

**ALCOA OF AUSTRALIA LIMITED**

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**FACTORS AFFECTING PLANT ROOT  
DISTRIBUTION IN SAND EMBANKMENTS OF  
BAUXITE RESIDUE DISPOSAL AREAS**

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## SUMMARY

The root distribution of three plant species was investigated in rehabilitated outer bauxite residue sand embankments of varying age. The study was undertaken at the residue disposal area (RDA) at Alcoa of Australia's Pinjarra refinery. Five sites were chosen in which the vegetation had been established for one to four years, and the residue sand had been treated with deep (to 1.5 m) or surface (to 0.6 m) incorporation of gypsum. Three representative plant species, *Eucalyptus gomphocephala*, *Acacia cochlearis*, and *Hardenbergia comptoniana*, were excavated using an Air-spade<sup>®</sup>. Rooting depth was measured and root and shoot characteristics were quantified. Chemical and physical properties of the residue sand profile at the sites were also determined.

Roots of all plant species were restricted to the depth of gypsum incorporation, between 0.6 m and 1.5 m deep. A compacted layer immediately below the gypsum incorporation zone appears to be the most likely cause of restricted growth. Vegetation that is performing poorly due to restricted root distribution would not be a high user of water, regardless of increased water availability during the wet winter months. If increased compaction is the primary cause for restricting root growth, this introduces uncertainty that the role residue sand chemistry has on restricting root growth. This aspect of residue rehabilitation performance warrants further attention.

From an operational perspective, maximising water use by the vegetation is critical if evapotranspiration (or store and release) covers are to be considered as effective systems to reduce deep drainage. If the restriction of rooting depth is a major factor in the poor performance of residue rehabilitation vegetation, as this investigation suggests, then improving root penetration by using a deeper ripping tine to incorporate gypsum to greater depths (say to 3 m) may encourage deeper root growth penetration. This has the potential to increase plant access to water, leading to better vegetation performance and greater potential use of water.

## INTRODUCTION

Rehabilitation of residue disposal areas (RDA) has both aesthetic and functional purposes. The aesthetic purpose is to cover and conceal the RDA with self sustaining native vegetation for public amenity. However, more importantly, the functional purpose is to reduce deep drainage of infiltrating water thereby reducing the risk of groundwater contamination with excessively alkaline water from the RDA. Such store and release vegetation cover systems rely on transpiration of water by the vegetation to reduce deep drainage. For this reason the distribution of the cover vegetation's roots will be an important factor in determining the capacity of this system to store and release infiltrating water. In addition, root distribution governs the vegetation's access to water over dry summers, thereby affecting the ability of the vegetation to survive and be self sustaining.

The cover vegetation being established on Alcoa's RDA sand embankments in Western Australia is a native assemblage of species based on the tuart woodland ecosystem of the Swan Coastal Plain in Western Australia. The plants from this ecosystem grow on coastal sandy soils that are naturally alkaline and were chosen for this reason to grow on the alkaline bauxite residue sands. The dominant tree species is tuart (*Eucalyptus gomphocephala*) which is likely to have the most extensive root system of the plant species in this rehabilitation. Tuart roots have been observed at depths of 8 m (Jasinska *et al.* 1996) and 15 m (Lamont and Lange 1976) in the limestone caves of the Swan Coastal Plain, and at depths of 8 m in soil profiles in Cyprus (Day 1959). Tuart roots extend only to the capillary fringe of the water table and are not observed in the saturated soil below the water table (Oracle Soil and Water Pty Ltd. 2002) but water table depth may be 5 m or more depending on the site characteristics.

RDA embankments are currently formed from sand separated from residue mud. This residue sand is inhospitable to plant establishment, being highly alkaline and having a high exchangeable sodium percentage (ESP). Residue sand is ameliorated by incorporating gypsum in the top layer of sand thereby leaching the alkalinity and sodium. Current practice (in 2008) is to incorporate 225 t/ha of gypsum using a ripping tine dragged behind a bulldozer (although in the past an excavator was used to turn sand over) to a depth of 1.5 m. This physical process of incorporating gypsum also reduces soil compaction of the embankment. Soil compaction may arise by the earthmoving

equipment used to lay the embankments (although many embankments are now laid hydraulically) and subsequent heavy traffic in pasture management (some embankments were planted to pasture prior to native vegetation establishment).

Previous investigations of the root distribution in rehabilitation on Alcoa's RDA embankments have identified compaction as a factor affecting the establishment of trees. Lockley and Morald (1997) observed stunted growth in trees with roots growing laterally rather than downwards, citing Cronin (1995) and White (1996) as examples. Eastham and Morald (2004) used augering methods to measure the root density ( $\text{kg/m}^3$ ) as a function of depth, to a depth of 1.8 m. Deeper, more substantial root development was seen in uncompacted embankments compared with compacted embankments. However, Eastham and Morald (2004) suggested that subsoil compaction aided plant growth (as measured by tree height) by increasing the water-holding capacity of the soil. Root distribution in RDA embankments and the factors affecting it are therefore not clearly understood.

The aim of this study was to investigate the distribution of roots in rehabilitated residue sand embankments. This was achieved by comparing the depth and distribution of roots of selected native plant species in various ages of rehabilitation, which have had different gypsum treatments. The information from this study will improve our understanding of the physiology of the vegetation growing in RDA. This will lead to better rehabilitation prescriptions that customise the water use and maximise the likelihood of the vegetation being self-sustaining.

## MATERIALS AND METHODS

### *Sites*

The sites were located at Alcoa's Pinjarra RDA on the outer residue sand embankments of RDA4 and RDA5. All sites were hydraulically laid in 2001 and 2002 for RDA5 sites and RDA4 sites respectively. These embankments were planted and seeded with native species from tuart woodland and most received the standard prescription of gypsum (225 t/ha), fertiliser (2.7 t di-ammonium phosphate/ha), and wood mulch. Five sites were chosen which varied in the age of vegetation (established in 2003, 2005 or 2006), the depth of incorporation of gypsum (0.6, 0.8 or 1.5 m deep), and whether they were irrigated or not during summer in the first two years of establishment (Table 1).

**Table 1:** Sites investigated for root distribution at Pinjarra RDA.

<b>RDA</b>	<b>Year rehab. established</b>	<b>Irrigated</b>	<b>Gypsum treatment</b>	<b>Rehabilitation planting rate</b>
5	2003	no	deep (100 t/ha to 1.5 m deep)	625 plants/ha
5	2005	no	surface (225 t/ha to 0.6 m deep)	2000 plants/ha
5	2005	yes	deep (225 t/ha to 1.5 m deep)	2000 plants/ha
5	2005	no	deep (225 t/ha to 1.5 m deep)	2000 plants/ha
4	2006	no	deep (225 t/ha to 0.8 m deep)	2000 plants/ha

### *Plant Species*

The tree species *E. gomphocephala*, the shrub *Acacia cochlearis*, and the ground cover *Hardenbergia comptoniana* were selected for excavation (Fig. 1). These species have previously been studied in a plant-water relation monitoring program (Burgess 2007). One plant of each species, selected to be representative of the size of the plants of that species at each site, was excavated in October 2007 from each of the five sites (Table 1).

**a**



**b**



**c**



**Figure 1:** The plant species in RDA rehabilitation selected for investigation of root distribution, **a**, *Eucalyptus gomphocephala* (tuart), **b**, *Acacia cochlearis*, and **c**, *Hardenbergia comptoniana*.

### *Root Excavation*

Roots were exposed by manual digging with a spade and mini excavator, and blowing sand aside with an Air-spade<sup>®</sup> Series 2000 (Guardair Corporation, Chicopee, MA, USA). First, plant heights were recorded and shoots were cut-off at ground level to determine above-ground biomass. The maximum distance that surface roots extended from the plant was assessed by digging with a spade; at this distance a trench was dug (maximum depth of 1.4 m without benching) with a mini-excavator. The first 250 mm of soil was blown into the trench using the Air-spade<sup>®</sup> to expose the surface root-plate (Fig. 2). All roots in this surface root-plate were collected for processing, being cut off from roots going below 250 mm where necessary.



