Tree growth and management in Ugandan agroforestry systems: effects of root-pruning on tree growth and crop yield

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Running head: ROOT-PRUNING EFFECTS ON TREE GROWTH AND CROP YIELD

Summary

Tree root pruning is a potential tool for managing below-ground competition when trees and crops are grown together in agroforestry systems. This study investigates its effects on growth and root distribution of *Alnus acuminata* (HB & K), *Casuarina equisetifolia* (L), *Grevillea robusta* (A. Cunn. ex R. Br), *Maesopsis eminii* (Engl.), and *Markhamia lutea* (Benth.) K. Schum. and on yield of adjacent crops in sub-humid Uganda. The trees were 3 years old at the commencement of the study, and most species were competing strongly with crops. Tree roots were pruned 41 months after planting by cutting and back-filling a trench to a depth of 0.3 m, at a distance of 0.3 m from the trees, on one side of the tree row. The trench was re-opened and roots re-cut at 50 and 62 months after planting. Effects on tree growth and root distribution were assessed over a 3 year period, and crop yield after the third root pruning at 62 months is reported here. Overall, root pruning had only a slight effect on tree growth: height growth was unaffected and diameter growth was reduced by only 4 %. A substantial amount of root re-growth was observed by 11 months after pruning. Tree species varied in the number and distribution of their roots, and *Casuarina* and *Markhamia* had considerably more roots per unit of trunk volume than the other tree species, especially in the surface soil layers. *Casuarina* and *Maesopsis* were the most competitive tree species with crops and *Grevillea* and *Markhamia* the least. Crop yield data provides strong evidence of the redistribution of root activity following root pruning, so that competition increased on the unpruned side of tree rows. Thus, one-sided root pruning will only be of use to farmers in a few circumstances.

Key words: *Alnus acuminata, Casuarina equisetifolia, Grevillea robusta, Maesopsis eminii, Markhamia lutea,* root distribution, root function

Introduction

Growing trees with crops in agroforestry systems can increase total productivity, reduce land degradation and improve recycling of nutrients, while producing fuel wood, fodder, fruits and timber in addition to products from annual crops (Sanchez 1995). However, the potential benefits of higher productivity, improved sustainability and reduced risk of such simultaneous agroforestry systems in comparison with monocultures are the outcome of a complex set of spatial and temporal interactions between the different components of the system. An important aspect of these interactions is the increasing dominance of the perennial trees as they mature (Ong et al. 2004) and compete with crops for light, water and nutrients (Ong and Huxley 1996).

Tree roots extend to considerably greater distances and depths than crop roots (Stone and Kalisz 1991). However, most tree species, like crop plants, exhibit a rapid decline in root mass, number and length with increasing soil depth. Consequently, although tree roots explore a far greater volume of soil, this volume includes the surface layers of soil where crop roots are also located, and thus there is the potential for both complementarity and competition in the use of below-ground resources (Schroth 1999), depending on the location and activity of the tree root system relative to the crop roots.

The management of below-ground interactions is most important in systems where trees and crops are grown in close proximity with the objective of producing multiple products, and where soil resources (water, nutrients) are limiting, as in seasonally dry climates, the semi-arid tropics and on infertile soils (Rao et al. 2004). Reducing below-ground competition may be achieved by selecting trees with less competitive root architecture, i.e. deep rooted trees with few roots in the upper soil layers, or by controlling tree roots in these upper layers by management (Rao et al. 2004; Schroth 1995). However, rooting behavior depends on many factors including site, tree age, provenance and method of propagation (Mulatya et al. 2002), and assessments of competition obtained under one set of circumstances may not be applicable elsewhere. Furthermore, even deep-rooted trees have some roots in the crop-rooting zone (Akinnifesi et al. 2004), and evidence that root activity shifts between deep and superficial soil layers with changes in soil moisture, suggests that selection of deep rooting species may only provide a limited solution to the problem (Green et al. 1997; Ong et al. 2002).

Tree management, rather than species selection, is attractive because it allows farmers to grow the tree species they want, rather than those with particular root architecture. Studies in the tropics have indicated that competition for below ground resources can be reduced by root pruning of trees and results have been encouraging in both semi-arid environments and wetland rice (Corlett et al. 1992; Hocking and Islam 1997; Korwar and Radder 1994; Singh et al. 1989). However, short-term benefits may not be sustained, and there is a lack of quantitative information of the effects on tree growth. This study examines the effects of root pruning on one side of tree rows on above and below ground growth of a range of indigenous and exotic tree species in Uganda, and the impact of this root pruning on the growth of adjacent crops. The root pruning method was designed to be compatible with farmers' traditional manual methods of land preparation.

Materials and methods

The study used a trial which had been planted in September 1995 (Okorio 2000) at Kifu Forest Research Station (0° 21' N, 32° 46' E, at 1250 m above sea-level) in Mukono district of Central Uganda, approximately 30 km east of Kampala. Rainfall at Kifu is bimodal, with a mean annual rainfall of about 1240 mm. Mean minimum and maximum annual temperatures are 21 and 25.3 °C respectively. Rainfall occurs with highest frequency from March – May and October – November. However, thunderstorms during the intervening relatively 'dry' periods ensure that monthly rainfall is fairly evenly distributed throughout the year (NEMA 1996). The soil, a ferralsol (FAO-UNESCO 1974), is a sandy loam, which averages 14% clay, 30% silt and 57% sand, with a pH 6.2 and 1.13% organic matter in the top 0 – 0.45 m (Okorio 2000).

The trial was set up as a linear simultaneous agroforestry system, with separate, replicated, plots of five tree species (*Alnus acuminata* (HB & K), *Casuarina equisetifolia* (L), *Grevillea robusta* (A. Cunn. ex R. Br), *Maesopsis eminii* (Engl.), *Markhamia lutea* (Benth.) K. Schum.), and 'no tree' controls. The two latter tree species are indigenous to Uganda and frequently planted by farmers, whereas the others are exotics and undergoing evaluation in several studies. As most farms are small, tree-crop interactions will be inevitable in most circumstances. Seed origins are provided in Table 1.

The trees were planted when they were four months old, in a single row along the central short E-W axis of the 30 x 25 m plots at a spacing of 1 m between trees, making a total of 24 trees per plot (Figure 1). Plots were replicated 4 times in a randomized block design, the layout of which was determined following soil analysis and assessment of the growth of a cover crop of maize (Wajja-Musukwe 2003). Seedlings which died were replaced during the first and second rainy seasons. By the time of this study, trees were competing strongly with crops (Okorio 2000; Wajja-Musukwe 2003). Root pruning commenced in February 1999 (month 41) and alternate trees were removed during the following month, so that there was then 2 m between trees. Root pruning was imposed in a split-plot arrangement (Figure 1), whereby the roots were pruned on one side of the tree row on half of each tree plot. One-sided root pruning was adopted to simulate that which might be used on boundary trees. Root pruning was done by digging a trench 0.3 x 0.3 m in width and depth on one side and 0.3 m away from the tree line, using mattocks and machetes. All roots were severed and the trench was then back-filled. The site has a gentle 5% slope, and in two of the blocks the pruning was done on the up-slope (northerly side) while the other two blocks were pruned on the southerly side. Root pruning was repeated at 50 and 62 months after planting.

