plots containing *Gliricidia* trees than in plots containing *Grevillea* trees. As expected, crop only control plots contained the most water which supports previous work at Machakos (Govindarajan et al., 1996; Smith et al., 1999) and elsewhere in Kenya (Livesley et al., 2000a). That there was more water in the *Grevillea* plots than in the *Gliricidia* plots from the start of the study, reflects the historically greater use of water by the latter prior to the commencement of this work. Thus, although the deciduous *Gliricidia* trees were smaller than the evergreen *Grevillea* trees, *Gliricidia* trees used more water than *Grevillea* trees which probably reflects the larger canopy of leaves carried for much of the time by *Gliricidia*. This result contrasts with earlier (unpublished) results from Machakos where transpiration by *Gliricidia* and *Grevillea* were similar when the trees were younger and of similar dbh. It seems possible that the large proportion of juvenile and immature leaves carried when the trees were younger and smaller may have diminished the opportunity for differences in water use per unit stem cross-sectional area to become manifest at that time. Juvenile leaves have poorer stomatal control than maturer leaves (Leverenz et al., 1982).

Root distribution

In stark contrast to Jones et al. (1998) and Smith et al. (1999) who found that tree roots dominated agroforestry plots at all times, in this study, tree roots were only the most numerous (lengthy) about half of the time. They dominated root populations at crop planting, but by harvest, there were approximately as many crop roots as tree roots in the

plots and there was no difference between amounts of crop roots colonising control plots and plots containing trees. This result is a consequence of the fact that whereas the crop roots grew and developed during the rainy season, concurrently, roots of both tree species died. While this result was surprising, tree root mortality was also the dominant process during the rainy season in hedged *Senna* plots at Machakos (Namirembe, 1999), and in *Grevillea* and *Senna* agroforestry plots in western Kenya (Livesley et al., 2000b) and, as in this study, root mortality was greatest near the soil surface where tree root concentrations were greatest. The presence of gramineaceous roots in proximity to those of trees can have detrimental effects on tree root growth and distribution, as well as on tree phenology. Howard (1925), Eastham and Rose (1990) and Schroth (1995) found that the presence of gramineaceous roots depressed tree root growth near the soil surface and in consequence, to some extent, tree roots exploited deeper layers. Results from the current study suggest that the presence of maize roots could have inhibited tree root growth which contrasts with results from Smith et al. (1999) who found that *Grevillea* roots displaced maize roots from surface horizons. However, in the latter study, tree spacing density, 5 m x 5 m, was much greater than in the current study and the soil was much shallower, which offered less opportunity for spatial separation between roots of the two species. The effect of tree spacing density on tree root distribution can be clearly seen in the studies of Jones et al. (1998) and Smith et al. (1999). Jones et al. (1998) found no pattern of distribution of tree roots relative to distance from trees and the latter found greatest tree root distributions at intermediate distances between trees. These results arise because trees were planted so closely together that patterns of lateral tree root distribution were obscured by the overlapping of adjacent tree root systems. By contrast, in both our own and most other studies in linear agroforestry where adequate separation of rows of trees occurs, there is a clear pattern of decreasing tree root length density with increasing distance from rows of trees and as a result, crop growth appears

inversely related to tree root spacing density. In this study, in plots containing trees, patterns of maize root spacing density mirrored those of maize growth above ground and spacing density of maize roots increased with increasing distances from tree rows. However, because above ground biomass of maize was smaller in plots containing trees and amounts of crop roots colonising plots containing trees and control plots did not differ, maize plants in plots containing trees must have partitioned more assimilates below ground than they did in control plots. This result suggests a direct effect of trees on crop C partitioning below-ground, probably because of the need to increase water and nutrient uptake.

