# Root Architecture of Jarrah (*Eucalyptus marginata*) Trees in Relation to Post-Mining Deep Ripping in Western Australia

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## Abstract

**This research aimed to investigate coarse root systems of Jarrah (*Eucalyptus marginata* Donn ex Sm.) trees at a 13-year-old restored bauxite mine site in south-western Australia. Excavations in an area with small trees (low-quality site) revealed that deep ripping equipment failed to penetrate the cemented lateritic subsoil, restricting coarse roots (roots >5 mm in diameter) to the top 0.5 m of the soil profile, resulting in fewer (1,344 stems/ha) and smaller (mean height 4.5 m) Jarrah trees. An adjacent area within the same pit (high-quality site), with a stand density of 3,256 stems/ha and a mean height of 8.0 m, had a kaolinitic clay subsoil which coarse roots penetrated to the average ripping depth (1.5 m). Trees at the low-quality site did not penetrate the subsoil with their taproot, relying instead on a large number of lateral (5.3–8.0/tree) and sinker (12.0–16.5/tree) roots. Taproots of trees on crests at the high-quality site also did not penetrate the subsoil, and in contrast to trees at the low-quality site, they produced fewer lateral and sinker roots (2.3 and 2.0/tree, respectively). Taproots of trees in riplines at the high-quality site directly penetrated the ripline and these trees also produced fewer lateral and sinker roots (5.0 and 3.7/tree, respectively) than those at the low-quality site. Jarrah trees appear to have opportunistic root systems capable of responding to a variety of soil conditions encountered in the post-mining landscape.**


**Key words: mine site restoration, root cross-sectional area, root morphology.**

## Introduction

The Jarrah (*Eucalyptus marginata*) forest is endemic to the Darling Plateau of south-western Australia and occurs on deep lateritic soil profiles created through in situ weathering of mainly granitic parent material (Sadlier & Gilkes 1976; Churchward & Dimmock 1989). The lateritic soils of the Darling Plateau are rich in aluminium hydroxide minerals, which are mined as bauxite (McArthur 1991). Bauxite mining is a major industry in the region, with approximately 550 ha of Jarrah forest mined and restored each year. The aim of Alcoa's restoration process since the early 1990s has been to create a sustainable Jarrah forest with the pre-mining values of the forest, including biodiversity, water production, timber resource, and recreation.

Techniques currently used in bauxite mine restoration such as direct return of topsoil, broadcast seeding, fertilizer application, and deep ripping of subsoil are largely successful at rapidly establishing vegetation across the landscape (Grant et al. 1996; Koch et al. 1996; Ward et al. 1996). However, despite identical restoration practices in all pits, some areas of poor tree growth appear several years after establishment.

Soil profiles in post-mining areas are heterogeneous and contain a range of regolithic materials that, due to their nature as well as the influence of mining, can prevent tree root penetration (Mengler et al. 2006). Previous studies on rehabilitated bauxite mines in south-western Australia have found that the root systems of young, eastern Australian eucalypt species were restricted to friable soil in riplines (Shea et al. 1975; Tacey 1979; Dell et al. 1983). Roots can be confined to riplines following deep ripping operations as a result of poor soil loosening and localized compaction caused by the ripping tine (Spoor & Godwin 1978). Deep ripping is employed in mining, agriculture, and forestry in order to improve root system development, despite its high cost and mixed success. Deep ripping has been shown to increase survival and height for a range of tree species on different soil types in contrasting environments in North America, Europe, and Australia (Varelides & Kritikos 1995; Ashby 1997; Nadeau & Pluth 1997; Lacey et al. 2001). A better understanding of root system development following soil disturbance and subsequent amelioration is essential for assessing the long-term survivability of vegetation in a variety of restored ecosystems.

To survive the summer drought, mature Jarrah trees rely on vertical roots that pass through fissures in the lateritic

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duricrust and mottled zone and access water-holding kaolinitic clay deep in the pallid zone and saprolite above the bedrock (Doley 1967; Kimber 1974; Carbon et al. 1980; Dell et al. 1983; Farrington et al. 1996). If tree roots are unable to penetrate deeper soil layers, the trees may have a reduced tolerance to long periods of drought (Ashby 1997).

The purpose of the present study was to determine the cause(s) of poor growth and survival in areas of a rehabilitated pit where tree establishment and growth were highly variable. Our hypothesis was that poor tree growth in older areas (>10 years old) is caused by restriction of root growth by impenetrable subsoil materials. This study aimed to quantify Jarrah coarse root system morphologies that have developed in response to different soil conditions encountered in the post-mining environment.

