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Root biomass and root fractal analyses of an open *Eucalyptus* forest in a savanna of north Australia

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Abstract

Below-ground biomass of a *Eucalyptus* open-forest savanna was estimated following trenching to depths of two meters around 16 mature trees in a tropical savanna of north Australia. Correlations among below-ground and various components of above-ground biomass were also investigated. In addition, root morphology was investigated using fractal analyses and a determination of an index of shallow rootedness was undertaken. Total root biomass was 38.4 t ha⁻¹, including 1 t ha⁻¹ of fine roots. About 77-90% of total root biomass was found in the upper 0.5 m of soil. While fine root biomass density was approximately constant (0.1 kg m⁻³) in the top soil, irrespective of distance from a tree stem, coarse root biomass showed large variation with distance from the tree stem. Significant positive correlations among total root biomass, total above ground biomass, diameter at breast height, leaf biomass and leaf area were obtained. It is likely that total root biomass can be reasonably accurately estimated from above-ground biomass and fine root biomass can be estimated from tree leaf area. We present equations that allow the prediction of below-ground biomass from above-ground measures of tree size.

Root morphology of two evergreen and two deciduous species was compared using three parameters. These were: the fractal dimension (D), which describes root system complexity; a proportionality factor (α), which is the ratio of the cross-sectional area before and after branching; and two indices of shallow rootedness (ISR). Roots were found to be amenable to fractal analyses. The proportionality factor α was independent of root diameter (D_r) at any branching level in all tree species examined, indicating that branching patterns were similar across all root sizes. The fractal dimension (D) ranged from 1.15 - 1.36, indicating a relatively simple root structure. Mean D was significantly different between *E. tetradonta* (evergreen) and *T. ferdinandiana* (deciduous), however, no significant differences were found among other pairs of species. *T. ferdinandiana* had the highest ISR, while *P. careya* (deciduous) had the lowest. In addition, differences in ISR between *P. careya* and the other three species were significant, but were not significant among *E. miniata*, *E. tetradonta* and *T. ferdinandiana*. There were clear relationships among above ground tree stem diameter at breast height, stem base diameter, horizontal and vertical proximal root diameter. Using mean values of α and stem diameter we estimated the total cross sectional area of root and root diameter class distribution for each species studied.

Keywords: Root biomass; DBH; Root fractal analysis.

Introduction

Forests significantly influence global carbon fluxes and regional hydrological cycles. They are also a significant sink for atmospheric carbon and account for about 40 % of global C stores (Eamus and Jarvis 1989, Eamus 1992). Their role in controlling regional and global carbon pools and fluxes has been studied in detail (Brown and Lugo 1984; Grieron et al. 1992; Dixon et al. 1994; Vogt et al. 1996, 1998; Cairns et al. 1997). While there are extensive studies of above-ground biomass of woodlands and forests, there have been fewer detailed studies of below ground biomass (Sanford 1989; Russell 1997; Eamus et al. 2000a), especially in Australia, where savannas cover approximately 25 % of the continental land area. Furthermore, a majority of published studies are confined to estimates based on sampling of the top 0.3 m of soil, despite clear evidence that significant root biomass occurs at greater depths (Vogt et al. 1996).

Accelerated rates of land use change, especially in tropical savannas, have occurred globally in the past 25 years. In any C budget analyses of savannas, as part of the Kyoto protocol, it is important to quantify total above- and below-ground biomass (Fearnside 1992), for disturbed and un-disturbed sites. Furthermore, there is considerable interest in determining relationships between above- and below-ground biomass because it is easier and cheaper to measure above-ground than below-ground biomass and therefore correlations may allow cheaper and more geographically distributed estimates of below-ground biomass.

In Venezuelan dry tropical forests, pre-dawn water potential declines in the dry season more rapidly in deciduous species than evergreen species (Sobrado 1986). Similar differences in water relations of evergreen and deciduous trees of Australian savannas have been observed (Myers et al. 1997). From such observations, and observations concerning stomatal behaviour (Prior et al. 1997a,b) and phenological patterns (Williams et al. 1997), it is often inferred that root distribution of evergreen and deciduous species differ (Eamus and Prior 2001). However, there have been few comparisons of root distribution among trees of different phenology (Eamus and Prior 2001).

Root production contributes about half of the carbon being cycled annually in many forests (Vogt et al. 1996) and 33% of global net primary production (Jackson *et al.* 1997). Therefore, any assessment of carbon density, total standing biomass and primary production requires detailed information about below-ground biomass. Given the areal extent of Australian savannas, estimates

of root biomass and their size and depth distribution will significantly aid the national carbon accounting process.

Coarse roots contribute more to total ecosystem biomass than fine roots (Vogt et al. 1987). Even though fine roots may contribute less than 2% of total ecosystem biomass, they may contribute up to 40% of total ecosystem production (Vogt et al. 1990) and are very sensitive to environmental change. Furthermore, climate variables and nutrient pool sizes are important determinants of total fine root biomass (Vogt et al. 1996). Therefore, estimates of root biomass should differentiate between coarse and fine root biomass. Knowledge of root biomass distribution and root biomass density (mass of roots per unit volume of soil) are important not only for carbon accounting purposes but also for modelling of root functioning.

Fractal models can describe the geometry of many natural objects and their application in ecology has become increasingly popular (Williamson and Lawton 1991; Berntson 1996; Fitter 1996). While root systems are complex structures, there is order within this complexity (Berntson 1996). Tatsumi et al. (1989) demonstrated that plant root systems have a fractal structure. Van Noordwijk et al. (1994, 1995) developed methods for quantifying root systems using fractal models. However, there have been no investigations of fractal properties of roots of Australian tree species and therefore it is unknown whether such an approach is applicable to Australian species. We apply these models to compare roots of two deciduous and two evergreen tree species in a north Australian savanna.

Recent work has suggested that an index of shallow rootedness (ISR) may be assessed by exposing only the upper 0.5 m of a root system (Van Noordwijk et al. 1995). An index of shallow rootedness may be a useful index for assessing the potential value of different species in revegetating landscapes in the arid and semi-arid environments that characterise much of Australia. Consequently we apply this methodology to compare a deciduous and evergreen savanna tree species in light of their inferred differences in rooting depth (see above).

The aims of the work described in this paper are four-fold. First, to quantify the root biomass of a natural savanna site in tropical Australia, to a depth of 2 m. Second, to investigate relationships among root biomass, diameter at breast height (D_{bh}), total above-ground biomass, leaf biomass and leaf area. Third, to investigate root morphology using fractal analyses and two indices of shallow rootedness. Finally, we compare the root morphology of evergreen and deciduous species to further

investigate the possibility that evergreen and deciduous species may differ in patterns of root distribution. More specifically, we test the hypotheses that first, there are no relationships among above- and below-ground measures of biomass; second, that roots of Australian species do not show fractal properties; and third that evergreen and deciduous tree species of Australian savannas do not differ in the depth distribution of their roots.

