Rooting pattern of *Acacia mangium* in pure and mixed stands of *Eucalyptus camaldulensis*, *Tectona grandis* and *Casuarina montana* in the coastal Tanzania

By

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ABSTRACT

This study investigates if *Tectona grandis, Casuarina montana* and *Eucalyptus camaldulensis* planted in mixture with *Acacia mangium* would send their roots toward *Acacia* in attempt to benefit from its symbiotic nitrogen fixation ability and also to investigate if the roots of mixed tree species would occupy different vertical soil layers for better utilization of site resources. A soil core method was used for root and soil sampling in a 22 months old mixed stand of *E. camaldulensis* (E), *C. montana* (C), *T. grandis* (T) and *A. mangium* (A) in a 1A:8A; 1A:8E; 1A:8T; 1A:8C; 1E: 8A; 1T:8A and 1C: 8A species combination replicated at three sites. Lateral distribution showed a decreasing root biomass with increasing distance from the tree stem. The highest total root biomass was obtained at 20 cm distance reaching 306.05 g m^{-2} for *Acacia*, 229.19 g m^{-2} for *Eucalyptus* 156.5 g m^{-2} for *Tectona* and 127.0 g m^{-2} for *Casuarina.* The lowest total root biomass was observed at 180 cm distance reaching 5.44 g m^{-2} for *Acacia* and 0.01 g m^{-2} for *Eucalyptus*, *Casuarina* and *Tectona*. Lateral spread of other species was higher in the upper layer (0-10 cm) with high density of *A. mangium* and high in the lower layer (10-20 cm) with low density of *A. mangium* in the species combination. Vertical distribution revealed a decrease in root biomass with increasing soil depth for all species except *T. grandis*. Mean root biomass decreased from 162.41 (acacia) to 4.58 g m^{-2} (teak) in the 0-10 cm layer to 90.26 (acacia) to 5.40 (casuarina) g m^{-2} in the 10-20 cm layer. Also fine root biomass was high in the upper layer and coarse root biomass was high in the lower layer. It is concluded that, there was not sufficient evidence of other species sending their roots toward *A. mangium* but there was clear vertical niche separation between *A. mangium* and other species, particularly with *T. grandis*

Key words: *Acacia mangium*, *Eucalyptus camaldulensis*, *Tectona grandis*, *Casuarina montana* nurse tree, mixed species, rooting pattern, root biomass, root distribution.

DECLARATION

I, Charles Joseph Kilawe, do hereby declare to the Senate of BOKU, University of Natural Resources and Life Sciences that this thesis is own original work and that it has neither been published nor concurrently being submitted for a higher degree award in any other University.

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1.0 INTRODUCTION

Sustainable production and profitability in fast growing single species plantations is being questioned (Khan, 1997). Decline in productivity and profitability in subsequent rotations is predicted due to limited nutrient reserves in highly weathered soils (Bouillet *et al.,* 2007; Silva *et al.,* 2009) and large amounts of biomass removal by harvesting (Bemhard, 1996). For sustaining productivity in such a land use system, intensive silvilculture activities which include nutrient retention on the site are unavoidable (Bouillet *et al*., 2007). Because fertilization is expensive and there is a risk of N loss by leaching, NH3 volatilization and nitrous oxide emission to the environment, it is advised to incorporate nurse trees in the mixed-species plantation (Bouillet *et al.,* 2007). Nurse trees supply nutrient requirements of fast growing plantations, accelerate growth rates and nutrient cycling, increase light use efficiency, improve tree form and self-pruning (Rothe and Binkley, 2001; Yang *et al.,* 2009). The nursing effect may result from crown architecture, shading, increases in soil moisture and nutrition, protection against herbivores, and enhancement of beneficial soil organisms (Yang *et al.,* 2009).

Acacia mangium is the major planted nurse tree species in the tropics (Turvey, 1995). Besides its ability to nurse understorey plants, *A. mangium* has high tolerance and growth rates on bare soils, grows well in degraded areas and can facilitate native trees due to its great ability to buffer temperature, to reduce radiation, to improve nutrition and to increase soil organic matter (Yang *et al.,* 2009). *A. mangium* has the strong potential to increase soil nutrient supply because it can form a symbiotic relation with *Rhizobium* bacteria, which have the ability to fix Nitrogen through their root nodules (Yang *et al*., 2009). It can also scavenge P, K and Mg from the subsoil (Ngoran *et al*., 2006).

The nursing ability of *Acacia* species has however not been adequately studied (Yang *et al*., 2009). The few studies conducted concentrated on above ground effects and usually involve only two species in combination. Below ground interactions have been neglected, probably by either the difficulties in estimating the nutrient input in ecosystem by a nurse tree (Forrester *et al*., 2006) or the scarcity of field based methods to estimate nutrient fixation through nurse trees (Bouillet *et al*., 2007).

To answer questions about below ground competition and dynamics, resource uptake and transfer to a neighboring tree, information on spatial distribution of coarse and fine roots is important (Millikini and Bledsoe, 1999). Relationship between nutrient dynamics and plant growth is incomplete without consideration of the whole rooting zone (Dambrine *et al*., 1997). With respect to nutrient and water uptake, coarse roots act indirectly, providing connections between shoots and fine roots, while fine roots directly absorb nutrients and water. In their nutrient absorption role, tree roots often influence neighboring species through competition (Millikini and Bledsoe, 1999). Rooting characteristics of *A. mangium* has been little studied up to now (Kunhamu *et al*., 2010).

Root architecture and distribution is an expression of its different functions such as anchorage and support, water and nutrient uptake and transport (Schmid and Kazda, 2005). The pattern of root distribution is mostly governed by the availability of soil resources (Linkohr *et al*., 2002). In forests the highest density of roots is found in the top layer, however some trees tend to show more superficial root distribution than others (Schmid and Kazda, 2005).

In mixed species stands, each species in the mixture may have different nutrient requirements and different nutrient cycling properties (Montagnini, 2000). Roots may occupy different soil strata for better utilization of site resources (Lamb and Lawrence, 1993). Vertical stratification within the rooting zone could occur with one species occupying the upper soil space and the other dominating the subsoil. Also, the ability of one species to exploit the resources can modify the distribution of other species associated with it in the mixture (Schmid and Kazda, 2005).

Comparative studies of roots systems containing more than one tree species are rare (Schmid and Kazda, 2002; Silva *et al.,* 2009). Also little is known about the distribution of coarse roots (>2 mm) and about the distribution of root less than 2 mm diameter (Schmid and Kazda, 2005, Montagnoli *et al*., 2009). In Africa, Tanzania information about rooting pattern in mixed plantations is rare (Kilawe, 2010).

This study therefore aims to examine vertical and lateral rooting pattern of *Acacia mangium* in mixed plantation with *Tectona grandis, Casuarina montana* and *Eucalyptus camaldulensis*.

1.1 Objectives

1.1.1 Main objective

The main objective was to find out if *Tectona grandis*, *Eucalyptus camaldulensis* and *Casuarina montana* planted in mixture with *Acacia mangium* would send their roots towards *A. mangium*

1.1.2 Specific objectives

i) To describe the impact of species combination on pH and bulk density

ii) To describe vertical and lateral distribution of *A. mangium* (a) when surrounded by *A. mangium* (2) when surrounded by *T. grandis*, *E. camaldulensis* and *C. montana*

iii) To describe the vertical and lateral root distribution of *T. grandis*, *E. camaldulensis* and *C. montana* (a) when surrounding *A. mangium* (b) when surrounded by *A. mangium*

1.2. Hypothesis

i) *T. grandis, E. camaldulensis and C. montana* would send their roots toward *A. mangium* in attempt to benefit from its nutrients fixing ability

ii) *A. mangium*, *T. grandis, E. camaldulensis and C. montana* would occupy different vertical soil strata for better utilization of site resources

iii) Distribution of fine and course roots would be governed by resource availability

iv) Bulk density would be high in the top soil as a result of soil compaction by machines during ploughing

2.0 LITERATURE REVIEW

2.1 Description of *Acacia mangium*

Acacia mangium is a medium to tall, spreading tree. Branches are glabrous; leaves are ovate, conspicuously veined and bark is corrugated or coarsely cracked grey to dark brown (Elliot and Jones, 1982). The tree can reach a height up to 30 m, with branches spreading from near ground level or with a bole to 4.5 m high (Duke, 1983).

The species is native to northeastern Queensland in Australia, the western province of Papua New Guinea, Papua, and the eastern Maluku Islands but it is wide spread in Asia, Latin America and Africa. It is known to adapt quickly to the local conditions of areas of introduction (Duke, 1983).

Figure 1: A photo of 1 year old *Acacia mangium* in Tanzania

The species is mainly used as a timber tree, for firewood (specific density = 0.65mg m^{-3}), for production of particle boards and could possibly be useful for furniture, cabinet making, and perhaps even pulp and paper (NAS, 1979). It has successively been used in restoration of degraded sites and degraded grassland by converting them to productive forest lands (Tham, 1979). It is widely used in many cropping systems, particularly in association with plantation crops due to its unique adaptability to local conditions (N'goran *et al.,* 2002).

It is capable of performing under a wide range of site conditions as from tropical very dry to moist through subtropical dry to wet forest life zones. The species has fast growth rates and short rotations. It has outperformed *Albizia falcataria* and *Gmelina arborea* which are considered among the fastest-growing useful trees on earth (NAS, 1979). It apparently tolerates annual precipitation of 100 to 450 mm; mean maximum temperatures of 31–34°C, mean minimum temperatures of 12–25°C, and pH values of 4.2–7.5 (NAS, 1983d).

Acacia mangium is an important leguminous species as it forms symbioses with the bacterium *Rhizobium* and the fungus *Thelephora*. The species quickly forms an effective root system, effective mycorrhiza and N -fixing root nodules (Hogberg and Wester, 1998).

2.1 Ability of *Acacia mangium* to fix nitrogen.

A study conducted in Brazil to find the nitrogen fixing ability of *Acacia mangium* planted in mixture with *Eucalyptus grandis* revealed that N concentration in the leaves of *A. mangium* was higher than in leaves of *E. grandis*, which suggests the ability of *Acacia* to fix atmospheric N_2. Similar results were observed when *A. mangium* was mixed with *E. urophylla* (Bouillet *et al.,* 2007). Another study conducted to compare the facilitation effect of *A. mangium* and *A. auriculiformis*, showed that total soil nitrogen was higher under the two *Acacia* species than in the open site and higher under *A. mangium* than under *A. auriculiformis* (Yang *et al*., 2009). Also, a study conducted to assess soil conditions in fast-growing plantations of *E. grandis* and *A. mangium* in Brazil, revealed that the stock of organic matter, the content of C and N and cation exchange capacity (CEC) were higher under *A. mangium* than under *E. grandis* (Garay, *et al.,* 2004).

2.3 Facilitation effect of *Acacia mangium*

In a study conducted in Tanzania, to asses survival, growth and productivity of pure and mixed stands of *E. camaldulensis*, *C. montana*, *T. grandis* and *A. mangium*, in the same stand where this research was undertaken, it was found that growth and productivity were higher in mixed stands compared to pure monoculture. In particularly, it was observed that growth and productivity of *E. camaldulensis* was higher when combined with *A. mangium*, than with other species. It was concluded that *A. mangium* was facilitating growth of *E. camaldulensis* (Kilawe, 2010). Another study conducted to examine growth dynamics in a mixed-species plantation of *Eucalyptus globulus* and *Acacia mangium* indicated that the volume and above ground biomass of *E. globulus* was higher in mixture than in monoculture, which suggests that *E. globulus* was facilitated by *A. mangium* (Forrester *et al*., 2004). The results from a study conducted in Australia to compare growth and nutrition of young monocultures and mixed stands of *E. globulus* and *A. meansii*, indicated that height and volume increment of individual *E. globulus* were positively affected by the presence of *A. meansii*. At an age of 33 months the 50E:50A treatment had the greatest height at the higher planting density. It was presumed that there was transfer of N from acacias to eucalypts during the early stages of plantation development probably resulting mainly from the below ground turn over on roots and nodules as the above ground litter decomposition had not commenced (Silva *et al.,* 2009).

2.4 Rooting pattern and spatial distribution of *Acacia mangium* and other species

2.4.1 Vertical root distribution

A study conducted in Brazil to assess the dynamics of fine root distribution after establishment of mono specific and mixed-species plantations of *Eucalyptus grandis* and *Acacia mangium*, indicated that fine root density (FRD) of *A. mangium* trees in 33% *Acacia (A)* :67 % *Eucalyptus (E)* were about half those in 100A:0E. In the 0–10 cm layer, the FRD of *E. grandis* trees in 100E:0A was significantly higher than the FRD of *A. mangium* trees in 100A:0E. The FRD of *A. mangium* trees in the upper layer was about three times higher in 100A:0E than in 33A:67E one year after planting. A trend of decreasing FRD with soil depth was observed 18 months after planting in all treatments except for *A. mangium* trees in 33A:67E. The FRDs of *A. mangium* and *E. grandis* trees were no longer significantly different in the 0–10 cm. *A. mangium* fine roots were almost absent in the upper soil layer of the mixed-species treatment 18 months after planting, and the highest FRDs were found in the 10-30 cm soil layer (Silva et al.,2009). In another study conducted in Malysia to examine root biomass and symbioses in *Acacia mangium* replacing tropical forest after logging it was found that root biomass declined with increasing soil depth (Hogberg and Wester, 1998). Muthukuma *et al*., 2003 in a study to examine the distribution of roots and arbuscular mycorrhizal associations in tropical forest in China observed similar results where fine root turnover was higher in the upper depth (0-10 cm) than in the lower depth (10-20 cm). Another study conducted to investigate biomass and distribution of fine and coarse roots from blue oak (*Quercus douglasii*) trees in the northern Sierra Nevada foothills of California, revealed a decrease of lateral root length and number with depth. Most roots concentrated in the upper layer with more than 71% of fine root biomass in upper layer while the coarse roots contributed only 26% (Millikini and Bledsoe, 1999).

2.4.2 Lateral root distribution

In a study conducted to assess the influence of stand density and pruning on root activity of young *Acacia mangium* trees, it was found that the distribution of physiologically active roots in 2 year-old *A. mangium* trees was profoundly influenced by planting densities. The highest root activity for the high stem density treatment, regardless of soil depth, was within a radial distance of 25 cm from the base of the tree and it decreased with increasing distance. For example, root activity at 25 cm was 50–53%, and it declined to 13–17% at 75 cm. Conversely, in the low density stands, a higher relative proportion of root activity was noted at a radial distance of 75 cm (e.g. 23–34% at 25 cm as against 41.5–42.4% at 75 cm), implying that stand density altered the horizontal distribution of absorbing roots (Kunhamu *et al*., 2010). Silva *et al*. (2009) observed that fine root density (FRD) of *A .mangium* was significantly higher close to A*. mangium* trees 30 months after planting in 100 % *Acacia* (E):0% *Eucalyptus* (E) species combination. It was also observed that development of *A. mangium* fine roots was greatly modified by planting *E. grandis* trees in a mixture. *A. mangium* FRDs were very low in each soil depth close to *E. grandis* trees in 33A:67E. Whilst the dynamics of *A. mangium* FRD were highly influenced by the proximity of *E. grandis* and *A. mangium* trees in 33A:67E, the dynamics of *E. grandis* FRDs were little influenced by the position (Silva *et al*., 2009).

Millikini and Bledsoe (1999) observed that distance from the tree had no significant influence on the distribution of fine or coarse roots. No decreases in fine root biomass with distance were observed for smaller trees. However, root biomass decreased with increasing distance from a larger tree which had a canopy radius of 3.6 m (Millikini and Bledsoe, 1999).

