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Root biomass distribution and soil properties of an open woodland on a duplex soil

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Abstract

Data on the distribution of root biomass are critical to understanding the ecophysiology of vegetation communities. This is particularly true when models are applied to describe ecohydrology and vegetation function. However, there is a paucity of such information across continental Australia. We quantified vertical and horizontal root biomass distribution in a woodland dominated by *Angophora bakeri* and *Eucalyptus sclerophylla* on the Cumberland Plains near Richmond, New South Wales. The site was characterised by a duplex (texture contrast) soil with the A horizon (to 70 cm) consisting of loamy sand and the B horizon (to > 10 m) consisting of sandy clay. The topsoil had a smaller bulk density, a smaller water holding capacity but a larger organic component and a larger hydraulic conductivity in comparison to the subsoil.

Root biomass was sampled to 1.5 m depth and declined through the soil profile. Whilst total biomass in the B horizon was relatively small, its contribution to the function of the trees was highly significant. Coarse roots accounted for approximately 82% of the root mass recovered. Lateral distribution of fine roots was generally even but coarse roots were more likely to occur closer to tree stems. Variation in tree diameter explained 75% of the variation in total below-ground biomass.

The trench method *suggested* the belowground biomass was 6.03 ± 1.21 kg m^{-2} but this method created *bias* towards sampling close to tree stems. We found that approximately 68% of root material was within a 2 m radius of tree stems and this made up 54% of the total number of samples but in reality, only approximately 5 to 10% of the site is within a 2 m radius of tree stems. Based on these proportions, our recalculated belowground biomass was 2.93± 0.08 kg m^{-2}. These measurements provide valuable data for modeling of ecosystem water use and productivity.

Key words: Below-ground biomass, root modeling, texture contrast soil

Introduction

Belowground biomass is a significant component of carbon stocks in terrestrial ecosystems and knowledge of root profiles is essential for measuring and predicting ecosystem dynamics and ecosystem function (Jackson et al., 1996, Mokany et al., 2006, Zeppel et al. 2008). Because measuring root biomass is labour-intensive and time consuming (Metcalfe et al., 2007), detailed studies of below-ground root biomass are sparse, especially for Australian woodlands. Of the 91 references included in the global analysis of root distributions by Jackson et al. (1996), only three pertained to Australia and two of those were for crops. Whilst there have been several reports of root biomass distribution in Australian woodlands since then (eg. Eamus et al., 2002, O'Grady et al. 2005, Barton and Montagu, 2006, Zerihun et al., 2006), the availability of data still remains limited.

The majority of previous root studies were undertaken with the aim of estimating carbon stocks, carbon turnover and characterisation of nutrient cycling (Barton and Montagu, 2006, Mokany et al., 2006, Zerihun et al. 2006), while little or no consideration was given to the influence of root biomass and distribution on uptake of water by vegetation (Guswa et al., 2004, Collins and Bras, 2007). Studies aiming to estimate carbon sequestration are generally focused on developing allometric relationships to estimate carbon stocks from measurements of diameter at breast height (DBH), stem volume and height (Montagu et al. 2005). These estimates are then extrapolated to regional-scales. In such studies and extrapolations, spatial (depth and lateral) distribution of root material is less important than the total biomass below ground (Barton and Montagu, 2006). In contrast, where studies involve modelling of ecohydrological processes such as vegetation water use, it is important to understand root

distribution in relation to soil properties, because this will influence a plant's ability to access and extract soil water (Chittleborough, 1992; Bréda et al., 1995, O'Grady et al., 2006).

Distributions of roots and water depend strongly on soil characteristics, including texture, porosity and hydraulic conductivity (Bréda et al., 1995). Sandy soils are generally associated with large soil pores, high hydraulic conductivity and hence better drainage than fine textured soils (Saxton et al., 1986, Berry et al. 2005, Saxton and Rawls, 2006). Furthermore, where there is a strong soil texture contrast between a topsoil and subsoil, there is a marked effect on soil hydrology and conditions for plant growth (Chittleborough, 1992). However, the relationships between vertical root profiles and soil properties in an Australian duplex (texture contrast) soil have not been investigated.

Analysis of lateral distribution of roots often indicates whether 'root closure' has occurred (Yanai et al., 2006). This is analogous to canopy closure where the soil profile becomes saturated with roots and the allocation of further biomass to the root system does not increase the uptake of water. Sampling of root material which considers lateral distribution of roots also provides information for determining whether an ecosystem should be sampled in a random or systematic fashion. Fine roots are *generally* homogenously distributed where water and nutrient distributions are not spatially patchy (Eamus et al., 2002, Resh et al., 2003); a random approach is therefore appropriate. In contrast, coarse roots are *generally* more abundant close to stems (Yanai et al., 2006) and their size tends to be proportional to that of stems (Eamus et al., 2002, Barton and Montagu, 2006), although exceptions to this may occur. This suggests that a systematic approach incorporating samples close to and further away from a range of stem sizes is most appropriate in many, but not all, ecosystems.