Methods

Study area

Three study sites within the greater Darwin area (NT, Australia) were used: Humpty Doo, 50 km south-east of Darwin (12°30'S, 130°45'E); the Casuarina campus of the Northern Territory University (120° 22'S, 130° 52'E); and the Tropical Ecosystem Research Centre of CSIRO (120° 25'S 130° 53'E). The highly seasonal distribution of rainfall is the dominant feature of the climate (McDonald and McAlpine 1991), with distinct wet (November-March) and dry seasons (April-October) (Eamus and Cole 1997). Mean annual precipitation is 1651 mm over the past 55 years (Australia Bureau of Meteorology Darwin, NT), with over 95% of rainfall occurring in the wet season. Mean annual minimum and maximum temperatures on the coast at Darwin are 23 °C and 32 °C respectively (McDonald and McAlpine 1991). The soil is an infertile loamy sand. Vegetation is classified as tropical Eucalypt open forest (Wilson et al. 1990; Williams et al. 1997), dominated by *Eucalyptus miniata* Cunn. Ex. Schauer and *E. tetradonta* F. Muell (both evergreens) with sub-dominant species, such as *Terminalia ferdinandiana* Excell (deciduous) and *Erythrophleum chlorostachys* (F.Muell.) Baillon (evergreen) accounting for less than 10 % of the standing tree biomass (O'Grady et al. 2000). The average height of the forest is about 10-15 m; mean diameter at breast height (D_{bh}) is 15 cm and the density of the forest is approximately 650 trees ha⁻¹.

Two of the sites were used in the root morphology study. The first root morphology site was the Casuarina campus of the Northern Territory University (NTU), in Darwin; the second was the Tropical Ecosystem Research Centre (TERC) of CSIRO, Darwin. Species composition and vegetation structure were little different between either site and both were relatively protected from fire. The root biomass site (Humpty Doo), in contrast, was influenced by fire, typically being burnt every 2-4 years, but had the same tree species complement.

Estimation of root biomass

The trench method (Komiya et al. 1987) was used to investigate root biomass and distribution. Eight trenches were made at the study site such that each trench included two mature trees of the same species at the two ends of the trench. The trench extended 0.5 m past the two study trees. The length of the trench was determined by the distance between the two study trees. It is important to note that the trench included the root stump, or the root crown, that is, the mass of root immediately below the tree trunk.

The trench was dug after marking the selected area with paint on the ground. A 5 tonne excavator with a 0.3 m wide 'bucket' was used throughout. Diameter at breast height of each study tree was recorded and then a chain-saw used to fell the tree, which was removed and used for above-ground biomass estimation (see below).

Each trench was divided into 3 or 5 vertical columns and approximately 10 horizontal rows of soil compartments were required. Each soil compartment thus defined was further subdivided vertically into 2 or 4 layers of soil blocks to a total depth of 0.6 to 2 m. Each soil block was excavated and arranged separately on plastic sheets laid on the ground. Each soil block was numbered and identified according to its original position in the trench.

Estimation of below-ground biomass

Approximately 15 % of the total volume of each 'soil block' was sub-sampled. Roots from each sub-sample of each soil block were collected manually (a team of eight people assisted), by spreading the soil out on a very large surface in the field, to a depth of approximately 1 cm, and sifting the soil by hand. Roots were sorted into coarse (> 2mm diameter) and fine (< 2 mm diameter) fractions and stored in plastic bags until taken to the laboratory and oven-dried at 70 °C to a constant weight. The large rootstock or lignotuber was removed and weighed. A sample of the rootstock was taken, oven-dried and re-weighed, and their weights were added to the coarse root mass of the corresponding soil blocks. Root biomass is expressed on a ground area basis (kg m^{-2}) or as a root density (root mass expressed on a soil volume basis, thus, kg m^{-3}).

Estimation of above-ground biomass

Using the harvest method of Satoo and Madgwuck (1982), the above-ground biomass of the trees studied was measured. After a tree was cut down, it was divided into wood, bark, branch and leaf components for study. Fresh weight of the components was determined in the field using a large (100 kg) portable electronic balance. Sub-samples were taken to the laboratory, oven-dried and weighed. Above-ground biomass for the forest was calculated using the allometric equation given below:

$$W = a D_{bh}^b \quad (1)$$

where, W is biomass, D_{bh} is diameter at breast height of the tree and a and b are constants.

Assessment of root morphology using fractal analyses

Four trees of each of the following species were identified at both the NTU and TERC site – *Eucalyptus tetradonta*, *E. miniata*, *Terminalia ferdinandiana*, and *Planchonia careya*. The first two species are evergreen, the latter two are deciduous (Williams et al. 1997). Using a high pressure water hose, soil was removed from a hemi-sphere of approximately 0.5 m radius, centred on the stem of each tree. Major roots that were confined to the upper 0.5 m were followed for distances of up to 5 m from the stem, where possible, using the high pressure hose. Root segments of approximately 2-3 m in length were removed from each tree. These segments had an intact branching structure down to fine roots of 1 mm diameter or less and were used for fractal dimension measurement (see below).

On each 2-3 m long root segment, a square frame of L cm was placed over each root and divided into $(L/r)^2$ squares of side r cm. We used a frame size, L , of 19.2 cm and r ranged from 9.6 to 0.3 cm. With the frame on top of a root segment, the number of the squares that intersected the root $N(r)$, were counted for each cell size r . If a linear relationship between $\log N(r)$ versus $\log r$ is obtained, the root is considered to be fractal (Berston 1996) and the slope of this (negative) relationship is known as the fractal dimension (D), since $N(r) = k \cdot r^{-D}$ ($1 < D < 2$), where k is a constant. This parameter was derived for all four species.

Proportionality constant, α

The proportionality constant, α , is the ratio of the squared diameter of roots before and after branching. This parameter was estimated using the root segments that were obtained to determine the fractal dimension, D . At each branching point along a root segment, the diameter and internode length (link length) of the current root (d_i) and the diameter of any branched roots ($d_{i+1,j}$) were measured, where i is the branching number and j is the number of branched roots arising at the i^{th} branching point. Alpha was calculated as:

$$\alpha = (d_i)^2 / \sum (d_{i+1,j})^2, \quad i = 1, 2, \dots, n; \quad j = 1, 2, \dots, n, \quad (2)$$

where n is the total number of branching points for a segment. A value of α was derived for each species.