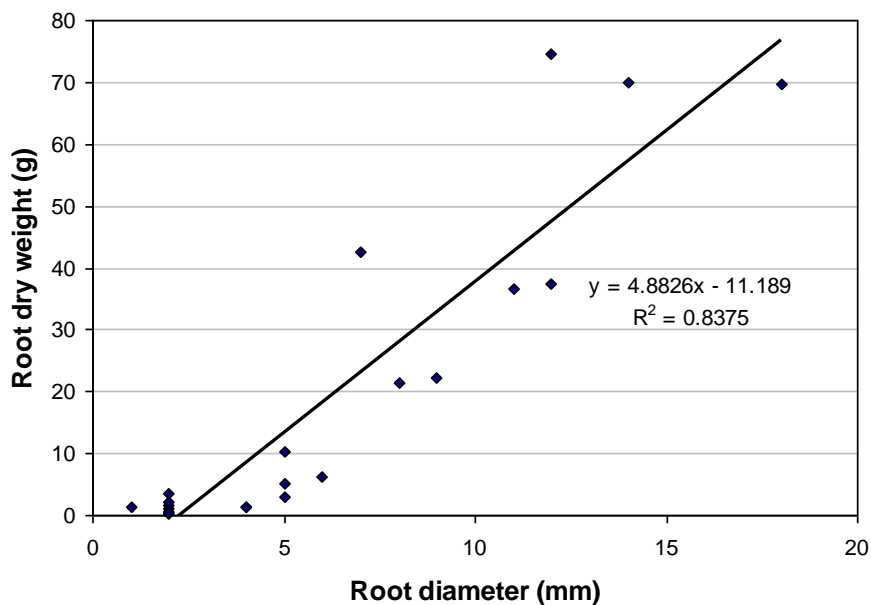
**Figure 2:** Displacement of the top 250 mm of sand to expose the surface root-plate using the Air-spade<sup>®</sup>.

Roots going deeper than 250 mm were excavated where possible. Additional air-spading and excavation trenches exposed deeper roots to quantify total depth of root penetration. The ultimate depth of excavation was dictated by the absence of roots. The diameters of any roots not excavated were recorded to allow for later estimation.

### *Plant Material Processing and Measurement*

The measurements taken for each plant were above-ground dry weight, root length and dry weight (separately for roots 0–250 mm deep and roots >250 mm deep. Root:shoot ratios were calculated. Root samples for each plant were washed. Root length, including fine roots, was measured. Roots and shoots were oven-dried at 70 °C until constant weight for dry weight determination.

To estimate the length and dry weight of roots not excavated, individual intact roots (i.e. cut only at the end closest to the shoot) were sampled from each plant. The diameter at the cut end, root length, and root dry weight was measured for each of 15–30 such root samples from each plant. The diameters of these root samples spanned the range of diameters of roots that were not excavated, so that the data could be used for interpolation. Using this individual root sample data, both root length and dry weight were regressed against both root diameter and root cross-sectional area (example seen in Fig. 3). The best of these two regression equations for each plant, as measured by  $r^2$ , was used to estimate root length and dry weight of those roots not excavated.



**Figure 3:** An example of the regression of root dry weight regression versus root diameter for *Eucalyptus gomphocephala* (2005 deep gypsum/irrigated treatment) for interpolation of roots not excavated.

### *Penetrometer Testing*

Penetrometer testing of soil compaction was done on all four non-irrigated sites (Table 1), i.e. sites of deep gypsum incorporation with rehabilitation established in 2003, 2005, and 2006, and the 2005 site of surface gypsum incorporation. Readings using a Perth Sand Penetrometer (AS 1289.6.3.3-1997) were recorded as the number of blows required to move the penetrometer through a 300-mm depth interval of the residue sand profile. Two replicate penetrometer readings were made, except for regions in the soil profile where compaction changed substantially, in which case four replicate measurements were made.

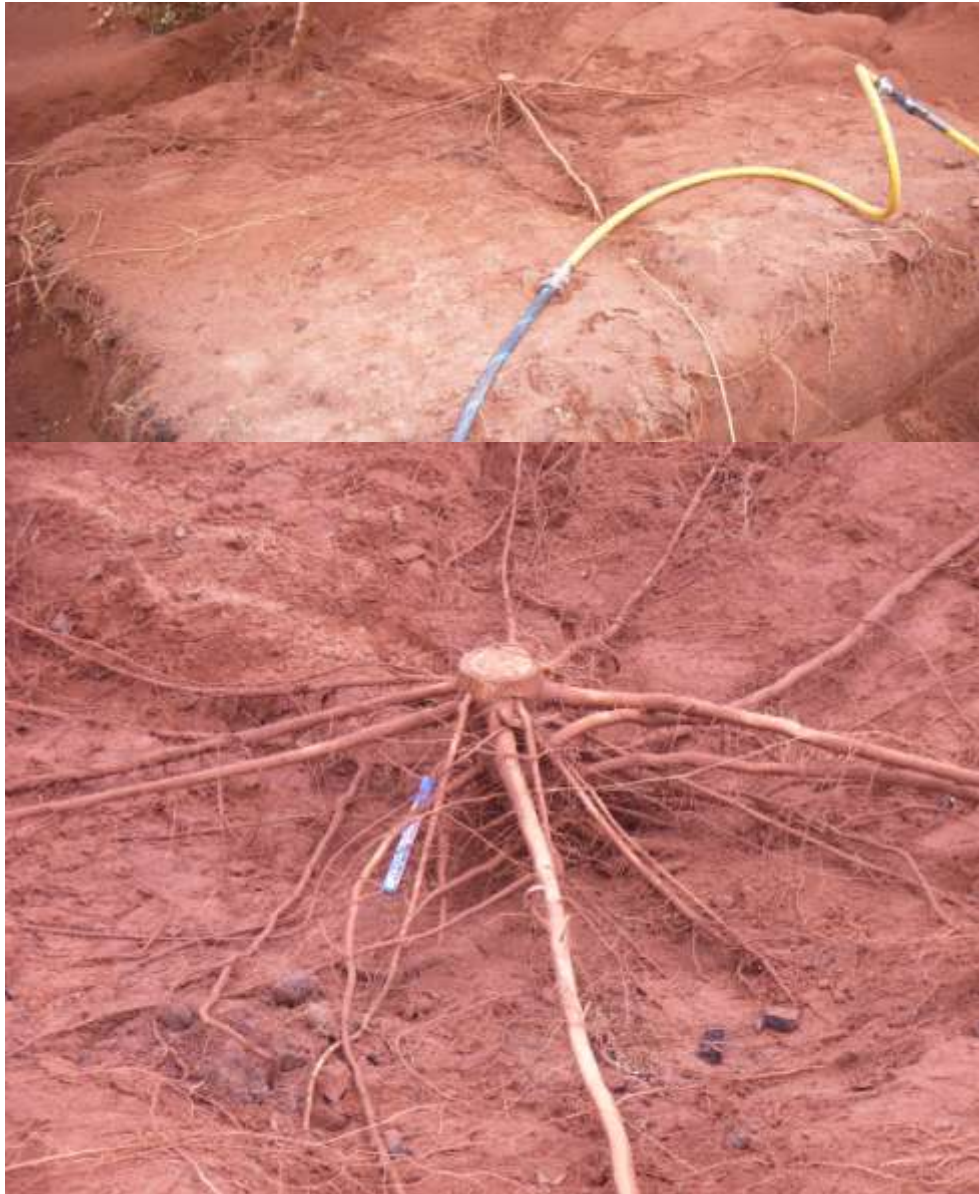
### *Soil Biological and Chemical Analyses*

Samples of residue sand throughout the profile were collected and stored in plastic bags on ice for biological activity and chemical analyses. Two replicate samples were taken at each of three depths, 0.3 m (the root zone), 1.0 m (below the root zone), and 1.8 m (in the compacted zone). All samples were taken from the excavations of tuart trees in the 2003, 2005, and 2006 non-irrigated rehabilitation sites with deep gypsum incorporation. Samples were analysed by an external NATA accredited laboratory (CSBP, Bibra Lake, WA, Australia) using the assays listed in Table 2.