In this study, we collected the below-ground data required for a widely used soil-plant-atmosphere exchange model (Williams et al. 1996; Fisher et al. 2006; Zeppel et al., 2008).

From their modelling analyses Zeppel et al. (2008) proposed that, first, there must be extensive uptake of water from the deeper clay layers of the study site described herein; and second, the lateral distribution of roots was uniform. Consequently we test two hypotheses arising from this. First, these Cumberland Plains woodlands have significant fine root biomass in the B horizon; and second, root biomass is uniformly distributed in the A horizon. In addition to measuring root biomass distribution we also measured soil particle size, bulk density, soil water retention characteristics and unsaturated hydraulic conductivity as these are key inputs to the soil-plant atmosphere model (Zeppel et al. 2008).

Materials and methods

Study site

The study site was located in a remnant Cumberland Plains woodland, near Richmond in western Sydney, New South Wales, Australia (33^{o} 40'S, 150^{o} 47' E, elevation 40 m). Mean annual rainfall was approximately 800 mm and mean annual maximum temperature was 24 ˚C. The highest mean maximum temperature (29.6˚C) occurred in January and lowest mean maximum temperature (17.2˚C) occurred in July. Mean monthly rainfall was largest in February (105.6 mm) and smallest in July (35.9 mm) (Richmond RAAF, Australian Bureau of Meteorology). The landscape was gently undulating with low rises.

Soils consisted of a duplex profile derived from sandstone and clay with leached sands overlying a clayey zone, defined as a red chromosol in the Australian Soil Classification which is equivalent to Haplic Xerosol in the Food and Agriculture Organisation Classification. Fertility is generally low as soils are strongly acid with low nutrient status and deficient in N and P (Bannerman and Hazelton, 1990). The A horizon (up to 70 cm depth) ranged from sand to sandy loam, as the texture changed with depth. The A1 horizon was a greyish-brown sand, occurring in the upper 30 cm. The A2 horizon was a dull yellowish-

brown sandy loam. The soil consistency in the A horizon was single-grained and apedal. The B horizon was weakly pedal orange heavy clays and clayey sands (Bannerman and Hazelton, 1990). The vegetation at the site was dominated by *Angophora bakeri* E.C. Hall (Narrow-leaved Apple) and *Eucalyptus sclerophylla* (Blakely) L.A.S.Johnson & Blaxell (Scribbly Gum) with an average height of 14 m. These two dominant species account for approximately 80% of tree basal area at the site. Mean tree basal areas were 6.05 $\pm$ 2.33 m^2 ha^{-1} for *A. bakeri* and 32 $\pm$ 10 m^2 ha^{-1} for *E. sclerophylla*, and leaf area index measured with a digital method (MacFarlane et al., 2007, Fuentes et al., 2008) averaged 1.3 throughout the study period. The understorey was dominated by shrubs and grasses including *Pultenaea elliptica, Cryptandra amara* and *Melaleuca thymifolia.*

Measurements

Soil physical characteristics

Four trenches measuring 1.5 m wide and 1.5 m deep were constructed between two mature trees located 6.0 to 10.0 m apart using a backhoe. Trench #1 had an *E. sclerophylla* at either end and was 10 m long. Trench #2 had an *A. bakeri* at either end and was 6 m long. Trenches #3 and #4 were bound by one of each tree species; these two trenches were 6 and 7 m long, respectively (Table 1). The end walls of the trenches were dug directly below the trunks of the end trees and the soil was piled on one side of each trench. One long wall of each trench was carefully excavated to provide a clean-cut vertical wall for access to the soil profile. Three replicate soil samples (1000 cm^3) were collected at 10 cm vertical intervals down the profile to 1.5 m depth by pressing metal corers (10 cm diameter) into the face of the trench, these were then carefully dug out and placed in zip-lock plastic bags, which were then transported in cooler-boxes to the laboratory. These samples were collected from the middle of the trench to minimise root occurrence.

139 One set of samples from each sampling position was oven dried at 105˚C for 2 days to
140 determine bulk density. Core samples of a known volume were weighed after drying and bulk
141 density was expressed as the dry mass divided by the soil volume (g cm^{-3}).

142 Another set of samples was used to estimate clay and sand content by wet sieving with a 100
143 µm sieve after the samples were oven dried at 60°C for 2-3 days, following the procedure
144 described by Allen (1989). The portion of the sample remaining on the sieve was dried again
145 to obtain the sand fraction. The portion passing through the sieve was the clay fraction.

146 The last set of samples was used to determine total organic matter of the soil using the loss on
147 ignition technique in a blast furnace (Allen, 1989). Dried samples of a known mass were
148 combusted at 550 °C for five hours. The samples were weighed again and the lost portion
149 was the organic content while the remaining portion was the mineral content.

