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# Depth distribution of roots of *Eucalyptus dunnii* and *Corymbia citriodora* subsp. *variegata* in different soil conditions

John C. Grant [a,*], J. Doland Nichols [a], R. Ling Yao [a,b], R. Geoff B. Smith [c,1], Paul D. Brennan [d], Jerome K. Vanclay [a]

[a] Forestry Program, School of Environmental Science and Management, Southern Cross University, Lismore, NSW 2480, Australia
[b] Guangxi Forestry Research Institute, Nanning, Guangxi 530002, China
[c] PO Box 200, Camperdown, NSW 2050. Australia
[d] WA Forest Products Commission, Locked Bag 388, Perth Business Centre, WA 6849, Australia

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ABSTRACT

Understanding depth distribution of roots may help develop an understanding of plant productivity and the limits to productivity by indicating which parts of the soil profile are being accessed for water and nutrients. The subtropical east coast of Australia provides climatic and soil conditions that produce some of the highest plant productivity rates in the country. This has been recognised by the hardwood plantation industry and over the last decade a substantial estate of plantations has been established with plans for further expansion. However, two of the major species used, *Eucalyptus dunnii* and *Corymbia citriodora* subsp. *variegata*, have had little published research directly related to root depth distribution in the area. We examined root depth distribution in established plantations of *E. dunnii* and *C. citriodora* subsp. *variegata* under three contrasting soil types using the techniques of soil trench profile and coring. The results showed that the fine roots of *C. citriodora* subsp. *variegata* are at lower densities in poorly structured subsoils than the roots of *E. dunnii*. The root densities of both species in the subsoils of a Vertosol soil (with high levels of reactive, shrink–swell clays) were lower than for the other soil types. In native vegetation Vertosols are often colonised by grasses with few, scattered trees from a limited range of species. Our findings show lower levels of root growth in the Vertosols, particularly into the subsoil and this is likely to be the reason that productivity on these, otherwise fertile soils, is restricted.



## 1. Introduction

Roots provide the basis for plant growth, providing access to both water and nutrients. Understanding their distribution, physiology and interaction with the below ground environment is an essential aspect of understanding plant productivity and the limits to productivity. This is true of species on an individual basis and even more so when considering the interactions between species (Huxley et al., 1994; Schroth, 1995; Van Noordwijk et al., 1996; Sudmeyer, 2002; Jose et al., 2006). Roots also play a primary role in the support and anchorage of the above ground system.

The use of soil trench profile and coring assessments of root depth distribution from a field situation combines complimentary techniques. Trench analysis, the quantification of roots revealed in an exposed soil profile of a trench or pit, provides a relatively quick and detailed qualitative view of root spatial distribution in relation to soil physical characteristics. It can underestimate the proportion of fine roots which are lost in the preparation of the profile wall as they are difficult to separate from the soil material surrounding them (particularly in clayey soils) (Van Noordwijk et al., 2000). Trench analysis can also underestimate the coarse root proponent due to the greater vertical bias to their growth (Falkiner et al., 2006). Core analysis provides greater potential for accurate analysis through replication and it also allows for the capture of a large proportion of the fine roots and the analysis of root distribution on a volumetric basis (Atkinson and Dawson, 2000; Oliveira et al., 2000). The combination of trench root counts with root coring is commonly used and provides a robust technique of root assessment (Moroni et al., 2003; Schroth, 2003; Falkiner et al., 2006).

Worldwide plantations of eucalypts continue to expand and now cover approximately 20 million hectares (Nichols et al., 2010). Eucalypt plantations can exhibit some of the fastest growth rates of any plantation species but the genus also includes species that can maintain acceptable growth rates under harsh conditions (Beadle and Sands, 2004). Both *Eucalyptus dunnii* and *Corymbia citriodora* spp. *variegata* are significant components of the existing plantation area and both have the potential for an expanded role in continuing plantation development (Nichols et al., 2010).

* Corresponding author. Tel.: +61 2 6620 3947; fax: +61 2 6621 2669.
*E-mail address:* john.grant@scu.edu.au (J.C. Grant).
[1] formerly Forests NSW.

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In this study, three contrasting soil types that supported *E. dunnii* and *C. citriodora* subsp. *variegata* plantations at a point in the rotation where they would be expected to have fully occupied the below ground environment were selected for the intensive analysis of root depth distribution (West, 2006; Grant et al., 2010). The study aimed to clarify the root depth distribution of *E. dunnii* and *C. citriodora* subsp. *variegata* in three common soil conditions and then determine what parts of the soil profile were most being utilised by the two species. The three soils provided contrasting soil conditions that were chosen to determine if one species was better able to utilise soil horizons with poor structure and/or impeded drainage, which will facilitate the effective prediction of growth from *E. dunnii* and *C. citriodora* subsp. *variegata* in different soil conditions.

## 2. Materials and methods

### 2.1. Study sites

Soil trench profile and coring root assessments were carried out at three sites covering three soil types common in sub-tropical north east NSW. The sites themselves occur around 28° 45′S, 152° 43′E, approximately 80 km from of the coast. The soils were; a Brown Chromosol on sandstone, a Grey Dermosol on mudstone and a Black Vertosol on basalt (soil classification according to Isbell, 2002). These soils provided a contrast in both physical and chemical characteristics. The sites and soils are summarised in Table 1 and Table 2.

Sites were selected in sections of two plantations where *E. dunnii* and *C. citriodora* subsp. *variegata* occurred in close proximity to each other on the three soil types of interest. Both plantations are owned by State Forests NSW and were established under the same silvicultural regimes. Each site consisted of a row of three neighbouring, healthy, dominant or co-dominant trees with good form surrounded by fully stocked, healthy plantation. The trench was placed around the middle tree of the central three trees and the cores taken around those central three trees (Fig. 1). The mean size (DBH) of the trees within each site was not significantly different to that of the other sites. Although all the soils could not be located within the same plantation the sites chosen had similar climatic conditions (Table 1). The chosen sites were consistently kept clear of weeds with herbicide (glyphosate) application for 12 months prior to root description by trench analysis and core sampling. This minimised the presence of non-target root material in the plots and ensured that any that were present were dead and thus easily identified and discounted. Site description, trench analysis and core sampling took place in early summer December 2005. Sampling was designed to coincide with the return of rains after the annual winter dry period as it was then that it was judged that root levels would be at the highest (Glinski and Lipiec, 1990; Passioura, 1991).

### 2.2. Root description methodology

Root description (through trench profile and coring) was focussed on individual trees within monoculture plantations. The degree of disturbance the site had undergone was one important variable that required incorporation into the assessment. The sites varied in slope from 5% to 18% (3–10°) and tree rows were aligned along the contour. The design of a replicated coring regime that adequately covered the site variation was a high priority for root description at the site. The trench, providing a detailed description of roots in relation to soil profile morphology, was designed to overlap with the soil cores as much as possible in order to correlate the two.