## Methods

### Study Site

This study was carried out in a 13-year-old restored bauxite mine pit, located approximately 10 km northwest of Dwellingup (lat 32°43′S, long 116°04′E), Western Australia, Australia. Silviculturalists generally use tree height as a measure of site quality. In this study, two plots (each measuring 25 × 50 m) were marked out with the first in a patch of small trees, subjectively classed as low quality, and the second in an adjacent area of taller trees (high-quality area) within the same restored pit. The study site was originally selected using aerial photographs, followed by ground checks to ensure that the variation in tree height was not due to human interference since initial post-mining restoration. Mining and restoration records of the area were also consulted to confirm that no atypical disturbance to the area was caused during mining and that the area had not previously been used for research trials.

The study area was restored according to the following general procedure used at the time (1992). Mine pit walls were smoothed down to create more natural contours and blend the pit into the surrounding landscape. Sandy gravel (overburden) was spread over the mine floor to a depth of approximately 0.5 m. Fresh topsoil (direct return) was spread over the returned overburden to a depth of 0.1 m. The site was then deep ripped using a Caterpillar D11 bulldozer with a single tine with 60-cm wings capable of ripping to a depth of 1.5 m, with 2-m spacing between riplines. The ripping produced crests and riplines, with approximately half of the final surface being crests and half riplines (Fig. 1) Seeds were broadcast, at rates based on pre-mining vegetation surveys, following break-of-season rainfall in autumn. The seed mixture was designed to produce a tree stand density of 2,500 stems/ha, with 80% Jarrah and 20% Marri (*Corymbia calophylla*). Nitrogen and phosphorus fertilizers were applied in spring (see this issue for details of the current mining and restoration process; Koch 2007).

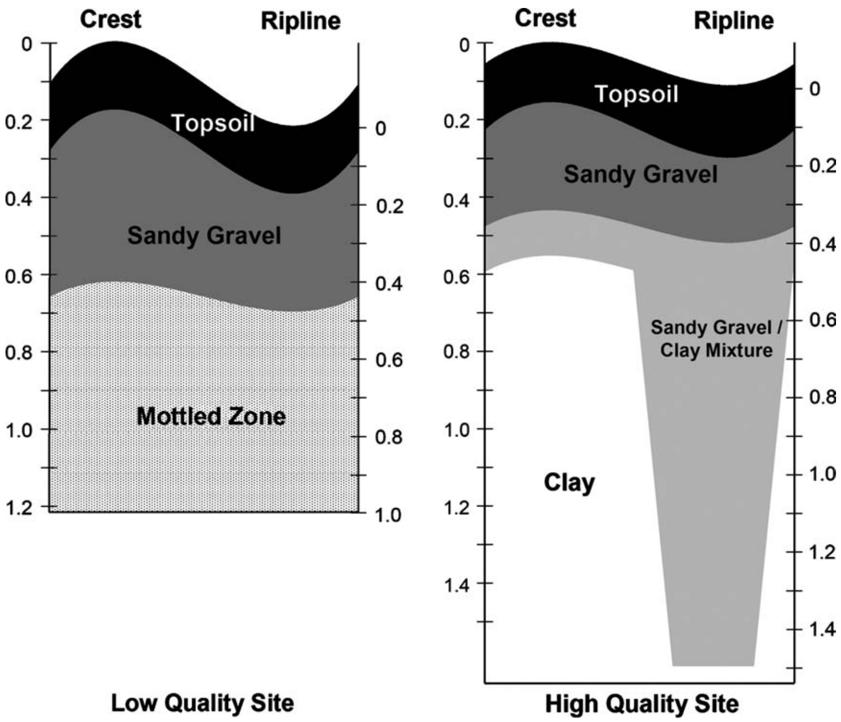


Figure 1. Diagram of the depth of soil horizons at low-quality (left) and high-quality (right) restored Jarrah (*Eucalyptus marginata*) forest sites. Scale bars represent depth (m) as measured from the soil surface of crests (left-hand scale bars) and riplines (right-hand scale bars) for both soil profiles.

#### Stand Characteristics

Stand density was determined by counting all Jarrah trees greater than 2 m tall in the 1,250-$m^2$ plots. Tree height was measured for all Jarrah trees greater than 2 m tall at both sites and recorded as the height of the tallest living section of the crown. Girth over bark at breast height (1.3 m) was recorded for all stems of all Jarrah trees greater than 2 m tall at both sites and converted to basal area (BA) over bark at breast height. In the case of multistemmed trees, total tree BA was calculated as the sum of the BA of each stem greater than 2 m tall. The location (crest or ripline) of each tree was also recorded.