Annual intercrops were planted in rotation (*Zea mays*, variety Longe 1 - maize and *Phaseolus vulgaris* variety K132 - beans) in the first (long) rains and second (short) bimodal rains respectively and yields were assessed each season. Plots were prepared before the onset of the rains by deep cultivation using hand hoes, and plots were weeded twice each season by hoe. A basal application of single super phosphate (298 kg ha^{-1}) was applied before each sowing, and an additional application of NPK (25-5-

5)(149 kg ha^{-1}) was made before maize was sown. Trenches were also dug between plots and between subplots, to reduce the crossover of roots between treatments. Following local practice, before every cropping season, the lower branches of all trees were removed to raise the crowns to reduce shade, *i.e.* the lower one-third of the tree stem was maintained branch-free. Bean seed was hand sown in rows 0.5 m apart, running parallel to the tree row. After germination, bean plants were thinned to 0.1 m apart within rows, with the first row planted 0.5 m from the tree row. Maize rows were 0.75 m apart, with 0.3 m between plants in a row. In this paper, the yield (air-dry weight of seeds) of beans, planted in November 2000, just after the third root pruning, and harvested in January 2001 is reported. Calculations of sub-plot yield excluded the outermost two rows, and were determined from 28 rows of beans, extending up to 14 m from the tree row.

The effect of root pruning on root regrowth and the overall distribution and number of roots on the plots was determined. Direct observations of the original root pruning trenches were made twice, 4 and 11 months after the third root pruning. For this, three central trees were selected in the tree row, and a 6 m long x 0.15 m wide x 0.3 m deep trench was dug 0.15 m away from and parallel to the original trench created by root pruning. From this new trench, soil was carefully removed back towards the original trench, using various hand tools. The roots were carefully exposed back to the point where the main roots had been severed at the time of pruning and to the depth of the original pruning. New roots which proliferated at the original severance points were termed ‘coppice roots’. Main and coppice roots were counted and their diameters measured using calipers. Main roots were >5 mm diameter at the time of the assessments and had been pruned. Coppice roots were roots which had re-grown from the main roots. Because of the laborious nature of this work, plots of each tree species were only examined in two of the blocks.

Twelve months after the third root pruning, profile walls (Schuurman and Goedewaagen 1971) were used to examine root distribution through the soil profile at 1.5 and 6 m from the tree row. For this, a single plot for each tree species was randomly selected from blocks 1 and 2, which had deeper soils (≥ 2 m deep) than blocks 3 and 4. Then vertical-sided trenches were dug parallel to the tree line in the root-pruned sub plot on both the TP^+ and TP^- sides (Figure 1b). Thus selected sub plots had four trenches (two each on side TP^+ and TP^-), with a depth of 2 m, a 2 m long face parallel to the tree row and a width of 1 m. For assessment, a wooden grid subdivided into 0.1 x 0.1 m cells was placed against the 2 x 2 m side proximal to the tree row and the roots in each cell were counted and their diameters measured. Data were collected from a width of 1.5 m and depth of 1.8 m for each profile wall, and the total number of roots and the total root cross-sectional area at each soil depth (0 – 0.3, 0.3 – 0.6 m etc) were determined. Roots counted and measured on the profile walls were divided into size categories for analysis (<2, 2 – 4.9, 5 – 9.9, 10 – 49.9, and ≥ 50 mm diameter). Ratios of root number: trunk volume were calculated using root counts from the profile walls cut at 1.5 m from the tree rows and the mean tree volume for the adjacent tree row.

Tree height and diameter at breast height (dbh) and crown diameter, were measured at regular intervals after planting. Leaf area was determined allometrically from weighing and scanning sub samples of leaves collected from branches of different cross-sectional areas (Wajja-Musukwe 2003).

Data analysis

Differences between treatment means were determined by analysis of variance (ANOVA) using Genstat (Lawes Agricultural Trust 1998). Data were checked for heterogeneity of variances using Bartlett's test, and square-root transformed if necessary. Significant differences between treatment means were assumed and least significant differences (LSDs) calculated when $p \leq 0.05$ in Fisher's F test. For tree growth (dbh and height), ANOVAs used a split-plot approach to test for the effects of tree species and pruning treatments (TP *vs.* TP0, Figure 1a) and interactions between species and pruning, using repeated measures for assessments at different times. Because tree measurements shortly after the first pruning at 43 months indicated that there was an unexpected (though non-significant) tendency for the root-pruned cohort of trees to be smaller than the unpruned cohort, the effects of pruning on height and dbh growth over the time series were assessed using the measurements collected at 43 months after planting (2 months after pruning), as a covariate in the analysis. The repeated measures with covariate analysis indicated that Box's test for the symmetry of the covariance ratio for both height and diameter was significant; consequently degrees of freedom were adjusted using the Greenhouse-Geisser epsilon before significances were calculated.

ANOVA of root re-growth in the pruning trenches evaluated differences between species, but replication was low. However, for the profile walls, since they were not replicated within species, analysis of root distribution across the plots was not possible at the species level. Profile wall data were analyzed using a split-plot ANOVA approach in the TP^+ and TP^- sub plots (Figure 1b) to examine the effects of pruning treatment, distance and depth, recognizing that no statistical comparisons of species differences were possible.

For crop yield, the effects of tree species and pruning treatment were analyzed at the sub plot level, comparing yield in the TP^+, TP^- and TP0 sub plots (Figure 1b), using data for the first 28 rows of beans, extending 14 m from the tree row. As effects of trees on crop yield were strongest close to trees (Wajja-Musukwe 2003), these data were subsequently sub-divided into proximal (0 – 7 m) and distal (7 – 14 m) components, containing rows 1 – 14 and 15 – 28 respectively. Finally, combined yields from both sides of the pruned tree rows (TP^+ + TP^-) were compared with yields adjacent to unpruned trees (TP0), with correction for the difference in plot area.

Results

Tree growth

Tree growth since planting is shown in Figure 2. Tree species grew at different rates, but there were no significant effects of pruning on height, however, a significant root pruning * time interaction ($p = 0.006$) on tree dbh was present, so that pruning began to have a significant effect on tree dbh by 9 months after pruning (Table 2). Overall, effects of one- sided root pruning on tree growth were very slight.

While *Alnus* grew slowly throughout the study, other species changed their rankings over time (Figure 2). *Casuarina* and *Grevillea* were jointly the best in terms of height growth for the first 30 months, after which the growth of *Grevillea* slowed. *Casuarina* continued to be the tallest species for the remainder of the study. *Grevillea* ranked first in terms of dbh for the first 30 months, but was then succeeded by *Maesopsis*. *Maesopsis* generally appeared slow to establish but over the time frame of the whole study proved its worth as a fast growing timber species. Six years after planting, *Casuarina* trees were 18 m in height, while *Alnus* were 7 m. *Maesopsis* reached 22 cm in dbh, while *Alnus* only achieved 11 cm. Impacts of thinning on tree height growth were not discernible, however, dbh appeared to respond to thinning after a lag of about 8 months.

Root re-growth

Four months after root pruning, roots of all species had regrown into the reopened root pruning trench (Table 3). There were no significant differences between species in the number or dimensions of these coppice roots. However, there were significant differences between species in the mean number of main roots found in the trench: *Grevillea* had the most main roots per tree, and *Casuarina, Maesopsis* and *Alnus* the fewest.