### 2.3. Trench analysis

At each site a semi-circular trench was dug around a central tree in a fully stocked part of the plantation (see Fig. 1). Most root profile trenches have been straight (Bohm, 1979; Atkinson and Dawson, 2000; Van Noordwijk et al., 2000) but a logarithmic spiral trench leads to more intensive sampling in areas farther from the focus tree where root density is lower but volume of soil is greater (Huguet, 1973). The semi-circular trench was chosen as it would both overlap with a set of the cores and hence allow correlation and it would also maintain a constant distance from the target tree which, being the closest, would be expected to be having the greatest influence on root density. Maintaining this constant distance was expected to reduce variation in a complex environment influenced by the many variables. Similar methodologies have been used in other studies (Curt et al., 2001). The distance of the trench from the target tree was determined by the tree spacing within the rows and it ranged from 1.3 to 1.5 m. The trench was placed midway between two trees along a row and that distance used as the radius of the semi-circle (Fig. 1). The root trenches in each species pair on each designated soil were dug within 30 m of each other. Trenches were dug to a depth of 1 m or bedrock using a mini-excavator.

The soil profile on the inner face of the trench was described and it was on this face that roots were counted. Soil description followed McDonald et al. (1990) and was carried out on a section of the trench with least disturbance (in the inter-row). The trench face was disturbed to a depth of 1 cm in order to reveal roots that were present and these were counted using a grid composed of 10 by 10 cm squares across the face of the trench. Root numbers were recorded in six diameter classes: <1, 1–2, 2–5, 5–10, 10–20 and >20 mm. These classes correspond, respectively, to the classes defined by McDonald et al. (1990) as very fine, fine, medium and three classes of coarse roots. Actual diameters of the roots in the two largest size classes were also recorded. Root numbers were adjusted on a density basis such that grids not entirely filled by soil (commonly occurring at the top of the profile) were analysed on

**Table 1**
Climatic characteristics of the plantation sites chosen for root analysis.

| Soil[a] | Plantation location | Year planted | Age of plantation sampled | Altitude (masl) | Mean annual rainfall (mm/y)[b] | Long term rainfall (cm/y)[c] | Mean max. hottest quarter (°C)[d] | Mean min. coldest quarter (°C)[e] | PI[f] |
|---|---|---|---|---|---|---|---|---|---|
| Brown Chromosol | Dyraaba | 1999 | 7 | 130 | 970 | 1060 | 31 | 4.6 | 0.90 |
| Grey Dermosol | Bonalbo | 1996 | 9 | 180 | 1030 | 1025 | 31 | 3.9 | 0.99 |
| Black Vertosol | Dyraaba | 1999 | 7 | 120 | 970 | 1060 | 31 | 4.6 | 0.90 |

[a] Soil classification follows Isbell (2002).
[b] Rainfall over life of plantation, drawn from points within the plantations using Jeffrey et al. (2001).
[c] From nearby Bureau of Meteorology Stations.
[d] Mean daily maximum of the hottest three months of the year derived from Jeffrey et al. (2001).
[e] Mean daily minimum of the coldest three months of the year derived from Jeffrey et al. (2001).
[f] Prescott Index is derived from monthly rainfall and potential evaporation as described in Prescott (1948).

**Table 2**
Soil characterisation of the root study sites.

| Soil | Horizon | Texture | pH (1:5 water) | Organic C (%) | Total N (%) | Bray 1 P (ppm)[a] | ECEC[b] |
|---|---|---|---|---|---|---|---|
| Chromosol[c] | A1 1–10 | SL | 5.6 | 1.4 | 0.09 | 4.0 | 11.7 |
| | A1 10+ | SL | 5.6 | 1.6 | 0.09 | 4.9 | 7.0 |
| | A2 | LS | 6.1 | 0.4 | 0.02 | 1.9 | 2.4 |
| | B2 | KSMC | 6.2 | 1.0 | 0.07 | 0.3 | 48.9 |
| | B3 | KSLMC | 7.3 | 0.5 | 0.03 | 0.4 | 73.7 |
| Dermosol[d] | A1 0–10 | CL | 5.4 | 2.2 | 0.15 | 8.1 | 9.4 |
| | A1 10+ | CL | 5.3 | 1.7 | 0.12 | 11.9 | 9.1 |
| | B1 | LC | 5.9 | 1.1 | 0.07 | 3.3 | 11.9 |
| | B2 | MC | 5.0 | 0.4 | 0.04 | 0.5 | 23.9 |
| | B3 | MC | 4.4 | 0.3 | 0.03 | 0.5 | 32.5 |
| Vertosol[e] | A1 0–10 | LC | 6.0 | 4.9 | 0.33 | 18.2 | 47.5 |
| | A1 10+ | LC | 6.2 | 3.8 | 0.23 | 13.9 | 45.3 |
| | B21 | MC | 6.6 | 1.9 | 0.12 | 1.6 | 42.3 |
| | B22 | MC | 7.2 | 0.8 | 0.06 | 0.3 | 43.4 |

[a] Rayment and Higginson, 1992 – 9E2.
[b] ECEC = sum of exchangeable bases and H and Al, this approximates CEC at low pH (Rayment and Higginson, 1992).
[c] Eutrophic, Brown Chromosol: Imperfectly drained to moderately well drained soil with weakly granular sandy loam to sandy clay topsoils with over a strongly prismatic to angular blocky medium clay subsoils. These horizons are commonly separated by a bleached loamy sand subsurface horizon. Total soil depth around 85 cm to decomposing sandstone bedrock. Soil parent geology – Jurassic quartzose to feldspathic sandstone (Kangaroo Creek sandstone).
[d] Eutrophic, Grey Dermosol: Imperfectly drained soil with a weakly granular clay loam to fine sandy clay loam topsoil grading into a lighter coloured massive fine sandy clay loam subsurface over a massive to angular blocky mottled grey medium clay subsoil. Total soil depth around 90 cm to decomposing mudstone bedrock. Soil parent geology – Jurassic sedimentary rocks (Walloon Coal Measures).
[e] Self-Mulching, Black Vertosol: Imperfectly to moderately well drained soil with a strongly granular light clay topsoil grading into a strongly subangular dark coloured medium clay subsoil with slickensides. Total soil depth around 100 cm to decomposing basalt bedrock. Soil parent geology – Tertiary basalt (Lamington Volcanics).