#### Soil Texture and Bulk Density

Three soil pits were dug among the excavated trees at each site, perpendicular to the ripline direction. Soil texture was determined through field texturing and observations of material using a hand lens (McDonald & Isbell 1998). Soil color was classified using Munsell soil color charts (Munsell Color Company, Inc., Baltimore, MD, U.S.A.). In each soil pit, bulk density samples were taken from both crests and riplines using brass soil cores with a volume of 280 $cm^3$. Bulk density samples were taken at 10-cm intervals to depths of approximately 1 m in the low-quality site and 1.6 m at the high-quality site, which were the maximum depths achievable. Due to the large proportion of rocks encountered, several attempts were required to retrieve complete samples. Complete samples were transferred to zip-lock bags in the field and then taken to the laboratory for analysis. In the laboratory, the samples were transferred into aluminum dishes and then oven-dried at 105°C for 12 hours. Dry weights of the samples were taken, and bulk density was calculated as dry weight of the sample divided by the volume of the sampling core. Samples were then passed through a 2-mm sieve to determine gravel content.

#### Tree Root Architecture

Six trees in the median height size class of each site were excavated to study coarse root (>5 mm in diameter) distribution. The median height class was 4–5 m in the low-quality site and 8–9 m in the high-quality site. Within each site, three trees were situated on crests and the remaining three situated in riplines. The coarse root system (all roots >5 mm in diameter) of each tree was excavated manually using a mattock and then a rock pick for finer work in order to minimize damage. Excavations focused on exposing the taproot (vertical root emerging from the base of the tree) as well as major lateral (horizontal roots emerging from the base of the tree) and sinker (vertical roots emerging from lateral roots) roots. The depth of excavation depended on the length of vertical roots (taproot and sinker roots). Due to hardness of the material, the maximum depth attainable was approximately 1 m on the low-quality site and 1.6 m on the high-quality site. This depth was more than adequate to trace coarse vertical roots to their end point at the low-quality site. Some fine roots (<5 mm in diameter) in riplines in the high-quality site continued beyond 1.6 m depth; therefore, root depth recorded was the depth achieved by coarse roots.

Root girth over bark was measured at regular intervals along the length of the root. Lateral root girth was measured at 0, 0.2, 0.5, 1, 1.5, 2, 2.5, and 3 m from the base of the tree. Sampling to 3 m maximum distance along lateral roots allowed the inclusion of all major sinker roots. Previous studies on Jarrah poles (10- to 30-year-old trees) found that the majority of sinkers occurred within 1 m of the root stock, with no sinker roots more than 3 m from the base of the tree (Kimber 1974). Sinker root and taproot girth was measured at 0, 0.2, 0.5, and 1 m depth from the soil surface. Sinker root girth was also measured at these standard distances from the lateral root/sinker root junction. The distance of sinker root emergence from the tree was recorded, as well as whether the sinker root emerged on a crest or in a ripline. Lateral root girth was also measured on both sides of lateral/sinker root junctions. For comparisons between sites (low and high quality) and situations (on crest or in ripline), girth was converted to diameter or cross-sectional area (CSA).

#### Root CSA Allocation Calculations

As a standardized measure, unaffected by tree size, the relative importance of different root types was calculated as a percentage of total root CSA, similar to the method used by Drexhage and Gruber (1998). Root CSA was measured at 2 m from the trunk for lateral roots and at 0.5 m depth for sinker roots and taproots. A 2-m radius from the trunk for laterals was used in order to include all sinker roots in the calculation, as all sinkers emerged within 2 m of the tree. A depth of 0.5 m was selected to include sinker CSA in all situations, as sinkers were not present below 0.5 m, with the exception of sinkers in riplines at the high-quality site. Measuring lateral root CSA at 2 m rather than closer to the trunk yields lower estimates for the allocation to lateral roots but ensures that the calculated total lateral root CSA only includes functionally horizontal surface roots and does not include a proportion of sinker roots.

#### Statistics

As the number of trees at each site (low and high quality) and in each situation (on crest and in ripline) was different, significant differences in mean tree height and BA were determined using a one-way analysis of variance (ANOVA), with no blocking using GenStat (v. 7.1). Similarly, as the total number of lateral and sinker roots differed between trees at each site and in each situation, one-way ANOVAs with no blocking were also used to determine significant differences in taproot and sinker root depth. Differences in soil bulk density and gravel content as well as differences in average lateral root, sinker root, and taproot diameters were tested at each depth sampled also with one-way ANOVAs. Differences between treatments with regards to proportion of total root CSA accounted for by each root type were also tested using a one-way ANOVA.

## Results

### Stand Characteristics

The low-quality site had less than half the number of trees of the neighboring high-quality site and approximately 60% of trees at both sites were located in riplines (Table 1). Trees on crests and in riplines at the low-quality site were approximately 40% shorter ($p < 0.001$) and had 13–47% less BA ($p < 0.001$) than those at the high-quality site (Table 1). There was no significant difference in either height or BA between trees growing on crests or in riplines at the low-quality site (Table 1). Trees growing on crests at the high-quality site, however, were 10% shorter ($p < 0.001$) and had 26% less BA ($p < 0.001$) than those growing in riplines (Table 1).