Eleven months after root pruning, some of the main roots of *Grevillea* and *Markhamia* had died. The number of main roots of *Alnus* had increased since the observations seven months previously due to expansion of pruned roots which had previously been below the 5 mm diameter threshold for main roots. Unlike the other tree species, the mean diameter of *Alnus* main roots did not increase between the two sets of observations, reflecting the recruitment of roots into this size class. However, cross sectional areas of main roots had increased since the previous assessment, and differences in root regrowth between species were becoming more distinct: *Grevillea* showed only a slight increase in root regrowth from the previous occasion, while *Alnus* coppice root numbers had increased four-fold. The cross-sectional area of coppice roots increased considerably between the two assessments.

Main and regrowth coppice root diameters were significantly positively correlated. Coppice roots of *Casuarina, Maesopsis* and *Markhamia* grew fairly horizontally in the top soil while those of *Grevillea* and *Alnus* tended to grow downwards ((Wajja-Musukwe 2003).

Root distribution

In the profile walls, root numbers decreased with increasing depth in the soil profile and with distance from tree (Figure 3), as expected. Fine roots < 2mm in diameter, accounted for approximately half the roots. Analysis of these data, collected 12 months after the last pruning, and shortly after the 11 month assessment of root regrowth in the pruning trenches, showed that pruning significantly reduced ($p = 0.005$) the numbers of roots in the ≥ 50 mm diameter size class, but not in the other classes. Numbers of roots in all size classes decreased significantly ($p \leq 0.05$) with both distance from trees and increasing depth in the profile, and distance x depth effects occurred with roots in all classes > 5 mm diameter. Pruning x depth effects were significant only in the ≥ 50 mm diameter size class ($p = 0.037$), where there were significantly fewer roots of this class in the upper soil layers, on the pruned side of the trees at 0 – 0.3 and 0.3 – 0.6 m below ground level. However, mean numbers of roots in this size class were very small, with 2 and 5.3 roots respectively per m^2 on the pruned and unpruned side of the tree in the top 0.3 m of soil when the two distances were combined.

When total cross sectional area of roots in the different size classes was determined, pruning effects were again seen in the large diameter classes: significant pruning x depth interactions ($p < 0.02$) and main effects of pruning ($p < 0.03$) occurred in 10 – 49.9 and ≥ 50 mm classes. In both these classes, root cross-sectional area was smaller in pruned trees at 0 – 0.3 m depth. Significant main effects of distance and depth occurred in all size classes.

Numbers of roots varied considerably between tree species. Although analysis of these data is restricted by the lack of replication, contour plots of data collected from the profile walls at 1.5 m from the trees on the pruned and unpruned sides of the tree rows highlight the differences present (Figures 4 & 5). *Grevillea* had consistently less roots than the other tree species. The *Maesopsis* unpruned profile contained up to 50 roots m^{-2}, whereas the pruned profile contained < 15 roots m^{-2} *Casuarina* had up to 50 roots m^{-2} in the pruned profile, but fewer in the unpruned profile. Combining data from the pruned and unpruned profiles, root numbers of *Grevillea* < *Alnus* < *Markhamia* < *Maesopsis* < *Casuarina.* The *Maesopsis* profile showed maximum roots at about 0.45 m below the soil surface, whereas roots of other species were most numerous closer to the soil surface. *Alnus* roots were not found at 6 m from the trees (data not shown), whereas roots of all other species were present at 6 m, though those of *Grevillea* were not numerous.

Trunk volumes varied considerably between species. When calculated as the volume of a cone from tree height and dbh, values of 0.021, 0.057, 0.076, 0.135 and 0.163 m^3 were obtained for *Alnus, Markhamia, Casuarina, Grevillea* and *Maesopsis* respectively. The number of roots per unit of trunk volume varied considerably between species throughout the soil profile (Figure 6). There was a 10 fold difference between the lowest (*Grevillea*) and highest (*Casuarina*) ratios in the top 0.3 m of soil. *Casuarina* and *Markhamia* had far larger numbers of roots in relation to their trunk volume than other species through most of the measured soil profile.

Crop yield

In the 28-row sub plots (TP^+, TP^- and TP0), there was no significant interaction between tree species and pruning treatment, and no significant differences between the pruning treatments. However, there was a significant main effect of tree species (Table 4): crop yield was significantly reduced with *Casuarina* and *Maesopsis* compared to the 'no tree' control, while yields with *Grevillea, Markhamia* and *Alnus* were not significantly different to the control. Analysis of the 0 – 7 m (proximal) and 7 – 14 m (distal) sub units, showed that crop yields were significantly reduced by all tree species relative to the 'no tree' control in the proximal unit but not in the distal unit. The effects of pruning treatment on crop yield were also significant in the proximal unit, with $TP^+ > TP0 > TP^-$ (Table 4).

As yields from the TP0 proximal sub plots were intermediate between those of the TP^+ and TP^- treatments (Table 4), crop yields on both sides of the pruned tree row were combined, and the yield from $(TP^+ + TP^-)/2$ was compared with TP0 (Table 5). When plots were combined in this way, there was no effect of pruning on crop yield, either in the full sub plot or its proximal unit.

Discussion and conclusions

Above ground tree growth

There were considerable differences between the growth rates and form of the five tree species in this study. In terms of height growth, the results are consistent with those of previous Ugandan studies by Okorio et al. (1994) who found that *Maesopsis* and *Casuarina* were faster growing than *Markhamia* and *Alnus.* Although *Alnus* performed poorly at this location, it grows faster at higher altitudes elsewhere in Uganda (Sande 2003)

Effect of root pruning on above-ground tree growth

Root pruning significantly reduced trunk diameter growth in all species. The effect increased, over time with the ratio of pruned to unpruned tree diameter declining from 0.98 at 6 months, to 0.96 at 28 months after first root pruning. While there was also a tendency for pruned trees to be shorter, this difference was not significant, possibly due to the difficulties of measuring tall trees with graduated poles. There was no evidence of tree mortality or wind throw as a result of root pruning.

Other studies of the use of root pruning or root barriers to control competition have also reported reductions in tree growth, however comparisons between studies are difficult, not only because of environmental and species differences, but also because of the wide variety of approaches to root pruning. Sudmeyer et al. (2002) found no effect on tree growth when root pruning was done to a depth of 0.4 – 0.7 m at about 5 m from one side of a *Pinus pinaster* windbreak, although other studies (Sudmeyer and Flugge 2005) showed that root pruning and root barriers on both sides of tree rows reduced the growth of *Pinus* and *Eucalyptus* spp. by 14 – 43%. Jose et al. (2000) reported that black walnut (*Juglans nigra*) stem diameter growth in 'trench' and 'barrier' treatments was significantly less than in a 'no barrier' treatment, but they pruned on both sides of the tree line to a depth of 1.2 m. Likewise, Miller and Pallardy (2001) reported reduced stem growth of *Acer saccharinum* trees after trenching to a depth of 1 m. Hocking and Islam (1997) reported a 19 % reduction in stem girth due to a combined effect of top and root pruning to a depth of 0.3 m in Bangladesh over a five year period.

Root pruning did not affect crown diameter (Wajja-Musukwe 2003). Crown diameter increased in size until about 60 months after planting. *Maesopsis* crowns were widest and *Markhamia* were narrowest at 7 and 3.5 m diameter, respectively. Leaf area assessments at the end of the study showed that *Maesopsis* also had the greatest leaf area (600 m^2 per tree) and *Alnus* had the smallest (70 m^2).