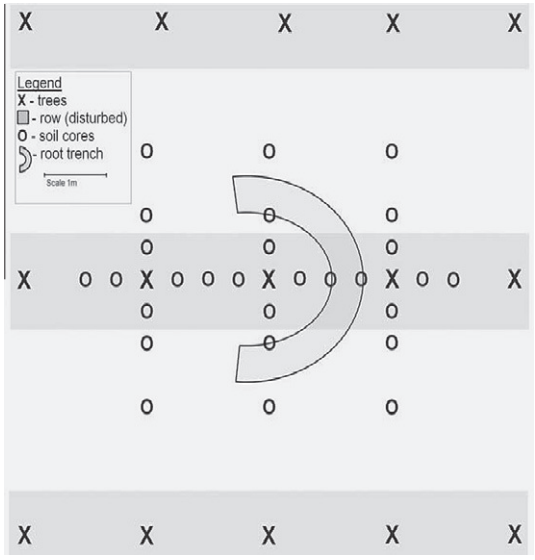


**Fig. 1.** Pit layout in relation to trees and core samples.

the same basis as 'filled' grids. Raw root counts were adjusted where horizons cut across grids by allocating root numbers within the grid proportionally to the two or three horizons occurring within that grid square. Results have been presented as a '2 dimensional slice' through the soil and the roots were analysed on a density basis (number of roots per 100 $cm^2$ quadrat) and also analysed with weighting according to size (by calculating the circumference of the roots intercepting the profile face and summing them to provide a measure of area of root surface per 100 $cm^2$ quadrat). In locating the roots, the profile was disturbed to a depth of around 1 cm. The average length of root exposed was around 1 cm and therefore the two dimensional measure of root surface area (cm/100 $cm^2$) would closely approximate a three dimensional surface area of roots expressed in terms of $cm^2$ of root surface per volume of soil ($cm^2$/100 $cm^3$).

### 2.4. Core analysis

A corer was custom built for the project. It consisted of a 1000 mm long, 100 mm diameter steel internal split sleeve which slotted into an external auger barrel with a bevelled cutting ring and hardened cutting teeth at the base and a collar at the top that could be altered to fit onto a range of machines' drive shafts. Cores were taken in the configuration illustrated by Fig. 1. There were 168 cores taken, representing two species, three soil types and 10 sampling positions around three replicated trees (overlap of sampling positions between adjoining trees reduced the core numbers from thirty to twenty eight at each soil-species site). Cores were divided in the field according to both depth and horizons. Sample depths in the top 30 cm were at 10 cm intervals and below that in 20 cm intervals. Samples were taken from the field and immediately placed in a freezer until the root washing could be carried out. On defrosting the roots were subjected to another washing to remove any remaining debris and dead roots. Root samples were then separated into the above mentioned six diameter classes. Root length of all but the smallest size class (<1 mm) was determined by direct measurement of samples while moist. The large number of roots in the <1 mm size class could not be directly measured so an oven dried sub-set of roots was correlated with the root length of the moist samples (from each species) to determine a relationship between moist root length and dry weight and allow the conversion of all oven dry weights to an equivalent length of moist root. The length of the roots in the weighed subsamples were determined by the intersect method described by Tennant (1975). The grid used in the assessment was 0.5 cm × 0.5 cm.

Analysis of the roots was carried out using analysis of variance (ANOVA) based on numbers, size class, depth and profile horizon and also a combined measure of root surface area compared to depth and soil horizon. Root surface area for the core samples was determined by calculating the mean circumference of each size class of roots and multiplying it by the length of root measured in each sample. This allowed roots of various size classes to be grouped together while maintaining a weighting based on size of the root that analysis of root length alone does not allow. Root

surface area density was determined from the calculated root surface area and the know volume from which the root samples were extracted. Where ANOVA results indicated a significant difference ($P < 0.05$), means were compared using SPSS 19.0.0.1 statistics software for least significant difference (LSD) analysis.

## 3. Results

### 3.1. Root assessment from soil trench profile

Table 3 shows the mean DBH (diameter at breast height) for the seven trees closest to each of the root description trenches (and therefore the trees considered to have the most influence on the roots in the trench). These were the two trees adjoining the target tree in the row and the trees beside the trench in the adjoining rows. There was no significant difference in DBH between the sites for either soil type or species.

An overview of trench analysis results shows roots as strongly concentrated in the upper parts of the soil profiles (Figs. 2 and 3). Approximately 30% of roots were recorded in the top 10 cm and 50% in the top 25 cm. Root density decreased logarithmically with depth, particularly in the upper parts of the profile, tending towards a linear decrease at depth. The $R^2$ for a logarithmic function was 0.98 ($P < 0.001$) and beyond 15 cm the $R^2$ for a linear function was 0.99 ($P < 0.001$). The data were reformatted to the form of cumulative root fraction and fitted it to the equation: $Y = 1 - \beta^d$ where $Y$ = cumulative root fraction, $\beta$ is a constant defined by the data and $d$ is depth in cm (Jackson et al., 1996). $\beta$ was determined to be equal to 0.960 ($R^2 = 0.978$).

Fig. 3 indicates a greater concentration of roots in the upper parts of the profile in the Chromosol soil compared to the other soils for both *E. dunnii* and *C. citriodora* subsp. *variegata*. This, in conjunction with overall lower total root numbers for *E. dunnii* on the Chromosol suggests lower subsoil root numbers for *E. dunnii* on the Chromosol but higher densities. *Corymbia citriodora* subsp. *variegata* root numbers had less variation in response to soil type.

The vast majority of the roots counted in the trench analysis fell into the three diameter classes <5 mm (the very fine, fine and medium size categories) with 98% of the approximately 10,000 roots recorded falling into that size range (88% in the <2 mm size classes). Analysis focussed primarily on those roots. Root density (measured in terms of surface area) when considered by horizon (Fig. 4) suggests that *C. citriodora* subsp. *variegata* was penetrating into the poorly structured subsoil of the Chromosol at lower levels than *E. dunnii*. There was no significant difference in the root densities between the species in the poorly structured and poorly drained subsoils of the Dermosol. *Eucalyptus dunnii* had higher root surface area densities in the finer structured subsoil of the Vertosol than did the *C. citriodora* subsp. *variegata*. However, absolute root densities were much lower for both plantation species in the Vertosol subsoil compared to the subsoils of the other soil types (Fig. 5).

**Table 3**
Mean diameters and standard deviation of the seven trees close to the trench.

| Soil | Species | Mean DBH (mm) | SD DBH (mm) |
|---|---|---|---|
| Chromosol | *E. dunnii* | 123.2 | 13.5 |
| | *C. citriodora* subsp. *variegata* | 136.2 | 47.0 |
| Dermosol | *E. dunnii* | 112.3 | 32.4 |
| | *C. citriodora* subsp. *variegata* | 131.9 | 29.5 |
| Vertosol | *E. dunnii* | 128.7 | 34.2 |
| | *C. citriodora* subsp. *variegata* | 119.6 | 43.0 |