**Table 2:** Soil biological and chemical assays measured on RDA soil samples.

<b>Soil property</b>	<b>Individual assays</b>
Microbiological properties	fungus:bacterial ratio, total microbial biomass, fungal biomass, bacterial biomass, rating
Water soluble ions	Na, Mg, Al, P, SO <sub>4</sub> , Cl, K, Ca, Fe, NH <sub>4</sub> -N, NO <sub>3</sub> -N, HCO <sub>3</sub> , CO <sub>3</sub>
Saturated paste soil properties	electrical conductivity, pH, gravimetric water content ( $\theta_g$ )
Available/ exchangeable ions	NO <sub>3</sub> -N, NH <sub>4</sub> -N, total N Available P, total P, SO <sub>4</sub> , Organic C Oxalate extractable Fe & Al Available K Exchangeable Ca, Mg, Na, K, Al & Fe Effective cation exchange capacity EDTA extractable Cu, Zn, Mn & Fe Total Al, total Fe, Phosphorus buffer index

Soil property results were analysed by two-way ANOVA, a full factorial design with the main effects being depth of sample and age of rehabilitation. Data were log transformed where appropriate to ensure homoscedasticity of variances. Where significant effects were found, post hoc pair-wise comparisons were made using Tukey's HSD ( $P = 0.05$ ) as if the analysis was a one-way ANOVA with nine treatment levels to overcome the problem of confounded pair-wise comparisons.



**Figure 4:** The top 250 mm of soil removed from *Eucalyptus gomphocephala* revealing the surface root-plate.

## RESULTS

### *Field Observations of Root Distribution*

Removal of the top 250 mm of soil revealed extensive surface root-plates in all excavated plants of *E. gomphocephala* (Fig. 4), which in the older rehabilitation had roots extending beyond the trench dug by the mini-excavator. Similar but much sparser surface root-plates were found with *A. cochlearis* and *H. comptoniana* plants, although one younger *H. comptoniana* plant only had sinker roots and no surface root-plate.



**Figure 5:** Roots of *Eucalyptus gomphocephala* growing sideways with a sharp bend at the compaction layer evident at the depth of incorporation of gypsum in the sand embankment.

At all sites, sinker roots did not penetrate below the depth of incorporation of gypsum, including those sites of greater rehabilitation age where there was substantial root development. All roots that reached this depth were deflected in a sharp bend at a compacted layer (Fig. 5). Some roots were observed to follow grooves in the compacted layer, presumably made by the excavator bucket used to incorporate the gypsum. Plants of all three species had both sinker roots radiating directly from the trunk and sinker roots branching from surface roots at some distance from the trunk.

The observed root density was greatest near the soil surface with many fine feeder roots ramifying through and just beneath the decaying wood mulch. Roots also proliferated in areas dominated by poorly incorporated gypsum. During gypsum incorporation, inefficient mixing below a depth of 0.8 m can result in a distinct gypsum band within the residue sand profile (Fig. 6). Phosphogypsum (that used in residue rehabilitation) contains a range of essential plant nutrients that are water-soluble to varying degrees (Phillips 2007), and can be regarded as a slow-release fertiliser. The finer texture of gypsum may result in this material having higher water content relative to the surrounding residue sand, as well as reducing the hostile chemical properties of residue sand (i.e. alkalinity and sodicity). These conditions may be more conducive to root growth than conditions in the bulk residue sand profile.



**Figure 6:** Gypsum banding within residue sand profile at about 0.8 m deep (arrowed).

Root nodules were observed on *H. comptoniana* roots, evidence that nitrogen fixation would have been occurring. Root density reduced markedly with depth, although in sites of deep gypsum incorporation, healthy fine roots were still observed at 1.2–1.5 m deep (Fig. 7). No roots were observed in the compacted layer below the depth of incorporation of gypsum at all sites for all species.



**Figure 7:** Healthy, fine root proliferation at depth (approximately 0.8 m) in *Eucalyptus gomphocephala* at the 2005 deep gypsum/irrigated treatment site.

#### *Root and Shoot Measurements*

In sites of similar rehabilitation age, root development was generally better on sites of deep gypsum incorporation without irrigation compared with sites with surface gypsum incorporation and sites that had been irrigated. This can be seen with *E. gomphocephala* in which a greater proportion of root length had developed below 250 mm in the soil profile in deep gypsum/non-irrigated sites compared with deep gypsum/irrigated and surface gypsum/non-irrigated sites (Fig 8). Similarly *A. cochlearis* showed a greater proportion of root length below 250 mm in both deep gypsum sites compared with the surface gypsum site (Fig. 8). Total dry weight measurements of shoots, roots <250 mm,

and roots >250 mm are less informative, chiefly because only single plants were measured, not a randomly selected, replicated sample of plants. However, the measurements do reflect the field observation that plants growing in deep gypsum sites had greater shoot biomass than plants in shallow gypsum sites and that this is proportionally reflected in root biomass, at least for *E. gomphocephala* and *H. comptoniana* (Fig. 9).

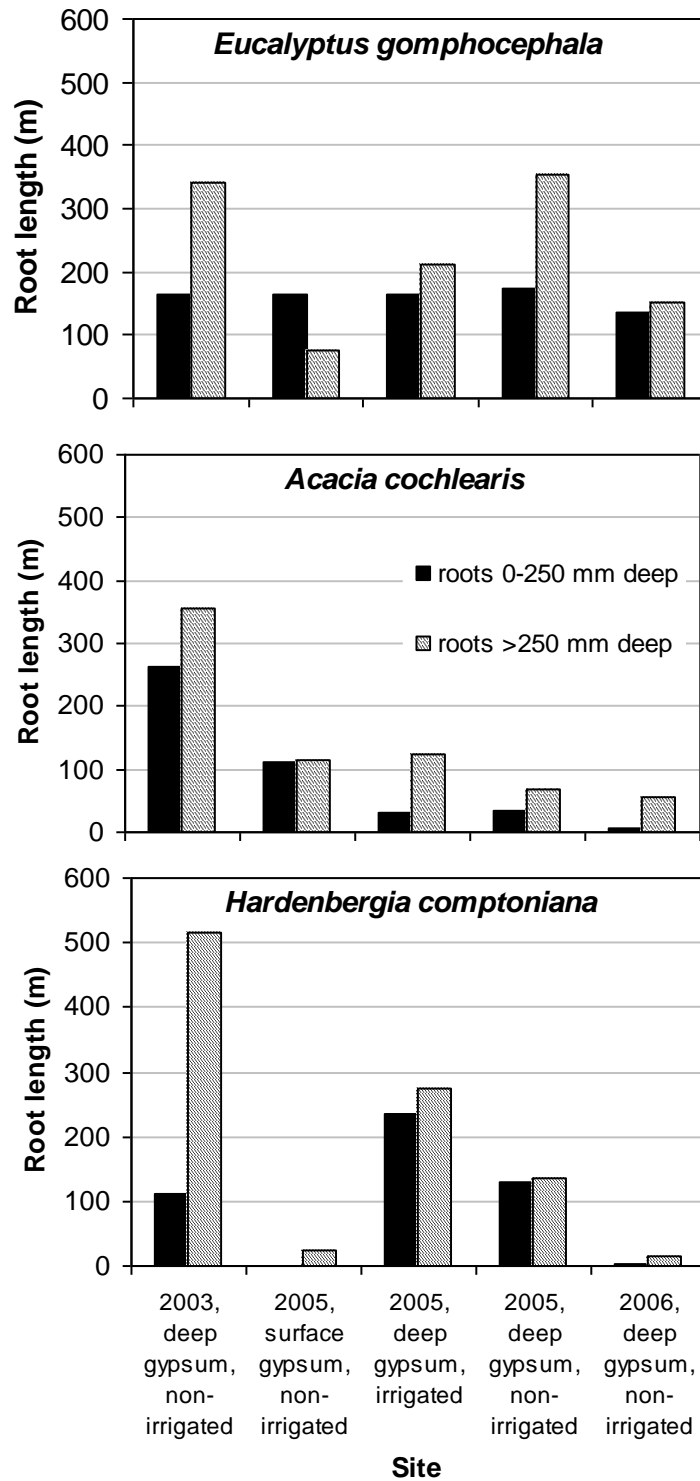
With increasing age of the rehabilitation, *E. gomphocephala* and *H. comptoniana* had a greater proportion of root length deeper in the soil (>250 mm) given the same deep gypsum incorporation/non-irrigation treatment (Fig. 8). Unsurprisingly, root and shoot dry weights increased with increasing age of the rehabilitation (Fig. 9). However, the proportions of shoots, roots <250 mm, and roots >250 mm did not differ dramatically for *E. gomphocephala* and *A. cochlearis* (Fig. 9), which was reflected in root:shoot ratios (Table 3).