Index of shallow rootedness

Measurements were made on roots from a total 38 trees, including 13 individuals of *E. tetradonta*, 10 individuals of *E. miniata* and *T. ferdinandiana* and 5 individuals of *P. careya*. Diameter at breast height of the trees studied ranged from 3 to 25 cm. 20 trees were measured at the NTU site and 18 trees were measured at the TERC site. For each tree measured, a half sphere of 0.5 - 1.0 m was carefully excavated at the stem base using a high-pressure water hose. Proximal roots (ie those roots originating from the stem base) were exposed and classified as either horizontal (root angle less than 45° with respect to the ground surface) or vertical (angle greater than 45°). For each tree, diameter were measured at breast height (D_{bh}), at the stem base (D_b), and for all proximal horizontal roots (D_h) and vertical roots (D_v). The sum of all proximal root diameters was calculated (D_p). The index of shallow rootedness (ISR, Van Noordwijk et al. 1995) was calculated as:

$$ISR = \sum (D_h)^2 / D_{bh}^2 \quad (3)$$

Results

Below ground biomass of the forest

Total dry weight of roots collected from all 8 trenches (total ground surface area: 117.5 m²; total excavated volume: 177.2 m³) was 450.69 kg, equivalent to a root biomass of 3.84 kg m⁻² (or 38.4 t ha⁻¹; Table 1). The maximum amount of root biomass per unit area was 8.09 kg m⁻², while the minimum was 1.11 kg m⁻². Root biomass density ranged from 1.39 kg m⁻³ to 5.66 kg m⁻³ (Table 2). The total biomass of fine roots for all eight trenches was found to be 11.5 kg, which is approximately equivalent to a fine root biomass of 0.1 kg m⁻² or a root biomass density of 0.06 kg m⁻³. The total coarse root biomass for all eight trenches was 439.19 kg, equivalent to a coarse root biomass of 3.74 kg m⁻² or a coarse root density of 2.48 kg m⁻³ (Table 1).

In the upper soil layer (0- ca 0.5 m), total root biomass density of *E. chlorostachys* ranged from 1.90 to 4.83 kg m⁻³, while for *E. tetradonta* trees total root biomass density ranged from 5.66 to 12.83 kg m⁻³ (Table 3). Total root biomass density in both species increased with increasing D_{bh} . No significant difference in root biomass density of the upper soil was observed between species (*E. chlorostachys*: 0.09 kg m⁻³- *E. tetradonta*: 0.10 kg m⁻³). Total root biomass in the topsoil did not vary with distance from tree stem.

Horizontal distribution of root biomass

Fine root biomass density varied significantly throughout each trench. Thus, for *E. chlorostachys*, root biomass density varied from 0.028 to 0.060 kg m⁻³, while coarse root biomass ranged from 0.21 to 2.59 kg m⁻³ (Fig. 1b,d). *E. tetradonta* also showed similar variability (Fig. 1a, c; fine root biomass ranged from 0.041 to 0.063 kg m⁻³ and coarse root biomass ranged from 0.91 to 6.23 kg m⁻³). The compartment number used in Figure 1 merely represents different parcels of soil and is used to reveal the horizontal spatial variability inherent in root biomass distribution.

Vertical distribution of root biomass

Total root biomass of both species decreased steeply from 77-90.5% of the total root biomass at a depth of 0-0.5 m to 4.9-6.3% at 0.5-1.0 m, and to 4.6-16.7% at 1.0-2.0 m in *E. chlorostachys* and from 84.3-87.2% to 8.4-8.9% and to 3.9-7.3% in *E. tetradonta* (Fig. 2). Coarse root biomass for both species exhibited a similar pattern: 77.5-91.8%, 4-5.7% and 4.2-16.8 % in *E. chlorostachys*;

85.1-87.8%, 7.8-8.5% and 3.7-7.1% in *E. tetradonta*, at 0-0.5 m, 0.5-1.0 m and 1-2.0 m respectively. In contrast, fine root biomass showed a more gradual decrease with depth for both species: 52.3-59.8%, 23.4-31.1% and 16.6-16.8% in *E. chlorostachys*; 34.3-53.4%, 28.9-39.2% and 18.4-26.5% in *E. tetradonta* at the three depths respectively (Fig. 2). An exponential decline in root biomass with depth was observed, with the following relationships observed: Fine roots, *E. tetradonta*: $y = 0.2119e^{-0.5324x}$; *E. chlorostachys*: $y = 0.1647e^{-0.574x}$; coarse roots: *E. tetradonta*: $y = 48.115e^{-1.5821x}$; *E. chlorostachys*: $y = 12.98e^{-1.5408x}$; total roots: *E. tetradonta*: $y = 47.082e^{-1.5473x}$; *E. chlorostachys*: $y = 13.246e^{-1.4879x}$. Values of r^2 ranged between 0.74 and 0.99.

Relationships among root biomass, above-ground biomass, D_{bh} , leaf biomass and leaf area

Total root biomass (W_{rb}) was highly correlated with total above ground biomass (W_{ab}) ($W_r = 26.99 * \ln(W_{ab}) - 57.024$; $R^2 = 0.87$; Fig. 3a); D_{bh} ($W_{rb} = 72.029 \ln(D_{bh}) - 158.05$; $R^2 = 0.83$; Fig 3b); leaf biomass (W_l) ($W_r = 27.447 * \ln(W_{lb}) + 24.361$; $R^2 = 0.88$; Fig. 3c). In addition, fine root biomass (W_{fr}) and leaf area (LA) were significantly correlated ($W_{fr} = 0.68 * \ln(LA) - 0.8166$ $R^2 = 0.94$; Fig. 3d).

Root fractal analyses

Root branching pattern was independent of root size (data not shown) as no significant relationship was found between α and root diameter, d_l , at any branching level for any species examined. Values of α ranged from 0.96-1.97 for *E. miniata*, 0.37-2.06 for *E. tetradonta*, 0.28-2.21 for *T. ferdinandiana* and 0.80-2.77 for *P. careya*. Similarly, link length of root segments was also independent of diameter for all four species (data not shown). The average link length for *E. miniata*, *E. tetradonta*, *T. ferdinandiana* and *P. careya* were 15.5 cm, 10.8 cm, 6.3 cm and 7.7 cm, respectively.

Fractal dimension

Plots of $\log N(r)$ versus $\log(r)$ produced linear relationships (Fig. 4) and the negative slopes were used to calculate D for each species (Table 4). Fractal dimension ranges theoretically between 1-2 (Sugihara and May 1990; Berntson 1996) and all trees sampled in this study fell within this range. The deciduous species *T. ferdinandiana* had the lowest value of D, 1.15, and the evergreen *E.*

tetradonta the highest at 1.36. Significant differences in D were found between *E. tetradonta* and *T. ferdinandiana*, with all other comparisons being non-significant (Table 4).

ISR, stem and root relationships

There was a strong relationship between tree stem size and proximal root size in all species (Fig. 5). Mean D_h^2 was smaller than mean D_v^2 and D_h^2 accounted for less than 50% of D_p in all species studied. Values of ISR varied widely between species and ranged from 1.34 for *T. ferdinandiana* to 0.33 for *P. careya* (Table 4). The ISR of this latter species was differed significantly from all others (Table 4).

Discussion

Root biomass of woody species is difficult to measure and data for savannas are limited. Estimates range from 9.8 to 29.8 t ha⁻¹ in grasslands and savannas of Venezuela, the Ivory Coast and South Africa (Menaut and Cesar 1979; Smit and Rethman 1998). In the present study, total root biomass was estimated to be 38.4 t ha⁻¹, comparable to, but higher than, previous values in savannas (as opposed to grasslands). Our higher values may reflect both the inclusion of the lignotuber, which is often not included in studies of root biomass (Snowdon et al. 2000) and the deeper excavations used in the present study. Most previous studies were confined to extraction to depths of 0.5 m or less (Singh and Singh 1981; Raich 1980). Typically approximately 15 % of root biomass was found between 0.5 – 2.0 m depth and therefore this amount is lost when excavations stop at 0.5 m depth.