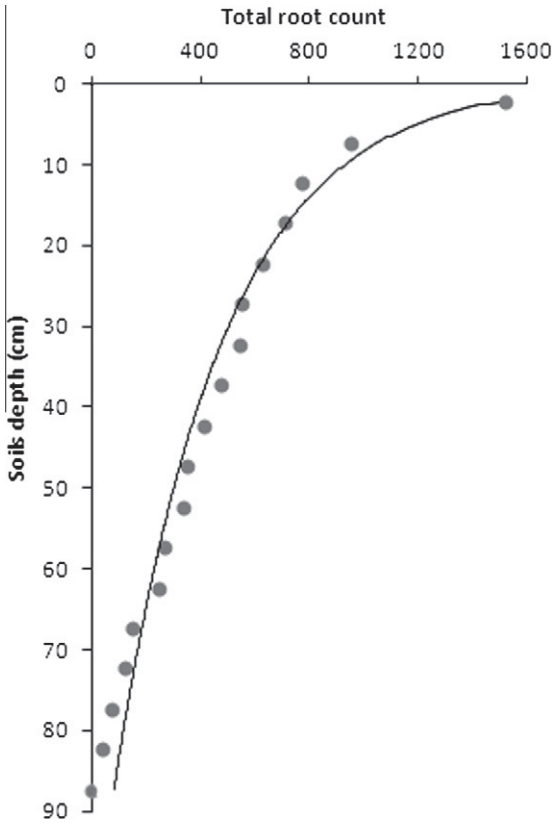


**Fig. 2.** Total root numbers across all trenches by depth.

The results for root density distribution by horizon for the Vertosol and the Dermosol are replicated when looking at root density distribution by depth (Fig. 5). *C. citriodora* subsp. *variegata* has higher root densities at depth in the Dermosol (Fig. 5b) than *E. dunnii* but that situation is reversed in the Vertosol (Fig. 5c). The root densities by depth of the two species on the Chromosol (Fig. 5a) shows higher root densities for *C. citriodora* subsp. *variegata* compared to *E. dunnii* in the upper parts of the profile with a reversal of that relationship in the lower parts of the profile. Fig. 6 indicates a higher overall density of roots on the Dermosol for both species, significant for *E. dunnii* and for *C. citriodora* subsp. *variegata* on the Dermosol compared to the Vertosol. Fig. 6 also shows a significant difference in the proportion of the total roots that were <2 mm diameter ($P < 0.001$). The fine roots composed a higher percentage of the total root numbers for *E. dunnii* on the Dermosol than for the other soil types. A similar trend was exhibited in the *C. citriodora* subsp. *variegata*, with the proportion of fine roots highest on the Dermosol (but not significantly higher than on the Chromosol) and significantly lower on the Vertosol.

### 3.2. Root assessment from core sampling

Regression of root length (estimated using the methods of Tennant, 1975) and oven dry mass of the very fine roots (<1 mm) determined the association:

$$\mathrm{Lr(root\ length\ in\ cm)} = 144.85 * \mathrm{Mr\ (oven\ dry\ root\ mass\ in\ gm)} + 2.228\ (n = 18, R^2 = 0.54).$$

This relationship was used to convert mass of roots in that size class to a length figure for incorporation with all other size classes (which were all recorded as length measures) into the analysis.

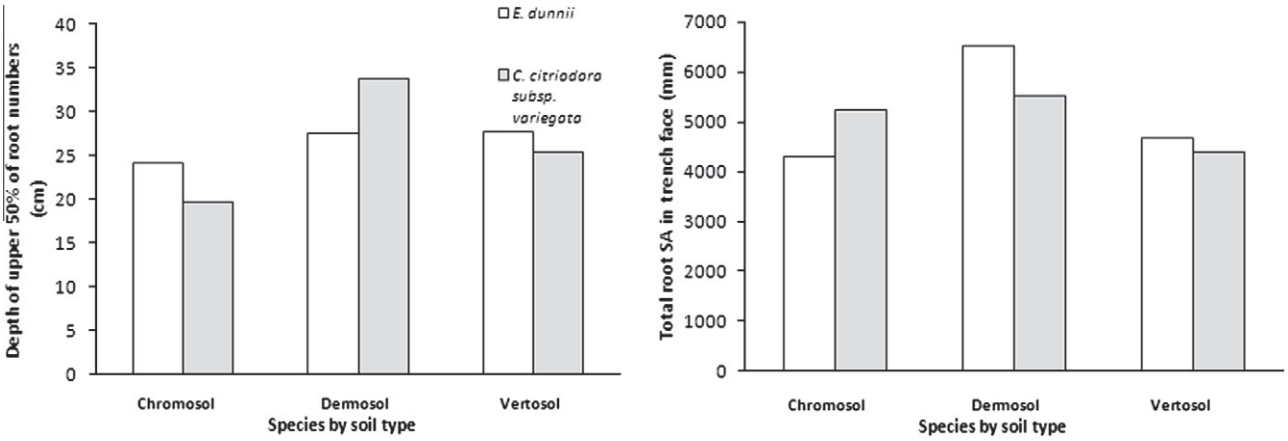


**Fig. 3.** Total root data from trench analysis. Left graph – root numbers focussed in top layers. Right graph – total root surface area.