Root:shoot ratios of *E. gomphocephala* and *A. cochlearis* did not differ substantially across sites of different age of rehabilitation or gypsum incorporation and irrigation treatment (Table 3). However, *H. comptoniana* showed increasing root:shoot ratio with age of rehabilitation (Table 3), indicating greater partitioning of energy into root development with increasing age.

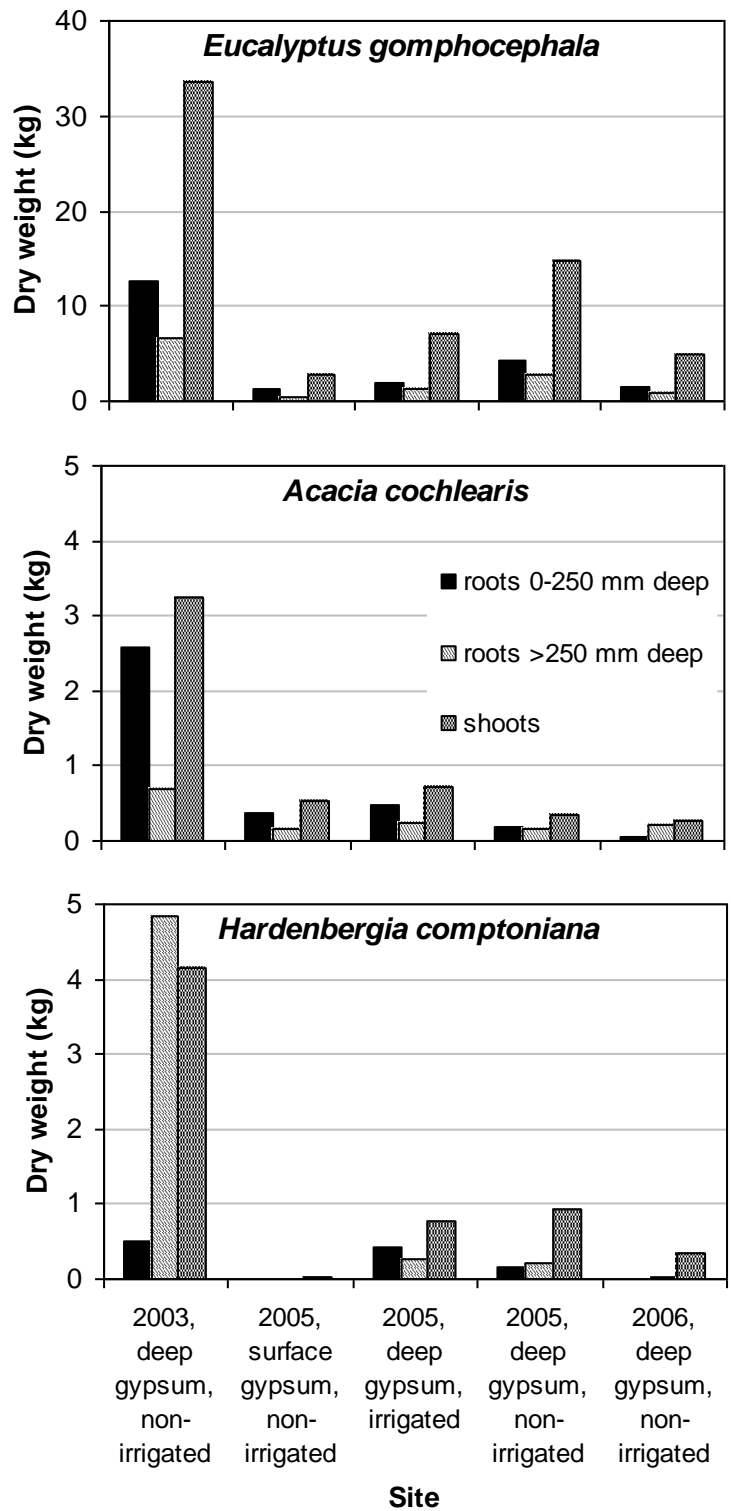
**Table 3:** Root:shoot ratios (dry weight) of *Eucalyptus gomphocephala*, *Acacia cochlearis* and *Hardenbergia comptoniana* in residue sand embankment rehabilitation sites of different age and treatment.

Species	Site				
	2003, deep gypsum, non- irrigated	2005, surface gypsum, non- irrigated	2005, deep gypsum, irrigated	2005, deep gypsum, non- irrigated	2006, deep gypsum, non- irrigated
<i>Eucalyptus gomphocephala</i>	0.6	0.7	0.5	0.5	0.5
<i>Acacia cochlearis</i>	0.2	0.2	0.2	0.1	0.2
<i>Hardenbergia comptoniana</i>	1.3	n.d.	0.9	0.4	0.1

n.d. = no data



**Figure 8:** Root length at two depth classes of *Eucalyptus gomphocephala*, *Acacia cochlearis* and *Hardenbergia comptoniana* in residue sand embankment rehabilitation sites of different establishment age and treatment.



**Figure 9:** Root dry weight at two depth classes and shoot dry weight of *Eucalyptus gomphocephala*, *Acacia cochlearis* and *Hardenbergia comptoniana* in residue sand embankment rehabilitation sites of different establishment age and treatment.

### *Soil Biological and Chemical Analyses*

There was zero or minimal biological activity at any depth in the soil profile from any of the sites (Table 4). Fungal:bacterial ratio, fungal biomass and bacterial biomass were not measurable in any samples, and total microbial biomass and rating were very low with no significant differences among treatments.

There were few chemical properties that consistently changed with depth. Across all three sites of different age rehabilitation sampled, only electrical conductivity (EC), water soluble  $\text{NO}_3\text{-N}$ , available P, and total P show a consistent change with depth of sampling, i.e. a significant main effect of depth with no interaction (Table 4). All other chemical properties that had significant differences due to sampling depth or rehabilitation age (main effects) also had a significant interaction, i.e. the main effect was not consistent across depths or ages.