Patterns of variation in root distribution with soil depth reported here are in agreement with most published studies but overall, root length density in this study was smaller than in other comparable studies. Maxima were 6.9, 3.8, 1.8 and 2.1 km m^{-3} for *Gliricidia* roots, *Grevillea* roots, maize roots in plots containing *Gliricidia* trees and maize roots in plots containing *Grevillea* trees respectively. These figures approximate only 25% and 40% of the root length density for *Grevillea* and maize respectively reported by Smith et al. (1999) and 70% and 20% of the concentrations found by Livesley et al. (2000b). The comparatively large tree root length density (17 km m^{-3}) for *Grevillea* reported by Smith et al. (1999) reflects the close inter tree spacing in that study. Values of root length density reported here and in the study by Livesley et al. (2000b), both of which utilised linear tree planting systems, are broadly comparable for *Grevillea* but contrast strikingly for maize. Greater maize growth at the site studied by Livesley and co-workers, probably reflects the much greater rainfall and better soil fertility which positively influenced maize growth in their study.

Roots in minirhizotron windows

In this study, root observations were made in minirhizotrons based on a design by Gijsman (1991). However, despite the fact that observation tubes had been installed for up to 3 years, very few observation windows became colonized by roots. It seems likely that this was related to the small root length densities found in this study. The paucity of data precluded a comprehensive analysis but nevertheless, some interesting data were collected. Some tree fine roots that were produced in 1995/1996 were still alive at the end of 1997 and thus, tree fine root turnover rates appeared smaller than anticipated. Each season, there was a single period of rapid tree fine root growth that more or less coincided with the onset of the rains but thereafter, root growth was detected infrequently. This pattern of root activity supports previous observations by Atkinson (1983) where a single growth period was followed by slow senescence. For maize roots, minirhizotron studies were less useful than soil/root cores because maize roots colonised even fewer minirhizotron windows than tree roots and the majority of the maize roots that did appear in minirhizotron windows, rapidly grew across them and their root tips then disappeared into the bulk soil. Lateral roots that emerged from such visible maize roots were rare and thus apart from being able to tell whether they were alive or not, these roots produced data which were of little value in the study of root dynamics. Namirembe (1999) also found poor colonisation of minirhizotron windows in agroforestry trials utilising hedged and unhedged *Senna spectabilis* trees which were grown with maize. Only 7.5% of Namirembe's 720 minirhizotron windows yielded usable sets of photographs. Thus, it seems likely that there is a minimum root length density below which it is inadvisable to utilise minirhizotrons in the study of root dynamics.

Conclusions

There was little evidence of complementarity of resource sharing in this study. Both tree species competed for resources with the crop plants. Despite being smaller than *Grevillea*

trees, *Gliricidia* trees produced larger numbers of roots and depressed crop yield to the greatest extent. They also used more water than *Grevillea* trees suggesting that competition for water was the most important interaction between the trees and crops.

Crop yield depression was greatest when crop plants grew close to rows of trees. In the immediate environs of tree stems, tree roots always formed the greatest fraction of the root population, however, elsewhere in the agroforestry plots, tree roots comprised the largest fraction of roots only at the beginning of the cropping season. At crop harvest, root length densities of tree and crop roots in agroforestry plots were similar and there were similar maize root length densities in agroforestry plots and in control plots. The growth of maize roots may have had a detrimental effect on tree roots because root length density for trees decreased concurrently with increasing maize root length density when conditions for tree root growth were apparently favourable. Between the start and end of the rainy season, populations of *Gliricidia* and *Grevillea* roots declined by 71 and 54% respectively when grown in plots containing maize.

For much of the growing season, there was less soil moisture in plots containing trees than in control plots which lacked trees. Differences were maximal at the beginning of the rains. In close proximity to tree stems, shortage of soil water may have delayed germination by about two weeks. Consequently, crop plants growing close to trees were always at an earlier stage of development than crop plants further away from the trees. Such retardation of development could be crucial for grain production in semi-arid zones where rainy seasons are frequently truncated.