Below-ground tree growth

The general pattern of decline in tree root numbers with distance from tree and depth (Figure 3) is consistent with that described in many other studies (e.g. Akinnifesi et al. 2004; Sudmeyer et al. 2004). The data confirm that tree roots are most numerous in the crop rooting zone (Odhiambo et al. 2001). However, the combined results presented in Figure 3, mask considerable differences between species in both number of roots and their distribution down the soil profile (Figures 4, 5). The reduction in number of the largest tree roots by pruning (> 50 mm diameter) might limit the overall lateral spread of the tree root system and tend to focus competition nearer the trees. Root number was not simply related to above ground tree biomass (Figure 6).

On the deep soil at Kifu, *Grevillea* and *Maesopsis* appear to have root architectures more compatible with crops than the other species, although this assumption is not consistent with the crop data which was obtained: while *Grevillea* was not competitive, *Maesopsis* was, and above-ground competition by its widely spreading canopy may have been an important contributory factor. Previous studies of *Grevillea* have shown it to be variable in its root architecture (Howard et al. 1997; Odhiambo et al. 2001; Smith et al. 1999), which highlights the importance of individual site studies.

The profile wall data only indicate laterally spreading roots. Root excavations reported elsewhere found that *Casuarina, Maesopsis* and *Markhamia* also had strong tap roots and that those of *Maesopsis* were of similar diameter to the tree dbh (Wajja-Musukwe 2003).

In the pruning trenches, some of the main roots of *Grevillea, Markhamia* and *Maesopsis* died, as did some of the coppice roots of *Maesopsis*. No assessments were made of unpruned trees, so this cannot be firmly attributed to the pruning.

Taking the data from the unpruned side of the tree as a guide (Figure 3), root pruning will have severed about 18% of the tree roots, yet all tree species had a high capacity for root regrowth and long-term effects on stem growth were slight. The increasing presence of coppice roots in the pruning trenches over the period from 4 - 11 months after root pruning indicates the need to determine appropriate pruning frequencies to control competition with crops, and the species variation in angle of descent of the coppice roots requires further investigation as it has implications for future competition with crops.

Crop yield

As this crop was planted immediately after the third root pruning, effects of root pruning would be expected to be strong as the number of active tree roots in the crop rooting zone should have been minimized.

Competition was strongest close to trees and all species reduced yields in the 0 – 7 m proximal sub unit. However, at the full sub plot level, from 0 – 14 m from the tree rows, only 2 species, *Casuarina* and *Maesopsis* significantly reduced crop yields (Table 4), reflecting the observations that *Casuarina* was the tallest species and *Maesopsis* had the greatest dbh (Figure 1). However, the magnitude of the competitive effect is not simply due to tree size, as *Grevillea*, which was one of the larger species, was the least competitive species at the full and proximal subplot levels. Root number: trunk volume ratios were also not a good indicator of competition as, while competitive *Casuarina* had the highest ratio, *Maesopsis* had a low ratio.

Although the effect of pruning was significant in the proximal sub unit (Table 4), combining crop yield data from both sides of the pruned tree rows (Table 5), eliminated the pruning effect, indicating that reduced root activity on the pruned side was compensated for by increased root activity by the same trees on the unpruned side. This compensatory root activity, not only removed the possible benefits of root pruning, but also was probably responsible for the relatively small effects of root pruning on tree growth.

While root pruning allows farmers to control competition with crops, this study highlights the importance of tree species selection. *Maesopsis* trees had the largest trunk volume, but were the most competitive species with crops, whereas *Grevillea* had the second largest trunk volume, and did not reduce crop yields at this site.

This study was designed to assess the effects of root pruning in boundary plantings. While one-sided root pruning to control competition would be justified and effective where trees are grown adjacent to uncropped land, such as roads, when production on land on both sides of the trees is considered, one-sided pruning has no effects on crop yields. In eastern Africa, tree planting on boundaries is particularly prevalent in bimodal rainfall zones (Kenya, Uganda, Rwanda, Burundi), as a means of claiming land and asserting rights of exclusion (Warner 1993). In this situation, when adjacent lands are in different ownership, the actions of one farmer to reduce competition would be detrimental to the yields of the adjacent farmer.

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References

Akinnifesi F K, Rowe E C, Livesley S J, Kwesiga F R, Vanlauwe B and Alegre J C 2004 Tree Root Architecture. *In* Below-ground Interactions in Tropical Agroecosystems: Concepts and Models with Multiple Plant Components, Eds M van Noordwijk, G Cadisch and C K Ong. pp 61 - 82. CABI International, Wallingford, UK.

Corlett J E, Black C R, Ong C K and Monteith J L 1992 Aboveground and Belowground Interactions in a Leucaena/Millet Alley Cropping System .2. Light Interception and Dry-Matter Production. Agric. For. Met. 60, 73-91.

FAO-UNESCO 1974 Soil Map of the World, 1:5000000, ten volumes. UNESCO, Paris.

Green S R, Clothier B E and McLeod D J 1997 The response of sap flow in apple roots to localised irrigation. Agric. Wat. Mgmt 33, 63-78.

Hocking D and Islam K 1997 Trees on farms in Bangladesh: 5. Growth of top- and root-pruned trees in wetland rice fields and yields of understory crops. Agrofor. Syst. 39, 101-115.

Howard S B, Ong C K, Black C R and Khan A A H 1997 Using sap flow gauges to quantify water uptake by tree roots from beneath the crop rooting zone in agroforestry systems. Agrofor. Syst. 35, 15-29.

Jose S, Gillespie A R, Seifert J R and Biehle D J 2000 Defining competition vectors in a temperate alley cropping system in the midwestern USA - 2. Competition for water. Agrofor. Syst. 48, 41-59.

Korwar G R and Radder G D 1994 Influence of root pruning and cutting interval of Leucaena hedgerows on performance of alley cropped rabi sorghum. Agrofor. Syst. 25, 95-109.

Lawes Agricultural Trust 1998 Genstat V release 4.1. Rothamsted Experimental Station, England.

Miller A W and Pallardy S G 2001 Resource competition across the crop-tree interface in a maize-silver maple temperate alley cropping stand in Missouri. Agrofor. Syst. 53, 247-259.

Mulatya J M, Wilson J, Ong C K, Deans J D and Sprent J I 2002 Root architecture of provenances, seedlings and cuttings of *Melia volkensii*: implications for crop yield in dryland agroforestry. Agrofor. Syst. 56, 65-72.

NEMA 1996 Empowerment for African Sustainable Development: State of the Environment Report for Uganda 1996, Ed National Environment Management Agency.

Odhiambo H O, Ong C K, Deans J D, Wilson J, Khan A A H and Sprent J I 2001 Roots, soil water and crop yield: tree crop interactions in a semi-arid agroforestry system in Kenya. Pl. Soil 235, 221-233.

Okorio J 2000 Light interception and water use in boundary planting agroforestry systems. pp 230. PhD thesis, University of Reading, UK.

Okorio J, Byenkya S, Wajja N and Peden D 1994 Comparative performance of seventeen upperstorey tree species associated with crops in the highlands of Uganda. Agrofor. Syst. 26, 185-203.

Ong C K and Huxley P, eds. 1996 Tree-Crop Interactions: A Physiological Approach. CAB International and ICRAF. 385 p.