3.0 METHODOLOGY

3.1 Site description

3.1.1 Location

This study was carried out at a farm earmarked for afforestation by Tanga Forests Co Ltd. at Pangani district in Tanga region, Tanzania. The farm is located at Mwera ward within Langoni and Mtango villages, at latitude 38°46' -38 °47' E and longitude 5 °29' - 5 °32' S. The farm under study is located at about 25 to 30 km south of Pangani (Fig.2).

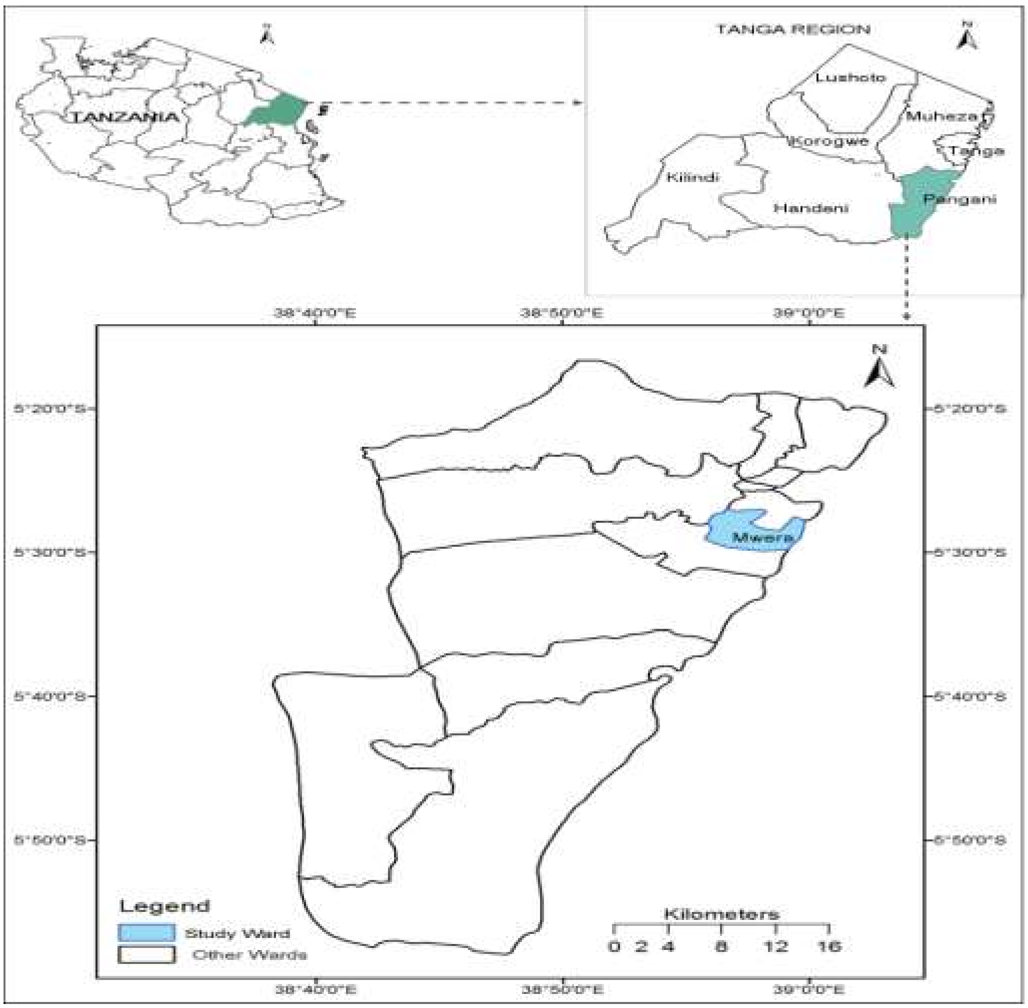

Figure 2: Location of the study site

Source: Kilawe, 2010

3.1.2 Climate

Seasonal pattern of rainfall in Pangani is greatly influenced by the Indian Ocean. Rainfall is bi-modal with the main rains falling in April and May and smaller or short rains falling between October and December. Annual rainfall is about 1270 mm. The mean annual temperature is 26°C with a maximum of 33°C and minimum of 20°C. May to July is the coolest period and December to February is the hottest period. Average diurnal humidity levels range from 81% in the morning to 68% in the evening. Fig 3 gives a rainfall and temperature diagram of a meteorological station located 47 km from the study area.

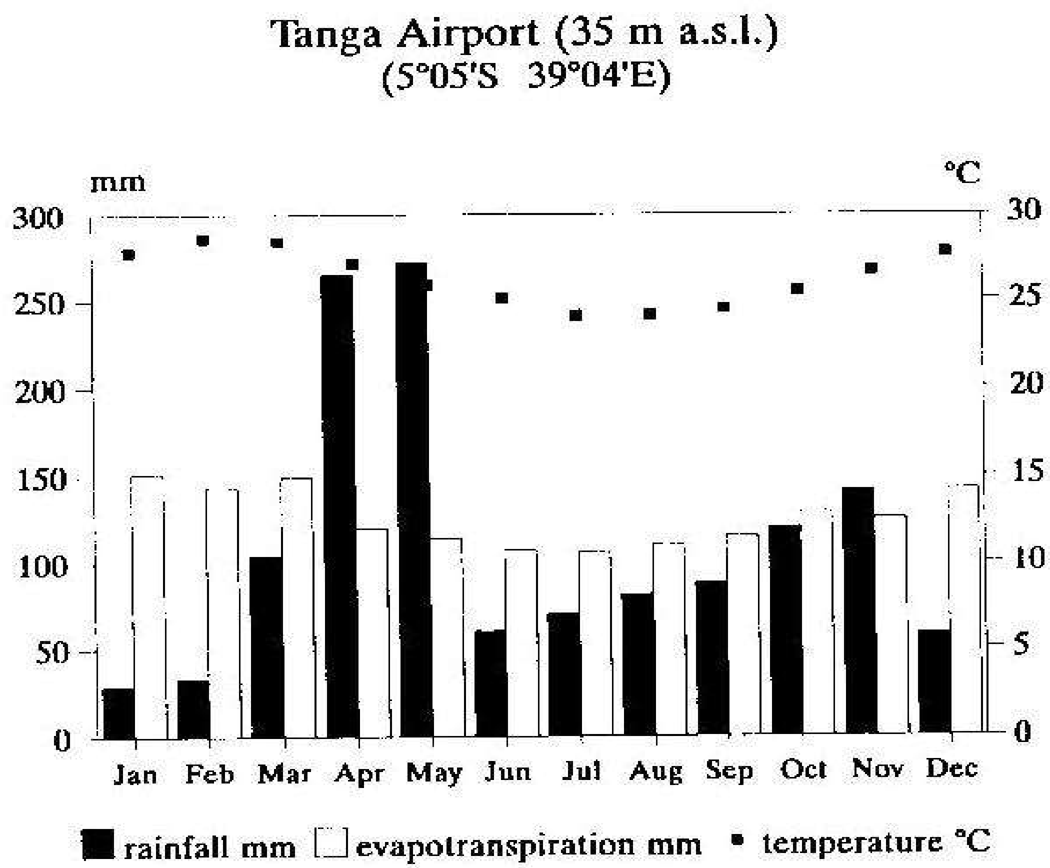

Figure 3: Rainfall and climate diagram for Tanga region.

Source: Hartemink, 1995

3.1.3 Soils

The type of soil in Tanga region is determined by geology and physiography. Areas adjacent to the coast for example have dominant Vertisols (Locally referred as 'Mbuga' or black cotton soils), in the uplands Arenosols, Ferralsols and Luvisols are dominant and in the alluvial plains Cambisols, Phaeozem and Rendzic leptosols are dominant. In the study area two main soil types were identified, Vertisols and Ferralisols (Hartemink, 1995).

3.2 Species studied

Nursery-raised seedlings of *Eucalyptus camaldulensis, Acacia mangium, Casuarina montana* and cuttings of *Tectona grandis* were used for field planting. *E. camaldulensis, A. mangium* and *C. montana* seeds were obtained from Tanzania Tree Seeds Agency (TTSA), and they were the provenances of Kisinga, Tanzania, Australia and Zanzibar, Tanzania respectively. *T. grandis* seeds were locally obtained from Longuza tree seed stand in Muheza, nearby to Pangani district in Tanzania. These four species were chosen because they are the main tree species planted by Tanga Forest Ltd forest plantations. They are intended to produce logs for poles, timber, pulp and paper production and fuel wood. Besides those functions *Acacia* and *Casuarina* have the potential for nitrogen fixation, so they were meant to facilitate the growth of the eucalypts and teak. Table 1 gives a short description of the species

Table 1: Characteristics of tree species grown in mixed and pure plantation.

Scientific name	Common name	Native area	Family
A. mangium	Mangium wattle	Australia, Papua-Guinea, Indonesia	*Fabaceae*
E. camaldulensis	River red gum	Australia	*Myrtaceae*
T. grandis	Teak	Southeast Asia	*Verbenaceae*
C. montana	Forest oak	Indonesia	*Casuarinaceae*

3.3 Planting sites

Within Tanga forest ltd. farm, three sites (replicates) were randomly selected to establish the mixed species stand. Site 2 was formerly an *Acacia mangium* compartment that was destroyed by fire, while sites 1 and 3 were virgin land. The descriptions of soil properties of the sites are as indicated in Table 2.

Table 2: Site properties

	Sites	
Soil Properties	**Site 1 and Site 2**	**Site 3**
Soil type (WRB)	Vertisols	Ferralsols
Sampling depth (cm)	0-15	0-20
Clay (%)	32	52
Silt (%)	59	8
Sand (%)	9	40
pH(H20)1:2.5	6.8	4.6
pH(1M KCl)1:2.5	6.0	4.0
Organic carbon (%)	0.63	1.8
Total Nitrogen (%)	0.52	0.15
Available P(Bray 1)($mgKg^{-1}$)	66	3.0
CEC (NH4OAc pH 7)($mmol_c kg^{-1}$)	526	89
Exchangeable Ca ($mmol_c kg^{-1}$)	543	7
Exchangeable Mg ($mmol_c kg^{-1}$)	100	5
Exchangeable K ($mmol_c kg^{-1}$)	12	1
Exchangeable Na ($mmol_c kg^{-1}$)	4	<0.5
Base saturation (%)	87	14
Exchangeable Al ($mmol_c kg^{-1}$)	Na	8
Al Saturation (% ECEC)	Na	40

Source: Hartemink, 1995.

Na: No information

3.4 Site preparation and planting

Planting sites were characterized by coastal vegetation, thus land preparation involved removal of debris and burning before strip ploughing took place. Round-up herbicide was sprayed after ploughing to control weeds, and then marking and staking were done at a spacing of 2 m by 2 m. Pitting was done in marked areas with the pit size of 30 cm by 30 cm by 30 cm. Planting was carried out in mid-March 2009, following on set of long rains. Aqua sols (South Africa) were applied at a rate 400 ml per tree, to increase stability against water stress.

3.5 Stand design

Nursery-grown *E. camaldulensis, A. mangium, C. montana,* and stumps of *T. grandis* seedlings were planted as a four-species replacement series in a 3 x 3 view point comprising 36 plots. Each plot had 9 trees with tree species planted as a replacement series with five relative densities: 9:0:0:0, 8:1:0:0, 6:3:0:0, 6:2:1:0, 3:2:2:2 as illustrated in Fig. 4 (Vanclay, 2006). Trees were planted at a density of 2500 stems per hectare (2 m by 2 m); thus plot size was 6 m x 6 m. The plots were surrounded by single external guard row. The whole design accommodated 400 seedlings with each species contributing 100 seedlings. The spacing chosen was a little bit smaller than usual (Spacing recommended for plantation trees in Tanzania is 2.5 m by 2.5 m or 3 m by 3 m) because of the need to study competition among trees at an earlier age and to speed up canopy closure so as to obtain early impacts on the soil (Montagnini, 2000).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	A	A	A	A	A	A	A	A	A	T	A	T	T	T	T	T	T	T	T	T
2	A	A	A	A	A	A	A	A	T	A	T	A	T	T	T	T	T	T	T	T
3	A	A	A	A	A	A	T	A	A	T	A	T	T	A	T	T	T	T	T	T
4	A	A	A	A	A	A	A	A	T	A	T	A	T	T	T	T	T	T	T	T
5	A	A	A	A	A	A	A	A	A	T	A	T	T	T	T	T	T	T	T	T
6	A	A	A	A	A	A	A	A	T	A	T	A	T	T	T	T	T	T	T	T
7	A	A	C	A	A	A	E	A	A	E	C	T	T	C	T	T	T	E	T	T
8	A	A	A	A	A	A	A	E	T	A	T	A	C	T	T	T	T	T	T	T
9	A	C	A	C	A	C	A	C	A	T	A	T	E	T	E	T	E	T	E	T
10	C	A	C	A	C	A	E	A	C	E	C	E	T	C	T	E	T	E	T	E
11	A	C	A	C	A	C	T	C	A	T	A	T	E	A	E	T	E	T	E	T
12	C	A	C	A	C	A	C	A	C	E	C	E	T	E	T	E	T	E	T	E
13	C	C	C	C	C	C	C	T	E	C	E	C	A	E	E	E	E	E	E	E
14	C	C	A	C	C	C	T	C	C	T	A	E	E	A	E	E	E	T	E	E
15	C	C	C	C	C	C	C	C	E	C	E	C	E	E	E	E	E	E	E	E
16	C	C	C	C	C	C	C	C	C	E	C	E	E	E	E	E	E	E	E	E
17	C	C	C	C	C	C	C	C	E	C	E	C	E	E	E	E	E	E	E	E
18	C	C	C	C	C	C	E	C	C	E	C	E	E	C	E	E	E	E	E	E
19	C	C	C	C	C	C	C	C	E	C	E	C	E	E	E	E	E	E	E	E
20	C	C	C	C	C	C	C	C	C	E	C	E	E	E	E	E	E	E	E	E

Figure 4: Design for the mixed species trial, showing planting positions

Where; A=*A. mangium; C= C. montana; E=E. camaldulensis and T=T. grandis.*

3.6 Design of the rooting pattern study

This study was carried out in already established mixed stands described in section 3.5 above. From the design, seven treatments were identified as in Fig 5.; 1 *Acacia* surrounded by 8 *Acacia* (1A:8A); 1 *Acacia* surrounded by 8 *Eucalyptus* (1A:8E); 1 *Acacia* surrounded by 8 *Tectona* (1A:8T); 1 *Acacia* surrounded by 8 *Casuarina* (1A:8C); 1 *Eucalyptus* surrounded by 8 *Acacia* (1E: 8A); 1 *Tectona* surrounded by 8 *Acacia* (1T:8A) and 1 *Casuarina* surrounded by 8 *Acacia* (1C: 8A).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	A	A	A	A	A	A	A	A	A	T	A	T	T	T	T	T	T	T	T	T
2	A	A	A	A	A	A	A	A	T	A	T	A	T	T	T	T	T	T	T	T
3	A	A	A	A	A	A	T	A	A	T	A	T	T	A	T	T	T	T	T	T
4	A	A	A	A	A	A	A	A	T	A	T	A	T	T	T	T	T	T	T	T
5	A	A	A	A	A	A	A	A	A	T	A	T	T	T	T	T	T	T	T	T
6	A	A	A	A	A	A	A	A	T	A	T	A	T	T	T	T	T	T	T	T
7	A	A	C	A	A	A	E	A	A	E	C	T	T	C	T	T	T	E	T	T
8	A	A	A	A	A	A	A	E	T	A	T	A	C	T	T	T	T	T	T	T
9	A	C	A	C	A	C	A	C	A	T	A	T	E	T	E	T	E	T	E	T
10	C	A	C	A	C	A	E	A	C	E	C	E	T	C	T	E	T	E	T	E
11	A	C	A	C	A	C	T	C	A	T	A	T	E	A	E	T	E	T	E	T
12	C	A	C	A	C	A	C	A	C	E	C	E	T	E	T	E	T	E	T	E
13	C	C	C	C	C	C	C	T	E	C	E	C	A	E	E	E	E	E	E	E
14	C	C	A	C	C	C	T	C	C	T	A	E	E	A	E	E	E	T	E	E
15	C	C	C	C	C	C	C	C	E	C	E	C	E	E	E	E	E	E	E	E
16	C	C	C	C	C	C	C	C	C	E	C	E	E	E	E	E	E	E	E	E
17	C	C	C	C	C	C	C	C	E	C	E	C	E	E	E	E	E	E	E	E
18	C	C	C	C	C	C	E	C	C	E	C	E	E	C	E	E	E	E	E	E
19	C	C	C	C	C	C	C	C	E	C	E	C	E	E	E	E	E	E	E	E
20	C	C	C	C	C	C	C	C	C	E	C	E	E	E	E	E	E	E	E	E

Figure 5: Design for mixed species trial, showing research plots

3.7 Sampling campaign.

3.7.1 Root sampling

A soil core method was adopted as it's relatively convenient for assessing fine root distribution (Millikini and Bledsoe, 1999). Sample points for root sampling were located at a distance of 20, 50, 100, 150 and 180 cm from the trees. At each point auger samples (6.7 cm diameter) at every distance were taken. The direction was random in all directions from the centre tree (Fig. 6). A total of 105 soil cores (7 treatments x 5 distances between the trees x 3 Sites) and a total of 210 samples (7 treatments x 5 distances x 2 soil depths x 3 Sites) were obtained. Soil cores were separated into two soil layers 0-10 and 10-20 cm (Montagnoli *et al*., 2009). In each layer 352 cm^3 of soil (Pi * 6.7^2cm/4*10 cm) was collected in a cylinder and roots were separated from soil and packed into well labeled bags.