Tree root length densities decreased with increasing distance from stems and conversely, crop root length density increased with increasing distances from trees. Root concentrations of both tree and crop roots decreased with increasing depth in the soil profile. Tree and maize roots were most heavily concentrated in surface horizons and potential for

inter specific competition for below ground resources was evident. Although there was some temporal separation of root growth for tree and crop roots, (tree roots declined concurrently with maize root expansion), because there were always at least as many tree roots as crop roots in agroforestry plots, potential advantages accruing to either the tree or the crop are likely to be small. Consequently, competition for resources rather than complementarity in resource sharing seems likely to be the commoner process in dryland agroforestry.

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Table 1. Analysis of variance table for tree root length density taken from agroforestry plots containing either *Grevillea robusta* or *Gliricidia sepium* trees grown with maize in semi-arid Kenya during the long rains of 1996.

Test	Probability			
	15th April	15th May	15th June	15th July
Distance from tree	0.001	0.019	0.129	0.045
Depth below surface	<0.001	<0.001	<0.001	<0.001
Distance x depth	<0.001	0.006	n.s.	n.s
Species	<0.001	n.s.	0.058	n.s.
Distance x species	n.s.	n.s.	n.s.	n.s.
Depth x species	n.s.	0.015	n.s.	n.s
Distance x depth x species	n.s.	n.s.	n.s.	n.s.

n.s. = not statistically significant

Captions to Figures

Figure 1. Rainfall received during the study period (bars) and longer term (1963-1971) averages (▲) for rainfall at Machakos, Kenya. The approximate timings of maize and beans growing seasons are shown.

Figure 2. Germination of maize seeds 2 weeks after planting in control plots lacking trees and at 1 metre intervals from single rows of *Grevillea robusta* and *Gliricidia sepium* trees at Machakos in semi-arid Kenya. Error bars indicate the standard error of the differences between the means.

Figure 3. Above ground dry biomass of maize plants at anthesis and milk stage in 1996 when grown in control plots lacking trees and at differing distances from rows of *Grevillea robusta* and *Gliricidia sepium* trees at a semi-arid site in Kenya. Error bars indicate the standard error of the differences between the treatment means.

Figure 4. Maize grain yield during 1996 and 1997 in control plots lacking trees and at differing distances from single rows of trees in plots containing *Grevillea robusta* or *Gliricidia sepium* trees at Machakos in semi-arid Kenya. Error bars indicate the standard error of the differences between the means.

Figure 5. Mean soil moisture content over the cropping season in control plots lacking trees and at differing distancesand depths from single rows of trees in plots containing *Grevillea robusta* (a) and *Gliricidia sepium* (b) trees during the long rains of 1996 at Machakos in semi-arid Kenya.

Figure 6. Average soil moisture to 1350 mm depth in the soil profile in control plots lacking trees and at differing distances from single rows of trees in plots containing *Grevillea robusta* or *Gliricidia sepium* trees during the long rains of 1996 at Machakos in semi-arid Kenya.

Figure 7. Patterns of variation in tree fine root length density at distances of 1.5, 3 and 4.5 m from single rows of trees in plots containing *Grevillea robusta* or *Gliricidia sepium* trees on four sampling occasions during the long rains of 1996 at Machakos in semi-arid Kenya.

