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Fine root biomass and its relationship to evapotranspiration in woody and grassy vegetation covers for ecological restoration of waste storage and mining landscapes

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ABSTRACT

Production and distribution of fine roots (≤ 2.0 mm diameter) are central to below-ground ecological processes. This is especially true where vegetation serves as a pump to prevent saturation of soil and possible drainage of excess water into or from potentially toxic waste material stored underground or in mounds aboveground. In this study undertaken near

Sydney in Australia, we determined fine root biomass and evapotranspiration (ET) on a waste disposal site restored with either a 15-year old grass sward or plantations of mixed woody species that was either five years old (plantation-5) with a vigorous groundcover of pasture legumes and grasses, or three years old (plantation-3) with sparse groundcover. These sites were compared with nearby remnant woodland; all four were located within 0.5 km radius at the same site. (you have already said this).

Ranking of fine root biomass was in the order woodland (12.3 Mg ha^{-1}) > plantation-5 (8.3 Mg ha^{-1}) > grass (4.9 Mg ha^{-1}) > plantation-3 (1.2 Mg ha^{-1}) and was not correlated with nutrient contents in soil or plant, but reflected the form and age of the vegetation covers. Trends in root length density (RLD) and root area index (RAI) followed those in root biomass, but the differences in RAI were larger than those in biomass amongst the vegetation covers. Annual ET in the dry year of 2009 was similar in the three woody vegetation covers (652 – 683 mm) and was at least 15% larger than for the grass (555 mm), which experienced poor growth in winter and periodic mowing. This resulted in drainage from the grass cover but there was no drainage from any of the woody vegetation covers. In plantation-5, root biomass, RAI and RLD were reduced in the rain shadow side of the tree rows. Similarly the amount and depth of rooting in the groundcover were reduced close to the trees compared to midway between rows.

Differences in the root variables were larger than those in ET, which suggested a presence of substantial amounts of necromass and/or that more roots were produced than were needed for water uptake. We conclude that vegetation covers, such as plantation-5 consisting of widely spaced trees and a heavy groundcover containing winter-active pasture legumes, will promote year-round water-use with a reduced risk of deep rooting that could breach buried wastes. This function could be sustained through progressive thinning of trees to account for not more than 25% of the whole canopy cover; this will minimise competition for limited soil-water and thereby constrain deep rooting as vegetation ages and attains climax.

Keywords: drainage, ecological restoration, evapotranspiration, land degradation, root area index, root biomass, root length density, waste disposal

INTRODUCTION

Clearance of land and its ecosystems is a major consequence of land-use for waste disposal and mining activities. Rehabilitation of such lands often aims to restore pre-clearance ecosystem services through revegetation using plant species similar to those removed (Grant and others 2002, Weir and others 2006). This basically involves isolation of the often hazardous wastes by emplacement underground or in mounds above which a soil profile is reconstructed that is deep enough to support plant establishment and growth. The reconstructed soil profile serves as the reservoir of rain water, preventing drainage into the emplaced wastes below, while supplying water for evapotransipration (ET) by the planted vegetation. This dual function of storing water, to prevent deep drainage, and releasing it to the vegetation for ET is why these remediation structures are termed store-release covers (SRC). Efficacy of SRCs thus relies on ET being maintained at rates that prevent saturation of the reconstructed soil profile.

Survival of the planted species, and sustenance of ET, is reliant on the adaptation of the root system to both immutable and transient properties of the reconstructed soil profile. For example, increases in the bulk density of the reconstructed soil compared to that of the undisturbed soil can reduce root length and rooting depth in the soil-cover (Bending and Moffat 1999, Weir and others 2006). Shallow roots reduce the potential soil volume that can be explored by the vegetation and is therefore undesirable where rainfall is seasonal with extended dry periods (Gwenzi and others 2011). Excessively deep roots can, however, be disadvantageous if there is a risk of creating preferential flow-paths for water (Yunusa and others 2002) into the wastes and potentially leaching into an underlying aquifer. This risk can be minimised using shallow rooting herbaceous species such as grasses, but their low water-use due to poor growth during cold and wet winters in temperate environments may cause saturation of the soil with the excess water draining into the waste. The challenge then, is to design vegetation mixes that optimise the beneficial features of deep-rooting perennial woody species with those of shallow-rooting herbaceous species, such as grasses.

Understanding the characteristics and behaviour of roots in different vegetation types due to changes in soil properties has received limited attention. In addition to providing anchorage for the plant and being a carbon store, roots are central to all edaphic ecological functions provided by the vegetation. The majority of these functions are performed by fine roots (those having diameters of ≤ 2.0 mm) that are the sites for uptake of water and nutrients, which sustain canopy processes and growth. Amounts and distribution of fine roots tend to reflect the patterns of soil-water extraction by the vegetation (Oliveira and others 1999), while strong correlations have been reported between leaf area index (LAI) and fine root area index (RAI), i.e. the total surface areas of fine roots produced per unit land area (Al Afas and others 2008).

Fine roots are dynamic and highly sensitive to transient soil and weather conditions in addition to plant phenology. In temperate environments, more roots are produced during the warm and moist spring than in winter (Farrish 1991, Hendrick and Pregitzer 1993, Tufekcioglu and others 1999). This difference can be up to a factor of two in natural and plantation forests (Yang and others 2004), and arise from a prolific root production during spring to mid-summer before the onset of root mortality in late summer through winter

(Hendrick and Pregitzer 1993). Root growth and distribution are also sensitive to the chemical, textural, structural and hydrologic properties of the soil (Gower 1987, Weir and others 2006). In environments that experience periods of limited water supply, deep and widely spreading roots confer significant adaptive advantage (Casper and Jackson 1997). Deep root systems maximise the soil volume that can be potentially explored for limited resources, and have been associated with the capacity to maintain high leaf water potentials, in response to declining soil water availability, and avoid desiccation (Bucci and others 2009). Deep roots are therefore critical to perennial species in environments with seasonal rainfall. A previous study (Schenk and Jackson 2002) showed that the depth and lateral spread of roots differ widely according to life- form and span of the species, such that root systems are smaller in grasses than in shrubs and largest in trees. Also, plants in dry environments tend to increase biomass allocation to roots that are deeply distributed in soil to enhance exploration for water (Markesteijn and Poorter 2009).

In this study we determined production and distribution of fine root biomass and soil water content in three vegetation covers, consisting of 5- and 3-year old plantations of mixed woody species and a 15-year old grass sward, established over a waste disposal site. These were compared with those in nearby remnant woodland as a surrogate of pre-clearance vegetation cover. Our objectives were to (1) characterise fine root biomass, root length density and root area index; and (2) determine how these correlate with annual water-use by the three restored vegetation covers relative to that by the remnant woodland.

