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ROOT PHYTOMASS RECOVERY AND ROOTING CHARACTERISTICS OF FIVE AGROFORESTRY TREE SPECIES IN EASTERN INDIA

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DAS, D. K. & CHATURVEDI, O. P. 2008. Root phytomass recovery and rooting characteristics of five agroforestry tree species in eastern India. Knowledge of the quantitative assessment and structural development of root system is essential to improve and optimize the productivity under agroforestry systems. We conducted studies on root phytomass recovery by sieves of different mesh sizes (2.0, 1.0, 0.5 and 0.25 mm) and root distribution for five, four-year-old agroforestry tree species, namely, *Acacia auriculiformis*, *Azadirachta indica*, *Bauhinia variegata*, *Bombax ceiba* and *Wendalendia exserta*. Results indicated that the 0.5-mm sieve was adequate for recovery for the majority of roots. Maximum rooting depth was recorded in *W. exserta* (2.10 m) and minimum, in *B. variegata* (1.00 m). Variation in horizontal root spread was 2.05 m in *B. ceiba* and 8.05 m in *A. auriculiformis.* Root spread exceeded the crown cover for all tree species. The first order lateral roots were more horizontal than the second order. The length and diameter of the main root were highest in *A. indica* (108.3 cm) and *B. ceiba* (23.2 cm) respectively. Maximum length of lateral roots was recorded in *B. variegata* (201.6 cm) and maximum diameter, in *A. indica* (1.8 cm). Total root phytomass among different species accounted for 18–38% of the total tree biomass. This study infers that although all trees have potential to conserve water and improve fertility status of the soil, *A. auriculiformis* is the most effective for promoting soil fertility. The deep rooted *W. exserta* and *A. auriculiformis* will be preferred for cultivation under agroforestry systems and could reduce competition for nutrients and water by pumping from deeper layers of soil.

Keywords: Competitive index, main and lateral roots, rooting depth, root spread, soil fertility

DAS, D. K. & CHATURVEDI, O. P. 2008. Perolehan fitojisim akar dan pencirian akar bagi lima spesies pokok perhutanan tani di timur India. Pengetahuan tentang penilaian kuantitatif dan pembangunan struktur sistem akar adalah penting untuk usaha pembaikan dan pengoptimuman produktiviti sistem pertanian tani. Kami mengkaji perolehan fitojisim akar melalui tapis pelbagai saiz (2.0, 1.0, 0.5 dan 0.25 mm) dan pengagihan akar untuk lima spesies pokok pertanian tani yang berusia empat tahun iaitu *Acacia auriculiformis, Azadirachta indica, Bauhinia variegata, Bombax ceiba* dan *Wendalendia exserta.* Keputusan menunjukkan bahawa tapis 0.5 mm sudah memadai untuk memperoleh kebanyakan akar. Kedalaman pengakaran maksimum dicatat untuk *W. exserta* (2.10 m) dan kedalaman minimum untuk *B. variegata* (1.00 m). Penyebaran akar mendatar ialah 2.05 m bagi *B. ceiba* dan 8.05 m bagi *A. auriculiformis.* Penyebaran akar bagi semua spesies melebihi tutupan silara. Susunan pertama akar sisi lebih mendatar berbanding susunan kedua. Panjang dan diameter akar utama paling banyak masing-masing dalam *A. indica* (108.3 cm) and *B. ceiba* (23.2 cm). Panjang maksimum akar sisi adalah dalam *B. variegata* (201.6 cm) and diameter maksimum pula dalam *A. indica* (1.8 cm). Jumlah fitojisim akar dalam spesies yang dikaji merupakan 18%–38% daripada jumlah biojisim pokok. Kajian ini menunjukkan bahawa walaupun semua pokok berpotensi untuk memulihara air dan meningkatkan kesuburan tanah, *A. auriculiformis* paling berkesan dalam memperbaiki kesuburan tanah. *Wendalendia exserta* dan *A. auriculiformis* yang mempunyai akar yang dalam menjadi pilihan bagi program penanaman sistem pertanian tani dan dapat mengurangkan persaingan nutrien serta air dengan menyerapnya daripada lapisan tanih yang lebih dalam.