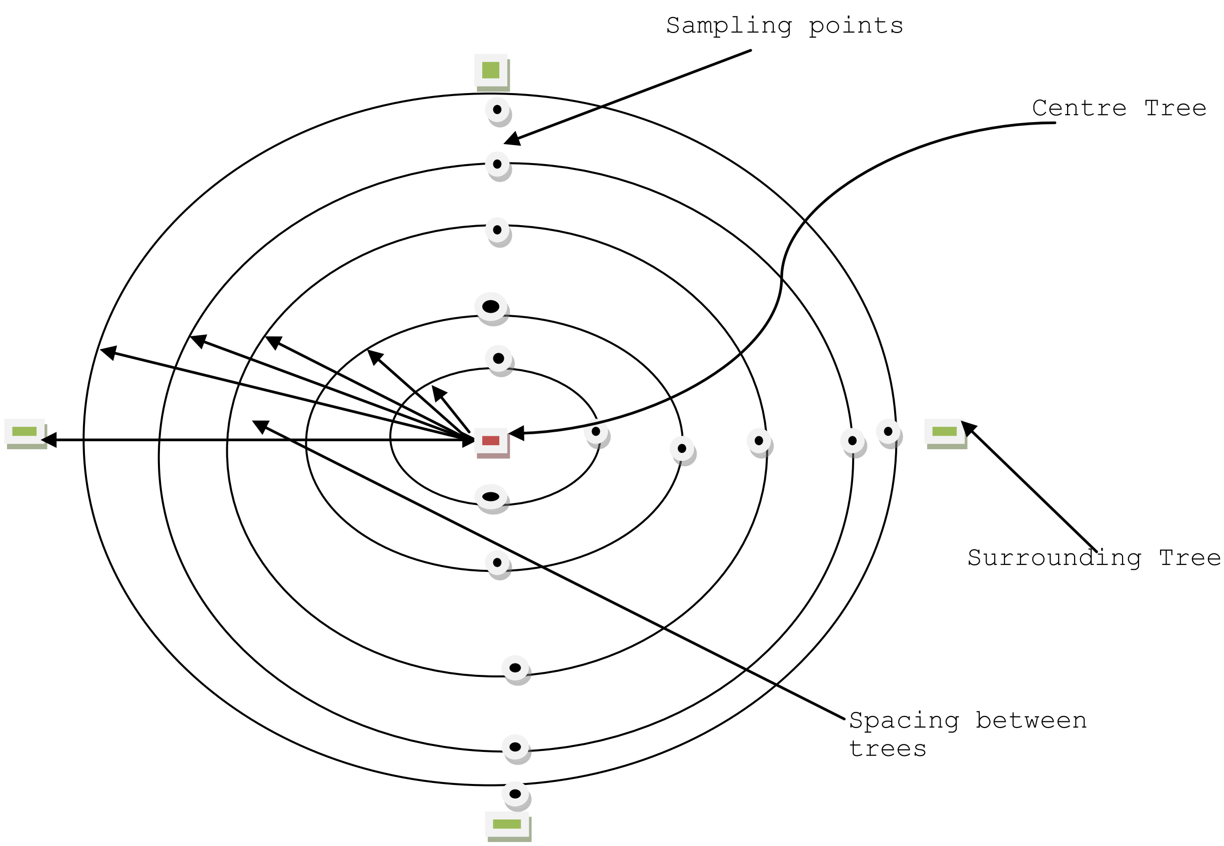

Figure 6: Diagram showing roots sampling positions

3.7.2 Soil sampling

Points were selected at 100 cm distance between the centre and the surrounding trees for each site. In each identified point soil for pH and bulk density determination was collected as follows; nearly undisturbed area was selected. Top vegetation which was not part of soil, for example litter and fresh organic matter were removed. By using a spade, a pit up to 30 cm was made. On a side wall between 0-10 cm and 10-20 cm horizons, a corer was immersed to collect soil for the computation of bulk density. The corer was carefully removed, covered and packed. Also soils were collected at each horizon for pH determination. Each soil sample was put in a clean plastic bag and the sample was thoroughly mixed. Each soil sample was put in a labeled plastic bag and stored in insulated containers (Muthukumar *et al*., 2003). A total of 42 samples were collected (7 treatments x 1 distance between trees x 2 soil depths x 3 sites).

3.8 Laboratory analysis

3.8.1 Determination of soil pH

Soils collected from field were sieved through a 2 mm mesh. Soil solutions were prepared by mixing 10 g of soil with 25 ml of deionised water (1:2.5) in a small plastic bottle. The mixture was put on a round shaker for 24 hours. Before starting the pH-measurement, the pH meter was calibrated with the two buffer solutions, pH 4 and pH 7. pH was then read by using Hanna Instrument pH meter. During the measurement, it was important to always measure in the same depth of the liquid of the samples

3.8.2 Determination of bulk density

Soil from the cylinders from the field were weighed in the Lab and then put in the oven to dry at 105°C for 24 hours. Bulk density was calculated as oven dry weight of soil minus weight of container divided by volume of the container.

$Bulk\ density\ (g/cm^3) = Soil\ mass_{oven\ dried}\ (g)/Volume\ (cm^3)$

3.8.3 Root extraction and measurements

In the Laboratory, roots were further separated from soil using running water in 0.5 mm mesh sieves. Fragments of organic matter and dead roots were removed. Living roots were sorted according to various criteria such as lack of flotation, living stele, bright colour and resilient aspect (Jourdan *et al.,* 2008). The species for all living roots were identified by separating *Acacia mangium* from the rest based on its colour and morphology (Smith *et al*., 1999). *A. mangium* has brighter color than *E. camaldulensis* and *C. montana* (Silva *et al*., 2009). The roots of acacia and teak were differentiated based on the color, structure and texture. Teak roots were brighter in color, showed less branching, no nodules, and more courser in texture than acacia (personal observation). Cleaned, live fine roots from each core were sorted according to diameter class**:** course roots (>2mm diameter) and fine roots (<2mm diameter) (Muthukumar *et al.,* 2003) and sample dried at 60 °C for 72 hours (Schmid and Kazda, 2002). After being dried at 60°C and weighed, root biomass was divided in to site, species, distance between the trees, soil depth and diameter class for subsequent analysis (Appendix 1).

3.9 Data analysis

For continuous data which showed normal distribution, one way analysis of variance of sample means was used and where a difference was noted, the least significant difference (LSD) multiple comparisons procedure at the 5 percent significance level was performed to determine the mean differences between those treatment combinations. Non parametric Kruskal Wall's test was used to find differences between the means of data showing no normal distribution.

4.0 RESULTS

4.1 Impact of species combination on Soil pH and bulk density

There was no significant effect (P>0.05) of species combination on pH and bulk density (Appendix 2). However, the lowest pH value was observed in a combination between *Acacia* and *Casuarina* (1A:8C) followed by *Acacia* and *Eucalyptus* (1A:8E) and the highest pH value was observed in monoculture of *Acacia* (1A:8A) (Table 3). On the other hand, the lowest bulk density was observed in the species combination between *Acacia* and *Tectona* (1A:8T) while the highest was observed in the combination between *Eucalyptus* and *Acacia* (1E:8A) (Table 3).

Table 3: Mean pH and bulk density of different tree species combinations

		Bulk density (g cm^{-3})		pH ($H_2 0$)	
Species combination	N	Mean	Std. Error of Mean	Mean	Std. Error of Mean
1A : 8A	6	1.35 a	.10	6.71 a	.34
1T : 8A	6	1.32 a	.10	6.51 a	.25
1A : 8T	6	1.27 a	.10	6.38 a	.15
1A : 8E	6	1.31 a	.05	5.95 a	.31
1A : 8C	6	1.33 a	.11	6.04 a	.36
1C : 8A	6	1.36 a	.08	6.36 a	.12
1E : 8A	6	1.42 a	.08	6.63 a	.26

Means sharing the same letter between treatments, for the same calculation method, were not significantly different at P < 0.05

4.2 Impact of soil depth on pH and bulk density .

Analysis of variance on the impact of soil depth on pH and bulk density, revealed no statistical significant effect (P>0.05) (Appendix 3). It was noted that soil pH was relatively higher in upper (0-10 cm) than lower soil layer (10-20 cm) and bulk density slightly increased with increasing soil depth (Table 4).

Table 4: Mean bulk density and pH of different soil layers

Soil depth	N	Bulk density (g cm^{-3})		pH (H_2O)	
		Mean	Std. Error of Mean	Mean	Std. Error of Mean
0-10 cm	21	1.33 a	.043	6.38 a	.146
10-20 cm	21	1.34 a	.050	6.36 a	.148

Fig. 7 demonstrates that soil pH was relatively higher in monoculture of *Acacia* (1A: 8A) and in combination between *Eucalyptus* and *Acacia* (1E:8A) while the lowest was observed in a combination between *Acacia* and *Eucalyptus* (1A:8E).

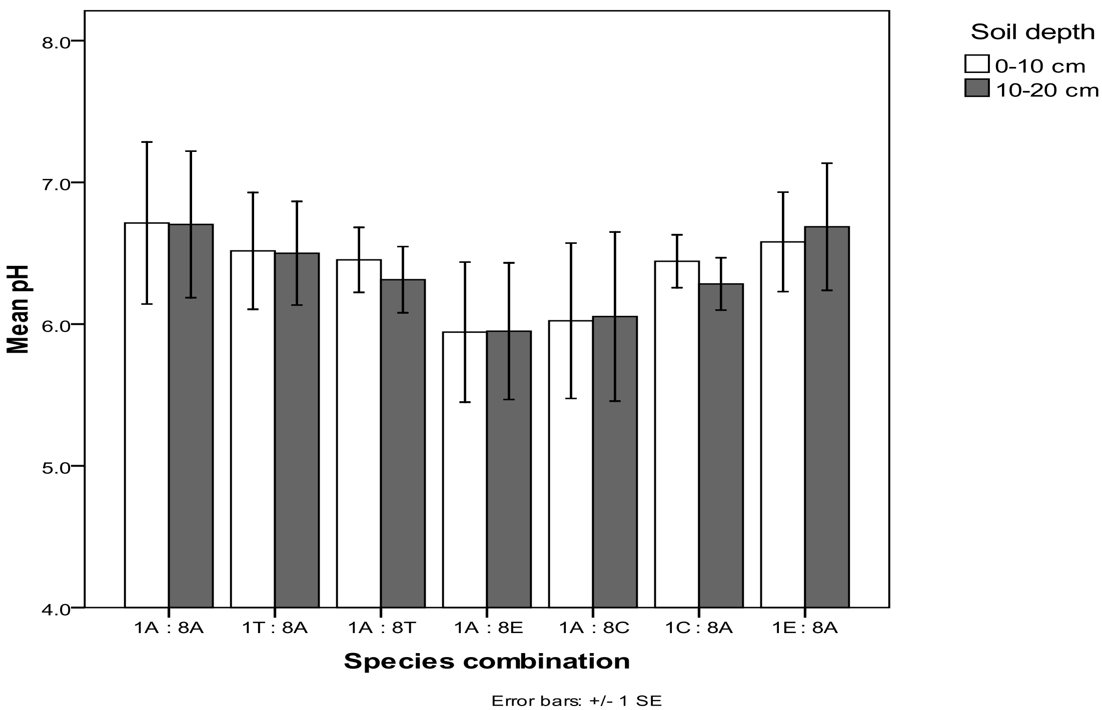

Figure 7: Soil pH of different species combination with soil depth

Fig. 8 shows that species combination between *Acacia* and *Tectona* (1A:8T) had the least bulk density while the rest species combination did not show any remarkable trend.

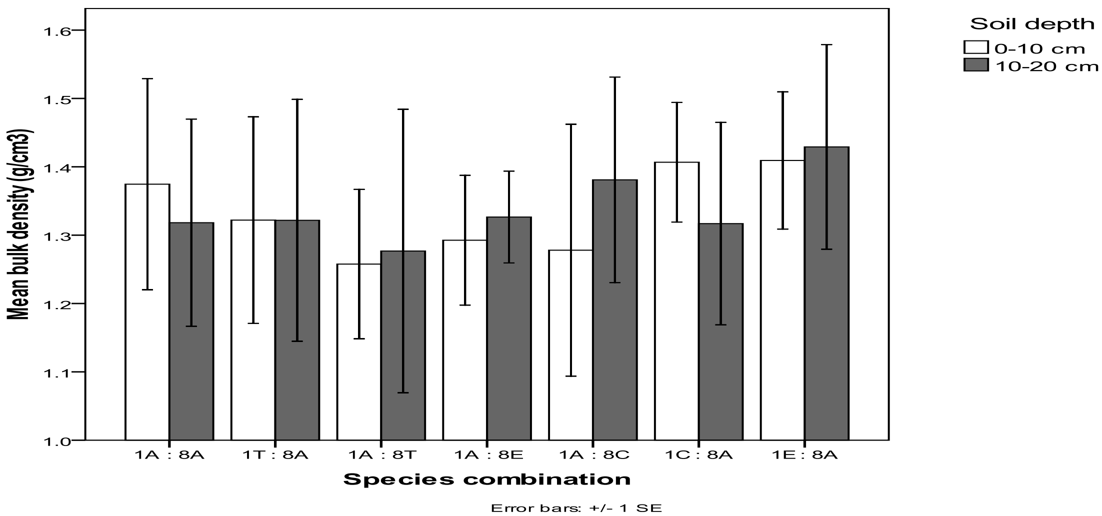

Figure 8 : Soil bulk density of different species combination with soil depth

4.3 Lateral and vertical root distribution of *Acacia mangium*

4.3.1 Root biomass of *A. mangium* when *A. mangium* was surrounded by *A. mangium* (1A:8A)

Analysis of variance for the impact of distance between trees on the distribution of root biomass of *Acacia* indicated no significant effect (P>0.05) (Appendix 4). The highest root biomass was obtained at a distance of 20 cm and 180 cm while the lowest was obtained at 100 cm distance (Table 5). Fig. 9 shows a decreasing trend of root biomass with increasing distance up to 100 cm and rise again at 150 and 180 cm, making a ‘‘V’’ shape in the upper layer. As for the lower layer, root biomass increased with increasing distance from the centre tree.