150 Saturated soil hydraulic conductivity was measured using a Guelph Constant Head
151 Permeameter (Soil Moisture Equipment Corp., CA, USA) *in situ* in the four trenches. These
152 measurements were made at two depths (approximately 50 and 70 cm) in the sandy A-
153 horizon and two depths (approximately 90 and 110 cm) in the clay B-horizon. We followed
154 the protocols described in the National Soil Survey Handbook (USDA, 1993).

155 The soil water characteristic ($\theta(\psi)$) was determined using 5 and 15 bar pressure chambers
156 located at the CSIRO sustainable ecosystems laboratory in Hobart, Tasmania. Replicate
157 samples were dried, ground and sieved (2 mm) before being soaked in 10% $CaCl_2$ for at least
158 24 h. Relative water content (RWC) was measured on soils equilibrated at 0.033, 0.1, 0.3, 0.5
159 and 1.5 MPa. Volumetric water content was calculated by multiplying RWC by bulk density
160 (Table 2). Soil water retention curves were analysed using the program RETC version 6, US

161 Soil Salinity laboratory (USDA, Ca, US). Retention curves were fitted using the van
162 Genuchten model (van Genuchten 1980):

163 $$S_e = \frac{1}{[1+(\alpha h)^n]^m}$$

164 Where S_e is the effective degree of saturation, also called the reduced water content, h is
165 suction (cm) and α, n and m are empirical constants affecting the shape of the retention
166 curve.

167 Soil saturated conductivity and water retention curve characteristics were compared to those
168 of Saxton and Rawls (2006) and those calculated with Soil Water Characteristics V. 6.02.70,
169 K. E. Saxton, USDA Agricultural Research Service, Washington (includes organic matter
170 component) using the appropriate texture classes for the A and B horizons.

171 *Root Biomass*

172 Root biomass was estimated in early July using the trench method (Komiyama et al., 1987,
173 Eamus et al. 2002). We used the four trenches described above from which we collected soil
174 cores at 10, 30, 50, 100 and 150 cm depths. These samples were collected by pushing in
175 metal corers of 10 cm diameter, 20 cm length, at distances of 50 cm apart from the reference
176 tree in the A-horizon, while in the B-horizon, samples were collected at intervals of 100 cm at
177 1.0 m depth and at 150 cm at 1.5 m depth. Clay samples were divided with a knife into pieces
178 no larger than 2 cm diameter. Due to heavy clay at 1.0 and 1.5 m depths the soil had to be
179 chiselled to obtain samples in a few cases. Where a large root could not be extracted with the
180 corer or shovel, a saw was used to remove the root at the appropriate points. These samples
181 were sealed in plastic bags and returned to the laboratory as described above. Root materials
182 were extracted from the soil samples by hand over a period of 30 minutes for each sample. A

183 previous study had established that 30 minutes represented a sufficient sample period to
184 account for approximately 90 % of the roots that could be observed by eye. Each sample was
185 spread on a tray and forceps were used to extract coarse and fine roots. The friable sandy soil
186 of the A horizon facilitated this process for the upper profile; for the clayey lower profile,
187 each sample of clay divided into separate pieces that were less than 2 cm in diameter and
188 close examination of the entire surface was undertaken to determine whether a root was
189 entering (or exiting) each small sub-sample. Where roots were observed at the surface a small
190 knife was used to extract the root, with a small amount of water added to assist in this
191 process. Roots that were recovered were then dried at 60 ^{o}C in paper bags for 48 h. Roots
192 were sorted into coarse (>2 mm diameter) and fine (<2 mm diameter) before weighing. A
193 total of 252 soil samples were collected during the root biomass survey. The four trenches
194 were more than 75 m apart and can be considered independent samples of each other and the
195 total area of each trench wall sampled for coring was approximately 13 % of the wall area.

196

197 *Data analyses*

198 The relationship between soil depth and root biomass was described with an exponential
199 function. The total root biomass in each trench was estimated by integrating the function to
200 find the area under the curve using SigmaPlot version 10 (Systat Software Inc. 2006). Linear
201 regression analysis was used to determine whether there was a relationship between DBH and
202 root biomass in each trench. Data conformed to a normal distribution of the residuals.

203 Root biomass contour plots were constructed using Statistica 6.0 (StatSoft Inc., Tulsa, OK.
204 USA; data not shown). Root distribution data from samples were analysed using the Spline
205 interpolation techniques considering all points measured per trench (n = 71).