### Soil Texture, Gravel Content, and Bulk Density

Both sites had similar upper soil layers (Fig. 1). Both had 15–20 cm of topsoil (dark-brown, sandy loam, 10YR3/3; 60–70% gravel) and 20–35 cm of sandy gravel (strong brown 7.5YR5/8 to yellowish brown 10YR5/8 sandy loam; 70–90% gravel) above the previous mine floor. The difference in height between the soil surface on crests and in riplines was 20–25 cm at the low-quality site and 10–15 cm at the high-quality site. The distance between riplines and their nearest crest was 1–1.2 m in the area sampled at both sites.

At approximately 0.5 m depth at the low-quality site was a cemented layer of mottled zone material, composed mainly of sandy loam soil, gravel, and large rocks. This material had no large cracks or fissures in the area excavated, and no roots were found to penetrate the cemented mottled zone layer. The cemented layer was flat and continuous, and therefore, the depth of soil situated above it depended on whether samples were taken from riplines or crests (Fig. 1). It appears that the deep ripper was unable to penetrate this material and that the ripping tine simply dragged on top of the cemented layer.

Below 0.5 m at the high-quality site was a mixed horizon of sandy gravel (overburden) and kaolinitic clay (white silty clay 10YR8/2), caused by the ripping process. Under crests, this layer was only 5–10 cm deep and often hard to distinguish. Under riplines, this mixed zone was up to 1 m deep, such that the ripped zone extended to approximately 1.2–1.5 m below the soil surface. Beneath the ripped zone was a kaolinitic white clay horizon that continued below excavation depth (approximately 1.6 m). Although difficult to distinguish in some cases, the width of the ripped zone was approximately 1 m.

Bulk density and gravel content results were highly variable due to the heterogeneous nature of the soil profile. Bulk densities were not significantly different for the majority of sampling depths (Fig. 2A & 2B). Soil under crests had higher gravel contents at both sites ($p < 0.001$); however, this difference only occurred for samples taken from the surface layers (Fig. 2C & 2D).

### Taproot and Sinker Root Depth

Taproots and sinker roots located on crests and in riplines at the low-quality site achieved an average depth of approximately 0.6 m and those on crests in the high-quality site reached an average depth of approximately 0.5 m (Table 2). Both distances were less than that from the soil surface to the level of the original mine floor. Taproots and sinker roots located in riplines at the high-quality site accessed the subsoil in the riplines to a depth of 1.3–1.6 m; however, they did not penetrate below the ripping depth (approximately 1.3–1.6 m).

### Root Number and Location

Trees differed in their average number of lateral and sinker roots, both within and between sites (Table 3). At the low-quality site, trees located on crests averaged 8.0 lateral roots, whereas those in riplines averaged 5.3 lateral roots per tree ($p = 0.002$). At the high-quality site, trees located on crests averaged 2.3 lateral roots, whereas those in riplines averaged 5.0 lateral roots per tree ($p = 0.002$).

Trees on crests and in riplines at the low-quality site had significantly more sinker roots ($p < 0.001$) than those at the high-quality site (Table 3). The percentage of sinker roots that were in riplines did not vary significantly between trees on crests or in riplines at either site (Table 3).

**Table 1.** Number of trees in plot (1,250 $m^2$), mean height (± SE), and mean BA (± SE) at breast height (1.3 m) of Jarrah (*Eucalyptus marginata*) trees in low- and high-quality restored bauxite mine sites.

| *Site of Tree Situation* | *Low-Quality Crest* | *Low-Quality Ripline* | *High-Quality Crest* | *High-Quality Ripline* | *p Value* |
|---|---|---|---|---|---|
| Number of trees | 70 | 98 | 160 | 247 | |
| Height (m) | 4.6 (± 0.2)$^a$ | 4.5 (± 0.1)$^a$ | 7.5 (± 0.2)$^b$ | 8.3 (± 0.1)$^c$ | <0.001 |
| BA ($cm^2$) | 95.0 (± 9.0)$^a$ | 77.7 (± 5.6)$^a$ | 109.6 (± 6.5)$^b$ | 148.4 (± 6.4)$^c$ | <0.001 |

Values are further categorized into whether trees are situated on a crest or in a ripline within each site. Within rows, different letters indicate significant differences ($p = 0.05$).