MATERIALS AND METHODS

THE SITE

This study was conducted in 2009 at a waste management site near Castlereagh (33° 39' 41" S, 150° 46' 57" E), about 65 km northwest of Sydney, Australia. The region has a sub-humid temperate climate with mild winters (June –August) having a mean daily temperature of 12.4 ^{o}C and warm summers (December –February) when daily temperature averages 23.0 ^{o}C. Mean annual rainfall (1900 –2007) is 810 mm with a monthly average of 65 mm and a slight peak in summer to early autumn (December – March) when monthly rainfall can exceed 80 mm; annual evaporation averages 1250 mm. In the four years preceding this study, the annual rainfall had been below average, except in 2008 when 839 mm of rain fell.

The soil at the site is a red Chromosol, which is equivalent to Haplic Xerosol (FAO 1974). It has a duplex profile of a loamy sand topsoil of 0.7 m thick overlaying a deep (> 10 m) sub-soil of dense impermeable Londonderry clay (Itakura and others 2005). Waste cells of 5 m deep trenches were constructed in the clay subsoil. Individual cells were 20 m long and 5 m wide and spaced 2 m apart in every direction resulting in approximately 65 cells/ha. Once filled, the cells were capped by returning the soil in the reverse order of their removal to form a profile of 2 m over the cells. Further details of the cell construction and rebuilding of the soil profile have been reported (Itakura and others 2005, Yunusa and others 2010). The caps were then planted with a mixture of Australian native woody species or grass. For the current study, three types of vegetation covers were compared with nearby remnant woodland, and all were within 500 m of each other (Yunusa and others 2010). These are described briefly here as follows:

Woodland: This was dominated by trees of *Eucalyptus parramattensis* and *Angophora bakeri* and an understorey of grasses and shrubs of *Pultenaceae eliptica, Cryptandra amara,* and *Melaleuca thymifolia*. The stand density for these dominant overstorey species varied widely, but averaged 86 stems/ha with an average height of about 14 m (Zeppel et al., 2008); mean stand density for all the woody species was 560 ± 32 stems ha-^{1} (Table 1).

Grass: This covered approximately 12 ha and was planted in spring (September-October) of 1994 with a mixture of seeds of *Cynodon dactylon* (couch), *Axonopus affinis* (carpet grass), *Paspalum dilatatum* (paspalum), *Pennisetum clandestinum* (kikuyu grass), and *Trifolium repens* (white clover) at a combined seeding rate of 90 kg ha^{-1}. The sward was mowed twice annually usually in mid-autumn (March-April) and spring (September – October).

Plantation-5: This consisted of a 9 ha plantation of mixed woody species planted in April-May 2004, and was five years old in September 2009. It contained a mixture of tree species (*Eucalyptus* spp, *Angophora spp*, *Casuarina glauca*, *Melaleuca linariifolia* and *Syncarpia glommulifera*) and shrubs (*Acacia*, *Callistemon*, *Gravillea*, *Hakea*, *Kunzea* and *Leptospermum*) planted in 5-m rows in northeast–southwest direction. The combined tree and woody shrub density was approximately 1050 stems ha^{-1}; this had fallen by 33% at the time of the current study due to mortality (Table 1). A groundcover of grasses [*Cynodon dactylon* (couch), *Axonopus affinis* (carpet grass), *Paspalum dilatatum* (paspalum), *Pennisetum clandestinum* (kikuyu grass)] and pasture legumes [*Trifolium repens* (white clover)] was planted at the same time. These trees were irrigated when required in the first year. The groundcover was mowed at the same times as the main grass pasture block.

Plantation-3: This was a 0.25 ha block containing six (15 x 15 m) plots that was planted in 2006 with the same tree species and at the same planting configuration and density as Plantation-5. Tree mortality was larger (45%) here, because unlike plantation-5 it was not irrigated after planting and hence stand density was just 566 stems/ha at sampling in 2009 (Table 1). It lacked sown groundcover, except for the uncontrolled broadleaved and grassy weeds. In January 2009 approximately 4 Mg ha^{-1} of compost was applied to the soil surface resulting in rapid tree growth and an almost complete canopy cover at the time of sampling.

SOIL SAMPLING

This was undertaken in September 2009 by extracting intact soil cores of 50 mm diameter to a depth of 2.0 m using a ProLine hydraulic corer mounted on a truck. Four cores were extracted from each of the woodland, grass and plantation-3. The four samples were taken at distances of about 50 m apart in the grass, from the middle of the selected four plots in plantation-3. The four cores in the woodland were separated by distances of at least 40 m and taken approximately 1.0 m from the butt of trees or base of shrub clumps that were randomly selected. In Plantation-5, four sets of samples were taken from each of four locations as follows:

Intra-row: within the tree row, approximately 1 m from the nominated tree
West: 1 m west of the tree row
East: 1 m east of the tree row
Inter-row: mid-way between adjacent tree rows, i.e. from within the groundcover.

All the cores were extracted near pre-installed aluminium access tubes used for monitoring soil-water with a neutron probe. The extracted soil cores were sectioned into depth intervals and quickly placed in plastic bags and kept in insulated storage boxes and transported for storage at a temperature of 4 ^{o}C in the laboratory. A second set of soil samples was collected from the top 0.3 m and used for chemical analysis.

MEASUREMENTS AND ANALYSES

Bulk density and soil-water content: These were made on the intact soil samples by weighing them fresh and again after drying at 80 ^{o}C for 48 hours.

Root mass and length density: these were measured on the root materials extracted from the soil cores by soaking and sieving. The recovered roots were then dried at 60 ^{o}C for 48 hours and then weighed; we made no attempt to separate out the dead roots (necromass). The samples were rehydrated for 24 hours and used to estimate lengths, diameters and surface areas using WinRhizo® (Regent Instruments, Quebec, Canada).

Soil analysis: a portion was taken from each of the second set of soil samples and dried at 60 ^{o}C for 48 hours. These were then ground to pass through a 20 μm sieve and were used to determine pH and electrical conductivity (in 1:5 water mixture), total C and N using the furnace method (LECO®, St. Joseph, MI, USA). Subsamples were taken to determine particle-size distribution using a hydrometer method (Gee and Bauder 1979). Data on soil texture were used to approximate water content limits at field capacity and permanent wilting points (Saxton and Rawls 2006).

Shoot characteristics: leaf area index (LAI) was estimated in September 2009 as described previously (Yunusa and others 2011); we used a combination of a photographic technique (Fuentes and others 2008) and remote sensing data from MODIS (Palmer and others 2008). Foliage samples were taken from representatives of each of the species at locations near where soil cores were taken on each block. These were dried and analysed for their carbon and nitrogen contents following the same procedures as for the soils.

Soil-water content (θ): pre-installed access aluminium tubes were monitored monthly with a neutron probe to 5.0 m depth in 2009. These data were used to determine total water stored in the soil profile and were used along with rainfall data to implement soil-water balance in quantifying evapotranspiration (ET), drainage and runoff as reported recently (Yunusa and others 2010). Reference ET was calculated using Penman-Monteith approach (Monteith and Unsworth, 1990).