206 **Results**

207 *Soil physical characteristics*

208 The soil had two distinct layers that are typical of duplex soils in Australia in which basic soil
209 properties were quite distinct (Table 2). The topsoil or A-horizon consisted of the upper 0.70
210 m is sandy with about 85% sand and 15% clay. This layer had a mean bulk density of 1.05 ±
211 0.11 g cm^{-3}, organic matter content of 7%, mineral content of 93% (Table 2) and saturated
212 soil hydraulic conductivity (K value) of 124.2 mm h^{-1} (Table 3). The subsoil that had higher
213 clay and mineral matter contents and bulk density, but lower K, than the top soil. The water
214 holding capacity of the subsoil was larger than that of the topsoil (Table 3). The water
215 holding capacity values predicted from the soil texture were approximately 11 and 8% for the
216 subsoil and topsoil respectively (Table 3). Soil water retention curves for each horizon are
217 shown in figure 1.

218 *Root biomass*

219 The mean total root biomass was 6 kg m^{-2} ground area for the four trenches with 82% of the
220 roots being coarse (Table 4). Distribution of root biomass also reflected the duplex nature of
221 the soil profile, with most of the roots associated with the soil with the larger K value (Fig.
222 2). The amount of coarse roots was highly spatially variable, particularly in trench 2 where
223 the standard error for the top 10 cm was almost 50% of the root biomass. Coarse root biomass
224 in the upper soil horizons were several magnitudes larger than in the subsoil in all the
225 trenches except Trench #3, where it was largely uniform throughout the soil profile. Trenches
226 #1 and #2 had similar coarse root profiles with biomass exceeding 10 kg m^{-3} in the topsoil,
227 while it was less than 8 kg m^{-3} in this layer for the other 2 trenches. Coarse root biomass
228 declined to less than 4 kg m^{-3} in the subsoil.

Fine root biomass was similar across the four trenches in the two layers of the soil profile (Fig. 2). Fine root biomass declined exponentially with depth (Figs 2 and 3) although the reduction in biomass was variable between trenches. Trench 3 had consistently more fine root biomass at any given depth than trenches 1, 2 or 4 (Fig. 3). Depth accounted for between 60 and 90% of the variation in root biomass through the soil profile (Fig. 3). The relationship between soil depth and total root biomass was strongest in trench 1 and weakest in trench 2 (Fig. 3).

Trenches 1, 2 and 4 had similar proportional distribution of root biomass through the vertical profile, with approximately 80% of the root biomass in the top 40 cm of the soil profile (Fig. 4). Trench 3 had only 50% of the root biomass in these top two layers and a greater proportion in the lower layers.

Using root biomass contour plots and analyses using the Spline interpolation techniques it was found that lateral root biomass distribution was highly variable through the soil profile in all trenches. For example, in trench 1, approximately 15% of root biomass was less than 1 m from the tree trunk at 10 cm depth, but this had increased to over 60% of the root biomass at 100 cm depth (data not shown). Coarse root biomass distribution was strongly related to distance from the tree trunk while fine root material was evenly distributed across the trench and fine root material was approximately evenly distributed in all four trenches. In contrast most of the coarse root material was found within 2 m from the tree stem in 3 of the 4 trenches. Total root biomass distribution was more heavily influenced by coarse roots than fine roots because the mass of the former was larger than that of the latter in all the samples.

The sum of the DBHs for each trench (Table 1) explained 75% of the variation in total root biomass in the trenches, 73 % of coarse root biomass and only 37% of variation in fine root

252 biomass (data not shown). Total below ground biomass was defined by the equation:

253

254 total measured root biomass = 0.62DBH – 19.72, $R^2 = 0.75$

255 This allometric equation should be treated with caution due to the similarity between the
256 summed DBHs for each trench and the low degree of replication of DBHs. This analysis also
257 assumes that the two trees at the end of each trench are the dominant source of the roots
258 found in the trenches. This assumption is most correct close to each tree but becomes
259 increasingly less true as distance from the trees increases. Furthermore the distribution of tree
260 size at the site has been influenced by fires so there was not a large range of tree sizes
261 available for this analysis.

262 **Discussion**

263 All methods used to estimate fine root biomass in soil are imperfect and laborious (Janos et
264 al. 2008). Trenching and coring are commonly applied methods (Jackson et al. 1996) and we
265 combined these methods by coring into exposed surfaces of trenches at different depths.
266 Extracting roots from small soil cores for 30 minutes was unlikely to have recovered all roots
267 from the samples. Consequently the estimates of root biomass are an under-estimate of the
268 actual biomass present. However, the error is likely to be small because the majority of the
269 roots were found in the friable upper sandy A horizon. Experience shows sampling of this
270 profile for 30 minutes would have accounted for approximately 90 % of the root biomass
271 (Eamus unpbl data). Furthermore the small volume of fine roots present in the lower B
272 horizon must mean that there was a small volume of fine roots which were missed. This
273 conforms to our experience in a structurally similar open woodland in northern Australia
274 which used the same protocol (Eamus et al. 2002). Finally, even if 50 % of the fine roots in