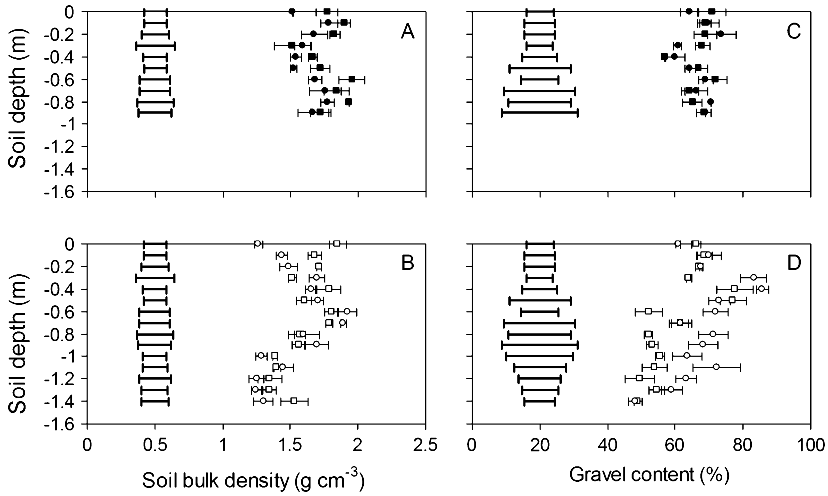


Figure 2. Mean (± SE) soil bulk density (A and B) and mean (± SE) gravel content (C and D), with increasing depth (m) on crest (squares) and adjacent ripline (circles) soil profiles at low-quality (A and C) and high-quality (B and D) restored Jarrah (*Eucalyptus marginata*) forest sites. Bars represent standard error ($n = 3$). Bold bars represent least significant difference at each depth sampled. Samples from the low-quality site were not taken below 1 m depth.

There was also no significant difference in the average distance from the tree that sinker roots emerged on crests or in riplines at both sites (Table 3).

#### Root Size

Lateral root size was significantly different between sites at each distance measured; however, there was no difference between trees on crests and in riplines within sites (Fig. 3). Lateral roots of trees on the low-quality site were 30–40% smaller ($p < 0.001$) than those at the high-quality site at the root origin.

The average diameter of sinker roots was dependent on their location in the landscape, regardless of where the tree was situated (Fig. 4A). Sinker roots originating on crests and in riplines at the low-quality site as well as those on crests at the high-quality site were 45–70% smaller ($p < 0.001$) than those located in riplines at the high-quality site at depths of 0, 0.2, and 0.5 m. Only sinker roots in riplines at the high-quality site penetrated past 0.6 m (Table 2), and therefore, only these roots were present at 1 m (Fig. 4A). Taproots of trees located on crests and in riplines at the low-quality site as well as those on crests at the high-quality site were 72–82% smaller ($p < 0.001$) than

**Table 2.** Total number of sinker roots in each location (on crest or in ripline) for 12 Jarrah (*Eucalyptus marginata*) trees excavated at low- and high-quality restored bauxite mine sites, as well as mean depth (± SE) achieved by sinker roots ($n$ = "total sinker number") and taproots ($n = 3$) initiating on crests and in riplines at low- and high-quality sites.

| *Site of Tree Situation* | *Low-Quality Crest* | *Low-Quality Ripline* | *High-Quality Crest* | *High-Quality Ripline* | *p Value* |
|---|---|---|---|---|---|
| Sinker number | 23 | 38 | 10 | 7 | |
| Sinker depth (m) | 0.58 (± 0.01)$^b$ | 0.61 (± 0.01)$^b$ | 0.48(± 0.02)$^a$ | 1.53 (± 0.05)$^c$ | <0.001 |
| Taproot depth (m) | 0.64 (± 0.03)$^c$ | 0.61 (± 0.07)$^b$ | 0.52 (± 0.02)$^a$ | 1.52 (± 0.06)$^d$ | <0.001 |

Within rows, different letters indicate significant differences ($p = 0.05$).

**Table 3.** Mean number of lateral and sinker roots per tree, percentage of sinker roots located in riplines, and mean distance of sinker roots from the base of Jarrah (*Eucalyptus marginata*) trees situated on crests and in riplines at low- and high-quality restored bauxite mine sites.

| *Site of Tree Situation* | *Low-Quality Crest* | *Low-Quality Ripline* | *High-Quality Crest* | *High-Quality Ripline* | *p Value* |
|---|---|---|---|---|---|
| Laterals per tree | 8.0 (± 0.6)$^c$ | 5.3 (± 0.7)$^b$ | 2.3 (± 0.7)$^a$ | 5.0 (± 0.6)$^b$ | 0.002 |
| Sinkers per tree | 16.5 (± 4.6)$^c$ | 12.0 (± 0.8)$^b$ | 2.0 (± 1.7)$^a$ | 3.7 (± 0.3)$^a$ | <0.001 |
| % Sinkers in riplines | 63.3 (± 12.6)$^a$ | 59.4 (± 10.8)$^a$ | 75.0 (± 25.0)$^a$ | 36.1 (± 7.3)$^a$ | n.s. |
| Distance from base (m) | 0.87 (± 0.09)$^a$ | 1.05 (± 0.12)$^a$ | 0.98 (± 0.18)$^a$ | 0.56 (± 0.09)$^a$ | n.s. |

Results are the mean (± SE) of three trees per site per situation ($n = 3$). Within rows, different letters indicate significant differences ($p = 0.05$). n.s., not significant.