DATA ANALYSES

Measurements from the four vegetation covers can be considered as independent with each having its own random variation arising from differences in the composition and ages of plant species, and also number of cores taken. The means for selected root variables and ET in the restored vegetation covers were therefore compared to those in the woodland that served as the control by computing the effect size (*d*) for the three revegetation strategies following Gurevitch and Hedges (Gurevitch and Hedges 1993):

$$d = \frac{\bar{X}_r - \bar{X}_w}{\sigma_{pooled}} j \qquad (1)$$

in which $\overline{X_r}$ and $\overline{X_w}$ are the respective mean values for the revegetated blocks (grass or plantation-5 or plantation-3) and the woodland,□σ_{pooled} the standard deviation for the pooled data for all the four vegetation covers, and *j* corrects for the bias due to differences in sample sizes amongst the vegetation covers and was determined based on the number of replicates (*N*) following Miller and others (2010):

$$j = 1 - \frac{3}{4(N_r + N_w - 2) - 1} \qquad (2)$$

Data for the other variables were compared amongst the vegetation covers using their standard errors of means.

RESULTS

PHYSICAL PROPERTIES AND WATER CONTENT OF SOIL

Restoration altered the texture and reduced the depth of the topsoil (Table 1) in the plantations and grass, largely because of inability to fully recover all the original coarse loamy particles; this, along with introduction of materials from the subsoil, increased fine particle content in the topsoil of the restored vegetation compared with the remnant woodland. The topsoil in the woodland had higher total C, but substantially lower water-holding capacity, phosphorus, cation exchange capacity (CEC) and electrical conductivity (EC), than the restored vegetation covers. The textural and structural properties of the subsoil were similar in all of the four vegetation covers, except for the water holding capacity, which was lower in the woodland, where a smaller volume of the subsoil was monitored, than in the rehabilitated blocks. Increases in the bulk density under the restored vegetation covers were marginal both in the topsoil and subsoil.

The woodland extracted almost all the available water in the 2 m soil profile by drying it to its nominal wilting point (Figure 1). By contrast, the restored covers dried out only the top 0.6 m of the soil, especially in plantation-3 but less so in plantation-5. Only plantation-5 amongst the restored vegetation covers extracted water throughout the 2 m soil profile, while θ increased significantly below 0.5 m depth reaching field capacity below 1.0 m depth in plantation-3 and grass. Average water content for the whole profile was in the order: grass (0.27 ± 0.01 m^3 m^{-3}) > plantation-3 (0.24 ± 0.02 m^3 m^{-3}) > plantation-5 (0.22 ± 0.01 m^3 m^{-3}) > woodland (0.17 ± 0.02 m^3 m^{-3}).

ROOT BIOMASS AND ROOT DIMENSIONS

Root biomass declined exponentially with depth in all the three restored sites (Figure 2a), but in the woodland it increased with depth in the top three layers before progressively declining in the lower layers. Except in the top 0.1 m layer, where plantation-5 had the most roots, root biomass was mostly in the order woodland > planation-5 > grass ≈ plantation-3. Only woodland produced fine roots below 1.6 m depth and its total fine root biomass (12.3 Mg ha^{-1}) was 48 % larger than in plantation-5, but was several factors larger than in the grass (4.9 Mg ha^{-1}) and plantation-3 (1.2 Mg ha^{-1}). More roots (~30%) were partitioned in topsoil by grass and plantation-5 compared with 21% in plantation-3 and 15% in the woodland.

Differences in the root area index (RAI) amongst the vegetation covers were strongest in the top 0.6 m of the soil profile (Figure 2b), but generally followed the pattern shown by the root biomass. Total RAI under the woodland was 21% larger than under plantation-5, but was twice that under grass and five times that under plantation-3.

The roots were thicker, but not necessarily longer, under the woodland than under any of the other three vegetation covers (Table 2). The root length density (RLD) was higher in plantation-5 than in any of the other vegetation covers, while differences in root diameter and RLD were more pronounced in the topsoil than in subsoil amongst the vegetation covers.

DISTRIBUTION OF ROOT BIOMASS AND ITS VARIABLES IN PLANTATION-5

Root biomass and other root variables were strongly related to sampling position in plantation-5, especially in the 0.1-0.6 m soil layer in which the west of the tree row contained smaller amounts of roots than the other three positions (Figure 3a). Below 0.6 m depth, there were no differences in the root biomass between the four cardinal positions, except that no roots were found below 1.6 m in the groundcover. Except to the west of the row, more roots were produced in total close to the trees than in the groundcover (Figure 3a). Spatial differences in the RAI were confined to the 0.1 – 0.6 m layers, in which RAI for the three positions proximate to the tree was larger than in the groundcover (Figure 3b). Differences in RAI between positions were not well defined below 0.6 m depth. For the whole profile, RAI was highest beneath the tree rows and lowest to the immediate west of the rows. Root diameter increased, while RLD fell, at positions further from the tree rows with the soil being more compacted under the groundcover than around the trees, where the soil was drier (Table 3).

RELATIONSHIPS AMONGST ROOT AND SOIL PROPERTIES

Both the bulk density and soil water content were individually negatively correlated with root biomass, RLD and RSA (Table 4). Root biomass was correlated with RLD and root surface area, but not with root diameter. These data were used to develop regressions that can be used to approximate stand-scale RLD and RAI from the root biomass (Table 5). All the regressions were highly significant ($p < 0.01$, n = 262). There was no significant correlation between ET with either root biomass (r = 0.78) or RLD (0.59) or RAI (0.83).

WATER-USE AND EFFECT SIZE

Runoff was negligible in this dry year of 2009 and so the soil-water water balance was dominated by ET, which was marginally lower in the grass than in the woodland in summer and winter. During these seasons the two plantations maintained parity with the woodland in their ET. In spring only plantation-3 maintained parity in ET with the woodland (Table 6). Annual ET for the woodland was only marginally (< 5%) larger than for either plantation-5 or plantation-3, but 23% larger than for the grass. Drainage occurred only in the grass and not in the other vegetation covers. The annual ET for the woodland and the two plantations was within 2% of the 640 mm rainfall, while it was 13% below the rainfall in the grass. It was also well below reference ET especially in the grass.

Effect size (d) was negative for responses in the key variables of root biomass, RAI and ET (Figure 4). The d for ET in the woodland (control cover) lies within the 95% confidence interval of d for each of the three restored vegetation covers (Figure 4c).