Total root biomass (on a ground surface area basis) was 3.84 kg m⁻² (or 38.4 t ha⁻¹), comprised of fine root biomass (0.1 kg m⁻², equivalent to 0.06 kg m⁻³) and coarse root biomass (3.74 kg m⁻² or 2.48 kg m⁻³). Such values are comparable to those of previous reports for savannas of Africa, Brazil, Venezuela and South Africa (Menaut and Cesar 1979; Castro and Kauffman 1998; Smit and Rethman 1998). Estimates of root biomass density are valuable inputs for estimates of ecosystem and national carbon density and models of water and nutrient uptake by roots and hence ecosystem water balance.

In general, root biomass was concentrated in the upper layers of the soil profile. Thus, between 77 % and 90 % of total root biomass was found in the upper 0.5 m, with about 5 % in the next 0.5 m and 5-15 % in the 1- 2 m depth range. Concentration of root biomass in the upper 50 cm of soil is generally reported (Smit and Rethman 1998; Compton et al. 1999; Snowdon et al. 2000) for most woody ecosystems. The rapid decline of biomass with depth was because of the steep decline in coarse root biomass rather than fine roots which were more evenly distributed with depth. Such a distribution of fine roots is required if, as calculated by Cook et al. (1998), water must be extracted from the entire upper 6-8 m of soil to account for the observed rate of canopy water use in the dry season. Therefore fine root biomass should be significant at depth.

Root biomass as a function of above-ground measures and root/shoot ratios

A significant positive correlation was observed in the present study between total root biomass and D_{bh} , above-ground biomass and total leaf area ($R^2 > 0.83$). Such correlations have been noted previously (Freezaillah and Sandrasegaran 1969; Sanford 1989; Kurtz et al. 1996; Cairns et al. 1997), but not for north Australian savannas. Such relationships allow estimations of below-ground biomass from measurements of above-ground parameters, a useful method to predict a hard-to-measure value (below-ground biomass) from a more easily measured value (above-ground biomass or D_{bh}).

The ratio of total root biomass / total above-ground biomass was 0.38 (38.4/ 99.9 <- *Not sure where 99.9 comes from, cant find it in results or Tables. Chen measured 61.4 t ha⁻¹ for live tree biomass at the 3 sites, making the ratio 0.63*). The default value used in the Greenhouse Challenge Vegetation Sinks workbook (see Snowdon et al. 2000) is 0.2. The default value in the National Greenhouse Gas Inventory Workbook 2 (1997) is 0.25 for all forest classes. Globally, this ratio is highly variable, ranging from 0.04 for boreal forests to 7.0 for deserts. For woodlands and forests (ie woody ecosystems), the ratio is typically 0.1 – 0.5 (Vogt et al. 1996; Keith et al. 2000). In a review of Australian woody ecosystems, using the Carnahan vegetation types L2 (low woodland), L3 (low open forest), L4 (low closed forest), M2 (woodland), M3 (open forest) and T3 (tall open forest), a mean root/shoot ratio of 0.4 was calculated (Snowdon et al. 2000). For the most productive native forests and mature plantation in Australia the mean ratio was 0.26, almost identical to the default value of 0.25. Similarly, Cairns et al. (1997) calculated a mean root/shot ratio of between 0.24 and 0.29 for boreal, temperate or tropical woody ecosystems. The rather higher value for the NT savannas is indicative of four features of these savannas. First, a highly

seasonal rainfall; second the dependency of the evergreen canopy on water stored at depth (6-8 m) for dry season transpiration (Cook et al. 1998, O'Grady et al. 1999; Eamus et al. 2000); third, the extremely weathered and nutrient poor lateritic soil; and fourth, average tree age is low and root-shoot ratio is larger in younger stands than older stands of trees (Snowdon et al. 2000). If the default value of 0.2 is used for estimating below-ground biomass from above-ground biomass, the estimate will be under-estimated by 90 %.

Many models of biomass allocation assume a functional relationship between fine root biomass and leaf area (Eamus 1996; McConnaughay and Coleman 1999), that is, fine roots must supply water, at sufficient rates, to leaves for transpiration. In the present study, the ratio of leaf biomass to fine root biomass was approximately 4. For several root size classes (0-1 mm diameter; 1-5 mm diameter; 1-5 mm diameter), Smit and Rethman (1998) found root to leaf dry mass ratio ranged from 6.65 to 3.14 at 10 sites in South Africa. In a study of 15 high and low productivity Douglas fir stands, the ratio of fine root biomass to foliage biomass averaged 0.33 (equivalent to a leaf to root biomass ratio of 3.0) (Vogt et al. 1987). Age, or more accurately, the degree to which canopy closure had occurred, influenced this ratio. The open savannas of north Australia do not attain canopy closure and the moderately high leaf to root biomass ratio is indicative of a canopy that is still growing and not limited by water availability, but by fire.

α and D values

Given the non-significant relationship between α and root diameter it is concluded that root systems of these savanna tree species have a fractal pattern (Van Noordwijk et al. 1994, 1995). Therefore fractal analyses can be applied in this system. The fractal dimension, D, represents the intricacy of root branching, with a highly complex branching structure having a higher value of D (Tatsumi et al. 1989; Sugihara and May, 1990; Berntson 1996). Values of D in crop species range from 1.24 to 1.58 (Tatsumi et al. 1989; Fitter and Stickland 1992; Eghball et al. 1993). In the present study, D was less than 1.4, similar to that calculated for the evergreen coniferous tree, *Pinus taeda* (Dieball and Feret 1993), indicative of a relatively simple root structure (Fitter and Stickland 1992). There was no significant difference between evergreen species and deciduous species when each pair of species was pooled. We are not aware of any other attempts to compare fractal patterns among leaf phenologies, despite the expectation that roots of deciduous trees, which avoid dry

season drought, would differ from those of evergreen trees, which transpire all year (Eamus et al. 2001).

ISR value

A higher ISR indicates shallower rooting (Van Noordwijk et al. 1995). In the present study there were no clear patterns of ISR, with all species showing similar values, except for the deciduous species *P. careya*, which exhibited a significantly smaller ISR than the other species (Table 4). Therefore, previous inferences about shallow rootedness based upon differences in leaf water status and stomatal behaviour in the dry season (Nepstad et al. 1994; Myers et al. 1997; 1998, O'Grady et al. 1999) appear to be incorrect. Rather, it is likely that differences in leaf water status and stomatal behaviour may reflect differences in root volume, root-length density, or hydraulic architecture (Eamus et al. 2000b) rather than depth of roots *per se* (see below).