Figure 8. Maize root length density in control plots lacking trees and at distances of 1.5, 3 and 4.5 m from single rows of trees in plots containing *Grevillea robusta* or *Gliricidia sepium* trees on four sampling occasions during the long rains of 1996 at Machakos in semi-arid Kenya.
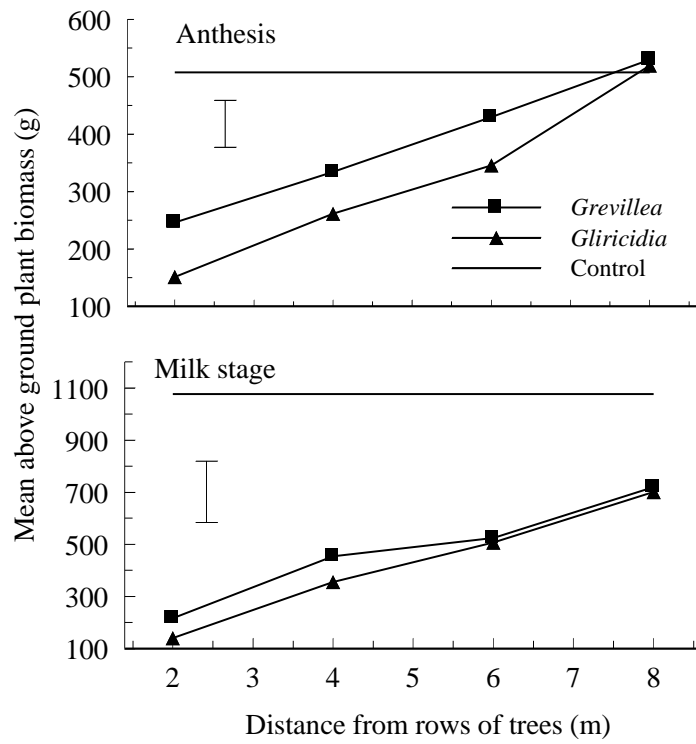
Figure 9 Changes of root length density in maize control plots that lacked trees and in plots containing maize and single lines of *Grevillea robusta* or *Gliricidia sepium* trees on 4 sampling occasions during the long rains of 1996 at Machakos in semi-arid Kenya. Data are