DISCUSSION

DIFFERENCES IN FINE ROOT BIOMASS

Differences in the fine root biomass primarily reflected the life-form and age of the vegetation covers. The presence of woody species increased root biomass (Figure 2) so that within five years plantation-5 attained 67% the amount of roots in the woodland, which was well above the 40% attained by the grass after 15 years. Information is limited on comparative root biomass production by grass and woody species in the same environment, but grasses are reported to produce as little as about a quarter of roots produced by trees (Mordelet and others 1997, Schenk and Jackson 2002). Reductions in root production in the grass was expected due to mowing, as found in an earlier study (Harradine and Whalley 1981), and would have been further exacerbated by the winter dormancy, when photosynthetic rates are low and assimilates are preferentially allocated to the shoots to facilitate reestablishment (Richards 1984). Root biomass produced by the three woody vegetation covers (Figure 2) consisting of the two plantations and the remnant woodland were consistent with their ages and did not show any correlations with carbon, nitrogen or phosphorus contents in the soil or in the foliage; we found only a marginal correlation between root biomass and C:N in soil and foliage ($r = 0.90$). Krämer and others (1996) reported an almost linear increase in root biomass with age of up to 34 years in *Juniperus occidentalis*, with the increase being almost 3-fold between the ages of three and five years. The almost 7-fold difference in the root biomass between plantation-3 and plantation-5 was probably due to the latter having a dense groundcover, which could account for up to half of the fine root biomass in natural woodland (Zerihun and others 2007).

The fine root biomass for the remnant woodland (Figure 2) was larger than about 4.0 Mg ha^{-1} reported for a similar vegetation having almost twice as many stems of over- and under-storey woody species (610 stems ha^{-1}) at a site in north-eastern Australia, where annual rainfall exceeds1000 mm (Zerihun and others 2006). Eastham and Rose (Eastham and Rose 1990) obtained a 38% increase (from 8 to 11 Mg ha^{-1}) in root biomass for *Eucalyptus* trees by reducing planting density from 2150 to 82 stems ha^{-1} at a site in eastern Australia with annual rainfall of 1150 mm; the increase was even larger (12.5 to 19.0 Mg ha^{-1}) where the trees were associated with pastures. Increases in fine root production under sparsely distributed trees have been associated with increased transmission of solar radiation to the soil (Eastham and Rose 1990) and/or reduced inter-tree competition (Puri and others 1994, Barton and others 2006).

The large amount of root biomass in this woodland could also be due in part to the low phosphorus content of the acidic soil in which increased partitioning of biomass to roots would be expected to enhance scavenging for this limited nutrient (Gower 1987). The root biomass in the 2-m profile under the woodland (Figure 2) was 12% higher than the unadjusted amount obtained from 1.5-m deep trench at this site in winter (Macinnis-Ng and others 2010). Root production in temperate environments normally peaks in spring, when we sampled, and is quite low in winter (Farrish 1991, Hendrick and Pregitzer 1993, Tufekcioglu and others 1999, Yang and others 2004).

The differences amongst the vegetation covers in their root biomass accounted for those in their root area index (RAI) (Figure 2b). The woodland had thicker roots and mostly larger RLD than either the grass or plantation-3 (Table 2) and so produced the highest RAI in all soil layers, except in the surface layer that was drier than in the other vegetation covers. The RAI was several times larger than the leaf area index (Table 1) producing RAI:LAI ratio of 2:1, 6.5:1 and 11:1 for plantation-3, plantation-5 and remnant woodland, respectively. This suggested that the RAI needed to support a unit LAI increases as woody vegetation ages and exploits increasing volumes of the soil profile. For the grass, the RAI:LAI of 3.7:1 might represent the optimum since the sward had almost certainly attained its climax.

Reductions in root biomass and its dependent variables on the western side of tree rows (Figure 3) were attributed to a rain shadow effect. Rain-bearing winds at this sites approach mostly from the east, resulting in marginally drier soil to the west of trees (Table 3). Such rain shadows in a three year old agroforestry system reduced RLD by up to 50% (Gautam and others 2003) and shoot growth due to low water potentials in soil and plant (Yunusa and others 1995). The influence of the rain shadow should wane as the trees become evenly distributed with thinning as part of the long-term management plan proposed for the site as?? described below.

Root biomass was generally inversely correlated with bulk density and θ (Table 4), indicating that root growth and subsequent water uptake was constrained in the finer and denser soil. All the other three root variables (diameter, RLD and RAI) were positively correlated with biomass, although the functions describing the relationship between the biomass and either RLD or RSA (Table 5) were different for the woody vegetation covers that had thicker roots compared with the grass (Table 2).

ASSOCIATION BETWEEN FINE ROOT BIOMASS AND WATER-USE

Clearly defined patterns in water extraction by the different vegetation covers were discernable from patterns in θ in the soil profile (Figure 1), which was consistent with the mass and distribution of roots. Unlike the restored vegetation covers that dried out mostly the topsoil, the woodland extracted all the available water in the 2-m soil profile. Using the mean values for the topsoil and subsoil, the correlation between θ and either RLD or root diameter was marginal ($p \leq 0.10$), but was significant ($p \leq 0.05$) with RAI and root biomass. The direction, but not magnitude, of differences in ET amongst the woody vegetation covers (Table 6) was consistent with those of root biomass, RLD and RAI. However, the differences in ET were much smaller than those in the root variables (in the root biomass it was by a factor of up to 10), but they produced only marginal influence on the *d* in water-use (Figure 4). Thus the entire root surface might not have been active in water uptake, i.e specific water uptake (water uptake/root area) declined with increased RAI similar to the effect of mutual-shading of leaves in dense canopies. This was not entirely unexpected given the oft-reported lack of correlation between water uptake and root biomass or RLD, as, for example, in legumes and cereals (Hamblin and Tennant 1987). Bowen (1985) showed that RLD of 1–2 km m^{-3} was adequate for water uptake and this was exceeded by the woodland and plantation-5 (Table 2). Using functions in Table 5, a root biomass of 2 Mg ha^{-1} even in the grass can produce an RLD of 1–2 km m^{-3}. Therefore the low ET from grass (Table 6) was largely due to constrained growth in winter and the periodic mowing. Mowing of the groundcover, which constituted 80% of the groundcover (Yunusa and others 2011), restrained ET in Plantation-5 such that its annual water-use was on a par with that for Plantation-3 (Table 6). There may also be some optimum RAI for water uptake above which no further benefit in terms of water extraction existed, which explains why the *d* for ET in the restored vegetation was only nominally negative (Figure 4). The poor relationship between ET with either root biomass or RLD was unlikely to be due to our inability to separate dead roots from the live ones since necromass was found to average 18% of total fine roots even in advanced temperate vegetation systems between the ages of 10 and 120 years (Børja and others 2008).

Reliance by the evergreen woodland on water stored in the deep soil layers is demonstrated in the apparent exhaustion of water in the 2-m soil profile (Figure 1). Some evidence had been presented earlier (Zeppel and others 2008) showing the woodland’s dependence on water stored deep in the clayey sub-soil during extended dry periods, when water extraction can extend beyond 4 m depth (Yunusa and others 2010). Although the four soil-water profiles were reflective of the age of the vegetation covers and the historical water-use before our measurements, the high water holding capacity of the topsoil reduced the need for water extraction below 1.0 m depth by the three restored vegetation covers. The coarse topsoil in the woodland had low water holding capacity compared with the fine textured and shallower topsoil in the restored vegetation covers (Table 1).