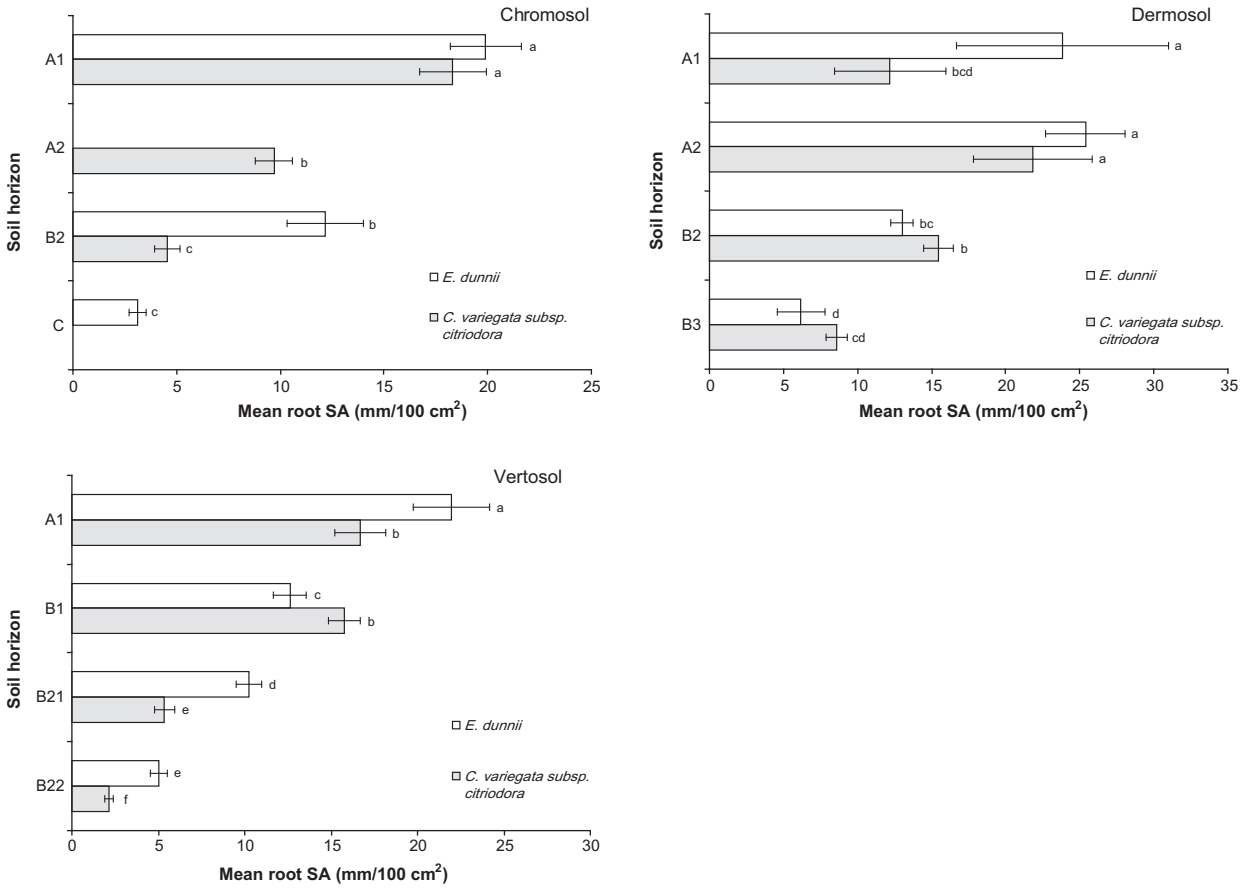


**Fig. 4.** Root density of *E. dunnii* and *C. citriodora* subsp. *variegata* from the trench analysis by horizon.

The mean size of the trees (in terms of DBH) around which each set of core samples were taken (the 'target trees') is given in Table 4. There was no significant difference between the tree size according to either soil type or species. The corer could take samples down to 100 cm but in most cases impenetrable B3 or C horizons were encountered before that point. The mean depth of the core on the Vertosol was 83.5 cm which was significantly deeper ($P = 0.023$) than the depth of the cores on the Chromosol and the Dermosol (79.5 and 79.0 cm, respectively). Mean depth of 136 cores in relation to soil and species is presented in Table 4. There was no significant difference in total core root length counts according to core position within the soil species combinations. Total root length counts did not vary from row to interrow or from row to channel. Neither was there any difference in root length density in the topsoil according to core position.

Measured root lengths were summed within each core to produce total root length per core. The means of total root length per core are presented in Fig. 7 which shows a significant

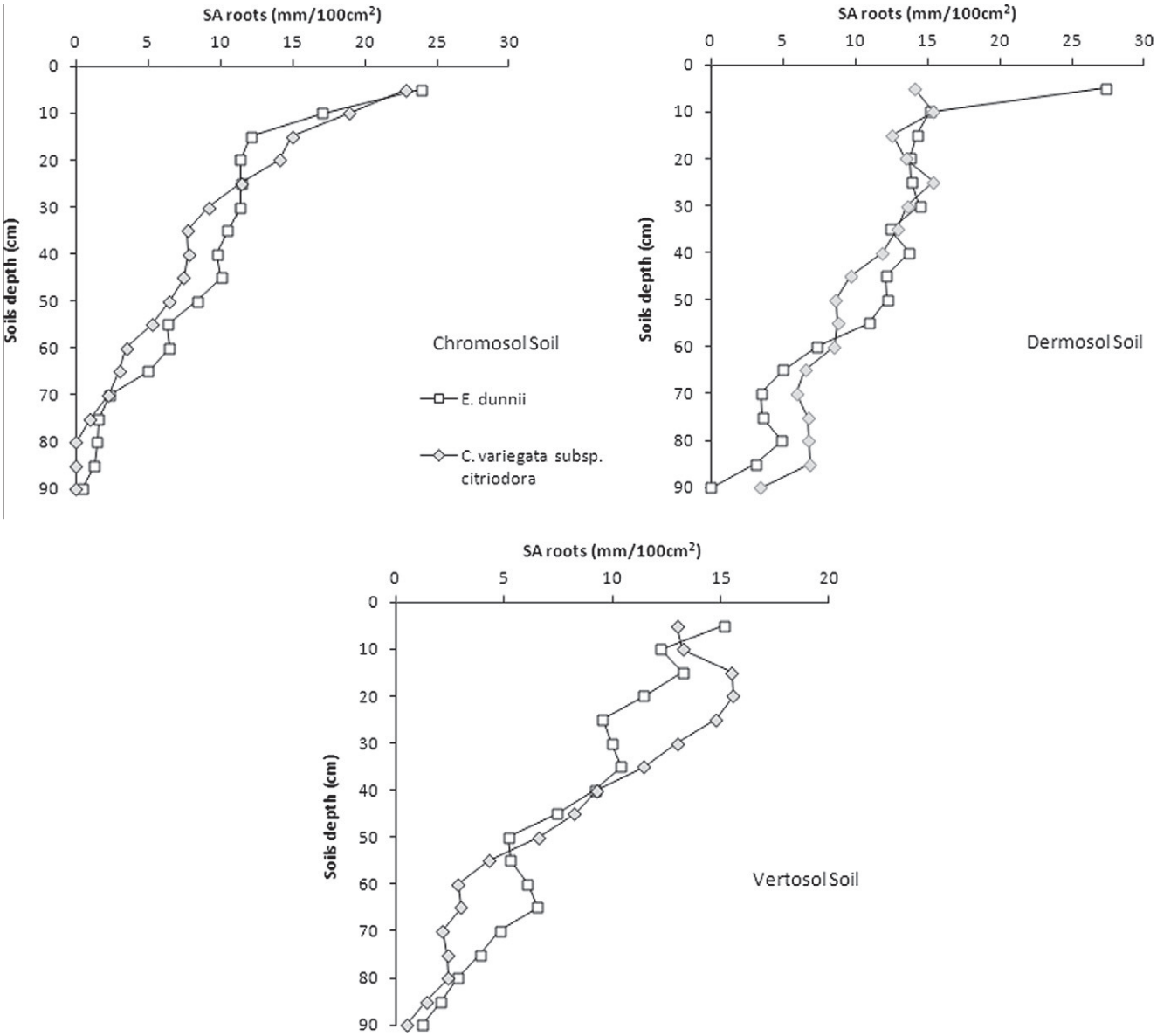


**Fig. 5.** Fine root distribution of *E. dunnii* and *C. citriodora* subsp. *variegata* from the trench analysis.

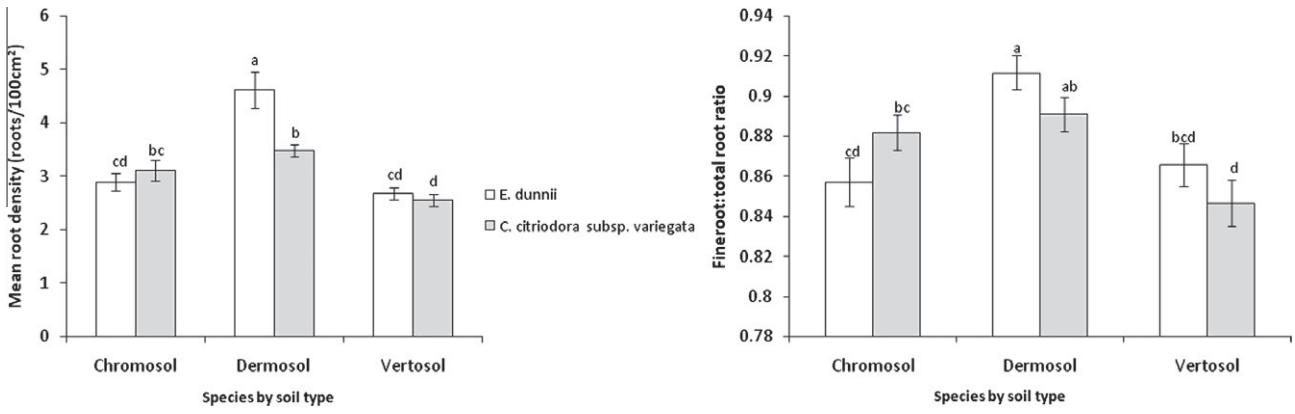


**Fig. 6.** Trench analysis results. Left graph – mean root density (± standard error) for *E. dunnii* and *C. citriodora* subsp. *variegata* by soil type. Right graph – ratio of fine roots numbers: total root numbers (mean of individual grids ± standard error). Significant differences at $P < 0.05$ level indicated.