The levels of most chemical properties measured in these samples were not inhibitory to root growth. The exceptions were in samples 1.8 m deep in 2005 and 2006 rehabilitation in which  $\text{pH} > 9$  and exchangeable sodium percentage (ESP) was 37% (Table 4). However these adverse chemical properties were not found in 2003 rehabilitation at 1.8 m deep, yet roots were not observed at this depth in this site. In addition to adverse pH and ESP, water soluble Al in 2006 rehabilitation at 1.8 m deep was 3.9 mg/L, the deepest sample in the youngest site (Table 4). However in similarly high pH samples at 1.8 m in 2005 rehabilitation, Al concentration was not significantly different to all other samples including those from depths with extensive roots (Table 4).

The high pH in samples 1.8 m deep at 2005 and 2006 sites (the youngest sites) was associated, not unexpectedly, with significantly higher water soluble Na,  $\text{HCO}_3^-$ , and  $\text{HCO}_3^- + \text{CO}_3^{2-}$  concentrations, and significantly lower water soluble Ca concentrations (Table 4). Clearly, within the zone of incorporation, the dissolution of gypsum has resulted in a displacement of exchangeable Na with Ca. The displacement of Na increases its potential for loss via leaching. The formation of  $\text{CaCO}_3$  will reduce pH and  $\text{CO}_3^{2-}$  concentrations, with a concomitant decrease in  $\text{HCO}_3^-$ .

**Table 4:** Mean soil biological, chemical, and physical properties in RDA soil samples from sites of different rehabilitation age at three depths.

Site	2003, deep gypsum, non-irrigated			2005, deep gypsum, non-irrigated			2006, deep gypsum, non-irrigated			Main effects		Inter-action	
Depth (m)	0.3	1	1.8	0.3	1	1.8	0.3	1	1.8	depth	age	depth*age	
Total microbial biomass (mg C/kg)	0.54	0	0	4.85	1.44	1.62	0	1.44	0	n.s.	n.s.	n.s.	
Rating (microbiological)	low	low	low	low	low	low	low	low	low	n.s.	n.s.	n.s.	
Saturated paste properties	EC (mS/m)	1.8 <sup>a</sup>	1.5 <sup>a</sup>	1.6 <sup>a</sup>	0.9 <sup>a</sup>	2.2 <sup>a</sup>	2.7 <sup>a</sup>	0.7 <sup>a</sup>	3.3 <sup>a</sup>	2.6 <sup>a</sup>	s.	n.s.	n.s.
	pH	6.8 <sup>a</sup>	7.2 <sup>a</sup>	7.1 <sup>a</sup>	6.7 <sup>a</sup>	6.6 <sup>a</sup>	9.2 <sup>b</sup>	7.0 <sup>a</sup>	6.8 <sup>a</sup>	9.6 <sup>b</sup>	s.	s.	s.
	θ <sub>g</sub> (g/g)	0.3	0.3	0.31	0.3	0.3	0.32	0.31	0.35	0.3	n.s.	n.s.	n.s.
Water soluble ions (mg/L)	Na	50 <sup>a</sup>	64 <sup>a</sup>	195	47 <sup>a</sup>	108 <sup>b</sup>	457 <sup>c</sup>	53 <sup>a</sup>	123 <sup>b</sup>	461 <sup>c</sup>	s.	s.	s.
	Mg	16	6	12	7	10	7	11	8	10	n.s.	n.s.	n.s.
	Al	0.001 <sup>a</sup>	0.602 <sup>a</sup>	0.015 <sup>a</sup>	0.012 <sup>a</sup>	0.002 <sup>a</sup>	0.850 <sup>a</sup>	0.012 <sup>a</sup>	0.001 <sup>a</sup>	3.906	s.	s.	s.
	P	0.10 <sup>a</sup>	0.10 <sup>a</sup>	0.10 <sup>a</sup>	0.10 <sup>a</sup>	0.09 <sup>a</sup>	0.15 <sup>bc</sup>	0.10 <sup>a</sup>	0.12 <sup>ab</sup>	0.19 <sup>c</sup>	s.	s.	s.
	SO <sub>4</sub>	230	179	177	100	284	215	68	455	102	n.s.	n.s.	n.s.
	Cl	9 <sup>ab</sup>	9 <sup>ab</sup>	12 <sup>ab</sup>	5 <sup>a</sup>	9 <sup>ab</sup>	19 <sup>b</sup>	10 <sup>ab</sup>	7 <sup>ab</sup>	7 <sup>a</sup>	s.	n.s.	s.
	K	13 <sup>a</sup>	12 <sup>a</sup>	12 <sup>a</sup>	13 <sup>a</sup>	13 <sup>a</sup>	18 <sup>b</sup>	17 <sup>b</sup>	23	12 <sup>a</sup>	s.	s.	s.
	Ca	289 <sup>b</sup>	210 <sup>ab</sup>	79 <sup>ab</sup>	115 <sup>b</sup>	288 <sup>b</sup>	3 <sup>a</sup>	70 <sup>ab</sup>	504 <sup>b</sup>	3 <sup>a</sup>	s.	n.s.	s.
	Fe	0.07 <sup>a</sup>	3.23 <sup>a</sup>	0.20 <sup>a</sup>	0.33 <sup>a</sup>	0.04 <sup>a</sup>	2.35 <sup>a</sup>	0.21 <sup>a</sup>	0.05 <sup>a</sup>	6.22 <sup>a</sup>	s.	n.s.	s.
	NH <sub>4</sub> -N	0.5 <sup>ab</sup>	0.5 <sup>ab</sup>	0.4 <sup>ab</sup>	0.5 <sup>a</sup>	0.3 <sup>a</sup>	0.7 <sup>ab</sup>	0.4 <sup>a</sup>	0.4 <sup>ab</sup>	1.1 <sup>b</sup>	s.	n.s.	n.s.
	NO <sub>3</sub> -N	2.1 <sup>a</sup>	3.9 <sup>ab</sup>	2.4 <sup>a</sup>	2.5 <sup>ab</sup>	2.7 <sup>ab</sup>	3.6 <sup>ab</sup>	2.9 <sup>ab</sup>	4.2 <sup>ab</sup>	5.1 <sup>b</sup>	s.	s.	n.s.
	HCO <sub>3</sub>	75 <sup>a</sup>	105 <sup>a</sup>	91 <sup>a</sup>	98 <sup>a</sup>	65 <sup>a</sup>	598 <sup>b</sup>	107 <sup>a</sup>	82 <sup>a</sup>	707 <sup>b</sup>	s.	s.	s.
	CO <sub>3</sub>	0 <sup>a</sup>	0 <sup>a</sup>	0 <sup>a</sup>	0 <sup>a</sup>	0 <sup>a</sup>	0 <sup>a</sup>	0 <sup>a</sup>	0 <sup>a</sup>	196	s.	s.	s.
NO <sub>3</sub> -N (mg/kg)	1	1	1	1	1	1	1	1	1	n.s.	n.s.	n.s.	
NH <sub>4</sub> -N (mg/kg)	1	1	1	1	1	1	1	1	1	n.s.	n.s.	n.s.	
Total N (%)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	n.s.	n.s.	n.s.	
Available P (mg/kg)	4 <sup>a</sup>	5 <sup>a</sup>	2 <sup>a</sup>	19 <sup>a</sup>	4 <sup>a</sup>	3 <sup>a</sup>	4 <sup>a</sup>	10 <sup>a</sup>	3 <sup>a</sup>	s.	n.s.	n.s.	
Total P (mg/kg)	49 <sup>b</sup>	42 <sup>ab</sup>	16 <sup>a</sup>	46 <sup>b</sup>	31 <sup>ab</sup>	28 <sup>ab</sup>	32 <sup>ab</sup>	52 <sup>b</sup>	28 <sup>ab</sup>	s.	n.s.	n.s.	