In a recent large study of 6 species growing on two sites in Queensland, Hector (Hector, Pers Comm. University of Technology, Sydney) found clear differences in the ISR between sites differing in clay content, but not between species at a site. The index of shallow rootedness was much higher, indicating shallower rooting, for all taxa at the site with the most clay in the upper soil profile. However, different irrigation systems were used at the two sites and such differences have been shown to influence root distribution (El-Lakany and Mohamed 1993 <- *Not in ref list*). Interestingly, Hector (1999 ← *pers. comm. ?? Not in ref list*) was not able to discern differences in ISR for two provenances of *Acacia camaldulensis* or two provenances of *Eucalyptus intertexta* derived from relatively moist or relatively dry sites. This is indicative of either a low genetic component to the determination of ISR or a high degree of plasticity in the trait.

Here, we introduce another parameter to express root shallow rootedness. Rather than using the parameter ISR, we propose use of the ratio of the sum of horizontal root diameter squared to the total proximal root diameter squared ($\Sigma D_h^2 / \Sigma D_p^2$). We believe this ratio is a better reflection of shallow rootedness than the previously published ratio because it expresses the fraction of horizontal roots as a proportion of the whole root system that is attached to the trunk directly, rather than as a proportion of the trunk diameter. The ratio $\Sigma D_h^2 / D_p^2$ is more reliable than $\Sigma D_h^2 / D_{bh}^2$ as a measure of root shallowness because (1) whether the root system is mostly shallow or deep is best

measured using a measure based on total root diameter, not stem diameter; and (2) the ratio $\Sigma D_h^2 / D_{bh}^2$ provides no information on the vertical component of root distribution.

In the present study the ratios of (D_v^2 / D_p^2) for all four species were less than 0.5, indicating that the proportion of horizontal roots is less than that of vertical roots. As was observed for the ISR, no differences between species of different phenologies were observed, supporting the view that for the upper soil profile at least, evergreen and deciduous species do not differ in rooting characteristics.

Relationships among measures of stem and root size

Leonardo da Vinci claimed that the cross sectional area of the main stem is equal to the sum of the cross sectional areas of tree branches. A similar rule might apply to root systems if the root systems exhibit a fractal branching pattern (Van Noordwijk et al. 1994), as has been shown. In the present study, several important ideas emerged from the relationship between tree stem and proximal and horizontal root areas.

First, as the roots were confirmed to be a fractal branching system, the distribution of root size of a tree can be calculated based on the D_{bh} and the fractal parameters. Table 5 shows the results of a calculation of the total cross sectional area and root size distribution of a given tree. For the given tree with a D_{bh} of 5 cm, D_p^2 can be obtained based on the equation of D_p^2 and D_{bh} for each species. According to the ratio of $(\Sigma D_h^2 / \Sigma D_p^2)$, D_h^2 and D_v^2 were obtained. The cross sectional area of proximal roots was obtained from the equation: $(\pi \times D_p^2) / 4$, and the cross sectional area of root at any branching level was calculated based on the relation between cross sectional area of proximal root and α , ie. $[(\pi \times D_p^2) / 4] \times \alpha$. Because the α value is independent of root diameter at any root branching positions, the cross sectional area of root should be the same for any given root size. As a result, the number of roots at any special size (D_s) can be calculated based on the equation:

$$[(\pi \times D_p^2) / 4] \times \alpha / (\pi \times D_s^2) / 4 \text{ or } (D_p^2 \times \alpha) / D_s^2. \quad (4)$$

Second, the predicted cross sectional area of proximal root increased with increasing tree size and evergreen and deciduous trees show different ratios of proximal root cross sectional area to stem D_{bh} (Fig. 5). Thus, for a tree with D_{bh} of 10 cm (the median D_{bh} of the Humpty Doo site) the cross sectional area of proximal root was 257.99 cm² for *E. miniata*, 262.82 cm² for *E. tetradonta* (both evergreen) and 192.30 cm² for *T. ferdinandiana* and 111.73 cm² for *P. careya* (both deciduous). We conclude that evergreen species in the north Australian savanna maintain 2-3 times more root mass (assuming proximal cross sectional area is proportional to total root mass) than deciduous trees, at a given tree size, as measured by D_{bh} . This may account for differences in stomatal behaviour and leaf water relations observed in many studies (Myers et al. 1997; Prior et al. 1997 *a or b??*). It is interesting to note that at our sites, the total leaf biomass in the two evergreen species is similar to the leaf biomass in deciduous trees (Chen unpublished), at a similar D_{bh} and that this is supported by twice the mass of roots (if root mass is proportional to proximal cross sectional area). We propose that this difference in ratio of root mass to leaf area is because the evergreen trees transpire in the dry season at high rates (Eamus et al. 2000b) while deciduous trees lose their entire canopy and do not transpire at significant rates. This supports the view that it is dry season conditions that influence much of the behaviour of trees in these savannas (Eamus et al. 2000b).

In conclusion, in relation to our original hypotheses, we state the following. First, there were significant relationships among above and below-ground measures of biomass and these should be useful for estimating below-ground biomass from above-ground measures of tree size; second, roots of the Australian savanna tree species tested did show fractal properties; and finally, evergreen and deciduous tree species of Australian savannas did not differ in their depth distribution or index of shallow rootedness. This is inconsistent with the oft-presumed difference in root distribution of deciduous and evergreen trees.

Acknowledgments

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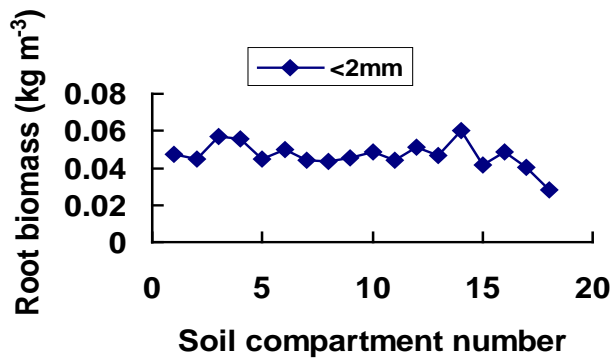
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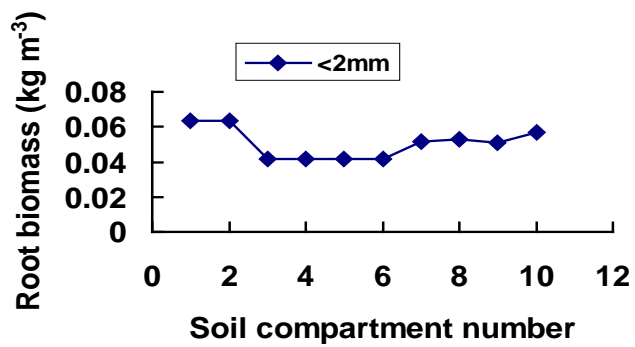
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Figures