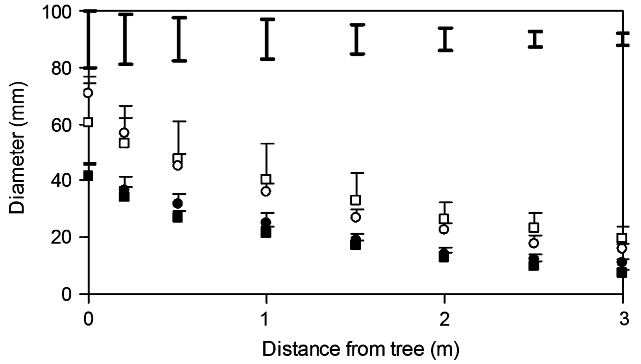


Figure 3. Mean diameter of lateral roots of Jarrah (*Eucalyptus marginata*) trees, with increasing distance from the base of the tree for trees situated on crests (squares) and in riplines (circles) at low-quality (solid) and high-quality (open) restored bauxite mine sites. Bars represent standard error (only positive bars shown). Bold bars represent least significant difference at each distance from the base of the tree sampled.

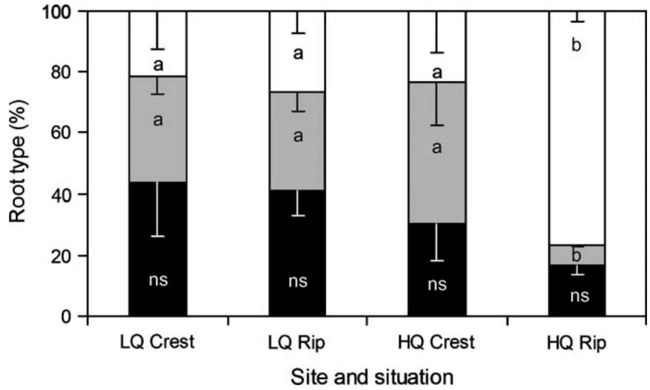


Figure 5. Mean proportion of total root CSA accounted for by lateral roots (black), sinker roots (gray), and taproots (white) for Jarrah (*Eucalyptus marginata*) trees situated on crests and in riplines at LQ and HQ restored forest sites. Bars represent standard error. Within each root type, bars with different letters represent significant differences ($p = 0.05$). HQ, high quality; LQ, low quality.

those of trees in riplines at the high-quality site at 0.5 m depth (Fig. 4B). Taproots in riplines at the high-quality site were the only ones that penetrated deeper than 0.6 m (Table 2). There was no significant difference between the size of taproots at ground level or at 0.2 m depth (Fig. 4B).

#### Allocation to Root Type

The taproots of trees on crests and in riplines at the low-quality site as well as those on crests at the high-quality site constituted 22–26% of total root CSA, whereas those of trees in riplines at the high-quality site represented 76% of their total root CSA ($p = 0.012$).

Sinker roots of trees on crests and in riplines at the low-quality site as well as those on crests at the high-quality site accounted for 33–47% of total root CSA compared with less than 10% for those of trees in riplines at the high-quality site ($p < 0.05$). There was no significant difference between trees in the total root CSA accounted for by lateral roots (Fig. 5).

Although trees on crests at the low-quality site and those from the high-quality site were similar in the proportion of total root CSA accounted for by each root type, they differed significantly in the number and size of roots they produced. The largest lateral root of trees at the low-quality site and trees in riplines at the high-quality site accounted for approximately 30% of the total CSA allocated to lateral roots (Fig. 6). Trees on crests at the high-quality site differed significantly in that their largest lateral root accounted for more than 80% of the total amount of lateral CSA ($p < 0.001$). Similarly, the largest sinker root of trees on crests at the high-quality site accounted for more than 80% of their total sinker root CSA, compared with trees in all other situations, which had a more even allocation among their sinker roots ($p < 0.001$).