averages for all depths and distances from trees.
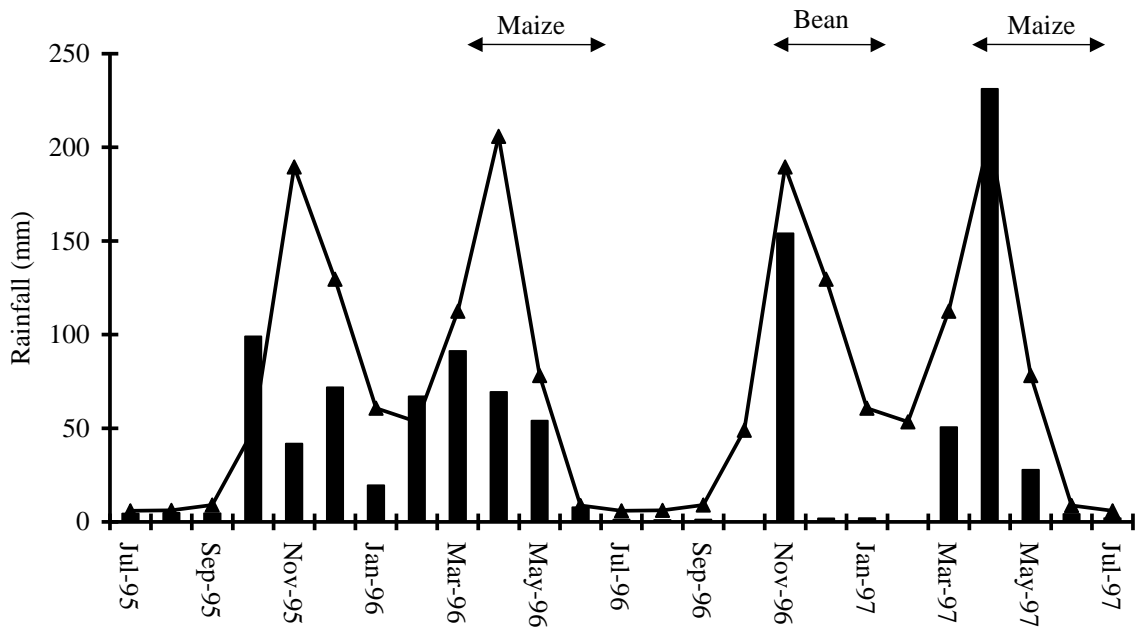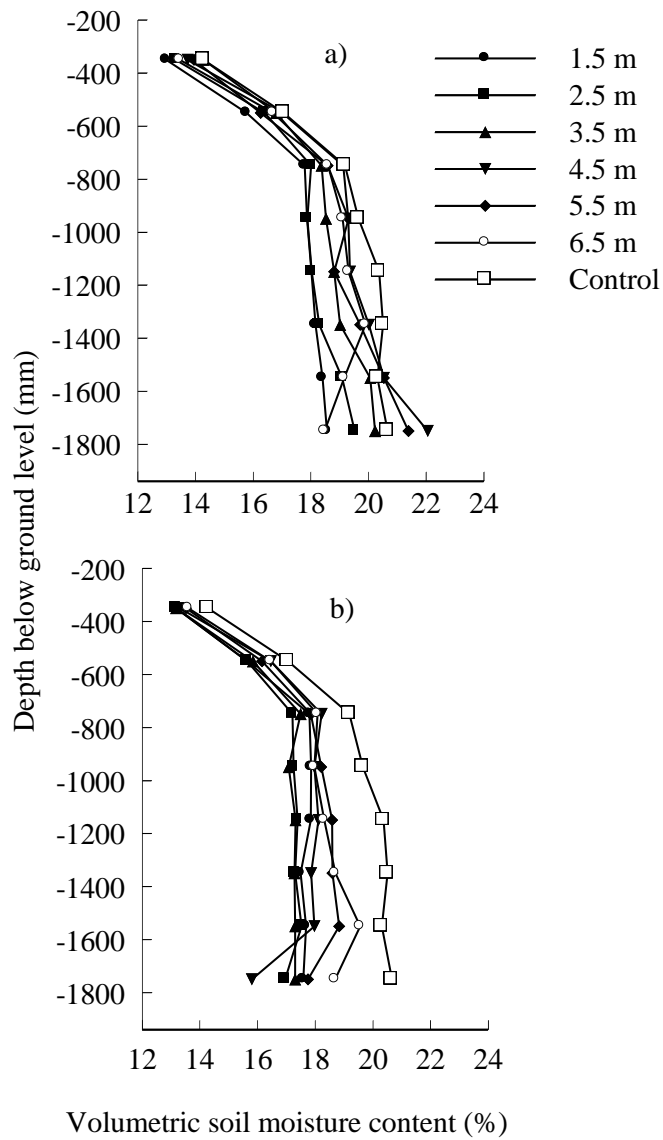
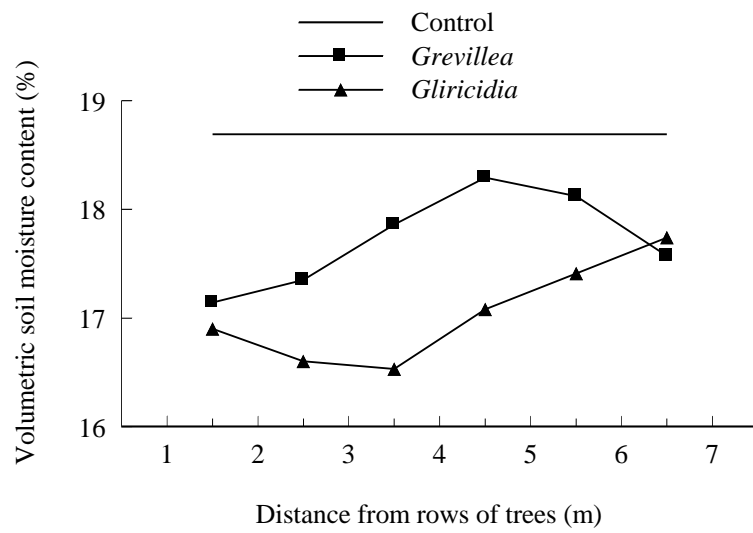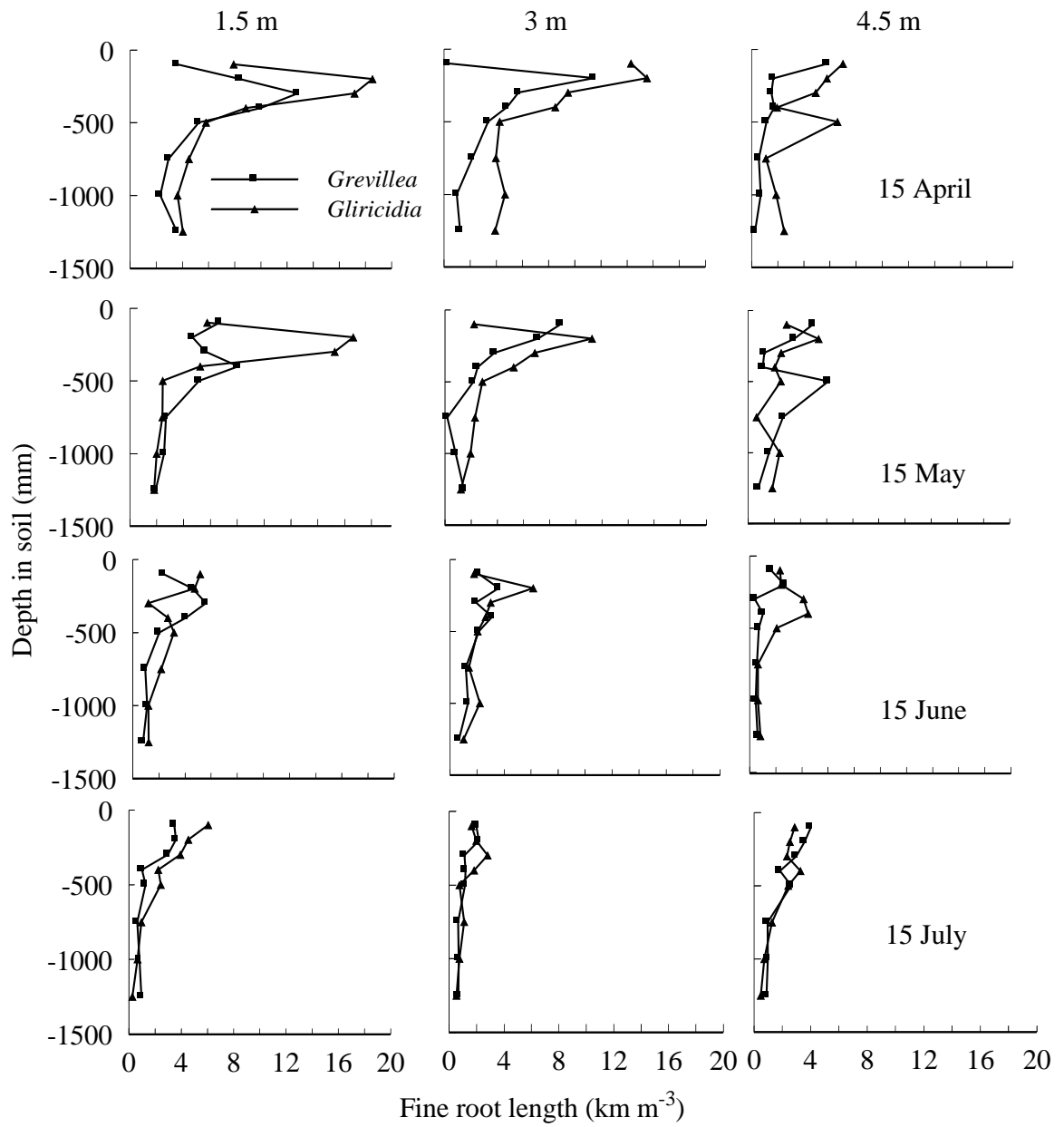Odhiambo et al. Figure 1
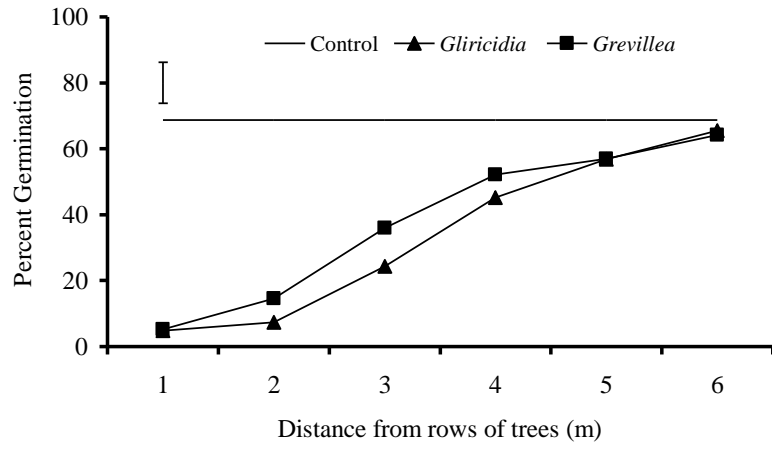
Odhiambo et al. Figure 2