275 the B horizon were missed, this would have had a minimal impact on the total biomass
276 estimates given the fact that the largest proportion of biomass was present as coarse root
277 biomass. Metcalfe et al. (2007) predicted that total root extraction from their 18 samples (of
278 smaller volume than the core volumes we used) would take about 239 h. Consequently we
279 would be required to spend at least 3346 h to achieve a complete manual root extraction from
280 our 252 samples. We compromised on the amount of root material extracted from each
281 sample, which allowed us to process more samples and therefore get a better understanding
282 of vertical and horizontal variation in root biomass. Uncertainties arising from sampling
283 method were much smaller than uncertainties arising from spatial variation according to
284 Metcalfe et al. (2007). Using the temporal prediction method of Metcalfe et al. (2007), our
285 initial estimates of root biomass may have increased by up to 32% after the correction for
286 time limitation was made. Consequently the total root biomass for this site would increase
287 from 6 kg m^{-2} to between 7.3 and 8.0 kg m^{-2} (see below).

288 The sampling regime used in this study is biased towards ground area close to tree stems. Our
289 design allowed us to consider the relationship between below and above ground biomass, but
290 it weighted the sampling effort towards soil close to the tree stem, leading to an over-
291 estimate of below ground biomass across the site. The reason for this is because the area of
292 trench that was close to a tree stem was a larger proportion of the total area of trench than of
293 the total area of the study area. To account for this bias in the sampling we did the following.
294 First, we define ground lying closer than a 2 m radius as being "close to the stem" and ground
295 more than 2 m away from stem as being "far" away from a stem. This length was chosen as it
296 is more than double the maximum radius of any lignotuber we have observed. The area of a
297 circle, of radius 2 m, is 12.6 m^2. With a stem density of 63 stems per hectare, the total area
298 close to a tree stem is about 8 % of the total land area. However, the area of trench within

each 2 m radius was almost 16 % of the area of ground close to the stem so we sampled close to the stem at double the frequency required (16/8 = 2) to be representative. Similarly, we sampled ground further far from the stem at a frequency that was 42.2% of that required to correctly sample this area. When applying this weighting to the observed root biomass, the corrected total root biomass is 2.93 kg m^{-2} (Table 5). This recalculated value is much closer to the values reported by Eamus et al. (2002), Barton and Montagu (2006) and Zerihun et al. (2006) (see below) and highlights the importance of ensuring a sampling strategy that accounts for this source of lateral variability in root distribution.

Unsaturated hydraulic conductivity of soil generally decreased with increasing depth in the present study. Lower hydraulic conductivity below 70 cm was also influenced by the higher proportion of clay in the soil (Saxton et al., 1986, Saxton and Rawls, 2006). Increasing bulk density through the soil profile was also a function of depth and increasing clay component. In the present study, the decline in K and increase in bulk density through the soil profile was associated with a decline in root biomass. Trenches 1, 2 and 4 had between 93 and 97% of their root material in the top 50 cm of the profile while trench 3 had only 69% in the top 50 cm. Therefore, it is likely that high compaction at depth in the B horizon was limiting root exploration and restricting the bulk of the root biomass to the A horizon.

A concentration of the root biomass in the upper sandy soil would allow the plants to have ready access to soil water during moist periods (Berry et al., 2005) because plants growing on sandy soils have better water status (higher leaf water potentials) than those growing in heavy-textured soil (Xu and Li, 2008). However, when there are long rain-free periods, the A horizon will dry out, potentially leaving plants without a water supply and making them vulnerable to xylem cavitation. In contrast, a deep B horizon containing a significant amount of clay can become saturated during large rainfall events (Chittlebourough, 1992). Roots

within or very close to the B horizon can access this stored water by direct uptake or by uptake after hydraulic lift has occurred (Burgess et al., 2001). Thus, there are three potential processes which allow improved water supply during dry periods at this site: 1) roots can access water directly from the B horizon, which effectively acts as a large wet sponge; 2) the clay layer underlying the sand reduces the rate of deep percolation of water because of its reduced hydraulic conductance and larger capacity to store water, thereby increasing the duration of the presence of water in the upper profile ; and 3) roots can redistribute water (hydraulic lift) from the moist clay (or the interface of the two soil horizons) to rehydrate the upper soil profile. These processes are consistent with the conclusion of Zeppel et al. (2008) who found that tree water use at this site was independent of water content in the upper 70 cm of the soil profile, particularly during dry periods and the results of the present study confirm our hypothesis that fine roots are found within the clay layer and therefore contribute to the uptake of water for transpiration.