## Discussion

#### Tree Productivity as a Function of Soil Texture, Deep Ripping, and Coarse Root Depth

The aboveground differences between the high- and low-quality sites were a direct result of both the depth achieved by taproots and sinker roots and the contrasting

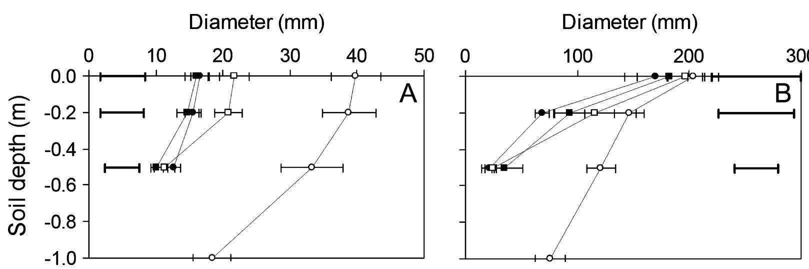


Figure 4. Mean diameter of (A) sinker roots and (B) taproots of Jarrah (*Eucalyptus marginata*) trees, with increasing soil depth of trees on crests (squares) and in riplines (circles) at low-quality (solid) and high-quality (open) restored bauxite mine sites. Only sinker roots and taproots of Jarrah trees situated in riplines at the high-quality site were present at 1 m depth. Bars represent standard error. Bold bars represent least significant difference at each depth sampled.

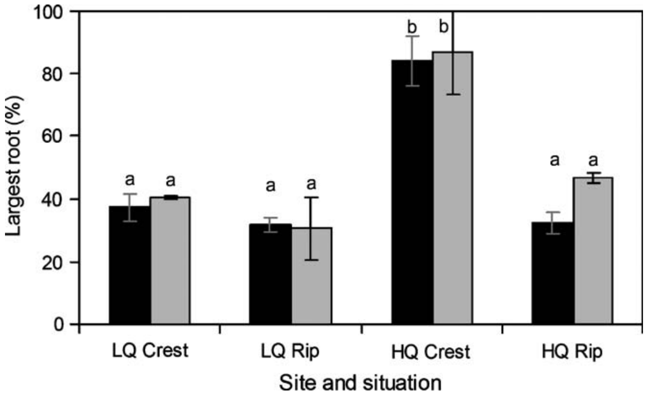


Figure 6. Mean largest representative of lateral (black) and sinker (gray) roots, expressed as a percentage of the total allocation of root CSA to that root type for Jarrah (*Eucalyptus marginata*) trees excavated at LQ and HQ restored forest sites. Taproot results are not included as all trees had only one taproot at the root origin. Bars represent standard error ($n = 3$). Within each root type, bars with different letters indicate significant differences ($p = 0.05$). HQ, high quality; LQ, low quality.

nature of the subsoil materials at each site. The tine of the deep ripper obviously did not break through the cemented subsoil at the low-quality site, resulting in a restriction of coarse roots to upper soil layers. It is unlikely that cemented lateritic material can be improved as a medium for root growth using a single-pass ripping operation (Mengler et al. 2006).

It is likely that the restriction of roots to the sandy gravel soil in the top 0.5–0.6 m at the low-quality site will cause these trees to experience water stress much earlier in summer (Enright & Lamont 1992) compared with those at the high-quality site. The restriction of root systems is the most likely cause of reduced stand density and tree size at the low-quality site. In contrast, trees at the high-quality site were larger as riplines facilitated access to the subsoil, allowing them access to a larger soil volume and a soil texture with a larger capacity to store moisture (McArthur 1991; Ashby 1997). A number of tree species have shown a similar trend in response to deep ripping (Varelides & Kritikos 1995; Nadeau & Pluth 1997; Lacey et al. 2001), including those regarded as having the ability to grow well on compacted soils (Ashby 1997).

All coarse roots that penetrated the subsoil at the high-quality site were restricted to riplines, a result consistent with previous studies on rehabilitated bauxite mines (Shea et al. 1975; Dell et al. 1983). Shea et al. (1975) stated that the trees in their study were only 3 years old and expected that they would penetrate the clay matrix below the ripline as they developed. Dell et al. (1983) studied these same species when the trees were 6–8 years old and found that roots remained restricted to the returned soil layers and in the rip fracture zone on granite-based rehabilitated profiles. Although no coarse roots penetrated below the ripping depth in the present study, some fine roots penetrated below the ripping depth via soil ped faces.

The restriction of coarse roots to friable subsoil in riplines may be due to the effect of ripping on soil structure rather than inadequate ripping depth. Ripping moist clay can have a molding effect rather than a shattering effect on soil structure, which could potentially result in localized compaction (Spoor & Godwin 1978; Mengler et al. 2006), causing roots to remain in the ripline. Chemical agents such as gypsum might be used in conjunction with ripping to improve soil structure at the rip edge and below the ripping depth. Coarse roots on unmined profiles access clay subsoil through natural root channels (Dell et al. 1983); however, no natural root channels were observed during excavations in the present study.

#### Tree Root Distribution in Response to Soil Texture and Deep Ripping

Tree root distribution is highly variable even in uniformly textured soil profiles. It is acknowledged that the implications of the results from the present study, particularly with regards to the development of different root morphologies in response to different soil conditions, are limited by the small number of trees excavated and the fact that the study was not replicated across several sites.