**Table 4:** continued.

Site	2003, deep gypsum, non-irrigated			2005, deep gypsum, non-irrigated			2006, deep gypsum, non-irrigated			Main effects		Inter- action	
	Depth (m)	0.3	1	1.8	0.3	1	1.8	0.3	1	1.8	depth	age	depth*age
SO <sub>4</sub> (mg/kg)		49	45	63	33	118	54	29	216	33	n.s.	n.s.	n.s.
Organic C (%)		0.04	0.01	0.04	0.01	0.03	0.02	0.01	0.01	0.01	n.s.	n.s.	n.s.
Oxalate extractable ions (g/kg)	Fe	4.61 <sup>ab</sup>	4.98 <sup>abc</sup>	4.82 <sup>abc</sup>	5.66 <sup>bcd</sup>	5.92 <sup>cd</sup>	6.53 <sup>d</sup>	5.00 <sup>abc</sup>	4.58 <sup>ab</sup>	4.40 <sup>a</sup>	n.s.	s.	s.
	Al	1.4	1.39	1.31	1.31	1.37	1.55	1.26	1.3	1.39	n.s.	n.s.	n.s.
Available K (mg/kg)		30 <sup>abc</sup>	30 <sup>abc</sup>	16 <sup>a</sup>	47 <sup>bcd</sup>	41 <sup>abcd</sup>	47 <sup>bcd</sup>	62 <sup>d</sup>	58 <sup>cd</sup>	20 <sup>ab</sup>	s.	s.	s.
Exchangeable ions (cmol/kg)	Ca	4.6 <sup>b</sup>	4.7 <sup>b</sup>	4.5 <sup>b</sup>	4.0 <sup>b</sup>	4.9 <sup>b</sup>	3.0 <sup>a</sup>	4.0 <sup>b</sup>	4.6 <sup>b</sup>	2.4 <sup>a</sup>	s.	s.	s.
	Mg	0.065 <sup>a</sup>	0.067 <sup>a</sup>	0.077 <sup>a</sup>	0.060 <sup>a</sup>	0.075 <sup>a</sup>	0.085 <sup>a</sup>	0.066 <sup>a</sup>	0.080 <sup>a</sup>	0.057 <sup>a</sup>	n.s.	n.s.	s.
	Na	0.22 <sup>a</sup>	0.27 <sup>a</sup>	0.50 <sup>b</sup>	0.25 <sup>a</sup>	0.41 <sup>b</sup>	1.82	0.30 <sup>a</sup>	0.42 <sup>b</sup>	1.48	s.	s.	s.
	K	0.056 <sup>ab</sup>	0.043 <sup>a</sup>	0.049 <sup>a</sup>	0.068 <sup>abc</sup>	0.058 <sup>abc</sup>	0.081 <sup>bcd</sup>	0.105 <sup>d</sup>	0.087 <sup>cd</sup>	0.043 <sup>a</sup>	s.	s.	s.
	Al	0.015 <sup>a</sup>	0.019 <sup>a</sup>	0.026 <sup>a</sup>	0.022 <sup>a</sup>	0.022 <sup>a</sup>	0.018 <sup>a</sup>	0.019 <sup>a</sup>	0.019 <sup>a</sup>	0.016 <sup>a</sup>	n.s.	n.s.	s.
ESP (%)		4 <sup>a</sup>	5 <sup>ab</sup>	10 <sup>e</sup>	6 <sup>abc</sup>	8 <sup>cd</sup>	37 <sup>f</sup>	7 <sup>bcd</sup>	8 <sup>de</sup>	37 <sup>f</sup>	s.	s.	s.
ECEC (cmol/kg)		5.0 <sup>ab</sup>	5.1 <sup>b</sup>	5.2 <sup>b</sup>	4.4 <sup>ab</sup>	5.5 <sup>b</sup>	5.0 <sup>ab</sup>	4.5 <sup>ab</sup>	5.2 <sup>b</sup>	4.0 <sup>a</sup>	s.	s.	s.
EDTA extractable ions (mg/kg)	Cu	1.1 <sup>bc</sup>	0.9 <sup>bc</sup>	1.0 <sup>bc</sup>	0.2 <sup>a</sup>	0.2 <sup>a</sup>	0.8 <sup>b</sup>	1.1 <sup>bc</sup>	1.6 <sup>d</sup>	1.3 <sup>cd</sup>	s.	s.	s.
	Zn	0.3	0.2	0.2	0.2	0.3	0.2	0.3	1.1	0.2	n.s.	n.s.	n.s.
	Mn	0.8	0.9	0.3	1.8	0.8	0.7	0.6	1.3	0.3	n.s.	n.s.	n.s.
Total Al (g/kg)		93 <sup>bc</sup>	90 <sup>abc</sup>	57 <sup>a</sup>	94 <sup>bc</sup>	112 <sup>c</sup>	112 <sup>c</sup>	91 <sup>bc</sup>	97 <sup>bc</sup>	68 <sup>ab</sup>	s.	s.	s.
Total Fe (g/kg)		28 <sup>abc</sup>	25 <sup>ab</sup>	23 <sup>a</sup>	35 <sup>d</sup>	35 <sup>d</sup>	33 <sup>cd</sup>	35 <sup>d</sup>	30 <sup>bcd</sup>	24 <sup>ab</sup>	s.	s.	s.
Phosphorus buffer index (L/kg)		155 <sup>a</sup>	147 <sup>a</sup>	140 <sup>a</sup>	203 <sup>b</sup>	196 <sup>b</sup>	203 <sup>b</sup>	160 <sup>a</sup>	148 <sup>a</sup>	140 <sup>a</sup>	s.	s.	n.s.
		114 <sup>a</sup>	120 <sup>ab</sup>	133 <sup>ab</sup>	153 <sup>ab</sup>	367 <sup>c</sup>	350 <sup>c</sup>	139 <sup>ab</sup>	167 <sup>b</sup>	296 <sup>c</sup>	s.	s.	s.

Where any effect is significant, means within a row sharing the same superscript are not significantly different from each other (Tukey's HSD,  $P < 0.05$ )