**Table 4**
Mean diameter of the trees around which cores taken and mean lower depth of sampling core with standard deviation.

| Soil | Species | Mean DBH (mm) | SD DBH (mm) | Mean depth (cm) | SD depth (cm) |
|---|---|---|---|---|---|
| Chromosol | *E. dunnii* | 119.3 | 13.5 | 82.8b* | 10.9 |
| | *C. citriodora* subsp. *variegata* | 119.0 | 19.5 | 76.4a | 8.8 |
| Dermosol | *E. dunnii* | 133.0 | 18.3 | 78.7ab | 6.9 |
| | *C. citriodora* subsp. *variegata* | 120.0 | 54.1 | 79.4ab | 9 |
| Vertosol | *E. dunnii* | 144.3 | 27.5 | 78.9ab | 8 |
| | *C. citriodora* subsp. *variegata* | 122.7 | 40.5 | 88.1c | 8.8 |

* Significant differences at $P < 0.05$ level indicated by letters.

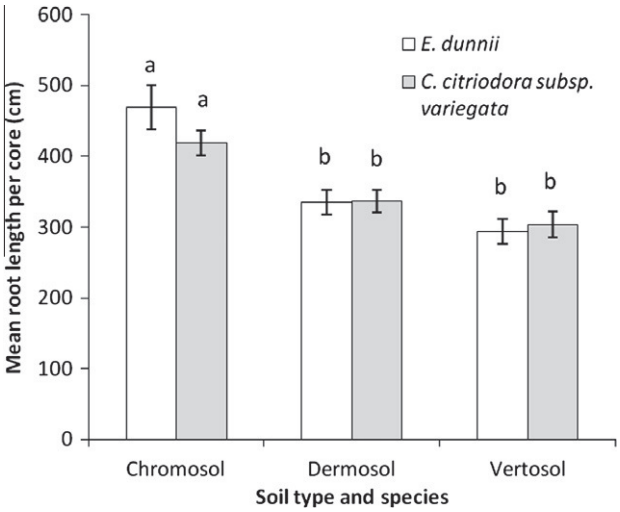


**Fig. 7.** Mean total root length per core sample (± standard error) by soil type and species. Significant differences at $P < 0.05$ level indicated by letters.

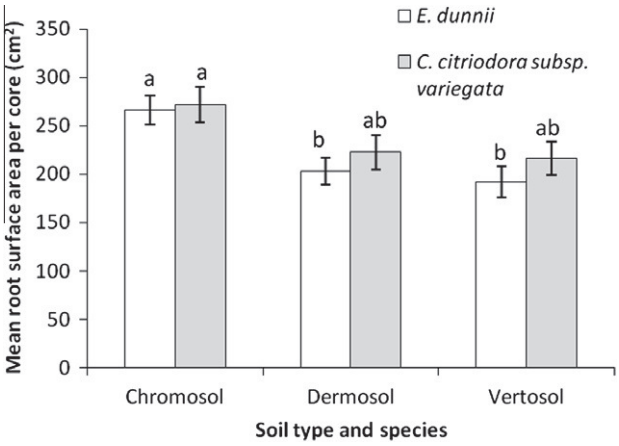


**Fig. 8.** Mean total root surface area per soil core sample (± standard error) by soil type and species. Significant differences at $P < 0.05$ level indicated by letters.

difference between root length by soil type but not by species. Root abundance in terms of mean root length per core was higher on the Chromosol than for the other soil types ($P < 0.001$). The difference in root abundance between the Dermosol and the Vertosols was marginal ($P = 0.071$). If the surface area of roots is considered, rather than length alone, the relationship changes such that there is no significant difference in root surface area between the soils for *C. citriodora* subsp. *variegata* but there is still a significantly higher root surface area on the Chromosol soil compared to both other soil types for *E. dunnii* (Fig. 8).

This higher total root length on the Chromosol soil was also reflected in analysis of Lr*d* (root length density) in the surface horizon (Fig. 9). Both species examined had significantly higher root length densities in the surface horizon of the Chromosol compared to both the Dermosol and the Vertosol. However in the subsoil the root densities of both species were lower in the Vertosol soil than both the other soils.

The variation in root density between the row and interrow did not show any significant difference within soil type but again showed the significantly higher root densities on the Chromosol soil (Fig. 9). At this stage of the plantations' life the roots appear to have occupied both the row and the interrow to an equal extent. Root densities in the topsoil reflect the same relationship as total root densities but root densities in the subsoil showed a significant difference between the row and interrow for the Chromosol soil (being higher in the interrow – see Fig. 9). The Vertosol had significantly lower subsoil root density than the other soil types.

Fitting the cumulative root fraction to the root length data amalgamated across all soils to the form: $Y = 1 - \beta^d$ where $Y$ = cumulative root fraction, $\beta$ is a constant defined by the data and d is depth in cm (Gale and Grigal, 1987). $\beta$ was determined to be equal to 0.966 ($R^2 = 0.967$) for *E. dunnii* and 0.965 ($R^2 = 0.959$) for *C. citriodora* subsp. *variegata*. The lower β value for *C. citriodora* subsp. *variegata* suggests a (very slightly) higher proportion of the roots occurring near the surface than *E. dunnii*. These models show that 50% of *E. dunnii* roots occur in the upper 20.1 cm and for *C. citriodora* subsp. *variegata* 50% of the roots are in the upper 19.3 cm ($d_{50} = \ln(0.5)/\ln\beta$ – Smith et al., 1999).

## 4. Discussion

The high concentration of roots observed in the upper soils in this study has been reported from other plantations for a range of species (Carbon et al., 1980; Nambiar, 1983, 1990; Livesley et al., 2000; Bouillet et al., 2002; Macinnis-Ng et al., 2010; Gwenzi et al., 2011; Levillain et al., 2011) and for native forests (Jackson et al., 1996). Cumulative root fraction down the profile was fitted to the model: $Y = 1 - \beta^d$ where $Y$ = cumulative root fraction, $\beta$ is a constant defined by the data and d is depth in cm (Gale and Grigal, 1987). This data returned a $\beta$ of 0.960 ($R^2 = 0.978$) which compares with the model – $Y = 1 - 0.962^d$ determined for tropical evergreen forests and $Y = 1 - 0.970^d$ for temperate and tropical trees by Jackson et al. (1996) suggesting a slightly greater proportion of roots are concentrated in the upper parts of the soil profile in this plantation system on these soils.