INTRODUCTION

Tree species that have deep and less dense roots and do not compete strongly with agricultural crops for water and nutrients are often selected for agroforestry systems. It is generally believed that these roots will draw nutrients and water from different depths than roots of crops,

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thereby reducing competition for resources. Also the tree roots act as a trap for nutrients that have leached out of the top soil. The scarce literature (e.g. Akinnifesi *et al.* 1999, Mohsin *et al.* 2000, Chaturvedi & Das 2002, Chaturvedi *et al.* 2005) available on rooting pattern and root biomass in agroforestry systems has not proven this hypothesis. Most studies tend to ignore fine root distribution even though fine roots play an important role in plant nutrient acquisition from the soil. Fine roots represent a small component of total tree biomass (O'Grady *et al.* 2005) but their production and turn over can be a significant component of carbon turnover, up to 40% (Chen *et al.* 2004).

The root system of a tree species is often guided by local edaphic and climatic conditions. The trees in this study are planted in Bihar under agrisivicultural systems as trees on crop land, either as boundary planting or intercropped with wheat (*Triticum aestivum*), maize (*Zea mays*), turmeric (*Curcuma domestica*), ginger (*Zingiber officinale*) and elephant foot yam (*Amorphophallus campanulatus*) during the first four to five years of planting till canopy closes. Banana (*Musa paradisiaca*) and papaya (*Carica papaya*) are also sometimes integrated in agrisilvicultural system along with trees and crops in spatial mixed arrangement. Belowground (root) interactions in agroforestry systems are widely recognized as one of the most important challenges in simultaneous agroforestry systems (Pandey 2003). The present study, therefore, aims at understanding the root distribution and biomass of five important multipurpose tree species under agroforestry systems of the north-west alluvial plains of Bihar. This study will be helpful in optimizing the production of agroforestry systems in the region.

MATERIALS AND METHODS

Study area

The study was conducted at the research farm of Rajendra Agricultural University, Pusa, Bihar, India. Plantations of four-year-old *Acacia auriculiformis, Azadirachta indica, Bauhinia variegata, Bombax ceiba* and *Wendalendia exserta* are located at 25° 59' N latitude and 85° 48' E longitude and an altitude of 53 m asl. Area of each plantation was 240 m^2 planted at 5 × 4 m in a randomized block design with four replications. Intercropping of maize in rainy season followed by wheat in winter was done each year until the fourth year. The crops under plantations received normal recommended doses of fertilizers, irrigations and other cultural practices. The $N:P_2O_5:K_2O$ doses for maize and wheat were 100:60:40 and 80:40:20 respectively. The distance between two stands (plots) was 5 m. The area is in a monsoon subtropical zone having three distinct seasons, namely, winter (November–February), summer (March–June) and rainy season (July–October). Average annual rainfall during the study period was 1160 mm, of which 80% was received during monsoon months between June till September. Mean monthly temperature varied between 37.2 °C in May and 7.2 °C in January. The experimental site was sandy loam in texture having a $pH–H_2O$ value of 8.2. The soil in the 0–15 cm soil depth contains 0.64 dS m^{-1} of electrical conductivity (EC), 0.38% organic carbon (OC), 165.2 kg ha^{-1} of available N, 16.9 kg ha^{-1} of available P_2O_5, 110.8 kg ha^{-1} of available K_2O and 32% free calcium carbonate. The soil is classified as an illitic ustic Typic Calciorthent according to the Soil Taxonomy, USDA (Soil Survey Staff 1975). Particle size of soil samples was determined by international pipette method as described by Piper (1966). The soil pH and EC were determined in soil:distil water suspension (1:2) (Jackson 1973). Available N in the soil was determined by alkaline permanganate method (Subbiah & Asija 1956), organic carbon by Walkely and Black method (1934), available P_2O_5 by sodium bicarbonate or Olsen method (Olsen *et al.* 1954), available K_2O by neutral normal ammonium acetate method (Jackson 1973) and free $CaCO_3$ by the titration method (Piper 1966).

Fine root sampling

Fine roots were sampled from two randomly selected trees in each stand during the mid rainy season (September 1996). A total of 60 soil cores were taken radially at set distances from each stand by driving a sharp edged steel tube, 5 cm inside diameter, into the soil to a depth of 0–20, 20–40, 40–60, 60–80 and 80–100 cm. Soil cores were placed separately in polythene bags and transported to the laboratory. Samples were soaked in a bucket of water for at least eight hours and then manually stirred. The soil root suspension was passed through a sequence of four sieves with decreasing mesh sizes 2.0, 1.0, 0.5 and 0.25 mm. To ensure maximum recovery of very fine roots by the 0.25 mm sieve, the process of sedimentation and decantation was repeated several times before the soil slurry was discarded. Live and dead roots retained on each sieve were sorted out on the basis of pliability and degree of cohesion between cortex and periderm. Live roots were much more resistant than dead ones and did not break easily when bent. Dead roots were often wrinkled and dark in colour, in contrast to the smooth and light coloured live roots. The live root fragments were then classified into diameter classes (> 2.0, 1.0–2.0, 0.5–1.0, 0.25–0.5 mm). Percentage root phytomass recovery by each sieve was defined as the proportion of total (cumulative) phytomass recovered by the four sieve sizes.