n.s. = not significant, s. = significant at  $P < 0.05$

### *Penetrometer Testing*

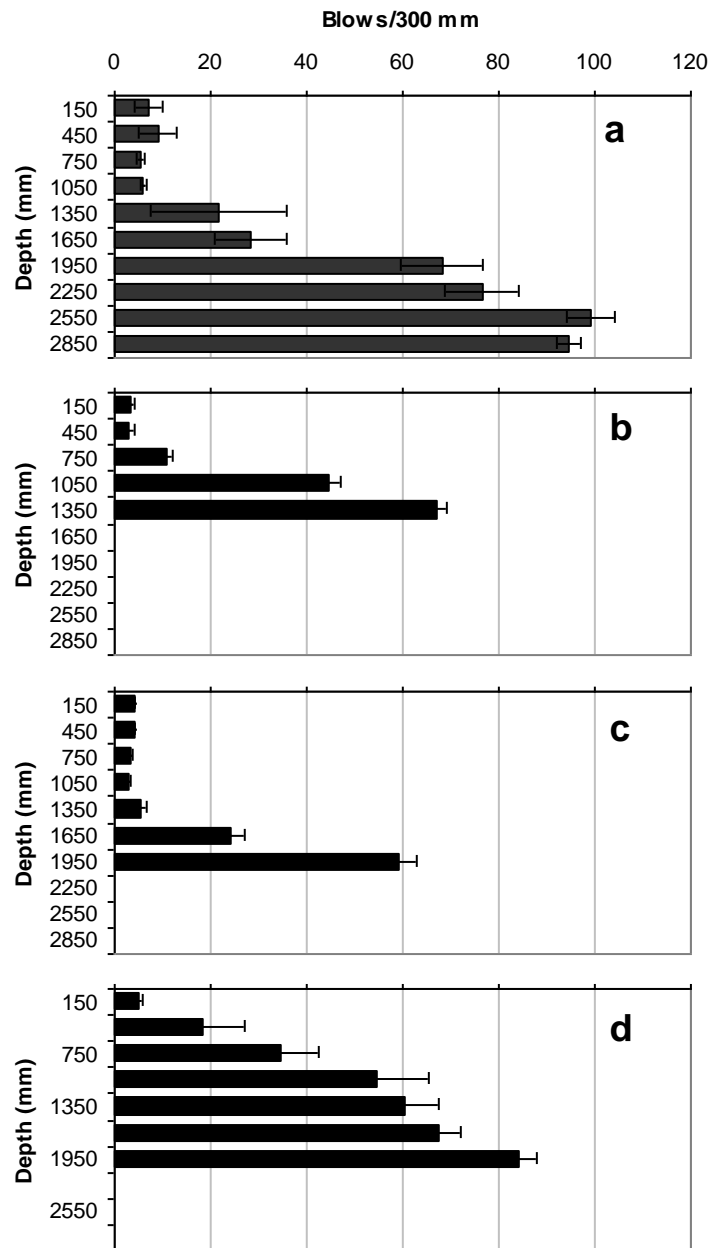
A marked increase in soil compaction was obvious at the maximum depth of gypsum incorporation. This was evident when digging with the Air-spade<sup>®</sup> and mini-excavator, and was quantified by penetrometer testing at the four non-irrigated sites (Fig. 11). At most sites, the number of blows required to penetrate 300 mm rose significantly, 5- to 10-fold, when the depth of incorporation of gypsum was reached, 1.5 m for the 2003 and 2005 deep gypsum sites (Fig. 11a&c) and 0.6 m for the 2005 surface gypsum/non-irrigated site (Fig. 11b). The penetrometer readings for the 2006 deep gypsum/non-irrigated site increased steadily with depth but to similar levels of compaction (Fig. 11d). At this site the depth of incorporation of gypsum was intended to be 1.5 m but due to excavator operator error, incorporation depth was limited to 0.8 m and variable across this site. This would explain the different pattern of penetrometer readings seen at this site.

## **DISCUSSION**

Roots growing in RDA embankments were restricted to uncompacted soil which had been incorporated with gypsum, regardless of the species investigated. The factor most likely responsible for restricting root distribution was the pronounced increase in compaction observed at all sites at the maximum depth of incorporation of gypsum, which varied depending on the site. The most striking evidence for this was the lack of roots below, and the deflection of roots at this compaction layer.

Root deflection is highly indicative of soil compaction impeding root growth (Bennie 1991). Root deflection at a compaction layer has been observed before in Alcoa's residue embankment soil profiles (Cronin 1995, White 1996) and recognised as an impediment to vegetation growth and survival. In addition to root deflection, root growth along grooves in the compaction layer, formed by the excavator bucket has also been observed previously at Alcoa's RDA embankments (Lockley 1997). This root growth could only be attributed to the physical improvement of the soil by the alleviation of compaction. The roots of these species are certainly capable of growing to greater depths, at least in the case of *E. gomphocephala* (see Jasinska *et al.* (1996), Lamont and Lange (1976), and Day (1959)). The compaction layer appears the most likely cause of their inability to do so on RDA embankments. However, our understanding of the role of chemical factors such as potentially toxic chemical species

such as  $\text{Al}(\text{OH})_4^-$  (aluminate), high alkalinity and nutrient deficiencies immediately below the zone of gypsum incorporation is limited and further research is warranted.



**Figure 11:** Mean penetrometer readings in residue sand embankments for **a**, RDA5 non-irrigated deep gypsum 2003 rehab, **b**, RDA5 non-irrigated surface gypsum 2005 rehab, **c**, RDA5 non-irrigated deep gypsum 2005 rehab, and **d**, RDA4 non-irrigated deep gypsum 2006 rehab. Error bars indicate standard error of the mean.

Shallow rooting as a consequence of subsurface compaction, has been identified as one of the key factors contributing to the poor performance of native vegetation used for rehabilitation of Alcoa's residue storage areas (Eastham and Morald 2004). Soil strength is a major factor determining whether a root will penetrate a given layer or

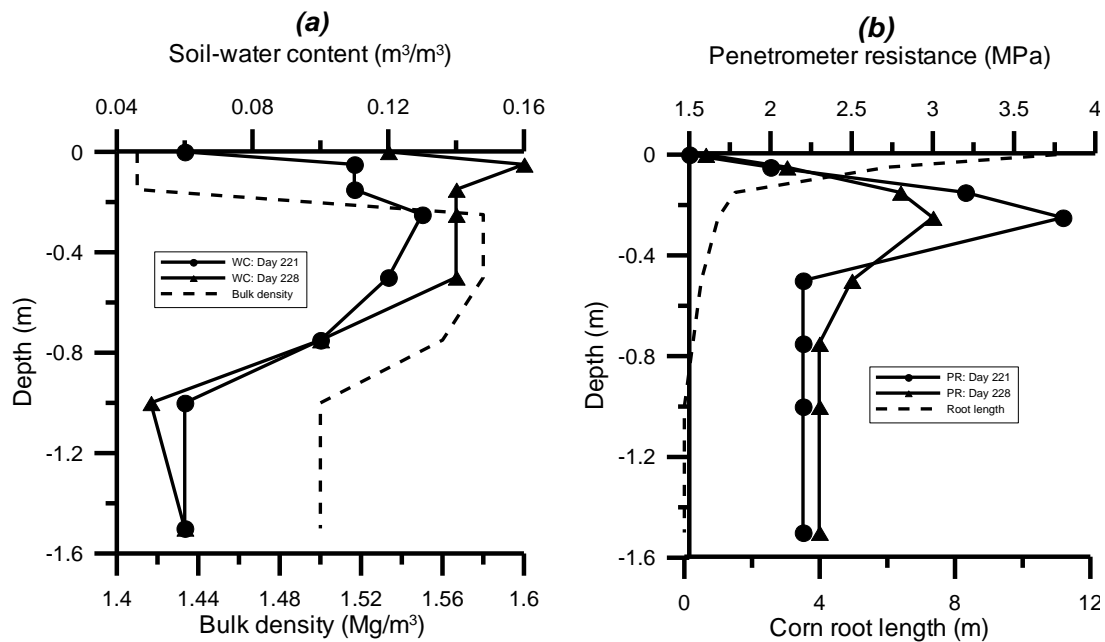
grow horizontally until a weaker zone or structural interface is encountered (Allmaras and Logsdon 1990). When a continuous compacted layer exists below the surface zone (such as observed in RDA embankments), root growth can be restricted almost exclusively to the surface, unless macropores are present (Allmaras and Logsdon 1990). When macropores exist in a compacted layer, preferential root growth occurs in the macropores resulting in a clustered root system. The absence of any identifiable macropores in the compacted zone of residue sand profiles would therefore encourage the shallow rooting and deflection readily observed *in situ*.

Other factors contributing to shallow rooting depths include soil-water retention capacity and frequency of water additions (Laboski *et al.* 1998). Dwyer *et al.* (1988) found that maximum rooting depth for corn increased as available water decreased, implying that coarse-textured and well-drained soils have a much greater rooting depth potential than poorly-drained soils. High-frequency water inputs (eg. rainfall or irrigation) results in more shallow rooting systems than low-frequency inputs due to relatively drier soil conditions at greater depths (Proffitt *et al.* 1985). These findings were consistent with those observed in this study for irrigated and non-irrigated residue rehabilitation (Phillips *et al.* 2008).

Laboski *et al.* (1998) observed corn roots were restricted to a depth of 0.6 m in a fine sandy soil, despite corn commonly having a rooting depth of about 0.9 m. This shallow rooting depth was attributed to a compacted layer within the soil profile that had sufficient mechanical impedance to restrict root growth to greater depths (Fig. 12). This was demonstrated by comparing soil penetrometer data with the upper critical mechanical limit (UCML)<sup>1</sup>. Although mechanical impedance decreased with increasing water content, the compacted layer required water contents exceeding field-capacity to achieve an impedance factor less than UCML. Given that coarse-textured (sandy) soils (such as residue sand) quickly drain to water contents less than field-capacity, reduced mechanical impedance for extended periods of time to allow root penetration would be limited.