Table 5: Lateral distribution of total root biomass in the top soil (0-20 cm depth) of *Acacia* when *Acacia* was surrounded by *Acacia*

Distance from *Acacia* (cm)	Mean root biomass (g m^{-2})	N	Std. Error of Mean
20	306.05 a	6	138.41
50	195.11 a	6	11.73
100	91.45 a	6	22.27
150	199.18 a	6	50.34
180	352.91 a	6	170.31
Total	228.94	30	45.50

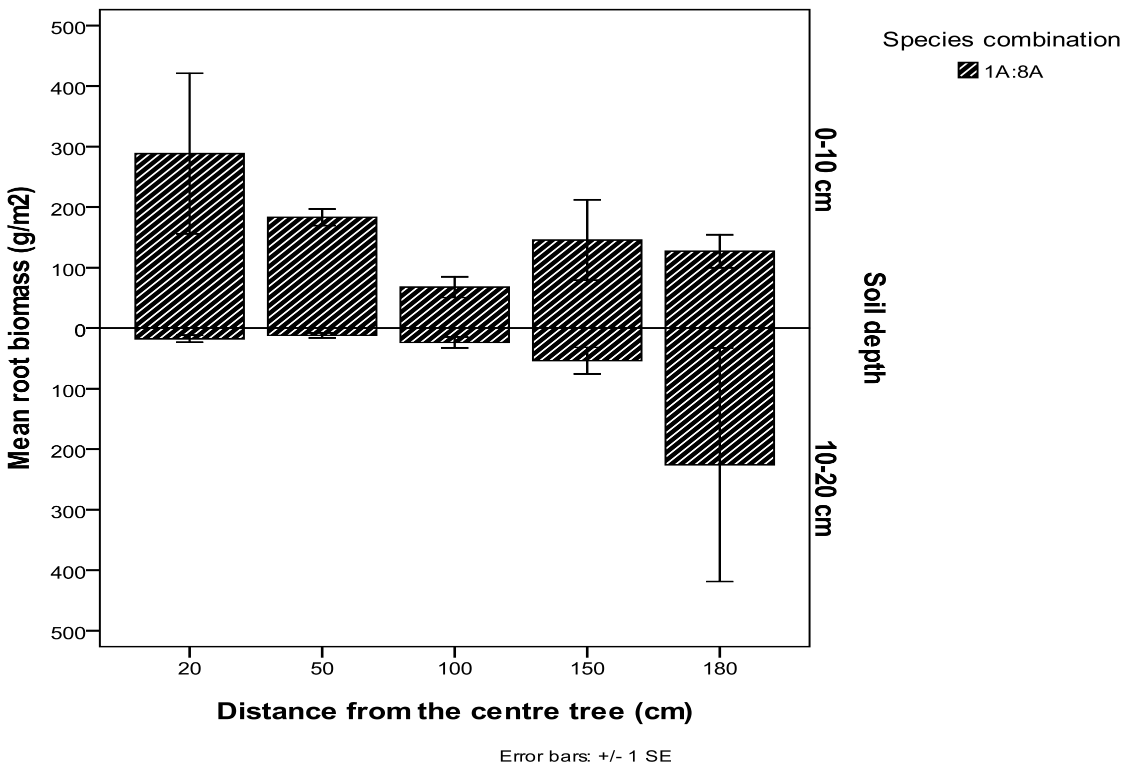

Figure 9: Vertical and lateral distribution of *Acacia* root biomass when *Acacia* was surrounded by *Acacia*

Analysis of variance on the influence of soil depth on *Acacia* root biomass distribution reveled significant effect (P<0.05) (Appendix 5). Higher root biomass was observed in the upper layer as compared to lower layer (Table 6).

Table 6: Vertical distribution of root biomass of *Acacia* when *Acacia* was surrounded by *Acacia*

Soil depth	Root diameter	Mean root biomass (g m^2)	Std. Error of Mean	N
0-10 cm	<2mm	127.48 a	14.59	15
	>2 mm	34.93 b	24.78	15
	Total	162.41		
10-20 cm	<2mm	27.23 b	6.03	15
	>2 mm	39.31 b	39.31	15
	Total	66.53		

Vertical distribution also indicates that fine root biomass of *Acacia* was confined on the upper layer where as coarse root biomass was confined on the lower layer (Fig. 10).

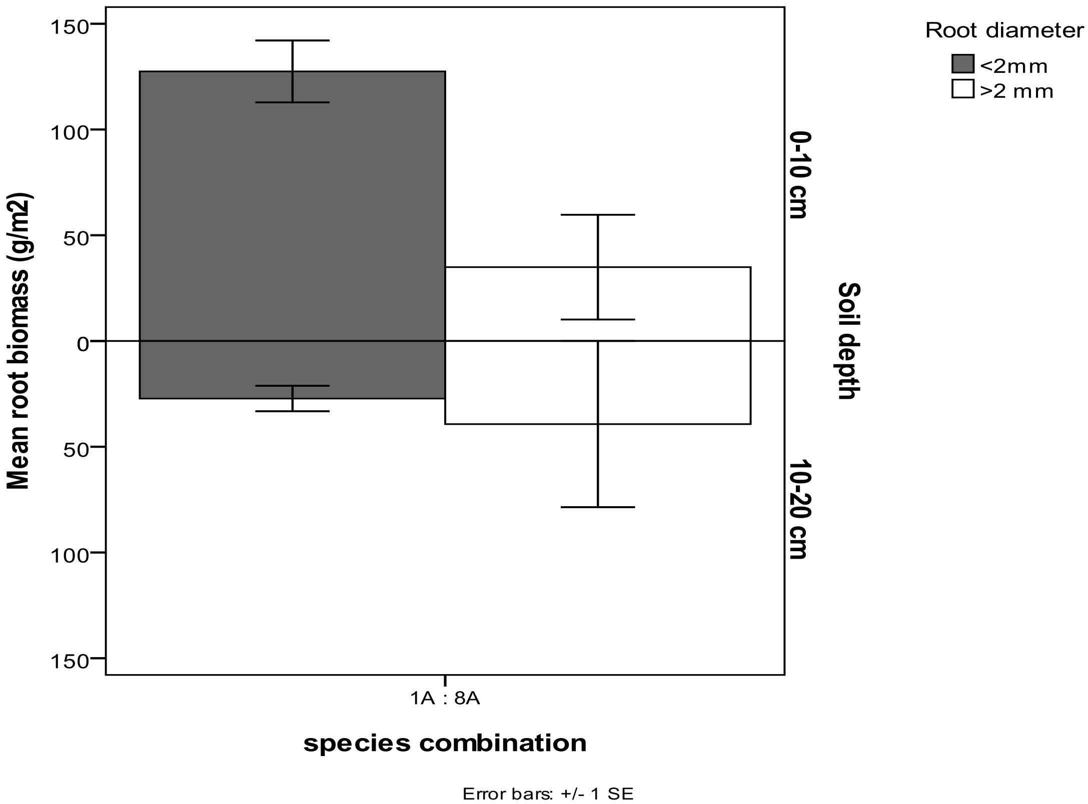

Figure 10: Vertical distribution of fine and coarse root biomass of *Acacia* when *Acacia* was surrounded by *Acacia*

4.3.2 Root biomass of *A. mangium* when *A. mangium* was surrounded by *T. grandis*, *C. montana* and *E. camaldulensis* (1A: 8T, 1A: 8C and 1A: 8T)

Evaluation of distribution of *Acacia* with distance indicated statistical significant effect ($P<0.05$) (Appendix 6). Further evaluation with LSD, revealed that root biomass of *Acacia* in a 1A:8C species combination, at 20 cm distance was significantly different from root biomass at 50, 150 and 180 cm distance (Appendix 7). The highest root biomass was obtained at 20 cm distance where as the lowest was obtained at 180 cm distance from *Acacia* (Table 7).

Table 7: Lateral distribution of total root biomass in the top soil (0-20 cm depth) of *Acacia* when *Acacia* was surrounded by *Tectona*, *Casuarina* and *Eucalyptus*

Distance from *Acacia* (cm)		Mean root biomass of *Acacia* ($g\ m^2$) Species combination 1A:8T	1A:8E	1A:8C	Mean total
20	Mean	303.21 a	417.67 a	665.13 a	462.00
	N	9	9	9	27
	Std. Error of Mean	229.37	288.59	179.54	129.86
50	Mean	181.25 a	222.66 a	102.81 b	168.90
	N	9	9	9	27
	Std. Error of Mean	83.69	89.04	24.12	40.02
100	Mean	241.54 a	123.82 a	120.03 a	161.80
	N	9	9	9	27
	Std. Error of Mean	203.35	34.81	95.40	68.58
150	Mean	153.83 a	50.17 a	27.07 b	77.03
	N	9	9	9	27
	Std. Error of Mean	84.64	41.28	17.03	33.81
180	Mean	93.62 a	24.80 a	0.00 b	39.47
	N	9	9	9	27
	Std. Error of Mean	92.77	16.35	0.01	30.59

Means sharing the same letter between treatments, for the same calculation method, were not significantly different at $P < 0.05$

Fig. 11 indicates that for the upper layer, the highest root biomass of *Acacia* was obtained at 20 cm distance in a combination between *Acacia* and *Casuarina* (1A:8C). The lowest root biomass was obtained at 180 cm distance in a combination between *Acacia* and *Eucalyptus* (1A:8E). For the lower layer, the highest root biomass of *Acacia* was obtained at 100 cm distance in a combination between *Acacia* and *Tectona* (1A:8T) as the lowest was obtained at 150 cm away in a combination between *Acacia* and *Casuarina.*

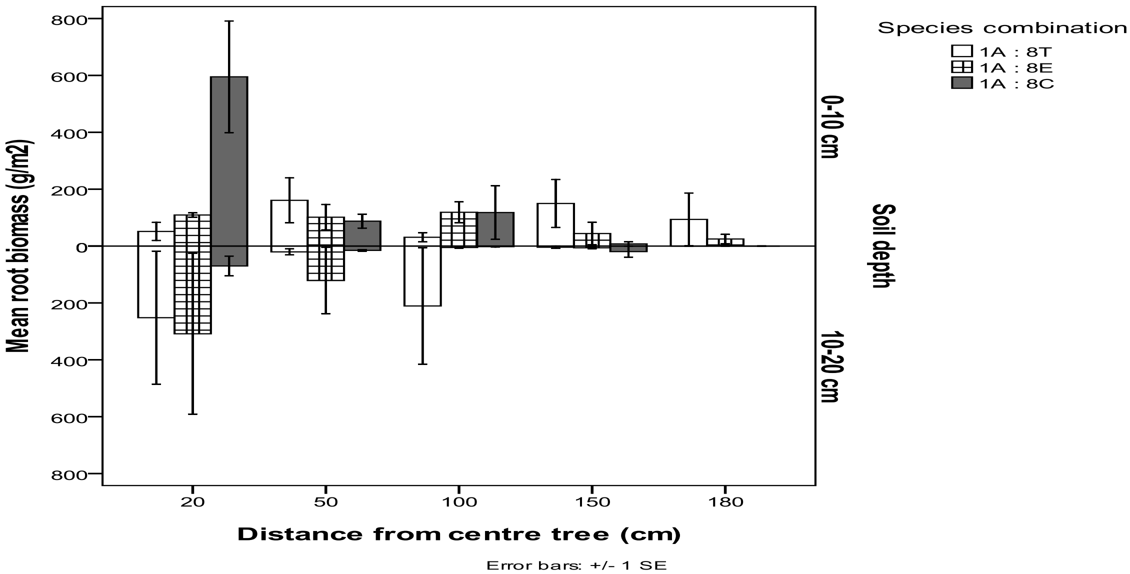

Figure 11: Vertical and lateral distribution of *Acacia* root biomass when *Acacia* was surrounded by *Tectona*, *Casuarina* and *Eucalyptus*

There was no statistical significant influence (P>0.05) of soil depth on root biomass of *Acacia* (Appendix 8). However, the highest root biomass was observed in the upper layer (Table 8).

Table 8: Vertical distribution of root biomass of *Acacia* when *Acacia* was surrounded by *Tectona, Casuarina* and *Eucalyptus*

Soil depth	Root diameter	N	1A:8T		1A:8T		1A:8T		
			Mean (g m^2)	Std. Error	Mean (g m^2)	Std. Error	Mean (g m^2)	Std. Error	Mean total
0-10	<2mm	15	51.0 a	18.93	73.46 a	15.88	47.96 a	14.86	
cm	>2 mm	15	46.2 a	19.87	6.15 b	4.51	115.06a	62.96	
	Total		97.23		79.61		163.02		113.29
10-20	<2mm	15	18.0 a	7.92	13.25 a	5.03	11.61 a	5.24	
cm	>2 mm	15	79.4 b	53.30	74.96 b	57.88	12.31 a	9.23	
	Total	30	97.46		88.21		23.91		69.86

Fig. 12 shows that, with exception of species combination between *Acacia* and *Casuarina* (1A:4C) fine roots of *Acacia* were dominant in the upper layer where as the coarse roots in the lower layer.

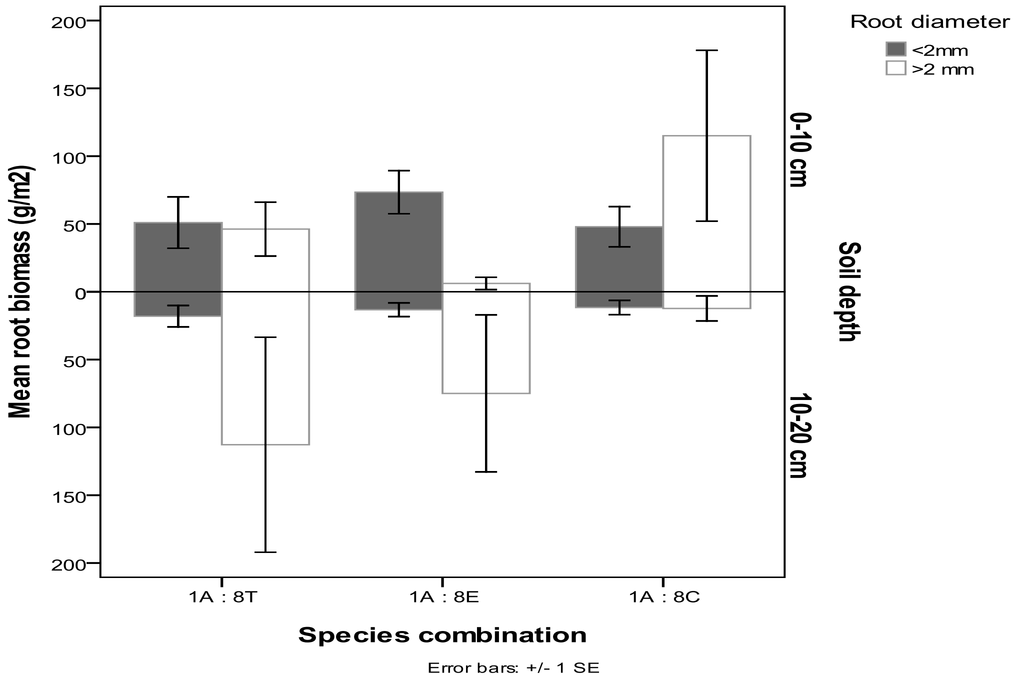

Figure 12: Vertical distribution of fine and coarse root biomass of *Acacia* when *Acacia* was surrounded by *Tectona, Casuarina* and *Eucalyptus*

4.3.3 Root biomass of *A. mangium* when *T. grandis*, *C. montana* and *E. camaldulensis* was surrounded by *A. mangium* (1T: 8A; 1C: 8 A and 1 E: 8 A)

Analysis of variance for the effect of lateral distance on root biomass of *Acacia* indicated statistical significant effect (P<0.05) (Appendix 9). Further evaluation with LSD, indicated that root biomass of *Acacia* in a 1C: 8A species combination at 20, 50 and 100 cm distance was significant different from root biomass of *Acacia* at 150 and 180 cm (Appendix 10). The highest root biomass was obtained at 50 cm while the lowest was obtained at 180 cm from *Acacia* (Table 9).