Tree growth measurements and root excavation

The diameter at breast height (dbh), height, crown height and crown spread of each selected tree were measured. Excavation was conducted in November–December 1996 to expose the root system and the tree was pushed to fall on the ground. During digging, the horizontal spread of roots was measured and after excavation, the entire root system was rearranged as far as possible into its original position. All categories of root cuts during excavation were carefully picked up from the soil and rearranged in the root system. The roots that originated from the main or tap root, irrespective of their size were designated as first order lateral roots. Second order and third order lateral roots originated from first order and second order lateral roots respectively. Root angles were measured from first and second order lateral roots with respect to main and first order lateral roots respectively. Biomass distribution into main and lateral roots in different soil strata, namely, 0–25, 25–50, 50–75, 75–100, 100–150, 150–200 and > 200 cm were estimated separately. For comparison among species the ratio of root and shoot biomass and the ratio of root and crown spread were calculated. All biomass estimates were based on oven dry weight (constant value of 70 °C). To calculate competitive index, the following formula was used (van Noordwijk & Purnomosidh 1995) and it was based on the ratio of cross horizontally-oriented roots to stem dbh.

$$\mathrm{CI} = \frac{\sum D^2 \text{ horizontal}}{\mathrm{dbh}^2}$$

where

CI = the competitive index
D^2 horizontal = the proximal diameter of the roots descending into the soil at an angle less than 45°
dbh = the stem dbh.

Soil sampling

Soil samples were collected after removing litter from the soil surface using a tube auger (3.4 cm diameter) on 2 November 1996 just before excavating roots to compare the water status below the canopy of each tree adjacent to barren field from 12 positions, i.e. near base, 50 cm and 100 cm away from tree base from all directions with that in open. Sampling was performed successively for 15 cm horizons down to 150 cm soil depth and the soil water content was determined gravimetrically. Soil samples collected from all 12 points for 0–15 cm soil depth were mixed together and analyzed for pH–H_2O, electrical conductivity (EC), organic carbon, available N, P_2O_5 and K_2O using common procedures mentioned earlier.

Statistical analysis

ANOVA and Duncan's multiple range test (DMRT) were run to compare the means at 5% probability levels for each variable among different tree species using the Statgraphics package (1986).

RESULTS AND DISCUSSION

Aboveground growth

Growth performance of tree species indicated maximum height in *A. auriculiformis* and this value of height was similar with the height of *W. exserta* and *B. variegata* (Table 1). Dbh, crown height and spread were maximum in *B. variegata* although dbh and crown height were similar with those of the *A. auriculiformis* (Table 1). The branching behaviour differed considerably among the tree species. Thus, tree height and dbh do not seem to be a suitable indicator for between species comparison of shoot growth patterns.

Recovery of root phytomass

Recovery of root phytomass decreased with decreasing sieve sizes and deferred among species (Table 2). Cumulative total root phytomass recovery by the 2.0, 1.0 and 0.5 mm sieves was > 97% of the total biomass for all the species. Recovery of coarser roots (> 2.0 mm) ranged from 80 to 92% of the cumulative root phytomass. The very fine roots that passed through the 0.5 mm sieve but trapped by the 0.25 mm sieve contributed a negligible proportion of the total root phytomass for most species. Thus, the 0.5 mm sieve greatly improved the recovery of root phytomass for all the species suggesting that this size was sufficient for the root phytomass estimation.

Root phytomass, growth and pattern

Except for *W. exserta,* all species had maximum phytomass (47–91%) of fine roots in the 0–20 cm soil horizon, which decreased with increase in soil depth (Table 3). *Wendalendia exserta* showed

Table 1 Aboveground morphometric characteristics of four-year-old trees[*]

Species	Height (m)	Dbh (cm)	Crown height (m)	Crown spread (m)
Acacia auriculiformis	7.2^{c} ± 0.3	14.1^{cd} ± 0.7	2.9^{bc} ± 0.5	4.0^{c} ± 0.3
Azadirachta indica	5.6^{b} ± 0.4	9.6^{b} ± 0.8	2.7^{b} ± 0.3	1.9^{a} ± 0.3
Bauhinia variegata	6.3^{bc} ± 0.4	16.1^{d} ± 0.7	3.3^{c} ± 0.2	5.1^{d} ± 0.8
Bombax ceiba	3.3^{a} ± 0.5	7.1^{a} ± 0.7	1.9^{a} ± 0.4	1.5^{a} ± 0.6
Wendalendia exserta	6.8^{bc} ± 0.5	13.0^{c} ± 0.8	2.8^{bc} ± 0.4	2.6^{b} ± 0.3

Mean values with the same superscript within a column are not significantly different ($p \leq 0.05$). [*]± 1 SE; n = 8.