Corrected total root biomass (2.93 kg m^{-2}) in the present study was slightly larger than that reported by Barton and Montagu (2006) who recorded values of 1.7 to 2.7 kg m^{-2} for irrigated and non-irrigated components of a 10-year-old *E. camaldulensis* plantation. Our corrected values are slightly less than that of 3.84 kg m^{-2} recorded in a savanna of north Australia (Eamus et al. 2002) but comparable to those recorded in woodland communities of northeast Australia (2.4 to 3.6 kg m^{-2}; Zerihun et al. 2006). The fine root mass reported by Eamus et al. (2002) of 0.1 kg m^{-2} was one fifth the values observed in the present study. However, the present values were much smaller than the root biomass in *Banksia* scrub of more than 10 kg m^{-2} (Low and Lamont, 1990). The high root to shoot ratio of 2.35 in the *Banksia* scrub was due to a high proportion of below-ground resprouting organs (such as lignotubers), deep,

346 easily penetrated sandy soils and morphological adaptations to low water and nutrient
347 availability (Low and Lamont, 1990).

348 The sampling of roots in the present study occurred in July following an exceptionally wet
349 June (285 mm of rainfall). If root biomass in the upper profile is proportional to soil moisture
350 content, as has been observed is a eucalypt woodland that is structurally identical to the
351 present study (Janos et al. 2008), we would expect that the root biomass estimates we
352 obtained are close to a maximum value for this site, since soil moisture was at a maximum
353 and had been for 5 – 6 weeks. However, further seasonal studies would be required to
354 confirm this.

355 High root biomass in proportion to shoot biomass is known to be associated with low mean
356 annual precipitation (Mokany et al., 2006, Zerihun et al., 2006), and sandy soils (Mokany et
357 al., 2006). The below-ground biomass in the present study may be driven by both the
358 moderately low rainfall and high sand content of the A horizon. Using the allometric equation
359 of Williams et al. (2005), based on stem diameter at breast height and tree height, the
360 aboveground tree biomass at the present site is approximately 34 t ha^{-1} and the root to shoot
361 ratio is approximately 0.8 (using the corrected below-ground biomass). This value is similar
362 to that for the savanna vegetation category (Mokany et al. 2006). Because only the tree
363 component of above-ground biomass is included in this calculation but all of the roots
364 (including those of shrubs and grasses) are included in the below-ground biomass value, root
365 to shoot ratio is overestimated. In the present open woodland, approximately half of the LAI
366 is in the trees and half in the understorey (unpublished data). Therefore, the true root to shoot
367 ratio may be more like 0.6 but this value is still similar to the range found for dry, sandy sites
368 in Queensland (Zerihun et al. 2006).

Root biomass contour plots and analyses using the Spline interpolation techniques showed that lateral root biomass distribution was highly variable in all trenches. This was because the distribution of coarse root biomass, which is the largest fraction of total biomass, was strongly related to distance from the tree trunk. In contrast, fine root material was evenly distributed across the trench in all four trenches. Thus most of the coarse root material was found within 2 m of the stem. Thus, our hypothesis that roots are evenly distributed laterally was supported for fine root distribution but was not supported for course root distribution.

In conclusion, despite limitations inherent in all estimates of root biomass, the results of this study are significant because they show how the lateral distribution of roots is not uniform across a eucalypt woodland and they also show that the presence of significant amounts of roots in a deep clay layer may account for the lack of response of tree water use to the water content of the upper soil profile, as hypothesized by Zeppel et al. (2008). The best estimate of total root biomass through the soil profile at the site is 2.93 kg m^{-2} ground area. Coarse roots were strongly associated with distance from tree stems with most (54%) of biomass found within 2 m of stems. Fine roots distribution was predominantly confined to the top 30 cm of the soil profile and the lateral distribution of fine roots at this site suggests that root closure had occurred (Yanai et al. 2006). The presence of a small but significant fraction of roots in the deeper clay layer is an important feature of the ecohydrological functioning of this site and highlights the importance of incorporating these types of data into models of landscape function.

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485 **Tables and figure captions**

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489 Table 1: Description of trenches

Trench	Length (m)	Tree species at either end of trench	DBH of trees (cm)
1	10	*E. sclerophylla, E. sclerophylla*	24.7, 19.4
2	6	*A. bakeri, A. bakeri*	(15.7, 13.0)*, 14.9
3	6	*A. bakeri, E. sclerophylla*	19.4, 21.2
4	7	*E. sclerophylla, A. bakeri*	19.2, 17.7

490 * tree with two stems

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493 Table 2: Measured soil bulk density and texture of the A and B horizons. Values shown are
494 means and standard errors of means.