Ong C K, Kho R M and Radersma S 2004 Ecological interactions in multispecies agroecosystems: concepts and rules. *In* Below-ground Interactions in Tropical Agroecosystems: Concepts and Models with Multiple Plant Components, Eds M van Noordwijk, G Cadisch and C K Ong. pp 1 - 16. CABI Publishing, Wallingford, UK.

Ong C K, Wilson J, Deans J D, Mulayta J, Raussen T and Wajja-Musukwe N 2002 Tree-crop interactions: manipulation of water use and root function. Agric. Wat. Mgmt 53, 171-186.

Rao M R, Schroth G, Williams S E, Namirembe S, Schaller M and Wilson J 2004 Managing Below-ground Interactions in Agroecosystems. *In* Below-ground Interactions in Tropical Agroecosystems: Concepts and Models with Multiple Plant Components, Eds M van Noordwijk, G Cadisch and C K Ong. pp 309 - 328. CABI Publishing, Wallingford.

Sanchez P A 1995 Science in agroforestry. Agrofor. Syst. 30, 5-55.

Sande B D 2003 Pollarding and root pruning as management options for tree-crop competition and firewood production. pp 117. MSc thesis, University of Stellenbosch, South Africa.

Schroth G 1999 A review of belowground interactions in agroforestry, focussing on mechanisms and management options. Agrofor. Syst. 43, 5-34.

Schroth G 1995 Tree root characteristics as criteria for species selection and systems-design in agroforestry. Agrofor. Syst. 30, 125-143.

Schuurman J J and Goedewaagen M A J 1971 Methods for the examination of root systems and roots. Wageningen, Pudoc. 86 p.

Singh R P, Ong C K and Saharan N 1989 Above and below ground interactions in alley-cropping in semiarid India. Agrofor. Syst. 9, 259-274.

Smith D M, Jackson N A, Roberts J M and Ong C K 1999 Root distributions in a *Grevillea robusta*-maize agroforestry system in semi-arid Kenya. Pl. Soil 211, 191-205.

Stone E L and Kalisz P J 1991 On the maximum extent of tree roots. For. Ecol. Mgmt 46, 59-102.

Sudmeyer R and Flugge F 2005 The economics of managing tree-crop competition in windbreak and alley systems. Aust. J. Exp. Agric. 45, 1403-1414.

Sudmeyer R A, Hall D J M, Eastham J and Adams M A 2002 The tree-crop interface: the effects of root pruning in south-western Australia. Aust. J. Exp. Agric. 42, 763-772.

Sudmeyer R A, Speijers J and Nicholas B D 2004 Root distribution of *Pinus pinaster, P-radiata, Eucalyptus globulus* and *E-kochii* and associated soil chemistry in agricultural land adjacent to tree lines. Tree Physiol. 24, 1333-1346.

Wajja-Musukwe T N 2003 Management of below-ground competition in simultaneous agroforestry systems. pp 237. PhD thesis, University of Dundee, UK.

Warner K 1993 Patterns of farmer tree growing in Eastern Africa: a socioeconomic analysis. Oxford Forestry Institute and International Centre for Research in Agroforestry, Oxford. 270 p.

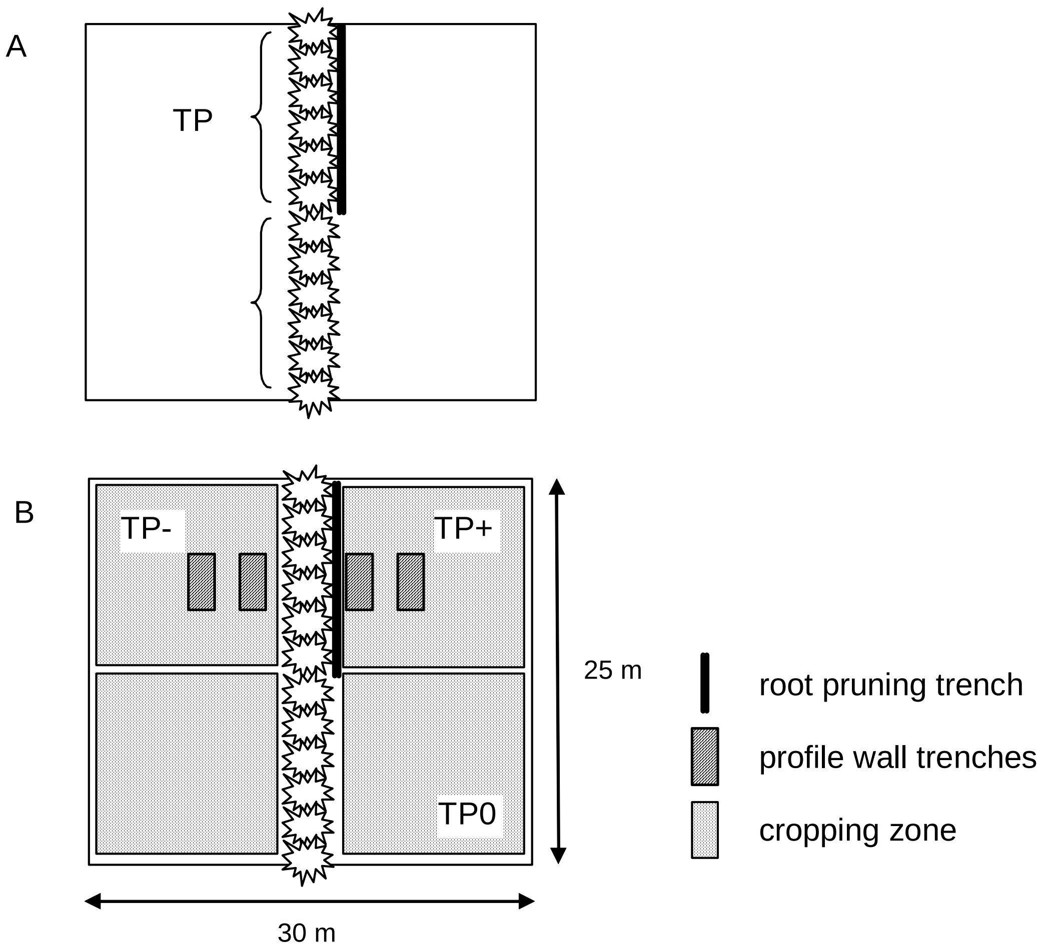

Figure 1. Diagrams of a tree plot at Kifu, showing the root-pruning trench, cropping zones and profile wall trenches in relation to the tree row, and sub-plot designations for the data analysis. 'A' represents layout for assessment of tree height and diameter growth, with trees root-pruned on one side (TP) being compared with those which were not root-pruned (TP0). 'B' shows layout for considerations of root growth and crop yield, in which the hatched sub-plots on either side of the pruned tree row (TP^+ and TP-) (root data) or TP^+, TP- and TP0 (crop data) were compared. Plots of all five tree species and a 'no tree' control were replicated four times in a randomized block design.