Table 9: Lateral distribution of total root biomass in the top soil (0-20 cm depth) of *Acacia* when *Tectona*, *Casuarina* and *Eucalyptus* was surrounded by *Acacia*

Distance from centre tree (cm)		Mean root biomass of *Acacia* (g m^2)			
		Species combination			
		1T:8A	1C:8A	1E:8A	Mean total
20	Mean	28.40 a	2.84 a	40.61 a	23.95
	N	9	9	9	27
	Std. Error of Mean	13.21	2.84	21.69 a	9.24
50	Mean	41.94 a	38.06 ac	46.77 a	42.25
	N	9	9	9	27
	Std. Error of Mean	21.10	28.09	12.39	10.83
100	Mean	199.56 a	28.87 ace	42.50 a	90.31
	N	9	9	9	27
	Std. Error of Mean	160.17	14.40	1.98	53.90
150	Mean	215.65 a	329.72 bdf	443.80 a	329.73
	N	9	9	9	27
	Std. Error of Mean	82.58	177.50	397.85	132.17
180	Mean	234.96 a	148.15 ace	350.27 a	244.46
	N	9	9	9	27
	Std. Error of Mean	89.88	33.80	302.23	96.11

Fig. 13 shows that *Acacia* root biomass increased with increasing distance from the centre tree. For the upper horizon the highest root biomass was obtained at a distance of 180 cm (20 cm from *Acacia*) in a combination between *Acacia* and *Tectona* (1T:8A) as the lowest root biomass was obtained at a distance of 20 cm (180 cm from *Acacia*) in a combination between *Acacia* and *Casuarina* (1C:8A). For the lower layer, the highest root biomass of *Acacia* was obtained at a distance of 150 cm in a 1E:8A species combination as the lowest was obtained at a distance of 20 cm in a 1C:8A species combination.

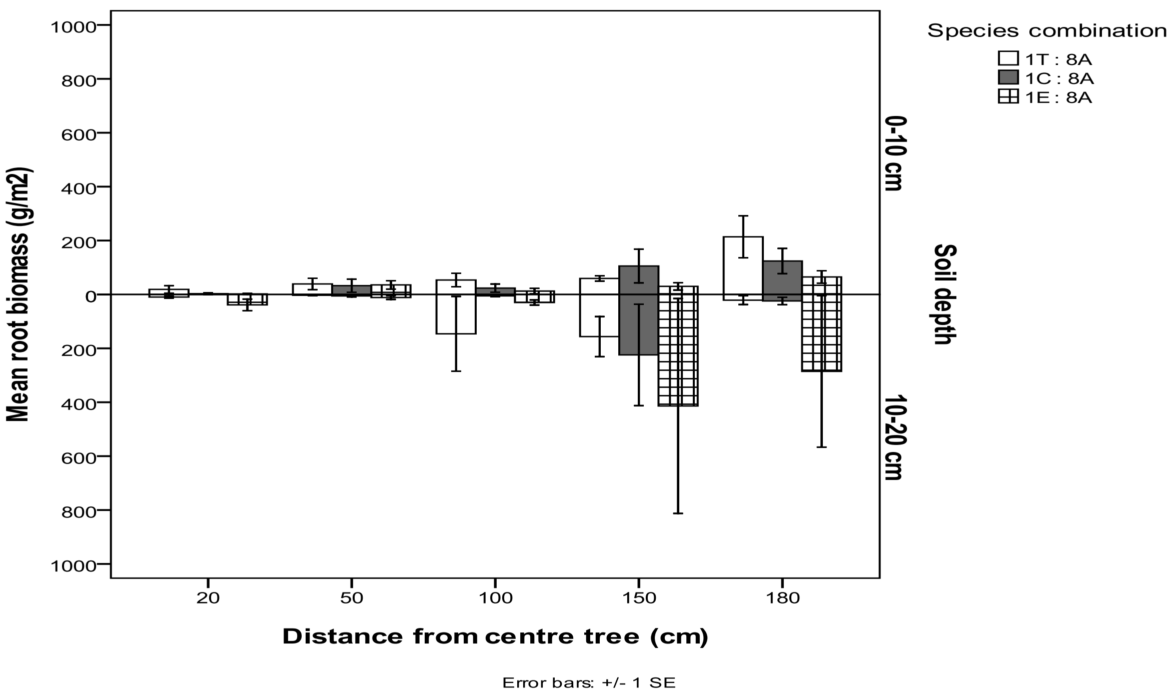

Figure 13: Vertical and lateral distribution of root biomass of *Acacia* when *Tectona, Casuarina* and *Eucalyptus* were surrounded by *Acacia*

Analysis of variance indicated no significant statistical effect (P>0.05) of soil depth on distribution of *Acacia* root biomass (Appendix 11). However, root biomass of *Acacia* in 1E:8A species combination was twice as much of root biomass was found on lower layer compared to upper layer (Table 10).

Table 10: Vertical distribution of total root biomass of *Acacia* when *Tectona, Casuarina* and *Eucalyptus* was surrounded by *Acacia*

Soil depth	Diameter	N	1T:8A		1C:8A		1E:8A		
			Mean (gm^2)	Std. Error	Mean (gm^2)	Std. Error	Mean (gm^2)	Std. Error	Mean total
0-10 cm	<2mm	15	43.17 a	7.39	57.69 a	19.04	34.57 a	7.50	
	>2 mm	15	33.68 a	23.01	.00 b	.00	.00 b	.00	
	Total		76.85		57.69		34.57		56.37
10-20 cm	<2mm	15	17.49 a	5.37	15.11 a	6.00	19.31 a	5.40	
	>2 mm	15	49.76 a	30.10	36.73 a	36.73	132.38 b	92.05	
	Total	30	67.25		51.84		151.69		90.26

It was also observed that, in all species combinations, fine root biomass was concentrated in the upper layer while coarse root biomass was high in the lower layer (Fig. 14).

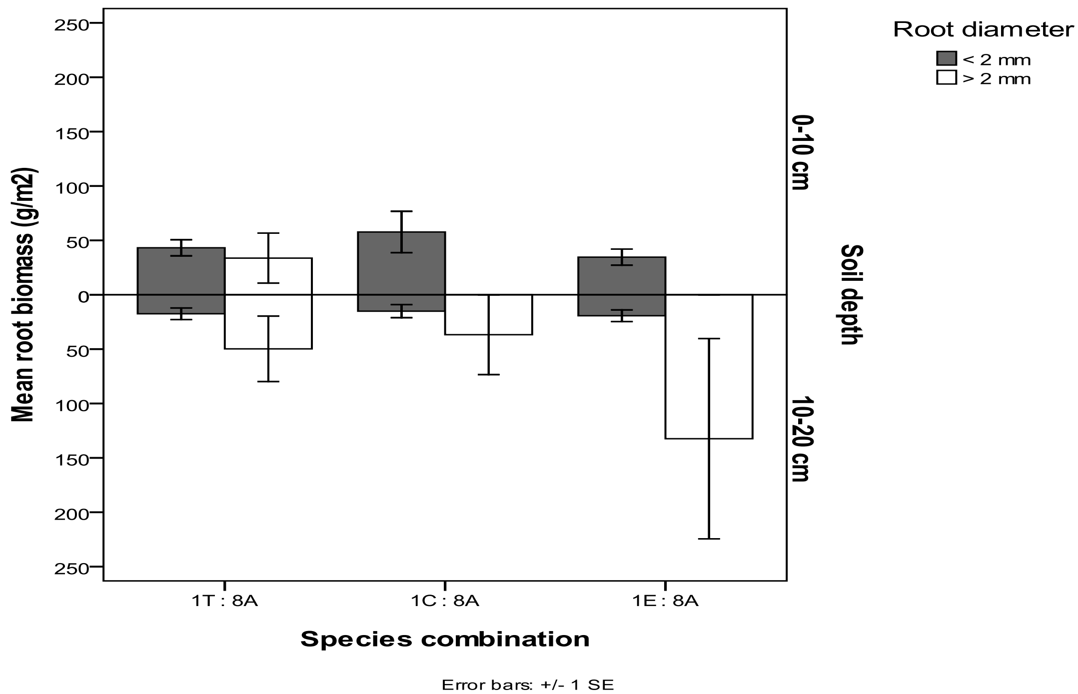

Figure 14: Vertical distribution of fine and coarse root biomass of *Acacia* when *Tectona*, *Casuarin*a and *Eucalyptus* was surrounded by *Acacia*

4.4 Vertical and lateral distribution of *T. grandis, E. camaldulensis* and *C .montana*

4.4.1 Root biomass of *T. grandis*, *C. montana* and *E. camaldulensis* when surrounded *A. mangium* (1A: 8T, 1A: 8C and 1A: 8T)

Analysis of variance (Appendix 12) indicates no significant effect (P>0.05) of distance on root biomass of *Tectona* and *Eucalyptus* but root biomass of *Casuarina* was significantly dependent (P<0.05) on distance. Further computation with LSD revealed that root biomass of *Casuarina* at a 180 cm distance differed significantly from 150, 100, 50 and 20 cm distance (Appendix 13). *Eucalyptus* had the highest root biomass at 180 cm from *Acacia* (20 cm to *Eucalyptus*), while *Tectona* had the lowest root biomass at a distance of 20 cm from *Acacia* (Table 11).

Table 11: Lateral distribution of total root biomass in the top soil (0-20 cm depth) of *Tectona, Eucalyptus* and *Casuarina* when surrounded *Acacia*

Distance from the centre (cm)		Mean root biomass (g m^2)			
		Tectona	*Eucalyptus*	*Casuarina*	Mean total
20	Mean	0.01 a	7.76 a	6.34 a	4.70
	N	9	9	9	27
	Std. Error of Mean	.00	7.76	6.34	3.13
50	Mean	121.27 a	3.98 a	18.18 ab	47.81
	N	9	9	9	27
	Std. Error of Mean	119.14	3.98	5.87	39.10
100	Mean	41.75 a	120.13 a	34.93 abd	65.60
	N	9	9	9	27
	Std. Error of Mean	38.39	113.24	18.31	37.50
150	Mean	32.38 a	66.17 a	134.14 abd	77.56
	N	9	9	9	27
	Std. Error of Mean	6.82	22.02	23.04	17.68
180	Mean	38.25 a	197.76 a	77.15 bce	104.39
	N	9	9	9	27
	Std. Error of Mean	14.72	153.58	36.06	51.66

Fig 15 indicates that for the upper layer, all species showed a similar trend of decreasing root biomass with decreasing distance from the centre tree. For the lower layer, *Tectona* and *Eucalyptus* root biomass showed a trend of increasing root biomass with decreasing distance from the centre tree up to a distance of 150 cm away.

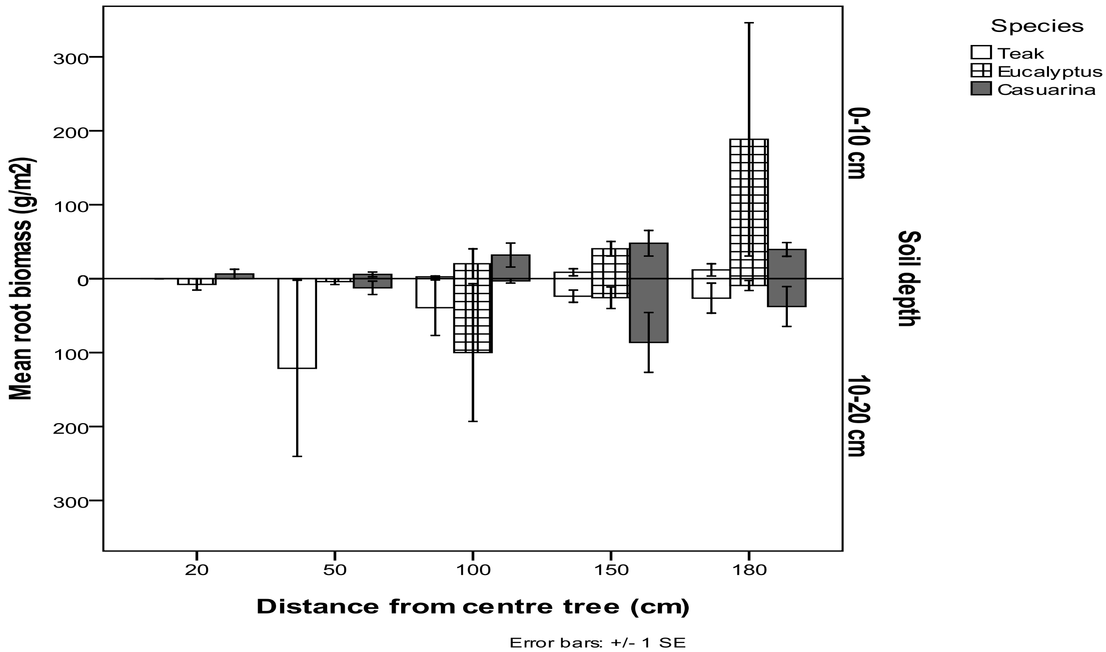

Figure 15: Vertical and lateral distribution of root biomass of *Tectona, Eucalyptus* and *Casuarina* when they surrounded *Acacia*

Analysis of variance of the effect of soil depth on the distribution of root biomass of *Tectona, Casuarina* and *Eucalyptus* indicated no significant influence (Appendix 14). While *Tectona* had higher root biomass in the lower layer, *Eucalyptus* and *Casuarina* had highest root biomass in the upper layer (Table 12).

Table 12: Vertical distribution of root biomass of *Tectona, Eucalyptus* and *Casuarina* when surrounded *Acacia*

Soil depth	Root diameter	N	*Tectona* Mean (g m^2)	*Tectona* Std. Error	*Eucalyptus* Mean (g m^2)	*Eucalyptus* Std. Error	*Casuarina* Mean (g m^2)	*Casuarina* Std. Error
0-10	<2mm	15	4.58 a	2.08	21.41 a	7.20	32.20 a	10.82
cm	>2 mm	15	.00 b	.00	28.40 a	28.40	.00 b	.00
	Total		4.58		49.81		32.20	
10-20	<2mm	15	37.70 a	24.22	29.34 a	18.72	21.57 a	7.53
cm	>2 mm	15	4.45 b	4.45	.00 b	.00	.38 b	.38
	Total		42.15		29.35		21.94	

Fig. 16 indicates that both fine and coarse root biomass of *Tectona* are concentrated in the lower layer. It also indicates that, while coarse roots of *Eucalyptus* are concentrated in the upper layer, few coarse roots were observed for *Casuarina.* There was no remarkable difference in distribution of fine roots of *Eucalyptus* and *Casuarina* between the soil layers.