IMPLICATIONS FOR LAND RESTORATION

The primary ecological objective of restoring vegetation covers on mining and waste disposal landscapes is to ensure a complete hydrological isolation of waste emplaced underground (Freeze 1972) or in mounds (Gwenzi and others 2011). The woody species used here showed a rapid root growth in the first three years, but this slowed thereafter since the lowest depth in which roots were found was similar for the two plantations (Figure 2). The deepest layer (1.6 m) in which roots were found in both plantations was approximately 75% of the 2.5 m reported as the average maximum rooting depths for woody species in environments with non-seasonal rainfall distribution (Schenk and Jackson 2002). Continued root extension into the lower depths of the soil poses a risk of breaching the waste cells and creates preferential pathways for water flow. This will significantly raise the risk of groundwater contamination in addition to possible phytotoxicity. . Although these risks would be minimal with the grass cover, its constrained growth especially in winter due to dormancy can cause excess water to drain beneath the root zone (Table 6).

To sustain year-round water-use with minimal risk of intrusion into buried wastes that would allow water flow into the wastes is the key issue for the sustainability of SRC systems. This is achievable by optimising the benefits of shallow and deep rooting systems. A By mixing species with contrasting growth forms and phenology as in plantation-5 in which the groundcover has shallow roots and preferentially exploits water in the top layers of the soil, while the deep rooted trees use water stored in the lower layers of the soil. Indeed from the third year of its establishment, plantation-5 has maintained parity in water-use with the woodland (Yunusa and others 2010). During this period the trees accounted for only a quarter of the total canopy cover (Yunusa and others 2011), just above the 20% woody vegetation cover estimated to minimise drainage in southern Australia (Dunin 2002). Expansion of tree canopy with age would increase inter-tree competition for water, and hence for deep rooting, but can be mitigated through thinning to restrict tree canopy cover to not more than 25% of the whole landscape vegetation cover. Hence the longevity and efficacy of tree–herbaceous covers in restoring ecological health on landscapes containing wastes can be ensured through: (1) progressive thinning of trees to increase moisture availability to those remaining and thereby obviates the need for deeper rooting, (2) increasing the pasture legume component, which is winter active, in the groundcover to sustain water-use during this season, and (3) periodic fertilisation especially if the mowed clippings are removed from the land.

In summary, root production and water-use increased with age of the woody species, although the differences in water-use were smaller than those in fine root biomass. Water use in the grass was constrained by seasonal growth and mowing resulting in drainage. We conclude that vegetation covers consisting of widely spaced trees over groundcovers that contain winter-active pasture legumes have the appropriate rooting characteristics for restoring ecological functions to landscapes containing buried wastes. Such a vegetation cover develops root systems that support year-round water-use with reduced risk of breaching buried wastes.

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Table 1. Mean values (± standard errors of means, where available) for key soil and vegetation characteristics for the four vegetation types in 2009 at Castlereagh, Australia

Site characteristics	**Woodland**	**Grass**	**Plantation-5**	**Plantation-3**
Soil				
		Topsoil [1]		
Texture	Sandy loam	Silty clay	Silty clay	Silty clay
Gravel (%)	3	12	17	10
Sand (%)	82	29	31	25
Clay (%)	12	48	46	50
Water holding capacity (mm)	115	171	165	175
Bulk density (Mg/m^3)	1.33 ± 0.07	1.48 ± 0.14	1.35 ± 0.06	1.37 ± 0.12
Total carbon (%)	0.90 ± 0.23	0.82 ± 0.21	0.31 ± 0.07	0.23 ± 0.06
Total nitrogen (%)	0.04 ± 0.00	0.07 ± 0.00	0.05 ± 0.00	0.04 ± 0.00
Total P (mg/kg)	4.4	18.4	80.0	51.6
pH_{CaCl} (1:5)	4.89	5.87	4.89	5.82
Effective CEC (cmol$^+$/kg)	2.27	9.62	9.82	10.22
Electrical conductivity (dS/m)	0.04	0.11	0.17	0.13
		Subsoil		
Texture	clay	clay	clay	clay
Sand (%)	41	41	41	41
Clay (%)	56	56	56	56
Water holding capacity (mm)[2]	352	389	389	389
Bulk density (Mg/m^3)	1.60 ± 0.11	1.65 ± 0.14	1.63 ± 0.08	1.62 ± 0.05
Vegetation				
Stem density (stems/ha)[3]	560 ± 32	*na*	704 ± 106	566 ± 33
Leaf area index	2.47 ± 0.24	2.01 ± 0.18	3.21 ± 0.37	1.98 ± 0.33
Foliage Carbon (%)	53.9 ± 0.58	47.8 ± 0.61	48.8 ± 1.66	51.5 ± 1.58
Foliage Nitrogen (%)	1.13 ± 0.06	1.16 ± 0.04	1.08 ± 0.08	1.38 ± 0.19
Stem diameter (mm)[4]	139.3 ± 12.2	*na*	49.7 ± 7.97	34.1 ± 4.63

[1] depth of topsoil was 0.0 – 0.8 m in the woodland and 0.0 – 0.3 m in the other vegetation covers; [2] water content limits based on Saxon and Rawls (2006); [3] taken in late 2009 after root sampling and included understorey stems where present; [4] measured at 1.0 m height, *na* data not applicable.

Table 2. Mean values (± standard errors of means) for the root variables measured in September 2009 at Castlereagh, Australia

Variables	**Woodland**	**Grass**	**Plantation-5**	**Plantation-3**
Mean root diameter (mm)				
Top soil	0.48 ± 0.03	0.38 ± 0.01	0.39 ± 0.01	0.29 ± 0.01
Subsoil	0.47 ± 0.04	0.27 ± 0.02	0.29 ± 0.02	0.26 ± 0.06
Whole profile	0.48 ± 0.07	0.31 ± 0.05	0.33 ± 0.06	0.27 ± 0.07
Mean root length density (km m^{-3})				
Top soil	13.9 ± 5.1	17.8 ± 3.2	40.8 ± 7.1	7.0 ± 2.1
Subsoil	3.5 ± 0.3	2.1 ± 0.4	5.2 ± 0.8	1.8 ± 0.3
Whole profile	9.7 ± 0.9	7.3 ± 1.5	17.1 ± 0.21	3.5 ± 0.9

Table 3. Mean values (± standard errors of means) for selected soil and root properties for positions in the Plantation-5 in September 2009 at Castlereagh, Australia