Table 2 Recovery of root phytomass of different species as determined with sieves of 2.0, 1.0, 0.5 and 0.25 mm mesh sizes

Species	Root phytomass ($g\ m^{-3}$)[*]			
	> 2.0 mm	1.0–2.0 mm	0.5–1.0 mm	0.25–0.5 mm
A. auriculiformis	2120^{c} ± 85	230^{b} ± 36	210^{b} ± 32	61^{b} ± 12
	(79.9)[**]	(10.0)	(8.1)	(2.0)
A. indica	640^{a} ± 32	60^{a} ±11	33^{a} ± 9	20^{a} ± 6
	(85.0)	(7.8)	(4.4)	(2.8)
B. variegata	3522^{d} ± 98	344^{c} ± 43	283^{b} ± 36	82^{b} ± 16
	(83.2)	(8.1)	(6.7)	(2.0)
B. ceiba	689^{a} ± 44	64^{a} ± 15	35^{a} ± 9	23^{a} ± 4
	(84.9)	(7.8)	(4.3)	(3.0)
W. exserta	1831^{b} ± 56	69^{a} ± 15	56^{a} ± 12	28^{a} ± 7
	(92.3)	(3.5)	(2.9)	(1.3)

Mean values with the same superscript within a column are not significantly different ($p \leq 0.05$); [*]± 1 SE, n = 48;[**] figures in parentheses denote the percentage of the total root biomass.

highest fine root phytomass (41%) in the 20–40 cm soil depth. The majority of nutrient uptake from the soil is believed to occur through fine roots and root hairs primarily due to larger uptake surface area. Root phytomass of maize and wheat is primarily found in 0–20 cm soil layer. Thus root competition is expected between agricultural crops and tree species, but least so for *W. exserta* and *A. auriculiformis*. *Wendalendia exserta* with the lowest phytomass of fine roots in top soil compared with the rest of the species should be less competitive for water and nutrients in this layer. This species has also a slender canopy. *Acacia auriculiformis* had almost equal phytomass in 0–20 cm and 20-40 cm soil depths. This had resulted in higher yields of crops in comparison to crops grown with other tree species. When planted with trees crop yields were in the order of *B. variegata* > *B. ceiba* > *A. indica* > *A. auriculiformis* > *W. exserta* and lower compared with sole crop (Table 4).

All the tree species exhibited well developed tap roots and highest density of roots around the root stock with a fan shaped appearance. First order lateral roots were thicker and further branched into several thin and long or small roots. Lateral roots are structural elements, which have the primary function to provide

Table 3 Phytomass* of fine roots (< 2 mm) at different depths

Species	Depth (cm)			
	0–20 cm	20–40 cm	40–60 cm	Total
A. auriculiformis	233.8^{b} ± 87.6 (46.7)**	206.5^{c} ± 88.6 (41.2)	60.5^{d} ± 12.5 (12.1)	500.8^{b} ± 199.7
A. indica	76.6^{a} ± 19.8 (67.4)	19.3^{a} ± 3.2 (17.0)	17.7^{ab} ± 3.6 (15.6)	113.6^{a} ± 27.8
B. variegata	645.2^{c} ± 93.8 (91.0)	37.6^{ab} ± 6.9 (5.3)	26.3^{ac} ± 4.2 (3.7)	709.1^{b} ± 100.8
B. ceiba	90.2^{a} ± 24.1 (73.6)	25.4^{a} ± 6.9 (20.7)	6.9^{a} ± 2.1 (5.7)	122.5^{a} ± 38.1
W. exserta	54.2^{a} ± 1.7 (35.4)	63.3^{b} ± 14.5 (41.4)	35.6^{bc} ± 5.9 (23.2)	153.1^{a} ± 22.1

Mean values with the same superscript within a column are not significantly different ($p \le 0.05$); *g m^{-3} ± 1 SE, n = 48; ** figures in parentheses denote the percent distribution of fine root biomass in respect of soil depth.