The relatively friable soil under trees located in riplines at the high-quality site facilitated the taproot of these trees to penetrate the subsoil, whereas the taproots of trees located on crests did not penetrate the old mine floor. Instead of a taproot, trees on crests at the high-quality site had one large sinker root supported by one large lateral root, which indicates a tendency for Jarrah to develop a single large vertical root where possible. The total sinker root CSAs of these large sinkers were, however, far lower than the taproot CSA of trees in riplines, which may explain why trees in riplines were taller and had a larger BA than those on crests at the high-quality site. Trees at the low-quality site also lacked a taproot; however, they produced a greater number of smaller lateral and sinker roots. The production of a large number of sinker roots per tree at the low-quality site may be due to the first sinker roots produced being unable to penetrate the subsoil, thereby triggering the development of more sinker roots along the length of the lateral root. The fact that these sinker roots were small as well as numerous indicates that once roots were unable to penetrate the subsoil, their growth stopped and resources were diverted (Thaler & Pagès 1999) to the growth of other sinker roots further along the lateral root, also demonstrated by coniferous species. This regular pattern of root development, similar to that observed for Norway spruce (*Picea abies*) (Drexhage & Gruber 1998), may also explain why trees on crests at the high-quality site only developed one major sinker root originating from one major lateral root. Many species have demonstrated the ability to alter the allocation of resources to different root types in response to physical barriers to growth (Enright & Lamont 1992; Misra & Gibbons 1996; Drexhage & Gruber 1998; Rokich et al. 2001; Poot & Lambers 2003). With regards to eucalypts in particular, Misra and Gibbons (1996) found that *Eucalyptus nitens*, grown in pots with high soil strength throughout, produced fewer but longer lateral roots, thus increasing the chance of finding more favorable soil away from the base of the plant.

Loss of the taproot is not necessarily detrimental to Jarrah tree survival. Kimber (1974) found no evidence to suggest that Jarrah must have a well-developed taproot but did conclude that factors such as slope, large boulders, and shallowness of the gravel layer influenced root system structure. Many conifers are able to develop different root system morphologies including taproot-dependant, sinker root–dependant, superficial, and plate-root systems in response to different soil conditions (Gruber 1994; Drexhage & Gruber 1998). The results from trees in the present study indicate that a single large taproot at depth is an advantage for trees on rehabilitated soil profiles. Production of a single large taproot on an unmined profile would not be an advantage in most cases. In order to maintain growth and survive the summer drought, taproots and sinker roots of mature Jarrah trees in the unmined forest must pass through fissures in the lateritic duricrust and root channels in the mottled and pallid zones in order to access water at depth (Kimber 1974; Dell et al. 1983). Roots of Radiata pine (*Pinus radiata*) have also been observed to access deeper soil via friable soil in old root channels and fissures in order to access stored moisture deep in the profile (Greenwood et al. 1981; Nambiar & Sands 1992).

Considering that trees in riplines at the high-quality site were taller and had larger BAs, it is likely that they will outcompete those on crests as the stand matures (Florence 1996). The root system structure of trees on crests may also affect survival of these trees. Using a high proportion of lateral allocation for sinker root production potentially reduces the root CSA available for surface nutrient and water uptake. Furthermore, nutrient uptake is restricted to the direction of the single major lateral, so these trees may exhaust their nutrient supply compared with trees that have many laterals foraging in a larger soil volume. The reduced anchorage of trees on crests, due to the asymmetry of their lateral roots and the loss of their taproot, may also make them more susceptible to windthrow (Coutts 1983; Mickovski & Ennos 2002).

## Conclusions

Deep ripping techniques used during bauxite mine restoration vastly improve vegetation establishment on the whole (Shea et al. 1975), with the majority of restored sites able to support trees at high stocking densities (Koch & Ward 2005). Due to the naturally variable soils of south-western Australia, it is difficult to predict where and how often hostile subsoils will emerge on restored bauxite mines and even harder to predict the long-term impacts on the restored vegetation. From the present study, it seems that Jarrah trees are able to develop a range of different root system morphologies in response to variable soil conditions encountered on restored bauxite mine sites. Further studies on the functionality of these different root system morphologies and how they influence tree growth and survival will greatly improve methods of Jarrah forest restoration.

### Implications for Practice

- Success of deep ripping in creating access to the subsoil depends on both the type of soil material and the species selected for site restoration.
- Species, such as Jarrah, with the ability to develop different root system morphologies in response to variable soil conditions, should be preferentially selected for use in site restoration.
- Where resources are unavailable for root system assessments, aboveground measurements of tree growth and morphology on known soil profiles will provide insights into restoration success.
- New techniques are currently being developed to measure soil strength during deep ripping operations, further assisting appropriate species selection on restored sites.

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