Odbiambo et al. Fig 3

Maize grain yield (t h^{-1})

Distance from rows of trees (m)
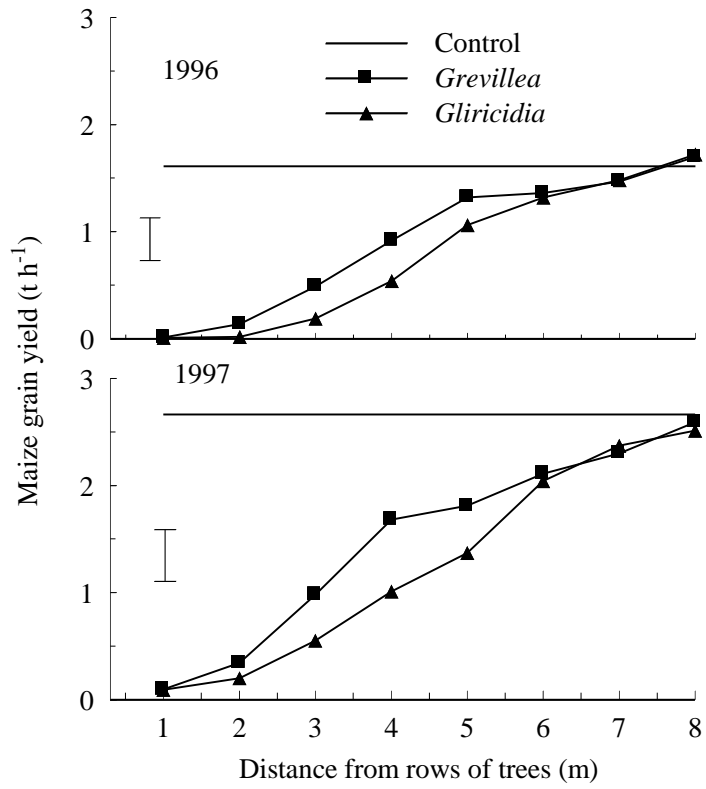
Odhiambo et al Fig 4

Odhiambo et al Figure 5

Odhiambo et al Fig. 6

Fine root length (km m^{-3})

Depth in soil (mm)

1.5 m   3 m   4.5 m

Grevillea
Gliricidia

15 April

15 May

15 June

15 July

Odhiambo et al Figure 7

1.5 m   3.m   4.5 m

Depth in soil (mm)

Control
Gliricidia
Grevillea

15 April

15 May

15 June

15 July

Maize root length (km m^{-3})

Odhiambo et al Figure 8

Odhiambo et al Figure 9