The fine (<1 and 1–2 mm diameter classes) and medium (2–5 mm diameter class) classes dominated the roots in terms of total measured root length such that 98% of the roots recorded fell into that size range (and 88% in the <2 mm size classes). This is consistent with a number of other studies. Nambiar (1990) found fine roots (there defined as roots with diameter <3 mm) accounted for 70–95% of total root length. Falkiner et al. (2006) found fine roots (defined as <1 mm) measured by trench analysis and horizontal cores accounted for around 93% of the total roots (but also found that trench analysis was biased towards fine roots and that vertical root cores gave a higher proportion of coarse roots). The consistent reduction in root surface area (RSA) down the profile also suggests that the major source of water and nutrients for these species in these plantations is the upper parts of the profile. There

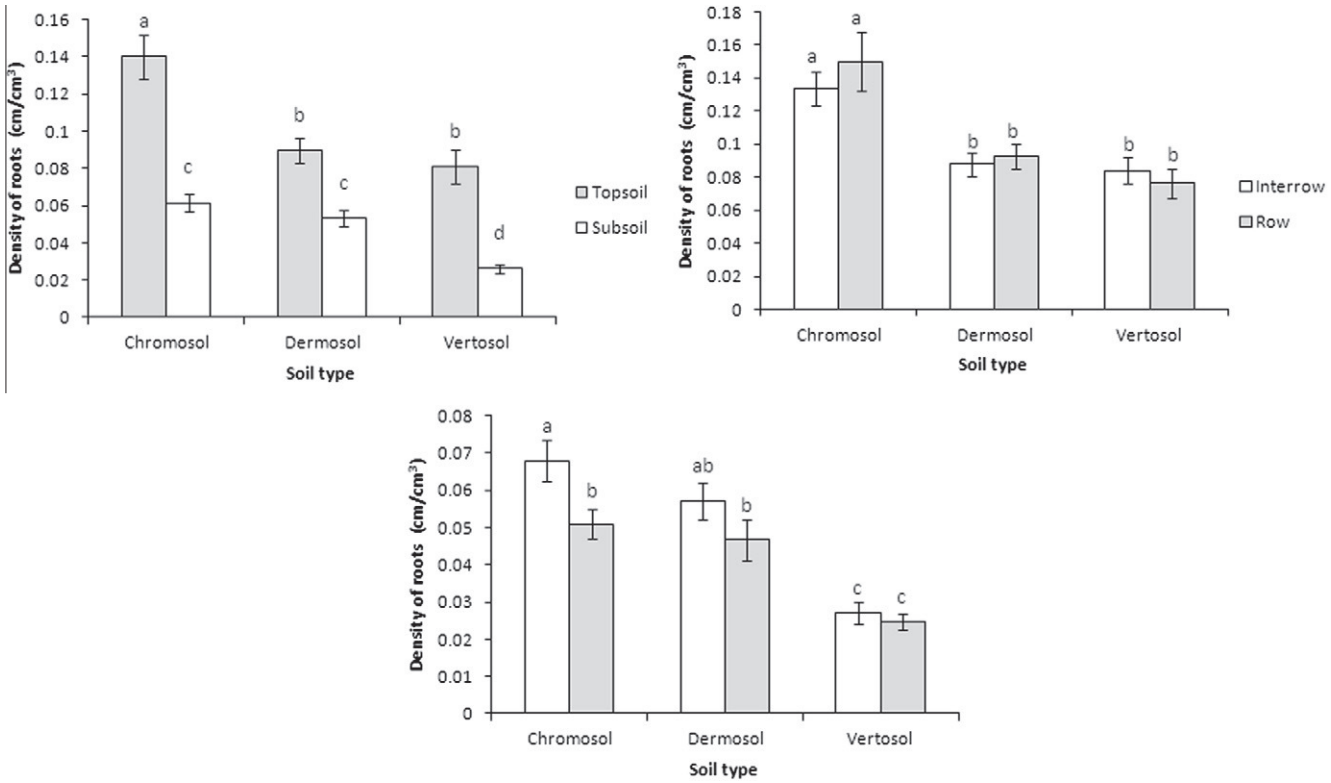


**Fig. 9.** Mean root length densities (± standard error) of core samples by horizon (top left). Significant differences at $P < 0.05$ level indicated. Topsoil includes A1 horizons, and subsoil to B2 horizons). Mean root length densities (± standard error) in topsoil and subsoil (top right) by position at site. Significant differences at $P < 0.05$ level indicated. Overall root length densities and cumulative root length across all soil types (bottom).

was no increase in root density in lower parts of the soil profile as observed in association with water accumulation at depth by Falkiner et al. (2006).

The root profiles illustrated by Figs. 3–5 display differences in root distribution by soil type, species and depth. Fig. 3 indicates (qualitatively) that a larger root surface area appears to be required to support both species on the Dermosol (which, although it was an older plantation, did not have significantly larger trees). Fig. 4, which illustrates the distribution of root growth in relation to soil horizons, shows that total root densities are lower for both species in the B2 subsoil on the Vertosol than for the other two soil types. It appears that either (i) the finer structure of the Vertosol subsoil compared to the structure in the Dermosol and the Chromosol does not compensate for the difficulties imposed by the reactive clays that dominate that soil or (ii) the higher nutrient status of the Vertosol means that sufficient nutrients and water can be obtained from the upper horizons without need for proliferation in the subsoil. Root distribution results by horizon from the Chromosol soil does not appear to support the hypothesis that *E. dunnii* has less roots in the a poorly structured subsoil (Fig. 4) than *C. citriodora* subsp. *variegata* and this is also reflected in the depth distribution (Fig. 5). The differences in horizonation between the Chromosol under the two plantation species is likely to have some influence on this. Even though the *E. dunnii* and *C. citriodora* subsp. *variegata* sites were chosen close to each other and both soils fall within the same soil classification, the soil under the *C. citriodora* subsp. *variegata* had a distinct A2 horizon that was not present under the *E. dunnii*. Fig. 6b shows *C. citriodora* subsp. *variegata* has greater root concentration at depth than *E. dunnii* on the Dermosol soil; in contrast *E. dunnii* appears to have greater root penetration into the deeper profile of the Vertosol than *C. citriodora* subsp. *variegata* (Fig. 6c). The Dermosol had relatively poorly structured subsoils that were massive or with large peds and colours indicative of periodic anaerobic conditions.