Variable	Topsoil (top 70 cm)	Subsoil (below 70 cm)
Bulk density (g cm^{-3})	1.05±0.11	1.56±0.05
Sand component (%)	85.3±1.6	47.7±2.0
Clay component (%)	14.7±1.6	52.3±2.0
Total organic matter (%)	6.6±0.5	1.6±0.6
Mineral matter (%)	93.4±0.5	98.4±0.6

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497 Table 3: Values for the soil water characteristic based on measured and predicted values
498 calculated from the soil texture values

Variable	Topsoil, loamy sand (top 70 cm)	Subsoil, sandy clay (below 70 cm)
Measured K (saturated hydraulic conductivity, mm h^{-1})	124.2±16.1	0.7
Predicted K (mm h^{-1}) based on texture classes*	96.7	1.4
Predicted WHC (%)*	7	11
Predicted field capacity (% v)*	12	36
Predicted wilting point (% v)*	5	25
Predicted K (mm h^{-1}) based on Soil Water Characteristics software package[#]	50.3	0.1
Predicted WHC (%)[#]	8.1	11.4
Predicted field capacity (% v)[#]	22.8	41.6
Predicted wilting point (% v)[#]	14.7	30.2

499 *Data from table 3, Saxton and Rawls (2006) (organic matter assumed to be 2.5%, no
500 salinity, gravel or density adjustment)

501 [#] Data calculated using Soil Water Characteristics V. 6.02.70, K. E. Saxton, USDA
502 Agricultural Research Service, Washington (includes organic matter component).

503

504 Table 4: Uncorrected root biomass in each trench. Corrected biomass estimates, taking into
505 account the sampling bias, are presented in Table 5

Trench	Uncorrected total biomass (kg m^{-2} ground area)	Uncorrected coarse root biomass (kg m^{-2} ground area)	Uncorrected fine root biomass (kg m^{-2} ground area)	Proportion of roots which are coarse (%)
1	6.49	5.45	1.04	84
2	9.13	8.13	1.00	89
3	5.04	3.93	1.11	78
4	3.44	2.58	0.86	75
Mean	6.03 ± 1.21	5.02 ± 1.19	1.00 ± 0.05	82 ± 3

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508 Table 5: Recalculation of root biomass according to distribution of roots within 2 m radius of
509 tree stems.

Trench	Corrected total biomass (kg m^{-2} ground area)	Corrected coarse root biomass (kg m^{-2} ground area)	Corrected fine root biomass (kg m^{-2} ground area)	Proportion of roots which are coarse (%)
1	3.15782	2.65179	0.50603	84
2	4.442357	3.95579	0.486567	89
3	2.452298	1.912208	0.540089	78
4	1.67379	1.255343	0.418448	75
Mean	2.93 ± 0.6	2.44 ± 0.54	0.4878 ± 0.024	82 ± 3

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Trench	Proportion of number of samples within 2 m of trees	Proportion of measured biomass within 2 m of trees	Range of recalculated root biomass using stem density of 63 stems ha^{-1} (kg m^{-2})
1	0.38	0.67	2.8-3.3
2	0.62	0.53	4.8-5.1
3	0.62	0.75	1.6-1.9
4	0.53	0.75	1.2-1.3
Mean	0.54	0.675	2.74 ± 0.08

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Figure captions

Figure 1: The soil water retention curves for 15 (a.) and 100 cm (b) depths. Curves were fitted using the van Genuchten model. The r^2 for fits are 0.992 and 0.998 for the 15 cm and 100 cm depths respectively.

Figure 2: Distribution of coarse (dark bar) and fine (light bar) root biomass through the soil profile for the four trenches. Error bars indicate standard error of the mean.

Figure 3: Distribution of total root biomass through the soil profile in each trench. The equation describing the curve is provided for each figure. All figures were best described by a second order polynomial except for the figure for trench 1 which was best described by a logarithmic equation.

Figure 4: Proportional root biomass distribution through the soil profile for each trench.

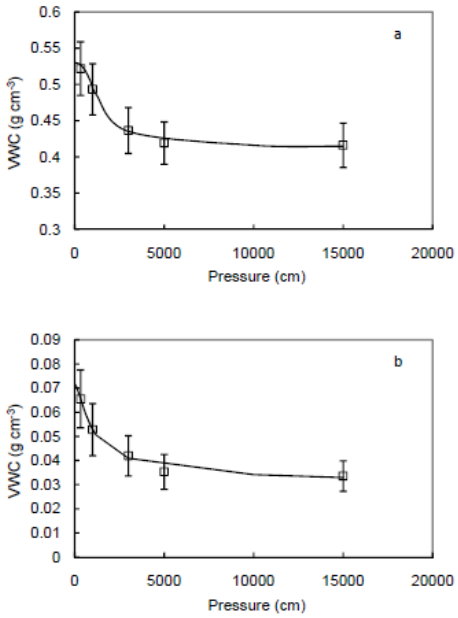

Figure 1: The soil water retention curves for 15 (a.) and 100 cm (b) depths. Curves were fitted using the van Genuchten model. The r^2 for fits are 0.992 and 0.998 for the 15 cm and 100 cm depths respectively.