Properties	**Tree row**	**West**	**East**	**Groundcover**
Mean root diameter (mm)				
Top soil	0.33 ± 0.01	0.36 ± 0.02	0.42 ± 0.03	0.45 ± 0.01
Subsoil	0.32 ± 0.03	0.27 ± 0.03	0.34 ± 0.03	0.25 ± 0.04
Whole profile	0.33 ± 0.07	0.30 ± 0.03	0.34 ± 0.02	0.32 ± 0.03
Mean root length density (km m^{-3})				
Top soil	46.8 ± 4.3	32.2 ± 1.8	38.7 ± 2.1	47.4 ± 4.2
Subsoil	7.3 ± 0.8	4.8 ± 0.3	4.5 ± 1.9	4.5 ± 0.5
Whole profile	20.4 ± 1.7	13.9 ± 2.8	15.9 ± 1.6	18.8 ± 0.8
Soil bulk density (Mgm^{-3})				
Top soil	1.28 ± 0.08	1.32 ± 0.03	1.34 ± 0.05	1.45 ± 0.09
Subsoil	1.38 ± 0.08	1.43 ± 0.07	1.44 ± 0.04	1.46 ± 0.04
Whole profile	1.35 ± 0.15	1.39 ± 0.13	1.41 ± 0.08	1.46 ± 0.08
Volumetric soil-water content (θ, m^3 m^{-3})				
Top soil	0.16 ± 0.03	0.14 ± 0.02	0.15 ± 0.01	0.24 ± 0.02
Subsoil	0.25 ± 0.01	0.24 ± 0.01	0.25 ± 0.01	0.25 ± 0.01
Whole profile	0.22 ± 0.01	0.21 ± 0.01	0.22 ± 0.01	0.25 ± 0.01

Table 4. Correlation coefficients (r) amongst selected soil and root characteristics for pooled data from the four vegetation covers at Castlereagh[1]

Characteristics	**BD ($Mg\ m^{-3}$)**	**θ ($m\ m^{-3}$)**	**RBM ($Mg\ ha^{-1}$)**	**RLD ($cm\ cm^{-3}$)**	**RSA (cm^2)**	**RDIAM (mm)**
Soil bulk density (BD)	1					
Soil water content (θ)	0.59**	1				
Root biomass (RBM)	-0.28**	-0.43**	1			
Root length density (RLD)	-0.17*	-0.29**	0.56**	1		
Root surface area (RSA)	-0.23**	-0.37**	0.87**	0.55**	1	
Root diameter (RDIAM)	-0.11	-0.25**	0.55*	0.25**	0.57**	1

[1] Coefficients are significant at $p < 0.05$ (*) or $p < 0.001$ (**) and df = 260

Table 5. Parameters for the regressions of root length density (cm cm^{-3}) or root surface area (cm^2) as dependent variables (y) on root biomass (g) as the independent variable (x) found for the four vegetation covers in 2009 at Castlereagh, Australia

Parameters	**Woodland**	**Grass**	**Plantation-5**	**Plantation-3**
Root length density				
Equation	$y = ax^b$	$y = bx + a$	$y = ax^b$	$y = ax^b$
Intercept (a)	3.05 ± 0.42	0.11 ± 0.03	17.7 ± 2.4	0.08 ± 0.01
Slope (b)	0.86 ± 0.21	6.42 ± 1.5	0.91 ± 0.27	49.8 ± 7.1
r^2	0.96	0.98	0.96	0.87
Root surface area				
Equation	$y = ax^b$	$y = bx + a$	$y = bx + a$	$y = bx + a$
Intercept (a)	675.7 ± 3.8	19.0 ± 4.1	75.9 ± 6.8	8.9 ± 1.9
Slope (b)	0.93 ± 0.12	693 ± 41	692 ± 81	1749 ± 126
r^2	0.86	0.92	0.98	0.74

Table 6. Seasonal mean values (± standard errors of means, where relevant) for evapotranspiration (ET) and drainage beneath 5 m depth between December 2008 and December 2009 for the vegetation covers at Castlereagh, Australia

Water balance variables (mm)	**Summer[1] (Dec 16 –Apr 15)**	**Winter (Apr 16 – Sep 16)**	**Spring[1] (Sep 17 – Dec 17)**	**Total**
Rainfall	365	167	109	641
Reference ET	451	278	361	1090
Evapotranspiration (ET)				
Woodland	346 ± 35	221 ± 20	116 ± 29	683 ± 53
Grass	309 ± 22	148 ± 28	98 ± 17	555 ± 44
Plantation-5	344 ± 34	218 ± 30	99 ± 12	661 ± 47
Plantation-3	350 ± 55	191 ± 16	111 ± 23	652 ± 55
Drainage				
Woodland	0	0	0	0
Grass	52	67	16	135
Plantation-5	0	0	0	0
Plantation-3	0	0	0	0

[1] The ground cover in Plantation-5 and the Grass were mowed during March/April (late Summer) and September/October (Spring)