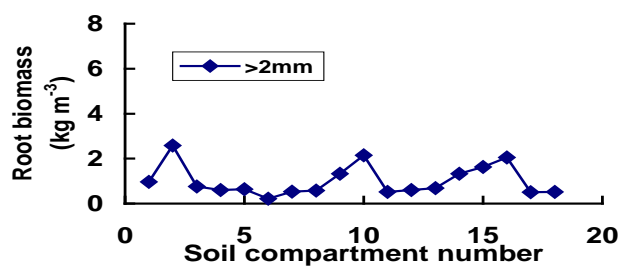
1a



1b



1c



1d

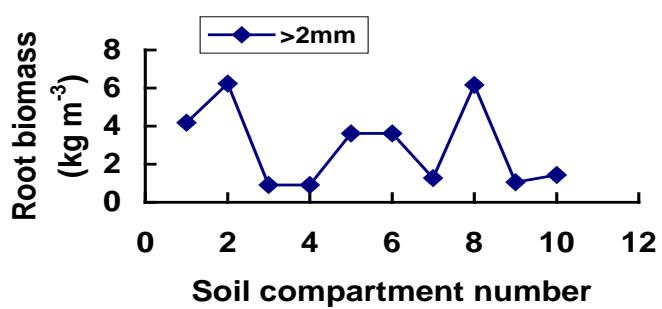
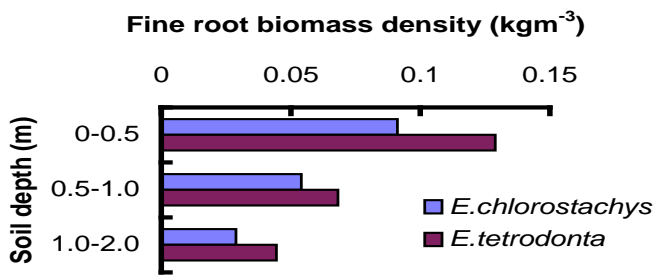


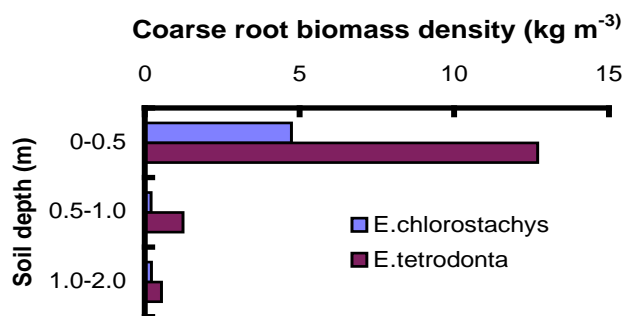
Fig. 1 (Previous page). Root biomass density for *Eucalyptus tetradonta* (1a; 1c) and *Erythrophleum chlorystachys* (1b, 1d) presented as fine (< 2 mm diameter) and coarse (>2 mm diameter) roots.

Soil compartment number refers to individual *ca* 0.5 m³ scoops of soil taken from the top 0.5m of the trench and therefore these data give some broad indication of horizontal distribution of roots in the upper soil profile.

2a



2b



2c

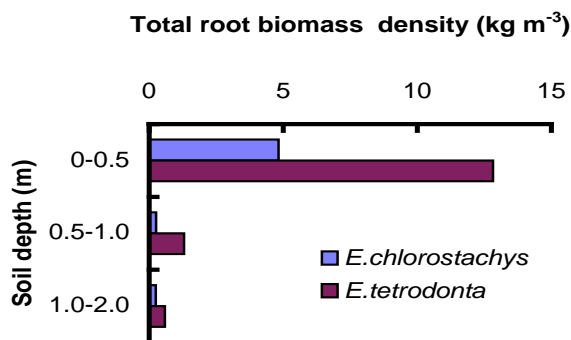
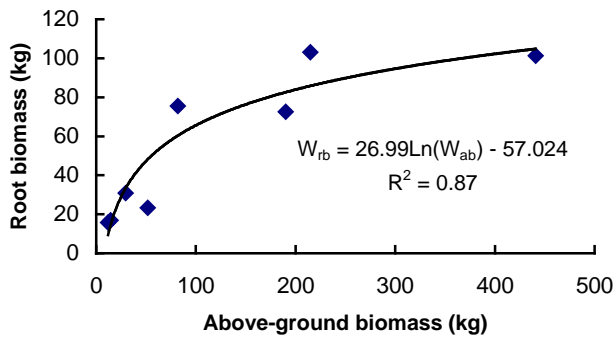
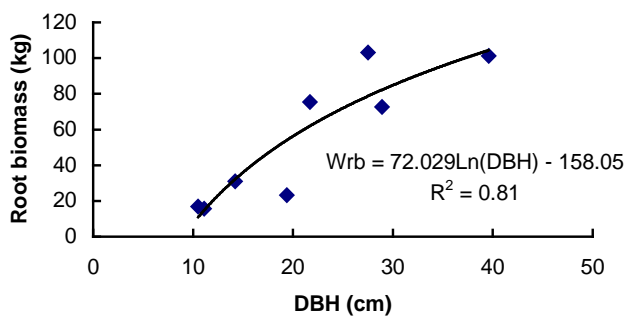


Fig. 2. Vertical distribution of root biomass density for fine root, coarse root and total root for two species of tree in an open *Eucalypt* forest of north Australia