According to the results of root assessment from coring, tree size (as measured by DBH) did not vary significantly between sites, however this result is likely to be influenced by the low number of replicates (three trees in each soil-species combination). There does appear to be a (non-significant) tendency for *E. dunnii* to be larger than *C. citriodora* subsp. *variegata* on the Dermosol and the Vertosol and for it to be smaller on the Chromosol than on the other soil types. The significantly higher total root length for both species on the Chromosol soil compared to the Vertosol and the Dermosol (Fig. 8) suggests both species are allocating a higher proportion of their productivity below ground on that soil type. This difference would be further enhanced by the fact that the above ground biomass of the trees on the Chromosol is smaller (though not significantly so) than the trees on the other soils (Table 4). The finding of higher root abundance on the Chromosol (at least for *E. dunnii*) is at odds with the root trench analysis (Fig. 3) which qualitatively suggested that the Dermosol had higher root densities. The trench analysis recorded a relatively low level of fine roots as a proportion of total roots lower than that recorded in the core analysis. The ratio of fine root surface area: total root surface area averaged 0.58 for the profile wall method on for the core samples it ranged from 0.77 to 0.79. Profile wall root analysis tends to underestimate fine roots compared to the core method (Falkiner et al., 2006) and this appears to be the case here, particularly as the average distance from the base of the target tree for the trench is larger than for the cores and the proportion of fine roots increased with distance from the trunk. (The fine root length:total root length ratio was 0.74 for those cores closest to the trunk, significantly different to the 0.79 for those cores further away). The Chromosol soil was the poorest in terms of nutrients (Table 2) and it is possible

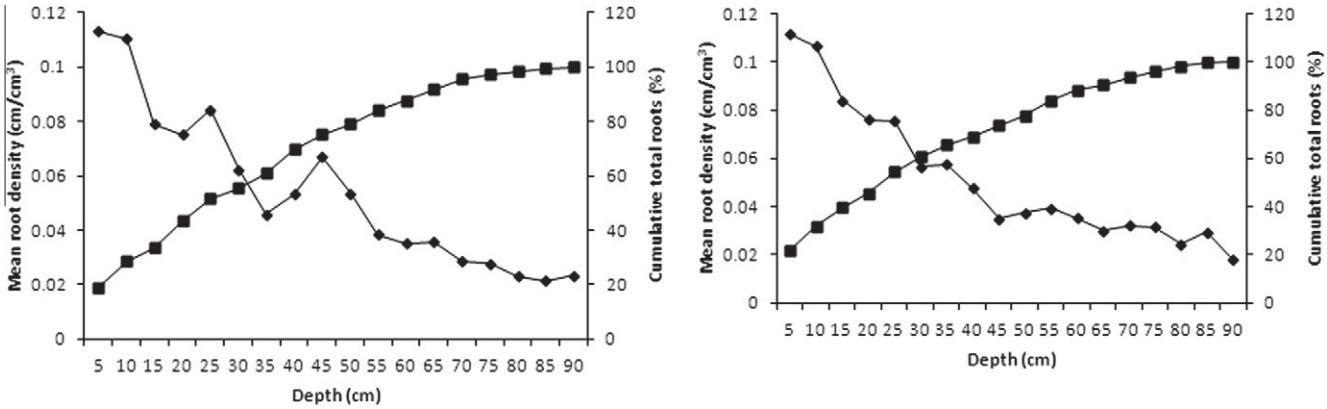


**Fig. 10.** Mean root density and cumulative root % (*E. dunnii* on left, *C. citriodora* subsp. *variegata* on right).

that the higher root densities were required to access sufficient nutrients.

Root abundance in terms of mean root length per core was higher on the Chromosol than for the other soil types ($P < 0.001$). The difference in root abundance between the Dermosol and the Vertosols was marginal ($P = 0.071$). The analysis of total root surface area provides a slightly different view (Fig. 10) suggesting, again that *E. dunnii* had a significantly higher level of roots on the Chromosol than on the Dermosol or the Vertosol but that for *C. citriodora* subsp. *variegata* there was no significant difference between the root abundance between the three soil types. This difference suggests a higher proportion of coarser roots (higher surface area per unit length) in the *C. citriodora* subsp. *variegata* on the Vertosol and the Dermosol soils and although this was supported to some extent by analysis, there was no significant difference. The ratio of fine roots to total roots was significantly higher ($P = 0.001$) for *E. dunnii* than for *C. citriodora* subsp. *variegata* in the topsoil (but not in the subsoil). The finding of higher densities of fine roots in the upper parts of the profile has previously been noted for eucalypt species that occur in moister environments as compared to those eucalypts from drier areas (Jacobs, 1955; Zimmer and Grose, 1958).

A comparison of the two methods of root assessment suggests that each has its place depending on the focus of the study. The trench analysis data, consolidated across both species and sites, returned as average density of roots of 0.0032 cm roots/cm$^3$ with a fine root length:total root ratio of 0.88. For the core analysis the average root density was 0.057 cm roots/cm$^3$ and the fine root length: total root length was 0.79. It appears from this work that the amount of roots being recorded from the trench analysis was substantially below that of the core sampling. The trench analysis, however, was far less labour intensive (requiring around 5% of the input in terms of time) and the relative distribution of roots down the profile is similar for both methods. The core analysis is likely to be most valuable where exact measures of root presence are required (for instance in biomass or carbon studies) but the trench analysis may be more suitable in studies of relative root occupation of soils across a variable site.

## 5. Conclusion

Three soils with contrasting physical characteristics were selected to determine if those characteristics produced different root depth distribution in *E. dunnii* and *C. citriodora* subsp. *variegata* using two different methodologies: soil trench profile and coring. The results showed a concentration of roots within the upper parts of the soil profile for both *E. dunnii* and *C. citriodora* subsp. *variegata* which accords with past studies of other species and indicates the importance that the upper horizons provide in the provision of nutrients and water.

The similarity between the root depth distributions of two species was greater than was expected. Both past research and anecdotal evidence suggested there would be marked differences, but this was not recorded. The trench root analysis and the core sampling provided some support for the hypothesis of different root depth distribution between the two species. *C. citriodora* subsp. *variegata* colonised the poorly structured deeper parts of the Chromosol subsoil at lower densities than *E. dunnii* and *E. dunnii* had higher root density in the Vertosol subsoil than did *C. citriodora* subsp. *variegata*.

The studies also showed markedly reduced density of roots for both species in the subsoils of the Vertosol compared to the other soils for both species. The Vertosol subsoils appear on initial appearance to be more hospitable to root growth than the subsoils of the other two sites due to their finer structure. However the reactive nature of the subsoil leads to shrinkage on drying and subsequent damage to roots may be an overriding factor. Vertosols are colonised by few eucalypt species in the subtropics (Specht, 1996). They pose major physical challenges to root growth and survival due to a combination of poor drainage, water storage that is determined more by limitations on water entry than on the rainfall regime and the depth and moisture characteristics of the soil itself, and soil movement (shrink and swell). Poorly drained soils in general appear to be problematic for *E. dunnii* (Herbert, 2000) and Vertosols provide particularly adverse conditions particular (Grant et al., 2010). The Vertosol soil had much higher nutrient levels than either the Chromosol or the Dermosol but the lack of deep root penetration restricted growth rates to that observed on the lower nutrient soils.

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