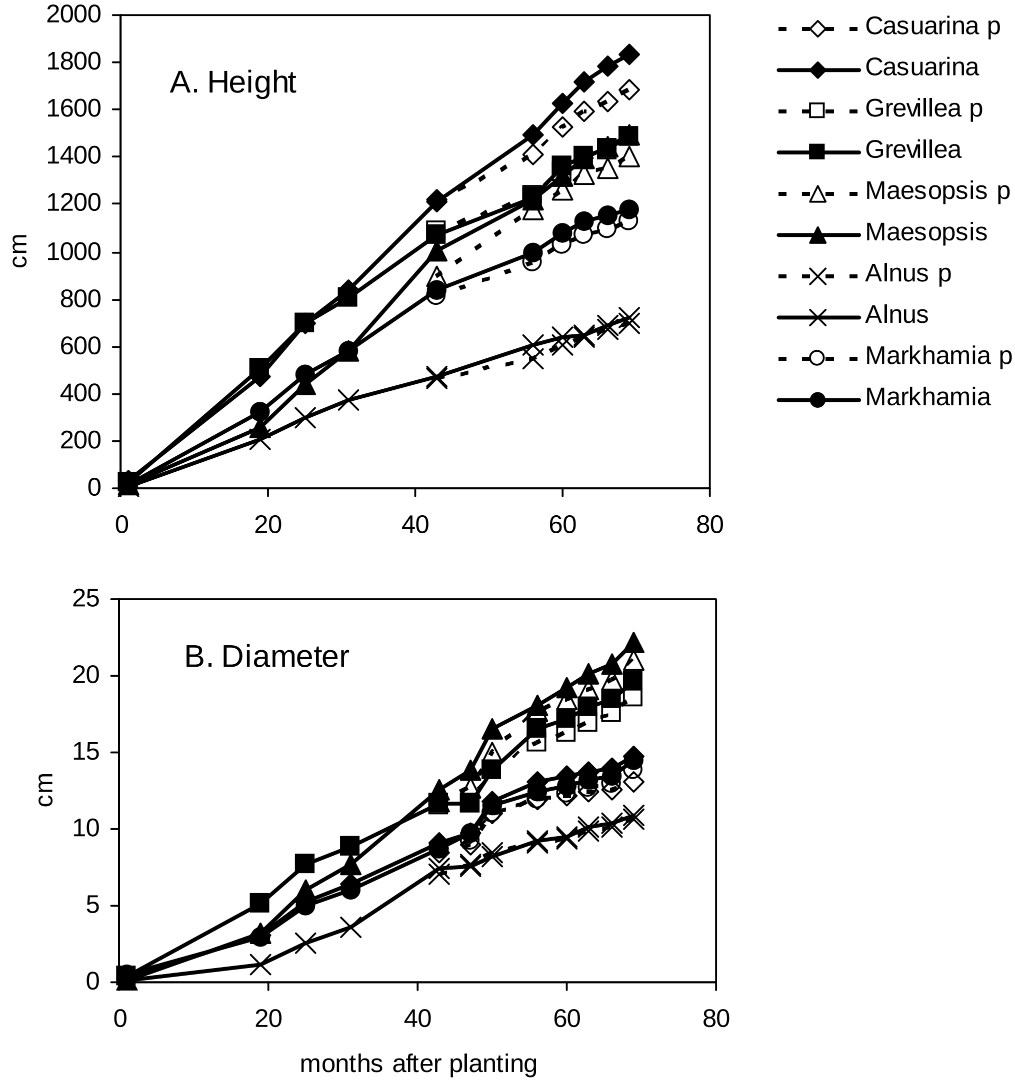

Figure 2. Height and diameter at breast height of trees planted at Kifu, Uganda, with (p) and without root pruning. Alternate trees were removed during month 42, and root pruning was conducted at months 41, 50 and 62. Data are actual means not adjusted for covariates.

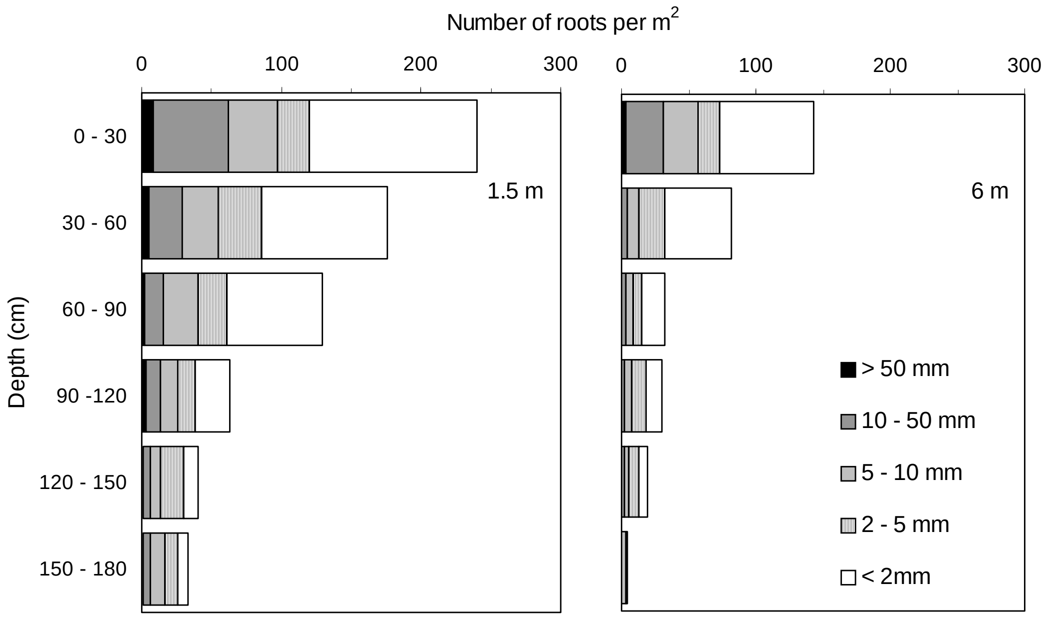

Figure 3. Numbers of roots in different diameter size classes at different depths in the soil profile, at 1.5 and 6 m from the tree row. Data from profile walls on the unpruned (TP-) side of the tree row, all tree species combined. Trees were approximately 6 years old.