Table 4 Variation in yield of crops as affected by different tree plantations

Species	Grain yield (Mg ha^{-1})	
	Maize	Wheat
A. auriculiformis	2.91^{c} (80)*	2.44^{c} (75)
A. indica	2.55^{b} (70)	2.15^{b} (66)
B. variegata	2.18^{a} (60)	1.79^{a} (55)
B. ceiba	2.29^{a} (63)	1.92^{a} (59)
W. exserta	3.09^{c} (85)	2.57^{c} (79)
Without tree (open area)	3.64^{d}	3.25^{d}

Mean values with the same superscript within a column are not signifcantly different ($p \le 0.05$); * figures in parentheses denote the percentage of the crop grain yield in open area.

anchorage of the tree in the soil. These lateral roots, particularly in the upper layer of the soil, showed a tendency of spreading parallel to the ground level but definitely exhibited positive geotropism. The distribution of roots through space and time is usually influenced by genetic characters of plant and localized soil conditions (Huck 1983). Among all the species studied, maximum rooting depth was observed in *W. exserta* followed by *A. auriculiformis* and minimum in *B. variagata* (Table 5). Dbh and $dbh^2 \times$ height of a species were significantly and positively related ($p < 0.01$) with its root phytomass. The horizontal spread of roots exceeded the crown in all the tree species and it was 1.35 to 3.29 fold greater than the crown spread (Tables 1 and 5). Root systems up to 230 cm in depth have been reported in *A. nilotica, Prosopis cineraria* and *Eucalyptus tereticornis* growing in an arid region of north-western India (Bisht 1990). Six-year-old *Prosopis cineraria, E. tereticornis and Populus deltoides* had root spread of 1.23, 1.24 and 1.26 fold higher respectively than crown (Toky & Bisht 1992).

Root angle is an important aspect of root system architecture (Ram Newaj *et al.* 2005). Generally, the first order, second order and further branches of lateral roots have the tendency to show positive geotropism, diageotropism and ageotropism respectively. The angles of first order and second order lateral roots varied highly within and among the species (Table 5). The angles of first order lateral roots were higher than the second order lateral roots in all the species, indicating a greater spread of the former. The angle of first order lateral roots in the top horizon was comparatively greater than the roots located in the lower horizon.

The length and the diameter of the main and lateral roots showed a wide range of variation within and among the species (Table 6). It is axiomatic that the species with deep main roots and more spread lateral roots take up nutrient and water more efficiently from deeper layers and greater areas and provide firm anchorage to the tree in soil thereby making the tree wind firm. In the present study *A. indica* and *W. exserta* with deep main roots and moderate lateral root lengths, can be more efficiently grown in dry conditions. Lateral root lengths of these tree species were similar or greater than those of *B. ceiba* and *A. auriculiformis.* Lieffers and Rothwell (1987) reported a positive correlation between root penetration and depth of water table. The root system of a tree species is often guided by local edaphic and climatic conditions.

Among the species, there was a wide range of variation in phytomass accumulated in the main and lateral roots (Table 7). Total root phytomass was highest in *B. variegata* followed by *A. auriculiformis.* Main roots accounted for most phytomass followed by first order, second order and third order lateral roots except for *B. variegata* and *B. ceiba* where first order lateral roots had more phytomass than the main root. Dbh showed a significantly positive relationship ($r = 0.640$, $p < 0.01$) with total root phytomass.

All trees showed decrease in root phytomass with increasing soil depth and 45 to 89% of the total root phytomass (main + lateral roots) was allocated in the top 25 cm of the soil profile (Figure 1). Phytomass accumulation in main roots in the top 25 cm soil varied from 21% in *W. exserta* to 41% in *A. indica,* whereas for lateral roots it varied from 23% in *A. indica* to 69% in

Table 5 Belowground morphometric characteristics of four-year-old trees*

Species	Rooting depth (m)	Root spread (m)	Root angle (°)		Root spread: crown spread
			First order	Second order	
A. auriculiformis	$2.0^{c} \pm 0.2$	$8.1^{e} \pm 0.2$	$78^{c} \pm 21$	$70^{d} \pm 10$	$2.0^{b} \pm 0.19$
A. indica	$1.2^{a} \pm 0.2$	$6.1^{c} \pm 0.3$	$71^{b} \pm 20$	$55^{b} \pm 15$	$3.3^{c} \pm 0.1$
B. variegata	$1.0^{a} \pm 0.2$	$6.9^{d} \pm 0.2$	$88^{d} \pm 22$	$60^{c} \pm 10$	$1.4^{a} \pm 0.2$
B. ceiba	$1.6^{b} \pm 0.3$	$2.1^{a} \pm 0.3$	$60^{a} \pm 24$	$48^{a} \pm 10$	$1.4^{a} \pm 0.1$
W. exserta	$2.1^{c} \pm 0.2$	$4.3^{b} \pm 0.3$	$71^{b} \pm 23$	$61^{c} \pm 14$	$1.6^{a} \pm 0.2$

Mean values with the same superscript within a column are not significantly different ($p \leq 0.05$); *± 1 SE, n = 8.