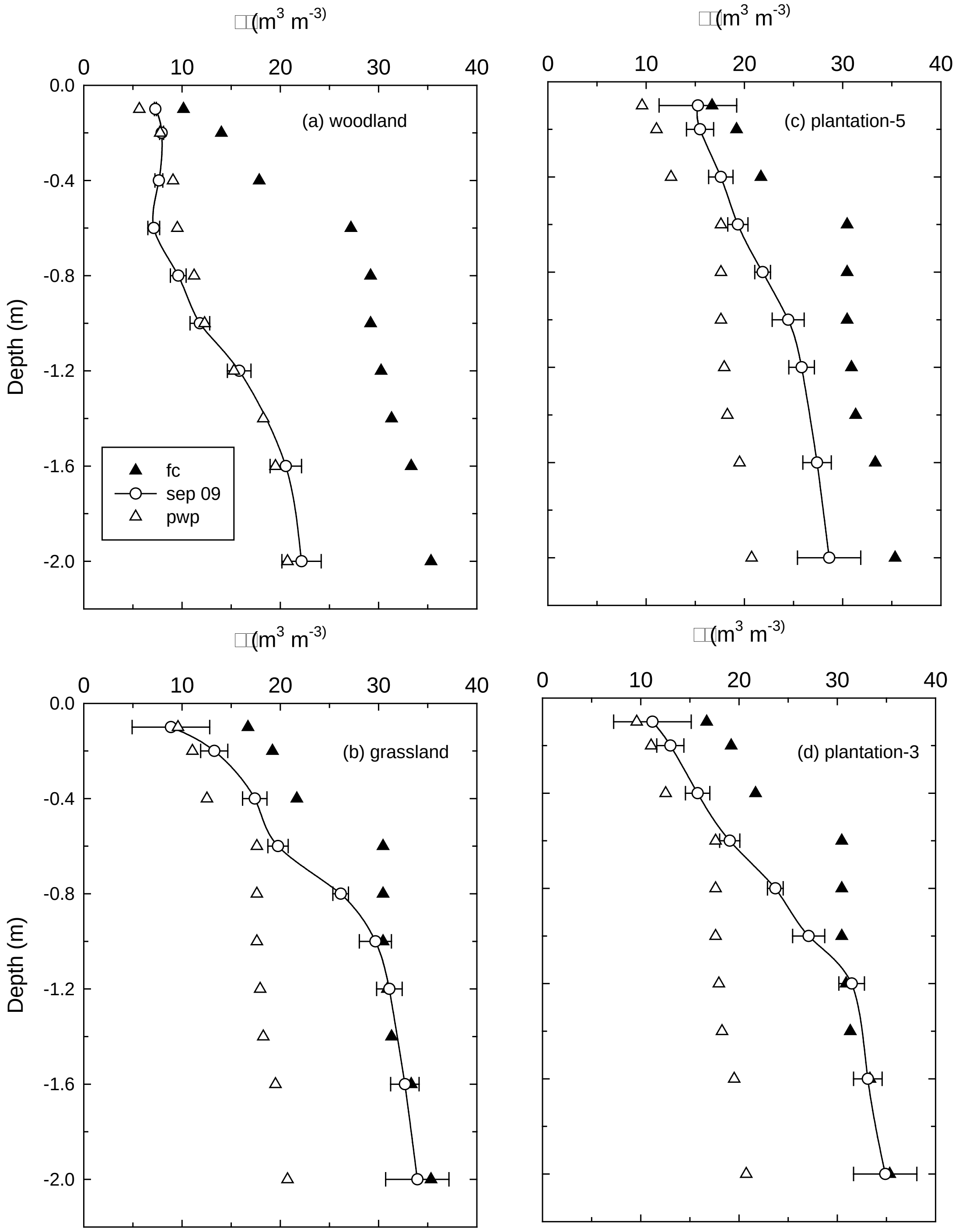


Figure 1. Distribution of volumetric water content (±standard errors of means) (solid curves) under (a) woodland, (b) grass, (c) plantation-5 and (d) plantation-3 at Castlereagh in September 2009. Also shown are the calculated water contents at field capacity (fc) and permanent wilting point (pwp).

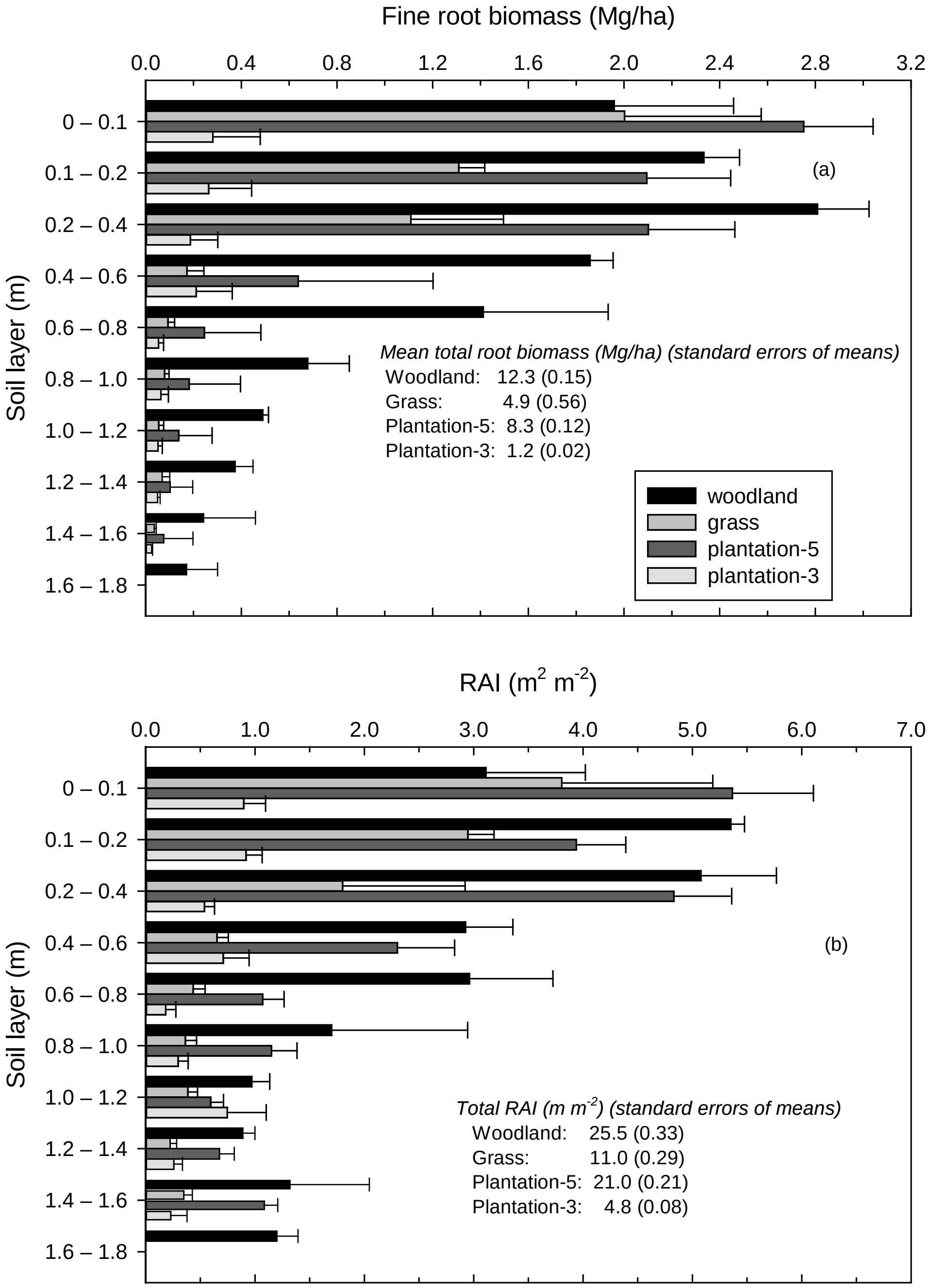
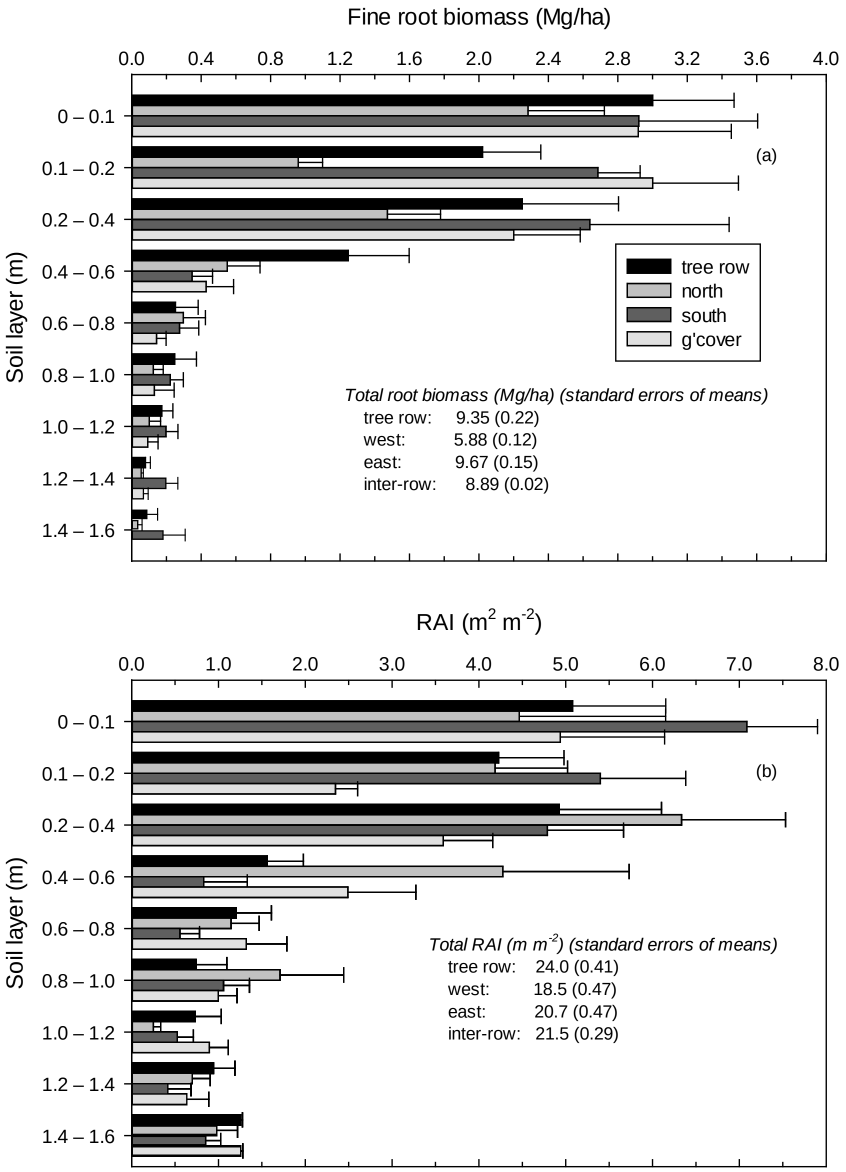