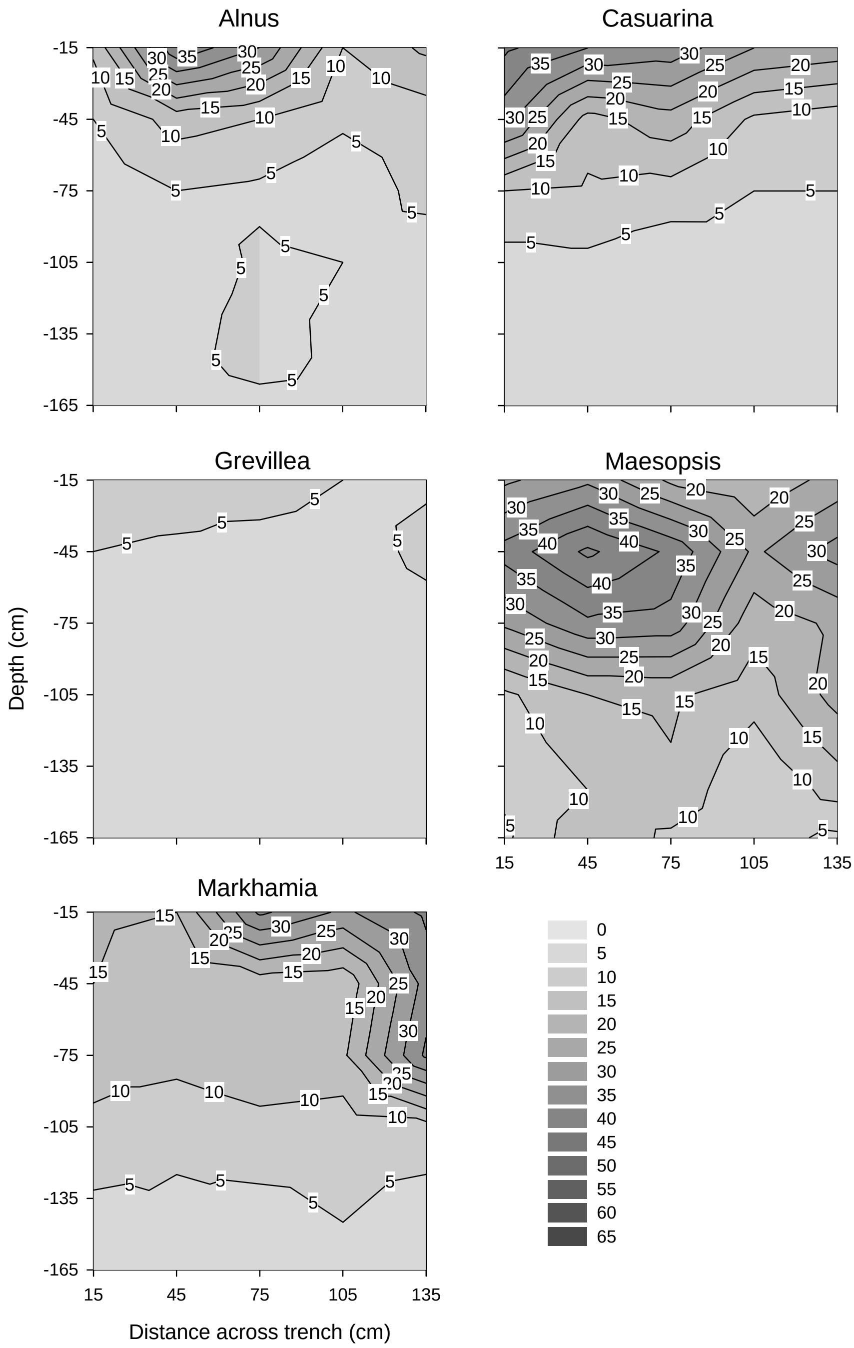

Figure 4 Distribution of tree roots on profile walls at 1.5 m from the tree rows, on the unpruned side of pruned trees (TP- see Figure 1b), 12 months after the third root pruning. Contour diagrams based on root counts per 0.3 x 0.3 m of wall surface, all size classes combined. Trees were approximately 6 years old.

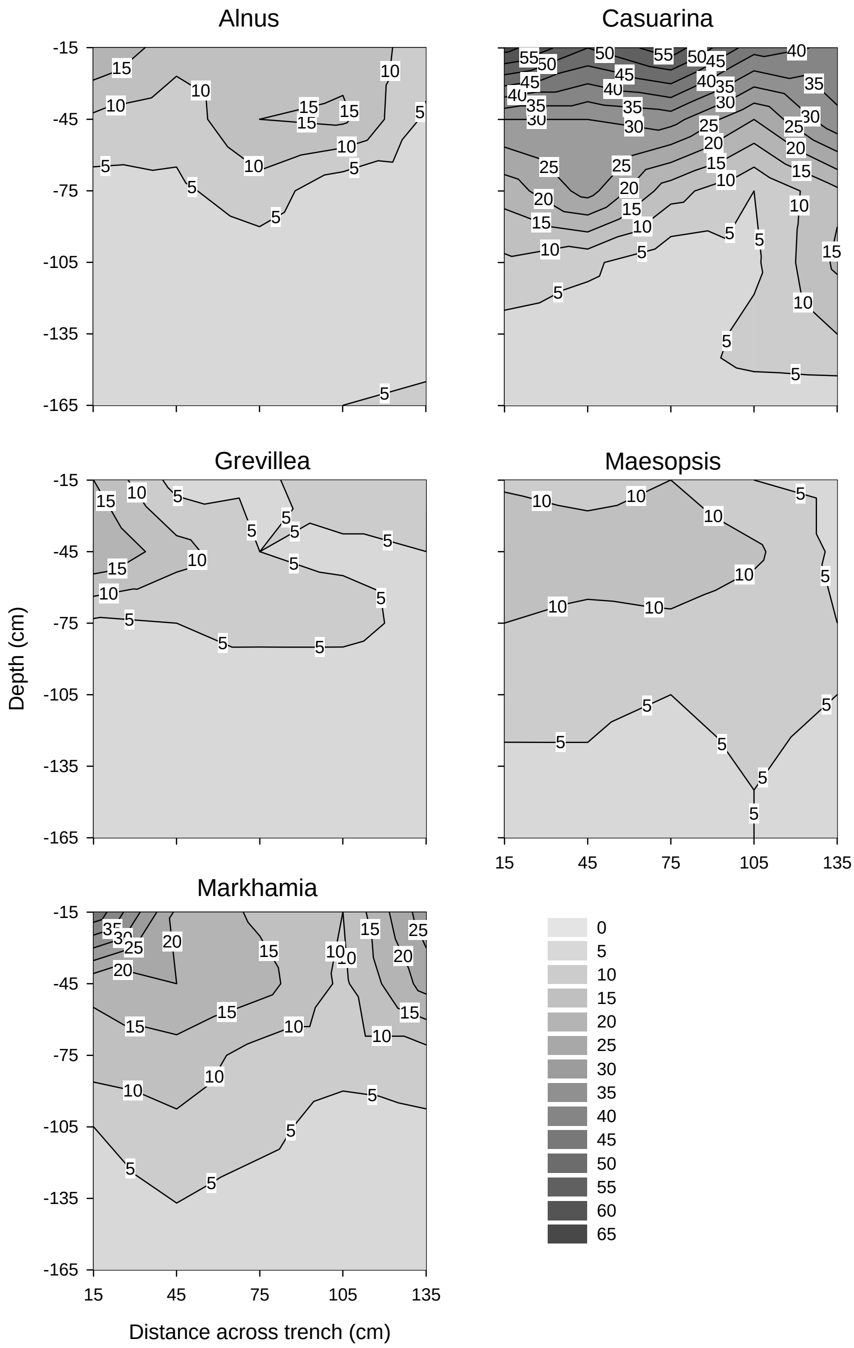

Figure 5. Distribution of tree roots on profile walls at 1.5 m from the tree rows, on the pruned side of pruned trees (TP^+ see Figure 1b), 12 months after the third root pruning. Contour diagrams based on root counts per 0.3 x 0.3 m of wall surface, all size classes combined. Trees were approximately 6 years old.