Table 6 Average length and basal diameter of main and lateral roots

Species	Main*		Lateral*	
	Length (cm)	Diameter (cm)	Length (cm)	Diameter (cm)
A. auriculiformis	94.2^{bc} ± 3.4	10.1^{a} ± 2.3	65.2^{b} ± 8.5	0.8^{a} ± 0.5
A. indica	108.3^{d} ± 6.6	10.1^{a} ± 1.8	110.2^{c} ±15.1	1.8^{c} ± 0.3
B. variegata	30.9^{a} ± 3.9	15.3^{c} ± 2.8	201.6^{d} ± 24.5	1.4^{b} ± 0.2
B. ceiba	90.2^{b} ± 8.9	23.2^{d} ± 2.9	50.2^{a} ± 8.7	1.2^{b} ± 0.4
W. exserta	98.3^{c} ± 5.6	10.8^{b} ± 1.5	100.2^{c} ± 20.9	0.8^{a} ± 0.5

Mean values with the same superscript within a column are not significantly different ($p \leq 0.05$); *± 1 SE, n = 8

Table 7 Biomass (kg/plant) of different root components, total root, shoot biomass and root: shoot ratio

Species	Main root (a)	Lateral roots			Total lateral (b + c + d)	Total root (a + b + c + d)	Shoot biomass	Root: shoot ratio
		First order (b)	Second order (c)	Third order (d)				
A. auriculiformis	3.2^{d}	2.1^{c}	1.3^{c}	0.87^{c}	4.3^{c}	7.5^{c}	23.1^{d}	0.32^{b}
A. indica	0.9^{b}	0.3^{a}	0.3^{b}	0.02^{a}	0.6^{a}	1.5^{a}	5.8^{b}	0.26^{a}
B. variegata	2.2^{c}	2.8^{d}	3.0^{e}	1.16^{d}	7.0^{d}	9.2^{d}	40.9^{e}	0.22^{a}
B. ceiba	0.5^{a}	0.8^{a}	0.1^{a}	0.03^{a}	0.9^{a}	1.4^{a}	2.5^{a}	0.56^{c}
W. exserta	2.3^{c}	1.4^{b}	1.6^{d}	0.23^{b}	3.2^{b}	5.5^{b}	9.0^{c}	0.61^{c}

Mean values with the same superscript within a column are not significantly different ($p \leq 0.05$).

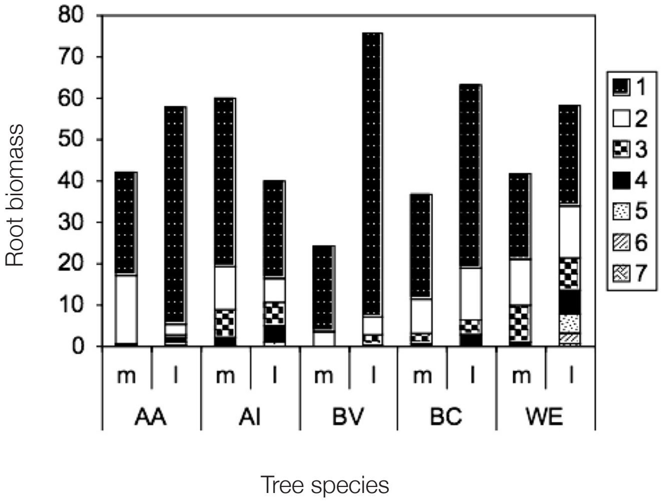

Figure 1 Percentage distribution of biomass in main roots (m) and lateral roots (l) along the soil profile. 1 = 0–25 cm, 2 = 25–50 cm, 3 = 50–75 cm, 4 = 75–100 cm, 5 = 100–150 cm, 6 = 150–200 cm, 7 = > 200 cm. AA = *A. auriculiformis,* AI = *A. indica,* BV = *B. variegata*, BC = *B. ceiba* and WE = *W. exserta.*