Figure 2. Means (± standard errors of means) for (a) biomass and (b) root area index in the soil profiles of vegetation covers in September 2009 at Castlereagh, Australia. Total root biomass and mean RAI density for the whole profile for the vegetation covers are also given in the respective graphs.



Total root biomass (Mg/ha) (standard errors of means)

tree row: 9.35 (0.22)
west: 5.88 (0.12)
east: 9.67 (0.15)
inter-row: 8.89 (0.02)

Total RAI (m m^{-2}) (standard errors of means)

tree row: 24.0 (0.41)
west: 18.5 (0.47)
east: 20.7 (0.47)
inter-row: 21.5 (0.29)

Figure 3. Means (± standard errors of means) for (a) fine root biomass and (b) root area index at various locations in the plantation-5 in September 2009 at Castlereagh: within the tree-row, east or west of the tree row or in the groundcover (mid-way between tree rows). Total root biomass and mean RAI density for the whole profile for the various positions are also given in the respective graphs.

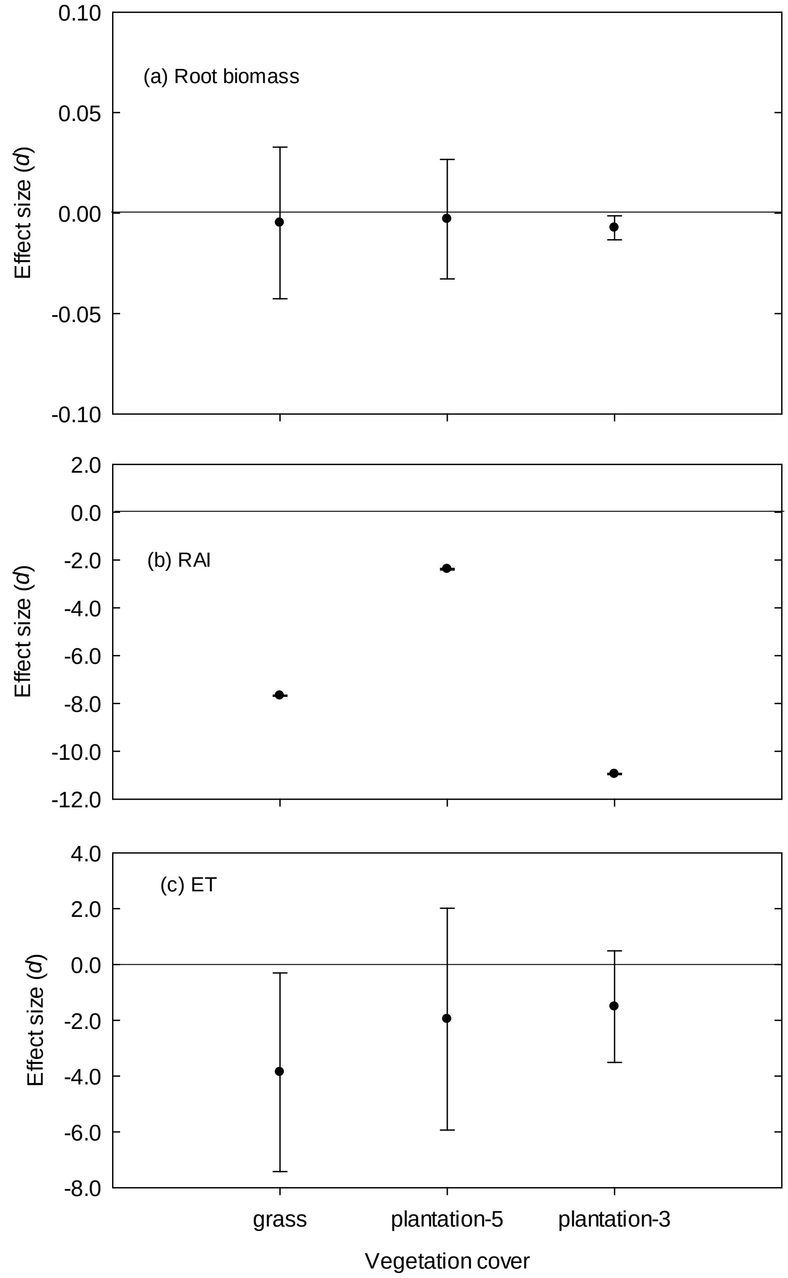


Figure 4. Mean effect size (±95% confidence intervals) for (a) fine root biomass, (b) root area index (RAI) and (c) evapotranspiration (ET) in 2009 at Castlereagh, Australia. Note the narrow confidence intervals for RAI in (b).