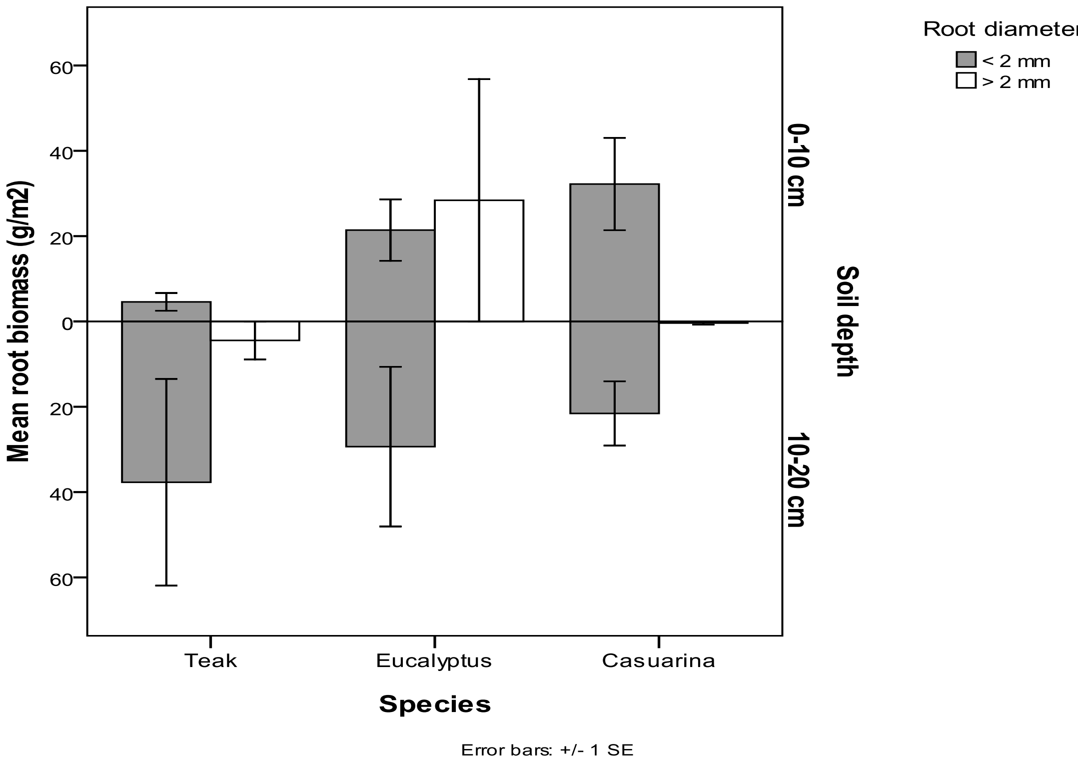

Figure 16: Vertical distribution of fine and coarse root biomass of *Tectona, Eucalyptus* and *Casuarina* when they surrounded *Acacia*

4.4.2 Root biomass of *T. grandis*, *C. montana* and *E. camaldulensis* when surrounded by *A. mangium* (1T: 8A; 1C: 8 A and 1 T: 8 A)

Analysis of variance indicated a significant influence (P<0.05) of distance on root biomass of *Tectona* and *Eucalyptus* (Appendix 15). Further analysis with LSD revealed that root biomass of *Tectona* at 20 and 50 cm was significantly different from root biomass at 100, 150 and 180 cm. Root biomass of *Eucalyptus* at 50 cm was significantly different from root biomass at 100, 150 and 180 cm (Appendix 16). *Eucalyptus* had the highest root biomass at 50 cm distance (150 cm from *Acacia*) where as the lowest root biomass was observed at 180 cm distance for all species (Table 13).

Table 13: Lateral distribution of total root biomass in the top soil (0-20 cm depth) of *Tectona, Eucalyptus* and *Casuarina* when surrounded by *Acacia*

		Mean root biomass (g m^2)			
		Tectona	*Eucalyptus*	*Casuarina*	Mean total
20	Mean	156.48 a	97.13 a	74.41 a	109.34
	N	9	9	9	27
	Std. Error of Mean	45.43	21.67	12.33	19.33
50	Mean	70.05 a	221.23 ab	57.47 a	116.25
	N	9	9	9	27
	Std. Error of Mean	52.71	75.75	25.49	38.16
100	Mean	13.92 b	0.95 ac	29.16 a	14.67
	N	9	9	9	27
	Std. Error of Mean	13.92	.95	21.70	8.49
150	Mean	0.01 b	0.01 ac	17.89 a	5.96
	N	9	9	9	27
	Std. Error of Mean	.00	.00	9.18	3.99
180	Mean	0.01 b	0.01 ac	0.01 a	0.01
	N	9	9	9	27
	Std. Error of Mean	.00	.00	0.01	0.01

With exception of *Eucalyptus* at 50 cm, all other species in both layers showed a decreasing trend of root biomass with increasing distance from the centre tree (Fig.17).

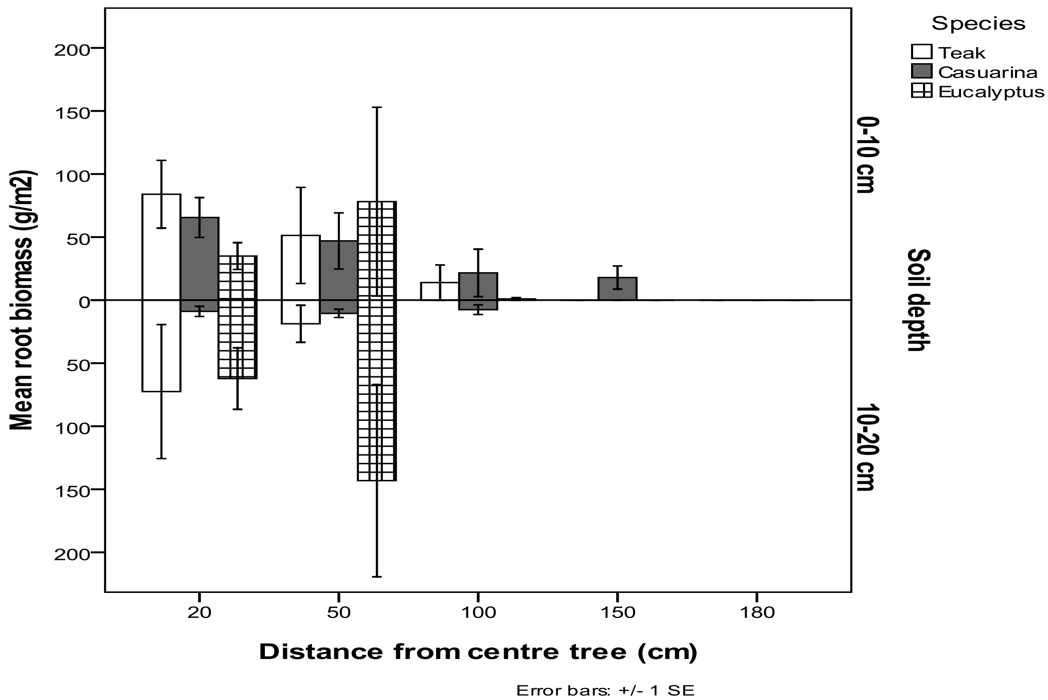

Figure 17 : Vertical and lateral distribution of root biomass of *Tectona, Eucalyptus* and *Casuarina* when surrounded by *Acacia*

Analysis of variance on the effect of soil depth on the distribution of the root biomass of Tectona, *Casuarina* and *Eucalyptus* indicated significant effect ($P<0.05$) on *Casuarina* (Appendix 17). There was higher root biomass in the upper layer than in the lower layer (Table 14).

Table 14: Vertical distribution of total root biomass of *Tectona, Casuarina* and *Eucalyptus* when surrounded by *Acacia*

Soil depth	Diameter	N	*Tectona* Mean (g m^2)	*Tectona* Std. Error	*Eucalyptus* Mean (g m^2)	*Eucalyptus* Std. Error	*Casuarina* Mean (g m^2)	*Casuarina* Std. Error
0-10 cm	<2mm	15	25.57 a	11.92	27.19 a	9.99	30.39 a	8.48
	>2 mm	15	4.37 b	4.37	13.03 a	13.03	.00 b	.00
	Total		29.84		40.21		30.39	
10-20 cm	<2mm	15	6.42 a	3.73	12.07a	6.38	5.40 a	1.63
	>2 mm	15	11.83a	11.83	19.23 a	19.24	.00 b	.00
	Total		18.25		31.30		5.40	

Fig. 18 indicates that fine roots were more confined in the upper layer, while coarse roots were dominant on the lower layer.

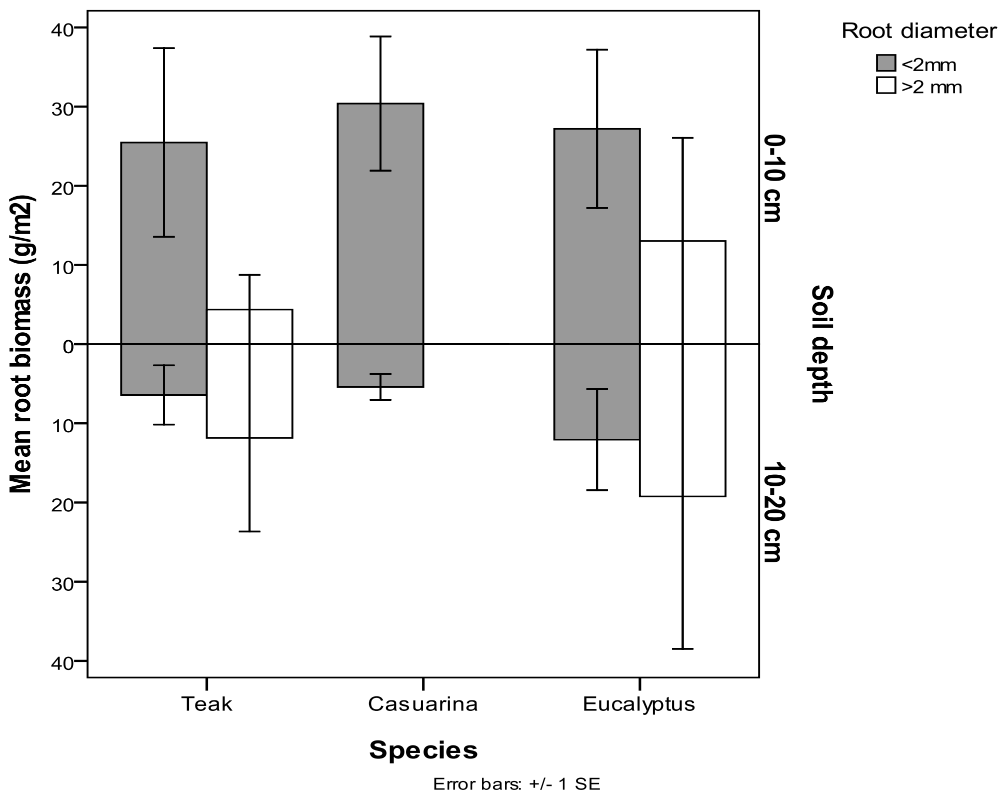

Figure 18: Vertical root distribution of fine and coarse root biomass of *Tectona, Eucalyptus* and *Casuarina* when surrounded by *Acacia*

4.5 Combined rooting pattern of *Acacia, Tectona, Eucalyptus* and *Casuarina* under different species combination

4.5.1 Lateral disribution of root biomass of *A. mangium, T. grandis , E. camaldulensis* and *C. montana* under different species combination

Table 15 shows a comparison of root biomass of all species in different species combinations with distance. Generally root biomass for all species was higher close to the stem of the respective species. It also shows that the highest root biomass was attained by *Acacia* when it was surrounded by other species followed by *Acacia* when it surrounded other species and *Acacia* in monoculture.

Table 15: Lateral distribution of total root biomass in the top soil (0-20 cm depth) of *Acacia, Tectona, Eucalyptus* and *Casuarina* in different species combination (g m^{-2}).

Distance from species (cm)	*Acacia*			*Tectona*		*Eucalyptus*		*Casuarina*	
	Mono	Mix 1	Mix 2	Mix 1	Mix 2	Mix 1	Mix 2	Mix 1	Mix 2
20	306.05	462.00	244.46	38.25	156.5	197.8	104.14	127.04	74.41
50	195.11	168.90	329.73	32.38	70.05	66.17	229.19	84.25	57.47
100	91.45	161.80	90.31	41.75	13.92	120.1	24.23	37.39	29.16
150	199.18	77.03	42.25	121.3	0.01	3.98	0.01	15.72	17.89
180	352.91	39.47	23.95	0.01	0.01	7.76	0.01	6.34	0.01

Where;

Mono: *Acacia* surrounded by *Acacia* (1A:8A)

Mix 1: *Acacia* surrounded by *Tectona*, *Eucalyptus* and *Casuarina* (1A:8T, 1A:8C and 1A:8T)

Mix 2: *Tectona, Eucalyptus* and *Casuarina* surrounded by *Acacia* (1T:8A; 1C:8A and 1T:8A)

Generally root biomass of *Tectona*, *Eucalyptus* and *Casuarina* increased with high density of *Acacia* in the species combination (1T: 8A; 1C: 8A and 1 T: 8A) as compared to low density of *Acacia* in species combination (1A: 8T, 1A: 8C and 1A: 8T).

Fig. 19 indicates that except *Acacia* in monoculture and *Tectona* in a 1A:8T species combination, the rest species in all species combinations showed a general trend of decreasing root biomass with increasing distance away. *Acacia* has dominated the lateral distance by having larger root biomass at every distance. *Acacia* had a wider coverage than other species. While *Casuarina* was able to send its roots up to 180 cm away and *Tectona* to 150 cm, *Eucalyptus* could not send its roots beyond 100 cm away.