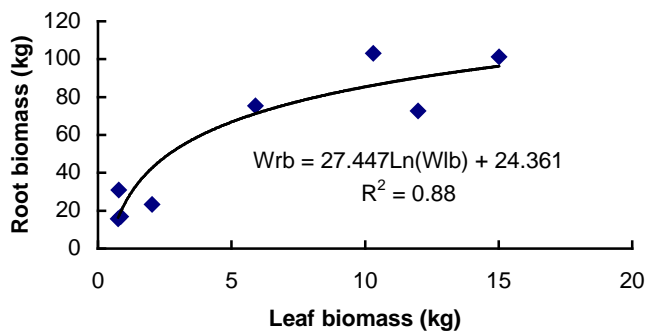
3a



3b



3c



3d

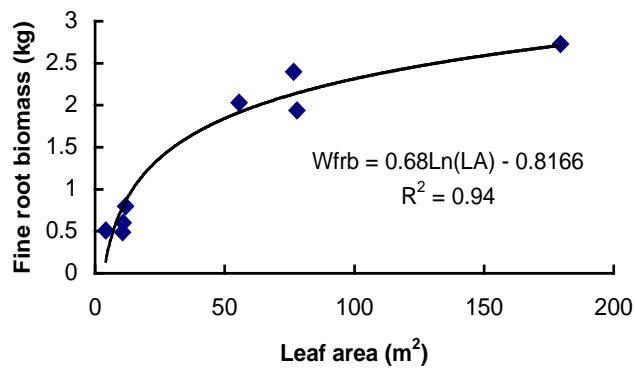
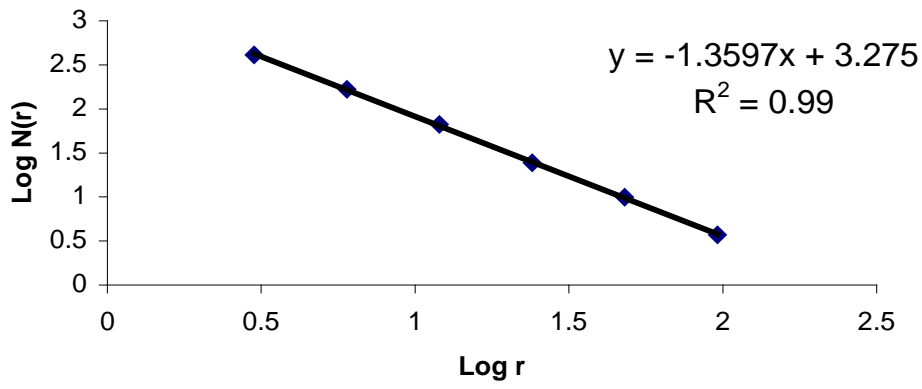
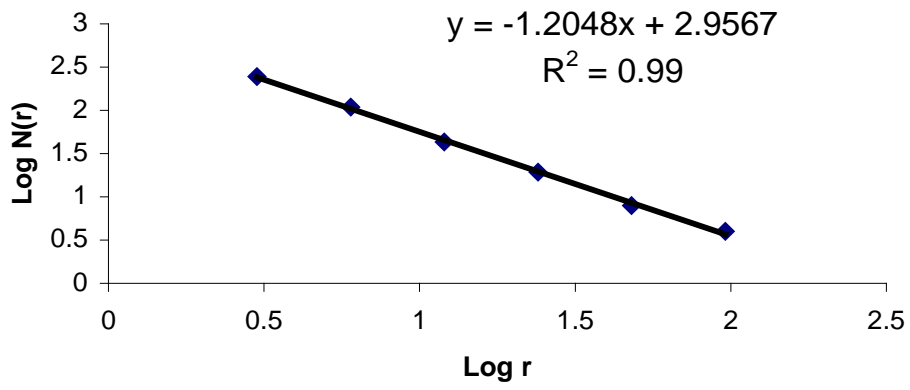


Fig. 3 Relationships between root biomass with above-ground biomass (a), DBH (b) and leaf biomass (c), and between fine root biomass and leaf area (d).

E.tetrodonta



E.miniata



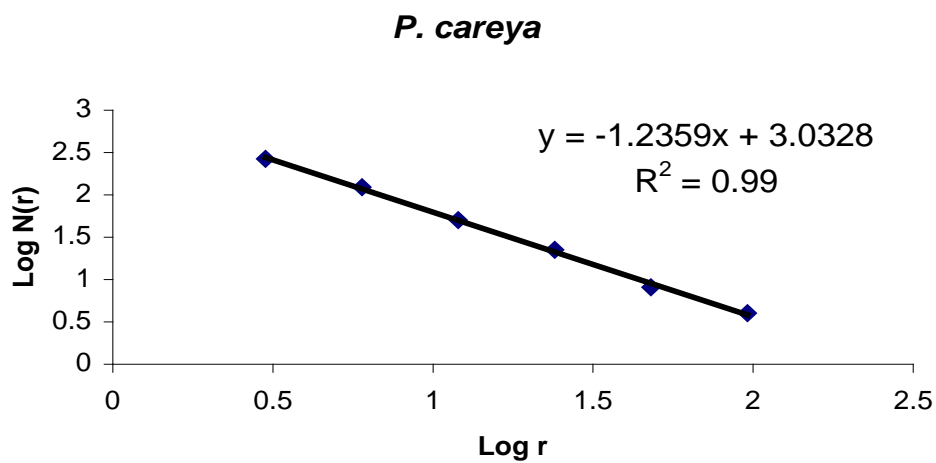
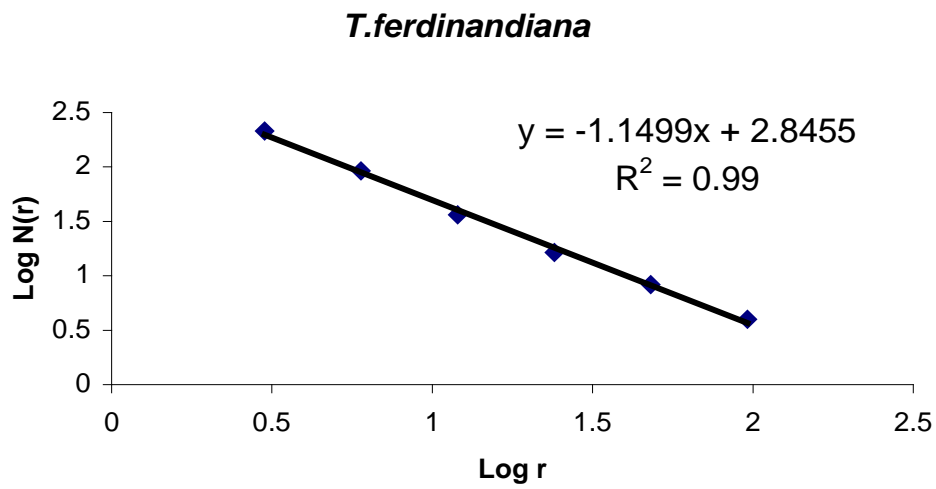


Figure 4. Relationships between Log r and Log N(r) for four north Australian savanna tree species. N(r) is the number of the squares that intersected the root, for each cell size, r.