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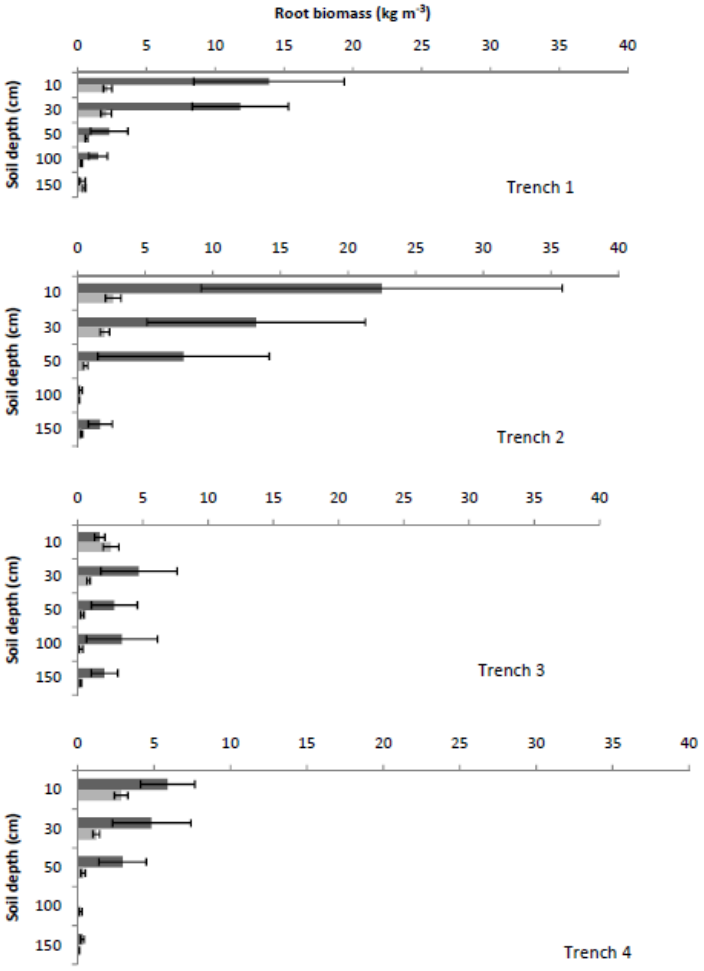

Figure 2: Distribution of coarse (dark bar) and fine (light bar) root biomass through the soil profile for the four trenches. Error bars indicate standard error of the mean.

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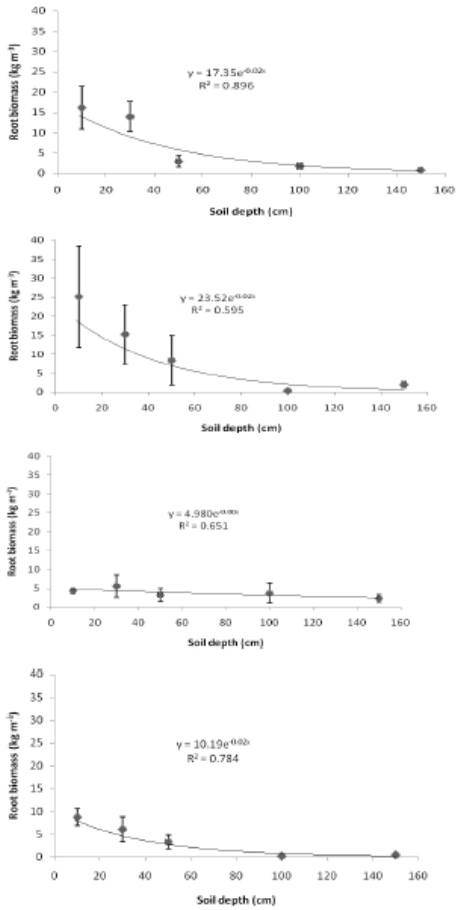

Figure 3: Distribution of total root biomass through the soil profile in each trench (trenches 1 to 4, top to bottom). The equation describing the curve is provided for each figure. All figures were best described by a second order polynomial except for the figure for trench 1 which was best described by a logarithmic equation.

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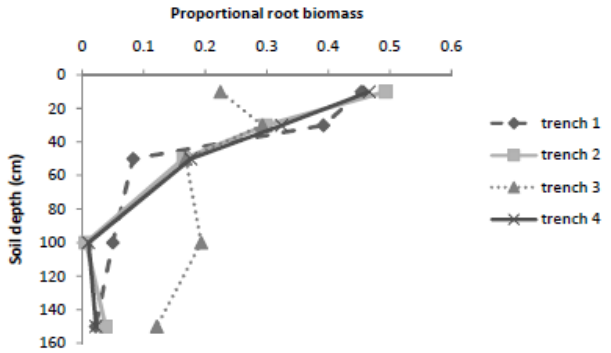

Figure 4: Proportional root biomass distribution through the soil profile for each trench.

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