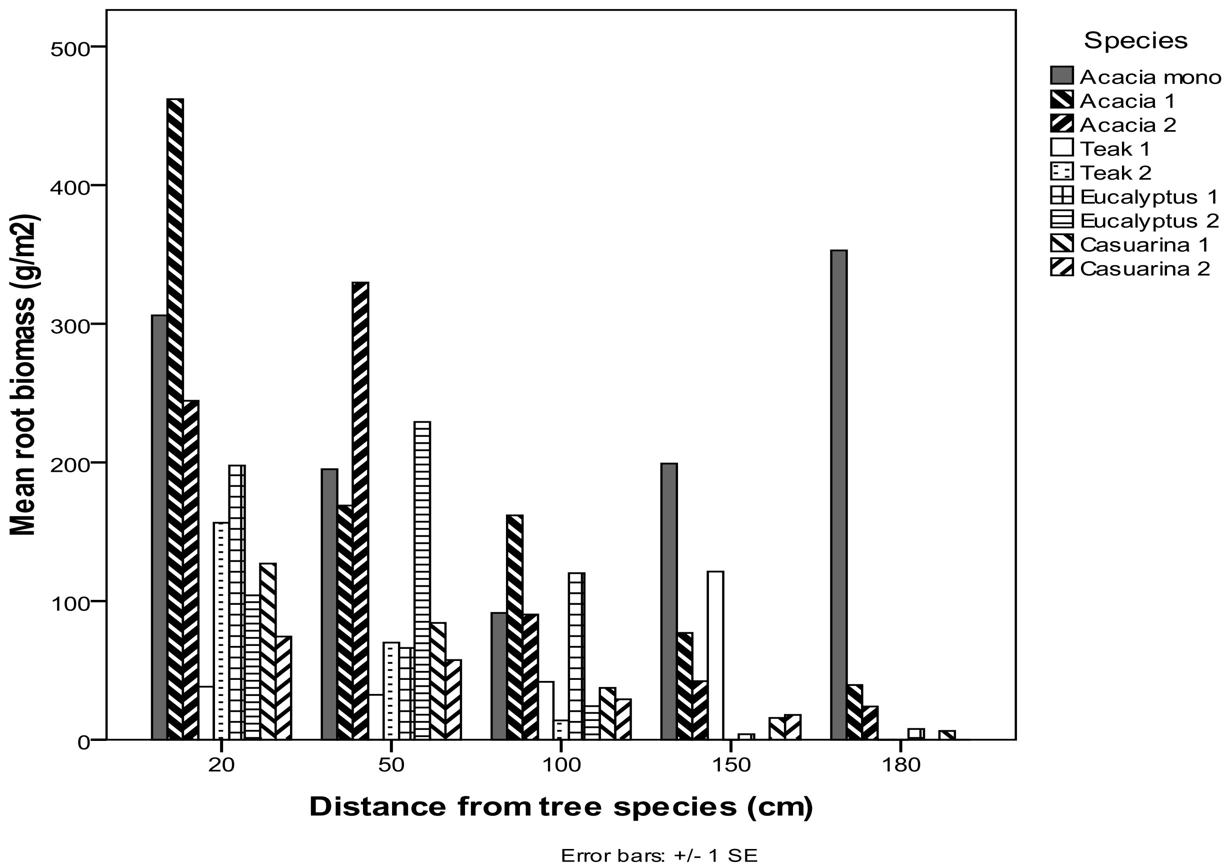

Figure 19: Lateral distribution of total root biomass in the top soil (0-20 cm depth) of *Acacia, Tectona, Eucalyptus* and *Casuarina* in different species combination

1. When *Acacia* surrounded by *Tectona*, *Eucalyptus* and *Casuarina* (1A:8T, 1A:8C, 1A:8T)
2. When *Tectona, Eucalyptus* and *Casuarina* surrounded by *Acacia* (1T:8A; 1C:8A, 1T:8A)

4.5.2.Vertical disribution of *Acacia, Tectona , Eucalyptus* and *Casuarina* under different species combination

In the situation with monoculture of *Acacia*, high root biomass was observed in the upper layer. In a situation with *Acacia* surrounded by other species, root biomass of *Acacia* and *Eucalyptus* was high in the upper layer but high root biomass of *Tectona* in the lower. In the situation with other species surrounded by *Acacia*, only root biomass of *Acacia* was high in the lower layer (Table 16; Fig 20).

Table 16: Vertical distribution of root biomass of *Acacia, Teak, Eucalyptus* and *Casuarina* under different species combination with distance (g m^{-2})

Soil depth (cm)	*Acacia*			*Tectona*		*Eucalypts*		*Casuarina*	
	Mono	Mix 1	Mix 2	Mix 1	Mix 2	Mix 1	Mix 2	Mix 1	Mix 2
0-10	162.41	113.29	56.37	4.58	25.47	49.81	40.21	32.2	30.39
10-20	66.53	69.86	90.26	42.15	18.25	29.35	31	22	5

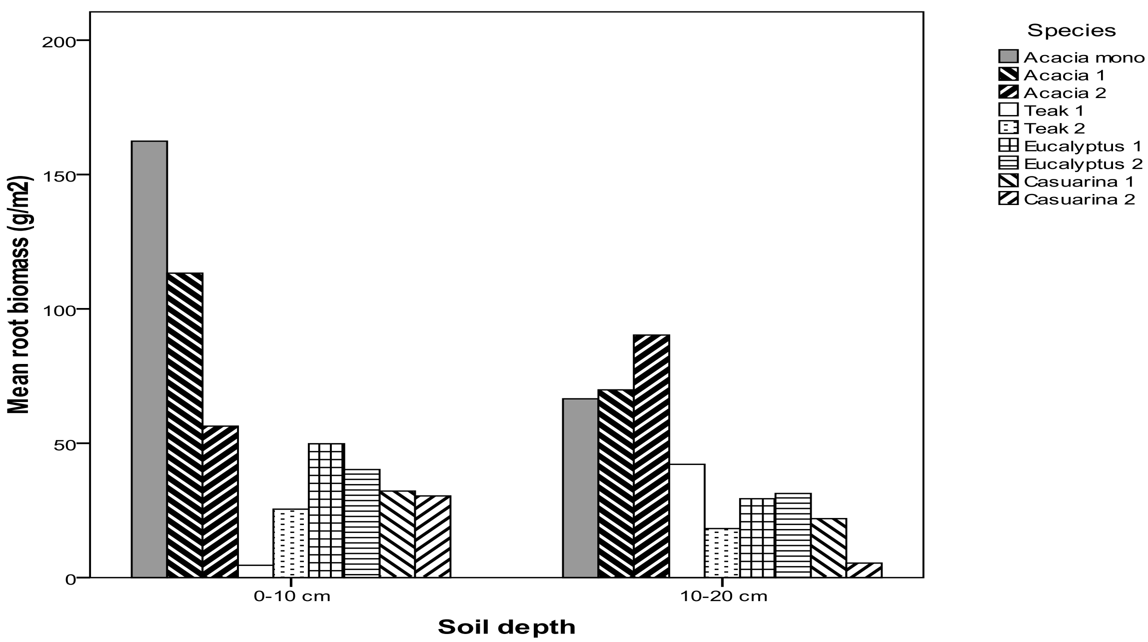

Figure 20: Vertical distribution of root biomass of *Acacia, Tectona, Eucalyptus* and *Casuarina* in different species combination

5.0 DISCUSSION

5.1 Impact of species combination on Soil pH and bulk density

Mean pH and bulk density ranged from 5.9 to 6.7 and 1.3 to 1.4 g cm^{-3} respectively for all species combinations and soil layers. Katety (2007) found mean pH and bulk density in the ranges 5.7 to 7.2 and 1.2 to 1.3 g cm^{-3} respectively at 0-20 cm soil depth in the same study area. Hartemink (1995) found mean pH ranging from 4.6 to 7.1 at 0-15 cm soil depth in similar soil types close to the study area. The pH values observed were within the optimum pH ranges (6.5-7.5) for good growth of tree species under study (Katety, 2007). Nutrient availability, biomass production, food for soil biota and mobilization of heavy metals are pH dependant. When soil is too acidic or alkaline, there is reduced biological decomposition of organic matter. Microorganisms can only grow in a defined pH-range (Bot and Benites, 2005). The common range of bulk density in mineral soils is between 1.1 and 1.8 g cm^{-3} (Blume *et al.*, 2009). Soils with low bulk density usually are well drained with higher infiltration and higher water storage and gas exchange capacity. They also have higher aggregate stability than dense soils. Soils with high bulk density could have zones with slack flow and also pores could clog at rainfall as a result, water cannot easily drain away and the soil surface could be sealed enhancing surface run-off. Dense soils can inhibit seed emergency and root growth (Blume *et al.*, 2009). In this study soil compaction was not as high in the upper layer as expected probably because ploughing was carried out during dry season (soil is drier and more stable than when soil is wet) as a result of low adverse effect on the soil structure (Grossman and Reinsch, 2002).

5.2 Lateral and vertical distribution of root biomass of *Acacia mangium*

Lateral distribution of *Acacia* root biomass in monoculture (1A: 8A) revealed a ‘‘V’’ shaped pattern (Fig 9). This pattern can be explained by the presence of *Acacia* as a centre tree and also as a surrounding tree. In both sides, root biomass was high close to respective tree stem. Root biomass of *Acacia* tends to be abundant immediately adjacent to the stem and to decrease with increasing distance (Silva *et al.,* 2009; Kunhamu *et al*., 2010). In other situations with *Acacia* surrounded by other species (1A: 8T, 1A: 8C and 1A: 8E) and other species surrounded by *Acacia* (1T: 8A; 1C: 8A and 1T: 8A), results indicated significant enhanced root biomass with lateral distance. Root biomass was abundant immediately adjacent to the tree stem and decreased with increasing distance away in the upper layer. In the lower layer, the highest root biomass was observed a little bit far from the stem of *Acacia* (Fig 11 and 13). Millikini and Bledsoe (1999) observed that most trees in dry areas would extend their roots far beyond their canopy for greater water access and when water is not limiting; the roots would grow under the canopy where nutrients are plentiful. Kunhamu *et al*., (2010) observed that, when trees are so close to each other, roots favor downward competition before lateral.

Except *Acacia* in monoculture, there was no significant difference on the distribution of the root biomass of *A. mangium* with soil depth. Except from a situation with *Acacia* surrounded other species (Table 10), root biomass of *Acacia* was higher in the upper than lower layer (Table 6 and 8). It was also revealed that fine root biomass was higher in the upper layer and coarse root biomass higher in the lower layer (Fig 10, 12 and 14). Concentration of fine root biomass in the surface layer could result from concentration of total N, extractable P and exchangeable K^+ in the topsoil (Jobbagyi and Jackson, 2001; Muthukumar *et al*., 2003;) and the accumulation of litter from above-ground parts of the tree, the decaying root material which in turn forms the bases for the complex biological cycles involving bacteria, fungi and soil animals in the topsoil (Persson and Stadenberg, 2007). Also aeration may be another factor. Fine roots may proliferate in surface horizons to avoid anoxia when subsurface horizons which have greater than 40 % clay content are saturated. Fine roots developed in the lower soil layer could be produced during dry season as an attempt to take moisture held in deep clay layers (Millikini and Bledsoe, 1999). Hoffman and Kummerow, (1978), commented that, even though fine root biomass often decreases continuously from the surface, research in water limited ecosystems has indicated peak biomass at intermediate depths.

5.3 Lateral and vertical distribution of root biomass of *Tectona grandis, Eucalyptus camaldulensi* and *Casuarina montana*

In a species combination with *Acacia* surrounded by other species results showed that only root biomass of *Casuarina* was significantly different with distance. Contrary, in a species combination with other species surrounded by *Acacia,* root biomass of *Tectona* and

Eucalyptus differed significantly with distance. As for the distribution of root biomass of *Acacia*, the distribution of root biomass of *Tectona*, *Casuarina* and *Eucalyptus* in the upper layer, decreased with increasing distance away. In the lower layer, the highest root biomass was obtained far away from the respective tree stem. It was also observed that in the upper layer, root biomass of *Tectona, Casuarina* and *Eucalyptus* was high and more lateral spread in a species combination with high density of *Acacia* (1T: 8A; 1C: 8A and 1T: 8A) where as root biomass of the species was high and more lateral spread in the lower layer in a situation with low density of *Acacia* (1A: 8T, 1A: 8C and 1A: 8T) (Fig. 15 and 17; Table 12 and 14). These results imply that teak, casuarina and eucalypts changed their rooting pattern as a response to acacia's roots competition. It was observed that in a mixed species, the superior competitors will have larger proportion of their root biomass in the uppermost soil layer (Smith *et al*., 1999; Forrester *et al*., 2006). Silva *et al*., (2009) found that *Acacia mangium* changed its rooting pattern when it was planted in mixture with *Eucalyptus grandis* with slower exploration of the inter-row and a narrowing trend for *A. mangium* trees throughout stand development. The increase and wide spread of root biomass of other species with in high density of *Acacia* in the upper layer can be explained as the facilitation effect of *Acacia* by improving nutrition in the upper layer (Forrester *et al*., 2004).

There was no significant difference of the distribution of root biomass of *Tectona, Eucalyptus* and *Casuarina* with soil depth. Generally, there was high fine root biomass in the top layer and high coarse root biomass in the lower layer. In a situation with *Acacia* surrounded with other species, fine roots of *Tectona* and *Eucalyptus* were higher in the lower layer while coarse root biomass of *Eucalyptus* in the upper layer. Contrary, in a situation with other species surrounded by *Acacia*, fine root biomass of all species was high in the upper layer, where as coarse root biomass was high in the lower layer (Fig 16 and 18). The increase of root diameter with soil depth could be an adaptation to degree of compaction of the soil horizon. Thick roots can exert greater force on the soil and might have greater ability to penetrate compact soils than smaller diameter roots (Muthukumar *et al*., 2003).

5.4 Combined rooting pattern and distribution root biomass of mixed *Acacia mangium*, *Tectona grandis, Casuarina montana* and *Eucalyptus camaldulensis*

Generally, root biomass of all species showed a decreasing pattern with increasing distance away. Each species showed different lateral distance coverage. At a mid-distance (100 cm) for example, root biomass of *Acacia* was highest, followed by *Eucalyptus* and *Casuarina, Tectona* root biomass was the least (Table 15). Only *Acacia* and *Casuarina* were able to send roots at 180 cm distance away (Fig 19). This observation extends the justification of the facilitation effect of *Acacia* (and probably *Casuarina*). If it was not facilitating other species, it would have competed with them intensively as a result they would become weak or die. Contrary, with exception of *Tectona*, the rest species, particularly *Eucalyptus* produced favorable above ground biomass (Kilawe, 2010). The reason why *Tectona* could not perform could be linked to its inability to tolerate shade from *Acacia* (Pandey and Brown, 2000). It was also found that, if high root biomass of *Acacia* was observed in the upper layer, high root biomass of other species was observed in the lower layer in the same species combination (Compare Fig 11 and 15; Fig 13 and 17). These results suggest niche separation between the roots of *Acacia* and the roots of other species for better utilization of site resources (Lamb and Lawrence, 1993). Silva *et al* (2009) found that development of fine roots of *Eucalyptus* was not affected by *A. mangium* trees in mixed-species plantation but *A. mangium* fine roots were excluded from the upper soil layer from 18 months after planting onwards. They were only found deeper and close to *A. mangium* trees 30 months after planting.

Root biomasses of *Acacia* and *Eucalyptus* obtained in this study both laterally and vertically were higher than reported findings by Silva *et al*.,2009 (Compare Table 16 and 17). The difference can be explained by favorable growing conditions in the study area. Bauhus *et al*., 2000 reported higher fine root biomass for *A. mearnsii* and *E. globulus* than the ones observed in this study (Compare Table 16 and 18). The difference can be explained by different experimental design which includes different species, age, fertilizer application, soil depth and spacing between the trees. There were no reported findings on rooting pattern of *Tectona and Casuarina* when grown in mixed species plantations.

Table 17: Total root biomass (g m^{-2}) in 1m soil depth of 18 months old *A. mangium* and *E .grandis* under different species combination

Lateral distance (cm)	*A. mangium* (100 A:0E)	*A. mangium* (33A:67E)	*E. grandis* (100E :0A)	*E. grandis* (33E:67A)
50-100	129.5	39.0	234.5	225.5
100-150	98.0	7.5	153.9	103.5
150-200	188.7	1.5	126.5	166.0
Soil depth (cm)				
0-10	60.0	9.0	80.0	60.0
10-30	40.0	10.0	40.0	30.0

Source: Silva *et al*., 2009

Table 18: Fine root biomass (g m^{-2}) of 6.5 years old *A. mearnsii* and *E .globulus* under different species combination

	Species combination				
	100 A	75A:25E	50A:50E	25A:75E	100E
0–15 cm	287	205	182	122	
acacia		57	163	258	231
eucalypt					
15-30					
acacia	134	143	98	40	
eucalypt		13	43	73	122

Source: Bauhus *et al*., 2000

6.0 CONCLUSION AND RECCOMENDATION

Using data collected from three sites in Tanzania, the results show that there was not enough statistical evidence to support the argument that *Tectona grandis*, *Casuarina montana* and *Eucalyptus camaldulensis* would send their roots toward *Acacia mangium* in attempt to benefit from its nutrient fixing ability. However, there was evidence of a facilitation effect of *A. mangium* as it was able to send its roots to the proximity of other tree species without reducing their above ground biomass. Also, root biomass of *T. grandis, E. camaldulensis* and *C. montana* was higher and more laterally spread with higher density of *A. mangium.*

For all species in the mixture, there was a general trend of decreasing root biomass with increasing distance from the stem. Moreover root biomass was decreasing with increasing soil depth, with fine roots concentrating in the top layer while coarse roots in the lower layer. There was a clear vertical niche separation between *A. mangium* and *T. grandis*. When high root biomass of *A. mangium* occurred in the upper layer high root biomass of *T. grandis* occurred in the lower layer and vice versa. *E. camaldulensis* had high root biomass in the upper layer regardless of the distribution of root biomass of *A. mangium* and *C. montana* had equal root biomass distribution between the soil layers.