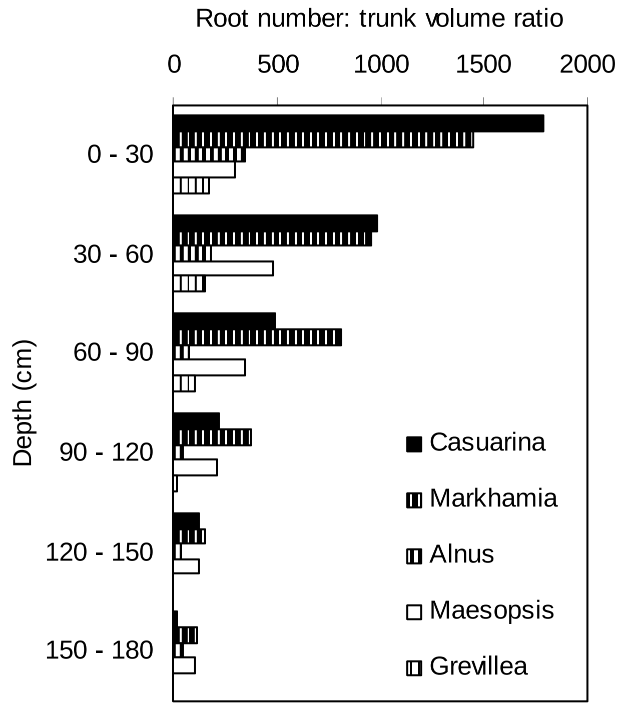

Figure 6. Effects of tree species on numbers of roots in all size classes per m^3 of trunk volume at month 69 at 1.5 m distance from the tree row and at different depths in the soil profile. Root numbers were calculated per 1 m width x 0.3 m depth of profile wall (root data for pruned and unpruned sides of tree combined). Trunk volume calculated as a cone, using dbh as basal diameter.

Table 1. Origins of tree seed (after Okorio, 2000)

Species	Provenance	Latitude	Longitude	Altitude (m..s.l)	Rainfall (mm year^{-1})
Alnus acuminata	Siguampar, Sacatepezuez (Guatemala)	14° 35′ N	90°48′W	1900	1400
Casuarina equisetifolia	Dhera Dun (India)	30° 15′ N	78°15′W	640	800
Grevillea robusta	Altenango, Sacatepezuez (Guatemala)	14° 30′ N	90°40′W	1350	1100
Maesopsis eminii	Ikulwe, Iganga (Uganda)	0° 50′ N	35° 50′E	1200	1200
Markhamia lutea	Seeta, Mukono (Uganda)	0° 23′ N	32° 40′E	1300	1250

Table 2. Effects of root pruning on diameter at breast height (dbh) (cm) and height (m) (averaged over the different species). First root pruning was done at 41 months after planting and was repeated at 50 and 62 months. Least significant difference for comparison of dbh between pruning treatments is 2.052. Means between treatments at a particular time of measurement are significantly different when they are succeeded by different letters.

Months after planting	47	50	56	60	63	66	69
Diameter at breast height (cm)							
Pruned trees	10.28a	12.25b	13.07b	13.57b	14.04b	14.45b	15.30b
Unpruned trees	10.45a	12.57a	13.47a	14.04a	14.61a	15.02a	15.95a
Height (m)							
Pruned trees			10.71a	11.59a	12.12a	12.45a	12.90a
Unpruned trees			10.86a	11.79a	12.39a	12.77a	13.18a

Data analyzed by repeated measures, using data collected at 43 months as a covariate in the analysis. Covariates for pruning effects on dbh and height were both significant at $p < 0.001$.

Table 3. Mean number, diameter and total root cross sectional area per tree (2 m trench length x 0.3 m depth) of main and regrowth ('coppice') roots, in the re-opened root pruning trench, 4 and 11 months after the third root pruning. Main roots were >5 mm diameter at the time of the assessments and had been pruned. Coppice roots had re-grown from the main roots.

	Species						
	Casuarina	*Grevillea*	*Maesopsis*	*Alnus*	*Markhamia*	P	LSD
4 months after pruning							
Main roots							
No. main roots per tree	6.2b	11.7a	4.7b	5.8b	8.0ab	0.020	3.94
Mean diameter (mm)	18.3	10.6	16.7	13.1	9.1	0.154	
Cross-sectional area per tree (mm^2)	1952	1715	2116	997	1381	0.845	
Regrowth							
No. coppice roots per tree	21.7	31.5	13.7	19.0	20.0	0.132	
Mean diameter (mm)	3.0	1.65	2.30	2.37	2.02	0.254	
Cross sectional area per tree (mm^2)	127	99	91	88	106	0.909	
11 months after pruning							
Main roots							
No. main roots per tree	6.7b	7.8b	4.8b	11.7a	5.2b	0.002	3.25
Mean diameter (mm)	17.9b	15.4b	33.9a	12.3b	20.2b	0.004	10.6
Cross-sectional area per tree (mm^2)	2819b	2215b	7038a	2003b	1883b	0.003	2699
Regrowth							
No. coppice roots per tree	64.7ab	36.7bc	31.3c	84.2a	33.7bc	0.011	33.2
Mean diameter (mm)	2.67bc	2.60bc	5.56a	2.14c	4.32ab	0.003	1.77
Cross sectional area per tree (mm^2)	784ab	368b	1069a	571b	768ab	0.034	431

Table 4. Effects of tree species and root pruning on *Phaseolus vulgaris* crop yield (kg ha^{-1} air dry weight of seeds) in full and subdivided root pruning subplots TP^+,TP^- and TP0 (Fig. 1) during the short rains of 2000 - 2001. Data from 28 rows of beans, extending up to 14 m from the tree row, either analysed at the full sub-plot level, or separated into proximal and distal units. Data within a column and factor, superseded by different letters are significantly different at $p \leq 0.05$ as determined by ANOVA and Fisher's *F*-test.

Factor	Full sub plot 0 – 14 m	Proximal 0 – 7 m	Distal 7 – 14 m
Tree species			
Casuarina	1115.24bc	831.43d	1399.05
Grevillea	1297.38ab	1139.52b	1455.24
Maesopsis	1079.52c	965.24cd	1193.81
Alnus	1237.38abc	1106.67bc	1368.10
Markhamia	1246.91abc	1035.71bc	1458.09
'No tree' control	1395.24a	1405.95a	1384.52
Pruning treatment			
TP^+*	1277.02	1200.95a	1353.10
TP^-	1183.45	964.52c	1402.38
TP0	1225.36	1076.67b	1373.81
F prob.			
Tree species	0.031	<0.001	0.342
Pruning	0.099	<0.001	0.694
Species x pruning	0.243	0.052	0.435

*TP^+ sub plot on the root pruned side of the tree row, TP^- sub plot on the opposite side of the tree row, TP0 sub-plot adjacent to trees which were not root-pruned

Table 5. Effects of tree species and root pruning on *Phaseolus vulgaris* crop yield (kg ha^{-1} air dry weight of seeds) combined from both sides of the pruned tree row (TP^{+} + TP^{-})/2, compared with unpruned treatments. Data from 28 rows of beans, extending up to 14 m from the tree row, either analysed at the full sub-plot level, or proximal unit alone. Data within a column and factor, superseded by different letters are significantly different at $p \leq 0.05$ as determined by ANOVA and Fisher's *F*-test.

Factor	Full sub plot 0 – 14 m	Proximal 0 – 7 m
Tree species		
Casuarina	1096.79b	823.57d
Grevillea	1312.26a	1146.90b
Maesopsis	1061.55b	950.95cd
Alnus	1232.02ab	1103.57bc
Markhamia	1265.95ab	1047.86bc
'No tree' control	1398.10a	1405.71a
Pruning treatment		
(TP^{+} + TP^{-})/2	1230.24	1082.86
TP0	1225.36	1076.67
F prob.		
Tree species	0.029	< 0.001
Pruning	0.888	0.865
Species x pruning	0.304	0.787