B. variegata. The accumulation of more root phytomass in upper layer of soil provides enough absorptive surfaces to exploit the moisture and nutrients available in the top layer of soil. Root competition between crops and trees is expected when they are intercropped, unless some mechanisms of root exclusion such as trenching and pruning of branches are practised. Similar observations on root distribution of five multipurpose tree species was recorded by Dhyani *et al.* (1990) and Singh (1994). Total root phytomass among different species accounted for 18–38% of the total tree phytomass (Table 6). Root:shoot phytomass ratio varied from 0.22 to 0.61 (Table 7). The lower root/shoot phytomass ratio indicates that the species has a tendency to accumulate more aboveground biomass for building up canopy and is still in the growing phase. Zerihun *et al.* (2006) found a marked decline in shoot biomass of *E. populnea*-dominated woodland communities with increased aridity whereas the root biomass was relatively stable, with root:shoot biomass ratio of 0.58 at the xeric end and 0.36 at the mesic end of the rainfall gradient.

The value obtained for the index of tree root competitiveness ranged from 0.98 (*W. exserta*) to 2.58 (*A. indica*) (Table 8). Competitive indices of 0.14–2.13 were reported for 19 tree species aged five to seven years old in Indonesia (van Noordwijk & Purnomosidh 1995). Competitive indices does not allow for differences in tree size when comparing species under field conditions.

Soil water profiles

Soil water data recorded during dry periods when drainage losses are least are of considerable importance, not so much in respect of total water consumption but as a guide to rooting and water uptake with depth and hence the degree of competition that might be expected in particular with intercropping system (Huck 1983). Soil water profiles showed that soil water under *A. auriculiformis, B. ceiba* and *W. exserta* increased with depth up to 150 cm (Figure 2). However, in *A. indica* maximum soil water was observed in between 105–120 cm soil depth and in *B. variegata*, between 90–105 cm (Figure 2). The soil water level under different tree species was 1.39 to 2.05 fold higher in top soil (0–15 cm) and 1.03 to 1.75 fold higher in 135–150 cm soil depth compared with soil water in the adjacent open area without trees. Root depth had a significant positive relationship (r = 0.957, $p < 0.01$) with water level in the top 0–15 cm soil below the tree.

Soil fertility status

The soil and tree species relationship is quite dynamic and, therefore, different plantation types will impart differences in soil properties (Kumar *et al.* 1993). Soil below the tree canopy had improved physico-chemical characteristics (Figure 3). Higher nutrient contents below the canopy were presumably due to return of nutrient-rich leaf litter to the soil surface and its subsequent release in the soil. *Acacia auriculiformis* improved the soil as shown by significantly higher values in soil organic carbon, available N, available P_2O_5 and available K_2O in the 0–15 cm soil depth. *Acacia auriculiformis* is a N_2-fixing tree. The activity of root symbionts such as nitrogen-fixing nodules could increase soil N levels. Suitable carbon substrates provide energy for bacterial mineralization and thereby enhance the availability of other soil nutrients as well.

Table 8 Variation in competitive index of different tree species

Species	dbh^2	$\sum D^2$ horizontal proximal roots	Competitive index
A. auriculiformis	198.8	298.2	1.50^a
A. indica	92.9	239.8	2.58^b
B. variegata	258.2	619.8	2.40^b
B. ceiba	50.1	106.9	2.13^b
W. exserta	167.7	164.4	0.98^a

Mean values with the same superscript within a column are not significantly different ($p \le 0.05$).

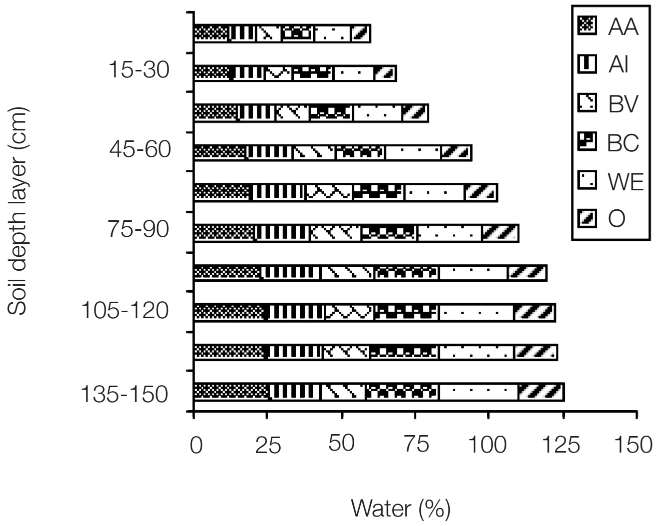

Figure 2 Soil water profile under tree canopy and in the open (without trees). AA = *A. auriculiformis*, AI = *A. indica*, BV = *B. variegata*, BC = *B. ceiba*, WE = *W. exserta* and O = open.