It might be recommended to include *Acacia* as a potential nurse tree in the mixed species plantation as it can occupy different soil vertical strata for efficient site resources utilization. It can also be used for restoration of degraded sites as its profuse rooting can bind the soil against erosion.

It is further advised that when *Acacia* is to be mixed with other species, wider spacing should be adopted because at young age or with adverse site conditions, *Acacia* can exploit associated species through its wide spreading lateral roots. For the same reason, caution should be given for the use of *Acacia* in agro-forestry systems. In this study, root nodules were observed which confirms symbiotic relationship between *Acacia* and *Rhizobium* described in the literature.

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APPENDICES

Appendix 1: Field form for data collection

Sites	Species Combination	Root diameter	Soil Depth	Distance	Root biomass	pH	B. density
1	1	1	1	1	√		
1	1	1	1	2	√		
1	1	1	1	3	√	√	√
1	1	1	1	4	√		
1	1	1	1	5	√		
1	1	1	2	1	√		
1	1	1	2	2	√		
1	1	1	2	3	√	√	√
1	1	1	2	4	√		
1	1	1	2	5	√		
2,3	2,3,4,5,6,7	2	1,2	1,2,3,4,5	√		

Appendix 2: ANOVA for the effect of species combination on pH and bulk density

Source of variation		Sum of Squares	df	Mean Square	F	Sig.
pH (H_2O)	Species combination	2.954	6	.492	1.128	.366 ns
	Error	15.275	35	.436		
	Total	18.229	41			
Bulk density (gcm^{-3})	Species combination	.080	6	.013	.265	.949 ns
	Error	1.764	35	.050		
	Total	1.844	41			

ns- The mean difference is not significant at the 0.05 level

Appendix 3: ANOVA for the effect of soil depth on soil pH and bulk density

Source of variation		Sum of Squares	df	Mean Square	F	Sig.
pH	Soil depth	.007	1	.007	.016	.90ns
	Error	18.222	40	.456		
	Total	18.229	41			
Bulk density (gcm^{-3})	Soil depth	.000	1	.000	.004	.95ns
	Error	1.844	40	.046		
	Total	1.844	41			

ns- The mean difference is not significant at the 0.05 level

Appendix 4: Kruskal wall's test on effect of distance on root biomass of *Acacia* when *Acacia* was surrounded by *Acacia*

	Root biomass of *A. mangium* (g/m^2)
Chi-Square	2.421
df	4
Asymp. Sig.	.659 ns

a. Kruskal Wallis Test

b. Grouping Variable: Distance

Appendix 5: Kruskal wall's test for the effect of soil depth on root biomass of *Acacia* when *Acacia* was surrounded by *Acacia*

	Root biomass of *A. mangium* (g/m^2)
Chi-Square	13.784
df	1
Asymp. Sig.	.001*

a. Kruskal Wallis Test

b. Grouping Variable: Depth

Appendix 6: ANOVA for root biomass of *Acacia* when *Acacia* was surrounded by *Tectona, Casuarina* and *Eucalyptus*

	Sum of Squares	df	Mean Square	F	Sig.
Distance	496414.345	4	124103.586	4.277	.003*
Error	2466684.802	85	29019.821		
Total	2963099.147	89			

*-The mean difference is significant at the 0.05 level

Appendix 7: LSD test for effect of distance on rooting pattern of *Acacia* when *Acacia* was surrounded by *Tectona, Casuarina* and *Eucalyptus*

(I) Distance	(J) Distance	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
20	50	146.54944*	56.78402	.012	33.6476	259.4513
	100	150.10278*	56.78402	.010	37.2009	263.0046
	150	192.48833*	56.78402	.001	79.5865	305.3902
	180	211.26444*	56.78402	.000	98.3626	324.1663
50	20	-146.54944*	56.78402	.012	-259.4513	-33.6476
	100	3.55333	56.78402	.950	-109.3485	116.4552
	150	45.93889	56.78402	.421	-66.9629	158.8407
	180	64.71500	56.78402	.258	-48.1868	177.6168
100	20	-150.10278*	56.78402	.010	-263.0046	-37.2009
	50	-3.55333	56.78402	.950	-116.4552	109.3485
	150	42.38556	56.78402	.457	-70.5163	155.2874
	180	61.16167	56.78402	.284	-51.7402	174.0635
150	20	-192.48833*	56.78402	.001	-305.3902	-79.5865
	50	-45.93889	56.78402	.421	-158.8407	66.9629
	100	-42.38556	56.78402	.457	-155.2874	70.5163
	180	18.77611	56.78402	.742	-94.1257	131.6779
180	20	-211.26444*	56.78402	.000	-324.1663	-98.3626
	50	-64.71500	56.78402	.258	-177.6168	48.1868
	100	-61.16167	56.78402	.284	-174.0635	51.7402
	150	-18.77611	56.78402	.742	-131.6779	94.1257

*. The mean difference is significant at the 0.05 level.

Appendix 8: ANOVA for the effect of soil depth on *Acacia* root biomass when *Acacia* was surrounded by *Tectona, Casuarina* and *Eucalyptus*

	Sum of Squares	df	Mean Square	F	Sig.
Soil depth	11749.128	1	11749.128	.616	.434 ns
Error	3396491.944	178	19081.415		
Total	3408241.072	179			

ns- the mean difference is not significant at the 0.05 level

Appendix 9: ANOVA for effect of distance on *Acacia* root biomass when *Tectona, Casuarina* and *Eucalyptus* was surrounded by *Acacia*

	Sum of Squares	df	Mean Square	F	Sig.
Distance	324947.028	4	81236.757	2.870	.028*
Error	2406203.386	85	28308.275		
Total	2731150.414	89			

*- Indicate significant different between subjects at 5% probability level.

Appendix 10: LSD Test for the effect of distance on rooting pattern of *Acacia* when *Tectona, Casuarina* and *Eucalyptus* was surrounded by *Acacia*

(I) Distance	(J) Distance	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
20	50	-9.15222	56.08354	.871	-120.6613	102.3569
	100	-33.18111	56.08354	.556	-144.6902	78.3280
	150	-152.88833*	56.08354	.008	-264.3974	-41.3792
	180	-110.25556	56.08354	.053	-221.7647	1.2536
50	20	9.15222	56.08354	.871	-102.3569	120.6613
	100	-24.02889	56.08354	.669	-135.5380	87.4802
	150	-143.73611*	56.08354	.012	-255.2452	-32.2270
	180	-101.10333	56.08354	.075	-212.6124	10.4058
100	20	33.18111	56.08354	.556	-78.3280	144.6902
	50	24.02889	56.08354	.669	-87.4802	135.5380
	150	-119.70722*	56.08354	.036	-231.2163	-8.1981
	180	-77.07444	56.08354	.173	-188.5836	34.4347
150	20	152.88833*	56.08354	.008	41.3792	264.3974
	50	143.73611*	56.08354	.012	32.2270	255.2452
	100	119.70722*	56.08354	.036	8.1981	231.2163
	180	42.63278	56.08354	.449	-68.8763	154.1419
180	20	110.25556	56.08354	.053	-1.2536	221.7647
	50	101.10333	56.08354	.075	-10.4058	212.6124
	100	77.07444	56.08354	.173	-34.4347	188.5836
	150	-42.63278	56.08354	.449	-154.1419	68.8763

*. The mean difference is significant at the 0.05 level.

Appendix 11: ANOVA for the effect of soil depth on *Acacia* root biomass

Sov.	Sum of Squares	df	Mean Square	F	Sig.
Soil depth	12921.156	1	12921.156	.860	.355 ns
Error	2674879.097	178	15027.411		
Total	2687800.252	179			

ns-Indicate non significant different between subjects at 5% probability level

Appendix 12: ANOVA for effect of distance on root biomass of *Tectona, Eucalyptus* and *Casuarina* when surrounded *Acacia*

		Sum of Squares	df	Mean Square	F	Sig.
Root biomass of *Tectona*	Distance	24126.679	4	6031.670	.631	.652 ns
	Error	95592.955	10	9559.296		
	Total	119719.634	14			
Root biomass of *Eucalyptus*	Distance	79987.964	4	19996.991	.901	.499 ns
	Error	221835.470	10	22183.547		
	Total	301823.433	14			
Root biomass of *Casuarina*	Distance	32631.160	4	8157.790	6.066	.010*
	Error	13449.388	10	1344.939		
	Total	46080.548	14			

ns- The mean difference is not significant at the 0.05 level

*- The mean difference is not significant at the 0.05 level

Appendix 13: LSD for the effect distance on the distribution of root biomass of *Casuarina* when *Casuarina* surrounded *Acacia*

Root biomass of *Casuarina*	20	50	-11.833	29.944	.701	-78.55	54.89
		100	-28.587	29.944	.362	-95.31	38.13
		150	-127.800*	29.944	.002	-194.52	-61.08
		180	-70.810*	29.944	.040	-137.53	-4.09
	50	20	11.833	29.944	.701	-54.89	78.55
		100	-16.753	29.944	.588	-83.47	49.97
		150	-115.967*	29.944	.003	-182.69	-49.25
		180	-58.977	29.944	.077	-125.70	7.74
	100	20	28.587	29.944	.362	-38.13	95.31
		50	16.753	29.944	.588	-49.97	83.47
		150	-99.213*	29.944	.008	-165.93	-32.49
		180	-42.223	29.944	.189	-108.94	24.50
	150	20	127.800*	29.944	.002	61.08	194.52
		50	115.967*	29.944	.003	49.25	182.69
		100	99.213*	29.944	.008	32.49	165.93
		180	56.990	29.944	.086	-9.73	123.71
	180	20	70.810*	29.944	.040	4.09	137.53
		50	58.977	29.944	.077	-7.74	125.70
		100	42.223	29.944	.189	-24.50	108.94
		150	-56.990	29.944	.086	-123.71	9.73

*. The mean difference is significant at the 0.05 level.

Appendix 14: ANOVA for the effect of soil depth on root biomass of *Tectona, Eucalyptus* and *Casuarina* when they surrounded *Acacia*

		Sum of Squares	df	Mean Square	F	Sig.
Root biomass of Tectona	Soil depth	5291.641	1	5291.641	2.245	.140 ns
	Error	136733.729	58	2357.478		
	Total	142025.370	59			
Root biomass of Eucalyptus	Soil depth	1570.714	1	1570.714	.350	.557 ns
	Error	260655.544	58	4494.061		
	Total	262226.258	59			
Root biomass of Casuarina	Soil depth	394.753	1	394.753	.480	.491ns
	Error	47689.095	58	822.226		
	Total	48083.849	59			

ns- The mean difference is not significant at the 0.05 level

Appendix 15: A NOVA for effect of distance on root biomass of *Tectona, Eucalyptus* and *Casuarina* when surrounded by *Acacia*

		Sum of Squares	df	Mean Square	F	Sig.
Root biomass of *Tectona*	Distance	54073.847	4	13518.462	4.474	.025*
	Error	30212.941	10	3021.294		
	Total	84286.787	14			
Root biomass of *Eucalyptus*	Distance	10819.794	4	2704.949	3.322	.050*
	Error	8142.870	10	814.287		
	Total	18962.664	14		.000	.000
Root biomass of *Casuarina*	Distance	113962.637	4	28490.659	7.649	.004*
	Error	37249.339	10	3724.934		
	Total	151211.976	14			

* The mean difference is significant at the 0.05 level

Appendix 16: LSD test for the effect of distance on root biomass of *Tectona Casuarina and Eucalyptus* when surrounded by *Acacia*

Dependent Variable	(I) Distance	(J) Distance	Mean Difference (I-J)	Std. Error	Sig.
Root biomass of *Tectona*	20	50	86.4300000	44.8797955	.083
		100	142.5666667*	44.8797955	.010
		150	156.4833333*	44.8797955	.006
		180	156.4833333*	44.8797955	.006
	50	20	-86.4300000	44.8797955	.083
		100	56.1366667	44.8797955	.239
		150	70.0533333	44.8797955	.150
		180	70.0533333	44.8797955	.150
	100	20	-1.4256667E2	44.8797955	.010
		50	-56.1366667	44.8797955	.239
		150	13.9166667	44.8797955	.763
		180	13.9166667	44.8797955	.763
	150	20	-1.5648333E2	44.8797955	.006
		50	-70.0533333	44.8797955	.150
		100	-13.9166667	44.8797955	.763
		180	.0000000	44.8797955	1.000
	180	20	-1.5648333E2	44.8797955	.006
		50	-70.0533333	44.8797955	.150
		100	-13.9166667	44.8797955	.763

		150	.0000000	44.8797955	1.000
Root biomass of *Casuarina*	20	50	16.9433333	23.2993133	.484
		100	45.2533333	23.2993133	.081
		150	56.5166667*	23.2993133	.036
		180	74.4100000*	23.2993133	.010
	50	20	-16.9433333	23.2993133	.484
		100	28.3100000	23.2993133	.252
		150	39.5733333	23.2993133	.120
		180	57.4666667*	23.2993133	.033
	100	20	-45.2533333	23.2993133	.081
		50	-28.3100000	23.2993133	.252
		150	11.2633333	23.2993133	.639
		180	29.1566667	23.2993133	.239
	150	20	-56.5166667*	23.2993133	.036
		50	-39.5733333	23.2993133	.120
		100	-11.2633333	23.2993133	.639
		180	17.8933333	23.2993133	.460
	180	20	-74.4100000*	23.2993133	.010
		50	-57.4666667*	23.2993133	.033
		100	-29.1566667	23.2993133	.239
		150	-17.8933333	23.2993133	.460
Root biomass of *Eucalyptus*	20	50	-1.2410333E2	49.8326127	.032
		100	96.1833333	49.8326127	.082
		150	97.1300000	49.8326127	.080
		180	97.1300000	49.8326127	.080
	50	20	124.1033333*	49.8326127	.032
		100	220.2866667*	49.8326127	.001
		150	221.2333333*	49.8326127	.001

		180	221.2333333*	49.8326127	.001
	100	20	-96.1833333	49.8326127	.082
		50	-2.2028667E2	49.8326127	.001
		150	.9466667	49.8326127	.985
		180	.9466667	49.8326127	.985
	150	20	-97.1300000	49.8326127	.080
		50	-2.2123333E2	49.8326127	.001
		100	-.9466667	49.8326127	.985
		180	.0000000	49.8326127	1.000
	180	20	-97.1300000	49.8326127	.080
		50	-2.2123333E2	49.8326127	.001
		100	-.9466667	49.8326127	.985
		150	.0000000	49.8326127	1.000

*. The mean difference is significant at the 0.05 level.

Appendix 17 : ANOVA for the effect of soil depth on the root biomass of *Tectona, Eucalyptus* and *Casuarina* when surrounded by *Acacia*

		Sum of Squares	df	Mean Square	F	Sig.
Root biomass of Tectona	Soil depth	503.557	1	503.557	.419	.520 ns
	Error	69720.359	58	1202.075		
	Total	70223.915	59			
Root biomass of Eucalyptus	Soil depth	298.240	1	298.240	.120	.731ns
	Error	144749.622	58	2495.683		
	Total	145047.862	59			
Root biomass of Casuarina	Soil depth	2342.250	1	2342.250	5.959	.018*
	Error	22797.098	58	393.053		
	Total	25139.348	59			

ns- The mean difference is not significant at the 0.05 level