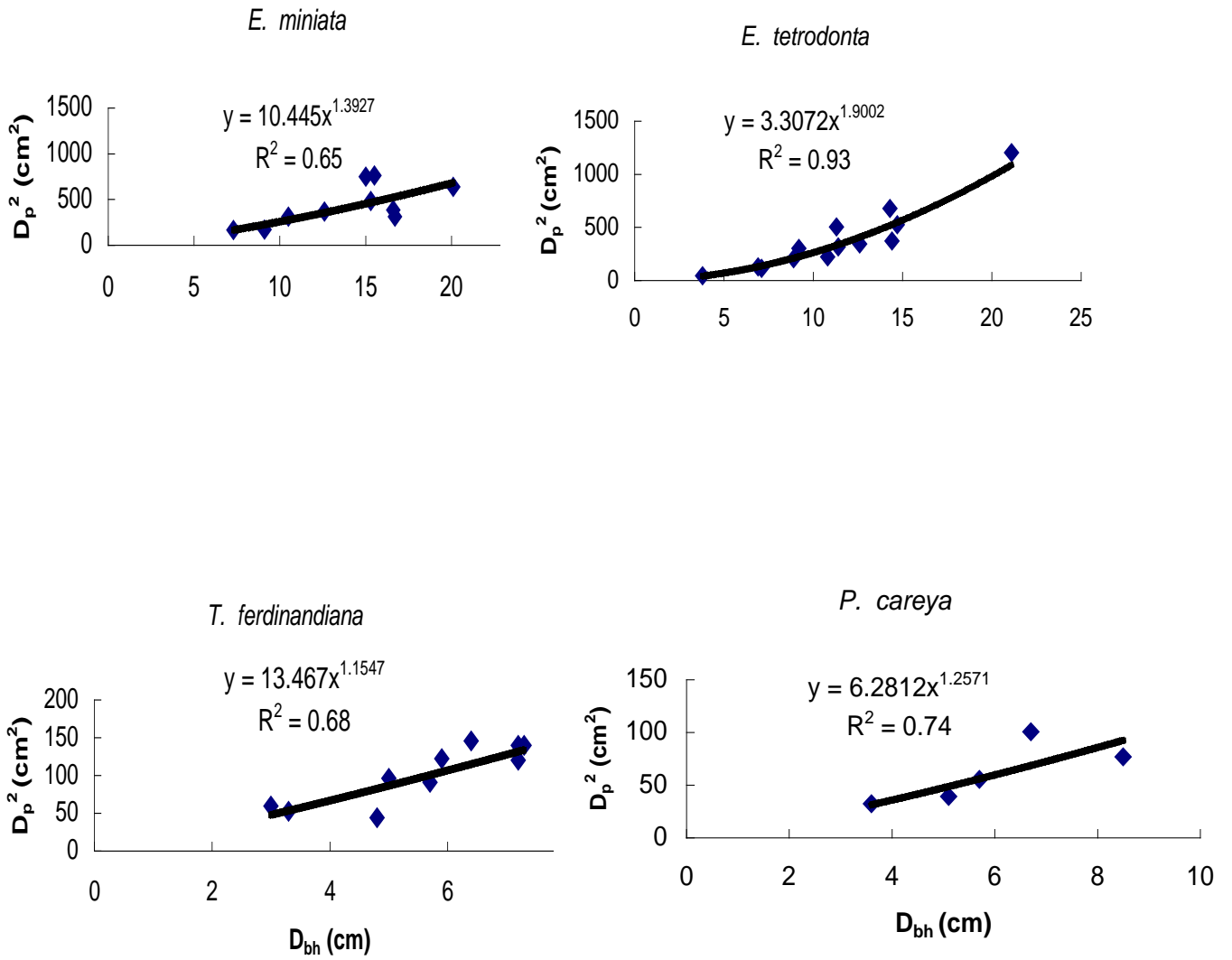


Figure 5. Relationships between diameter at breast height (D_{bh}) and proximal root diameter squared (D_p^2) of four savanna tree species.

Table 1. Below ground biomass of an open *Eucalyptus* forest in north Australia

Root biomass	<2 mm	>2 mm	Total
kg/eight trenches	11.50	439.19	450.69
kg m ⁻²	0.098	3.74	3.84
kg m ⁻³	0.065	2.48	2.54

Table 2. Fine (< 2 mm) and course (>2 mm) root biomass within each trench, expressed on a ground area and soil volume basis

Trench No	root biomass (kg/trench)			root biomass (kg/m ²)			root biomass density (kg/m ³)		
	<2 mm	>2 mm	Total	<2 mm	>2 mm	Total	<2 mm	>2 mm	Total
1	2.73	72.60	75.33	0.10	2.69	2.79	0.05	1.34	1.39
2	2.40	75.45	77.85	0.11	3.35	3.46	0.05	1.68	1.73
3	0.80	16.87	17.67	0.05	1.06	1.11	0.09	1.82	1.91
4	0.49	15.73	16.22	0.06	1.79	1.85	0.09	2.98	3.07
5	1.94	101.25	103.19	0.14	7.50	7.64	0.07	3.75	3.82
6	2.03	103.06	105.09	0.16	7.93	8.09	0.08	3.96	4.04
7	0.60	23.31	23.91	0.07	2.78	2.85	0.12	4.70	4.82
8	0.51	30.92	31.43	0.06	3.73	3.79	0.09	5.57	5.66

Table 3. Root biomass density in the upper (0-0.5 m) soil profile and tree diameter at breast height (D_{bh}) of the two species

Trench No	Species	D_{bh} cm	Root biomass density (kg m ⁻³)		
			<2 mm	>2 mm	Total
1.	<i>E. chlorostachys</i>	28.9	0.09	4.74	4.83
2.	<i>E. chlorostachys</i>	21.7	0.11	4.45	4.56
3.	<i>E. chlorostachys</i>	10.5	0.08	1.82	1.90
4.	<i>E. chlorostachys</i>	11.1	0.09	2.98	3.07
5.	<i>E. tetradonta</i>	39.6	0.13	12.69	12.83
6.	<i>E. tetradonta</i>	27.5	0.08	12.60	12.68
7.	<i>E. tetradonta</i>	19.4	0.12	4.70	4.82
8.	<i>E. tetradonta</i>	14.2	0.09	5.57	5.66

Table 4. Mean fractal dimension (D), proportionality constant (α) and index of shallow rootedness (ISR) for each species. Standard deviation of the mean is given in parenthesis. Means with the same letter in a column are not significantly different at $P=0.05$.

Species	D	α	ISR
<i>E. miniata</i>	1.21 (0.011) ^a	1.27 (0.26) ^a	0.97 (0.36) ^a
<i>E. tetradonta</i>	1.36 (0.03) ^{a,b}	1.11 (0.40) ^a	1.19 (1.14) ^a
<i>T. ferdinandiana</i>	1.15 (0.13) ^{a,c}	1.14 (0.41) ^a	1.34 (0.35) ^a
<i>P. careya</i>	1.24 (0.023) ^a	1.26 (0.38) ^a	0.33 (0.28) ^b

Table 5. Estimates of total cross sectional area and root diameter distribution for a hypothetical 5 cm or 10 cm D_{bh} tree of each of the four tree species studied.

	<i>E. miniata</i>	<i>E. tetradonta</i>	<i>T. ferdinandiana</i>	<i>P. careya</i>
D_{bh} (cm)	5	5	5	5
D_p^2 (cm ²)	98.26	70.41	86.37	46.75
D_h^2 (cm ²)	43.23	28.16	35.41	9.82
D_v^2 (cm ²)	55.03	42.25	50.96	36.93
D_p (cm)	9.9	8.4	9.3	6.8
csa of D_p (cm ²)	77.17	55.30	67.83	36.72
csa of D_r^* (cm ²)	98.31	61.55	77.60	46.08
Number of root (max.):				
≥ 1cm	125	78	99	59
≥ 0.1cm	12517	7837	9880	5867

	<i>E. miniata</i>	<i>E. tetradonta</i>	<i>T. ferdinandiana</i>	<i>P. careya</i>
D_{bh} (cm)	10	10	10	10
D_p^2 (cm ²)	257.99	262.82	192.30	111.73
D_h^2 (cm ²)	113.52	105.13	78.84	23.46
D_v^2 (cm ²)	144.47	157.69	113.46	88.27
D_p (cm)	16.1	16.2	13.9	10.6
csa of D_p (cm ²)	202.63	206.42	151.03	87.75
csa of D_r^* (cm ²)	258.15	229.75	172.78	110.13
Number of root (max.):				
≥ 5cm **	10	11	8	4
≥ 1cm	329	293	220	140
≥ 0.1cm	32869	29253	21999	14022

* These are roots that exclude the proximal roots.

** All are proximal roots.