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<sup>1</sup> UCML is defined as the soil strength where root growth ceased or was completely a function of mechanical resistance. The lower critical mechanical limit (LCML) is defined as the soil strength where root growth is reduced to 50% of unimpeded growth (Boone *et al.* 1986).



**Figure 12.** (a) Soil-water content and bulk density profiles, and (b) penetrometer resistance and root length profiles, for a sand with a compacted layer between the 0.15–0.6 m depth interval. Day 221 and Day 228 represents soil moisture status prior to and immediately following, a rainfall event (Data from Laboski *et al.* 1998).

Field trials by Eastham and Morald (2004) indicated that subsurface compaction in residue sand may have benefited plant performance (as measured by plant height) due to higher soil-water contents and available soil-water of compacted subsoil. These workers did not undertake a detailed soil-water balance, nor determine key soil hydraulic properties (e.g. hydraulic conductivity) which could have provided evidence to support their conclusions. Furthermore, root densities tended to be markedly less in their compacted treatment, particularly below a depth of 0.5 m where the magnitude of compaction increased significantly (Eastham and Morald 2004). Laboski *et al.* (1998) however did monitor soil-water contents in a sandy soil with compacted subsoil between the 0.15–0.6 m depth interval. These workers found the compacted layer altered the soil’s moisture regime because the lower hydraulic conductivity of the compacted layer increased the volume of plant-available water in this layer. Analysis of the data of Laboski *et al.* (1998) clearly showed that the soil immediately above the compacted layer remained moister than the layers immediately below, and much of the plant roots were located within this upper moisture zone (Fig. 12). This upper zone also exhibited the lowest mechanical impedance. Thus, an alternative description of the effects of a compacted layer on soil-water dynamics could be that while the compacted layer may reduce vertical soil-water flow, this results in more plant-available water

being present above this compacted zone for (non-determined) periods of time. With more plant-available water present in the upper layers of the profile, plants roots may be expected to preferentially extract this water before exploiting water reserves lower in the profile (Klepper 1990; Laboski *et al.* 1998). Whether impedance of vertical water flow by the compacted layer occurs in the residue sand profile is uncertain, but moisture monitoring over the 6 m profile does not support this mechanism. Nevertheless, even small increases in moisture content along this uncompacted/compacted interface may be sufficient to encourage preferential root growth. However preferential root growth was not observed in this study, rather an absence of root growth below the compaction layer and a deflection of roots at this layer. Thus increased mechanical impedance to root penetration and not increased availability of water above the compacted layer is likely to explain the observations made in this study.

The excessive sodicity (as measured by ESP), alkalinity, and presence of soluble Al in residue sand observed at 1.8 m depths in 2005 and 2006 sites may be sufficiently toxic to inhibit root growth. For example with alkalinity, root necrosis occurred in *E. gomphocephala* plants, and other local species, exposed to increasingly alkaline conditions by addition of NaOH by drip irrigation in sand pot experiments (Bell *et al.* 1993). These plants died quickly in sand pH > 10 and were exhibiting reduced growth rates and stress symptoms well before this at pH > 8 (Bell *et al.* 1993). With soluble Al, the dominant Al species at pH > 9 is expected to be  $\text{Al}(\text{OH})_4^-$ ; however it is unknown if the presence of  $\text{Al}(\text{OH})_4^-$  would have a detrimental effect on root growth. Fuller and Richardson (1986) consider it to be toxic to plant growth but Kinraide (1990) does not. Kopittke *et al.* (2004) found that  $\text{Al}(\text{OH})_4^-$  was not toxic to mungbean root growth, but subsequent formation of polycationic Al was the main cause of poor root growth. The effect of soluble Al on root growth by native coastal vegetation grown in residue sand is currently unknown and warrants further research. However the levels of ESP, alkalinity, and soluble Al observed at 1.8 m in the 2003 site were not excessive or significantly different to shallower samples where roots were growing; however roots were also absent at this depth in this site. Therefore the only property of residue sand common to all the ages of rehabilitation investigated that could explain the restriction of root growth at depth is soil compaction.

This conclusion supports the contention that the role of residue sand chemistry on root growth is currently uncertain and warrants more fundamental research. Importantly, this conclusion also suggests that if the chemical characteristics of residue sand are not a major limitation to root growth, then greater root penetration may be accomplished by deep ripping only.

The root distribution observed in this study appears to be strongly related to gypsum incorporation depth and distribution within the residue sand profile. Below the zone of gypsum incorporation, changes in residue sand chemistry will be dependant on the rate of gypsum dissolution and subsequent movement with drainage. Since gypsum dissolution is low (approximately 2 g/L), amendment of residue sand below the zone of incorporation will be dependant on dissolution rate coupled to leaching rate. Results from this and related studies (Phillips *et al.* 2008) suggests gypsum leaching to depths below the zone of incorporation may not be evident for 3 to 4 years after addition. As these changes in residue sand chemistry occur at depth, like those seen in the 2003 rehabilitation site, concomitant root growth into underlying residue sand may be expected. However this was not observed in 2003 rehabilitation site, most likely due to soil compaction.

The restriction of root distribution in RDA embankments due to mechanical impedance by soil compaction is likely to have a number of physiological impacts on the rehabilitation vegetation. The roots will be restricted to a smaller volume of soil, primarily the surface 1.5 m, so plants will more quickly suffer drought stress going into the summer months as the residue sand moisture content declines to wilting point ( $\theta_{pwp} \approx 0.03$ ). *E. gomphocephala* at least, if not other species in the rehabilitation, has the potential to be much deeper rooted than was observed on RDA embankments. Nutrient uptake could be reduced as a result of restricted rooting depth, leading to deficiencies, especially in more mobile elements such as K and Cl, in the initially very low levels of Mg, and in essential micronutrients (Bennie 1991; Bell *et al.* 2008). These physiological impacts will ultimately lead to reduced plant survival and performance.

## CONCLUSIONS

This study has identified restricted root distribution in vegetation growing in rehabilitated residue sand embankments. The presence of greater compaction

immediately below the gypsum incorporation zone appears to be the most likely cause of restricted growth. Poorly performing vegetation (evident by stunted growth) due to restricted root distribution would not be expected to be a high user of water, regardless of increased water availability during the wet winter months. The suggestion that increased compaction represents the primary cause for root growth introduces uncertainty into the role of residue sand chemistry on restricting root growth. This aspect of residue rehabilitation performance warrants further attention.

From an operational perspective, maximising water use by the vegetation is critical if evapotranspiration (or store and release) covers are to be considered as effective systems to reduce deep drainage. If rooting depth restriction is a major factor in the poor performance of residue rehabilitation vegetation, as this investigation suggests, then improving root penetration by using a deeper ripping tine to incorporate gypsum to greater depths (say to 3 m) may encourage deeper root growth penetration. This has the potential to increase plant access to water, leading to better vegetation performance and greater potential use of water.

## **RECOMMENDATIONS**

It is recommended that:

- The role of chemical properties of residue sand on restricting plant root growth be determined. The finding from this work will provide important information on whether compaction relief will encourage deeper root penetration, or improved chemical properties of residue sand is also required.
- The findings from this study be combined with results from similar university studies to quantify the importance of plant-water use on controlling water movement in residue sand embankments.
- Undertake monitoring of trial plots which were established in 2007 and had gypsum incorporation to a depth of 3 m. Given that root growth can be approximated to occur at roughly 1 m per year, then data in 2010 may demonstrate the benefits of very deep gypsum incorporation.

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