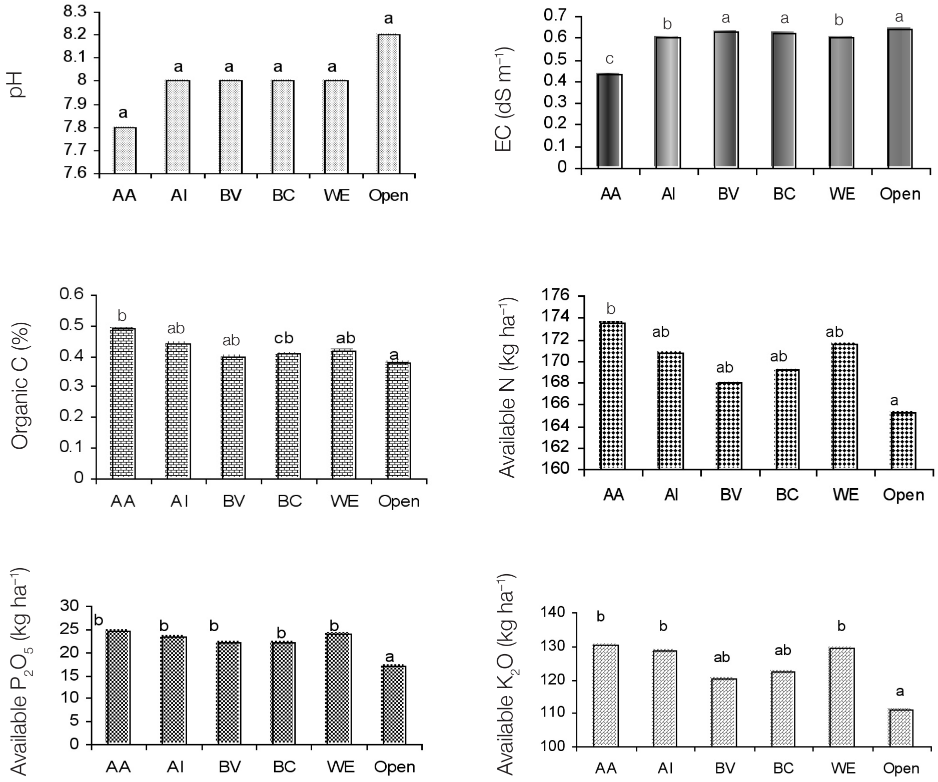

Figure 3 Effect of trees on nutrient status in 0–15 cm soil depth. AA = *A. auriculiformis*, AI = *A. indica*, BV = *B. variegata*, BC = *B. ceiba* and WE = *W. exserta*. For each soil parameter, columns with the same letter are not significantly different ($p \le 0.05$).

There was no significant impact of afforestation on pH of the calciorthent soils, but some reduction was observed in almost all plots. The very high free calcium carbonate content in the soil (32%) might be the reason for low influence of acidity caused by the decomposition of leaf litter and dead root biomass and root exudates. The effectiveness of tree species in improving the soil by lowering its electrical conductivity might be due to increased biomass of roots and leaf litter, which probably mobilized after decaying. However, *B. variegata* and *B. ceiba* did not show significant effect on EC of the soil. The variation in ameliorative efficiency of different trees may be due to differences in absorption and translocation of sodium and its salts (Suwalka & Qureshi 1995). Root depth of the tree species was positively correlated with the available major nutrients in the top soil.

CONCLUSIONS

From this experiment we conclude that three successive sieves down to 0.5 mesh is sufficient to estimate 97% of the root phytomass of the studied tree species. Deep rooted species like *W. exserta* and *A. auriculiformis* are suitable for dry areas and may be mixed with shallow rooted species in plantations or in agroforestry systems. Since all species in the present study had most of their root biomass in the upper soil layer, the deep rooted species like *W. exserta* and *A. auriculiformis* will be preferred for agrisilviculture and will have potential to pump nutrients from deeper layers of the soil. However, to reduce the strong competition for water and nutrients with the intercrops, the lateral roots of the tree have to be pruned (Singh 1994). Although, all the tree species showed great potential for improving soil fertility status and soil water level, *A. auriculiformis* as a N-fixing species was most effective for promoting soil fertility.

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