REVEGETATION OF GOLD RESIDUES IN THE EASTERN JARRAH FOREST IN THE SOUTH-WEST OF WESTERN AUSTRALIA[1]

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Abstract. Revegetation of mine residues (tailings) is an important aspect of rehabilitation after mining, and represents a substantial investment. Therefore it is important to increase our understanding of all aspects of re-establishing a sustainable vegetation community on these materials. We report here on a multi-disciplinary, collaborative research program, focusing on vegetation establishment, soil development, and water-balance modeling on a large residue revegetation experiment.

The study focused on gold residues produced at the Boddington Gold Mine (BGM) and Hedges Gold Mine (HGM), in the south-west of Australia. The residue storage areas will be rehabilitated once no longer required, but revegetation may be hampered by the alkaline, saline, and sodic properties of the residue. A large field experiment was established to examine soil amendments and capping strategies. The treatments were three depths of gravel-rich subsoil (0 cm, 15 cm, and 30 cm) overlying residue treated with gypsum (30 t/ha). All plots subsequently received an application of topsoil (10 cm). The plots were established in 1999 with species from the local jarrah (*Eucalyptus marginata* Donn. ex Smith) forest, or salt- and waterlogging-tolerant native species.

Ten months after application, gypsum had contributed to a decrease in residue pH and salinity. By March 2000, approximately 90% of the directly seeded species had emerged and survived, and 100% of transplanted seedlings had survived. Applying gravel subsoil in addition to topsoil did not improve plant growth in the first two years. In fact, aboveground biomass production was higher, from 4 to 8.5 t/ha/yr, in the absence of a gravel subsoil. However, in the third growing season, this trend was less apparent.

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Plant roots were found to grow into the residue, preferentially following shrinkage cracks and exploring coarser-textured layers. Vigorous plant and root growth, and thus high plant water use, has resulted in substantial drying of the residue profile. On-going studies are examining water and salt movement through these profiles and long-term plant performance. At the same time, an overall model is being developed to predict the net water balance if the whole residue area was vegetated.

Additional Key Words: root growth, salinity, topsoil, water balance modeling.
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Introduction

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Revegetation of mine residues (tailings) is an important aspect of rehabilitation after mining, and requires a substantial investment. Therefore it is important to increase our understanding of all aspects of re-establishing a sustainable vegetation community on these materials. A multi-disciplinary, collaborative research program, focusing on vegetation establishment, soil development, and water-balance modeling was conducted on an area of gold-processing residue near Boddington in the eastern jarrah (*Eucalyptus marginata* Donn. ex Smith) forest, 125 km south-east of Perth, Western Australia. Gold-processing residue was produced at Boddington Gold Mine and at Hedges Gold Mine, and deposited in valley impoundments known as Residue Storage Areas (RSAs). These areas will be rehabilitated once no longer required, but rehabilitation efforts may be hampered by residue properties that are not only very different from the soil properties of the surrounding jarrah forest, but also generally unfavorable for plant growth (Ho et al. 1999).

As part of the mining companies' commitments to environmental management and closure planning, the RSAs must be rehabilitated, by stabilizing and revegetating the residue. The major issues confronting rehabilitation are impacts on the hydrology of the surrounding jarrah forest, quality of groundwater and surface water, the time taken for the RSAs to fully consolidate, and the long term success of revegetation of the RSAs.

The natural vegetation cover of the area surrounding the mines is open eucalyptus forest. The ecosystems that exist within this vegetation are self sustaining, characterized by high biodiversity, and efficient nutrient cycling and water use (Dell et al., 1989). Relatively little water or nutrients are lost from these ecosystems (Dell et al., 1989). They are resilient to periodic fire and drought stresses. End land uses for the rehabilitated residue storage areas have to be compatible with the vegetation and land uses of the surrounding forest.

Gold oxide residue, like most ore-refining residues, is a challenging material to revegetate and it is characterized by chemical and physical conditions not found in the jarrah forest, and which limit soil biological processes and the growth of most plants. It generally has a very low hydraulic conductivity, high pH, high surface salinity, and moderately saline at depth. Residue storage areas therefore tend to have dry, salt-crusted surfaces in summer, and in winter become waterlogged with areas of perched surface water (Ho et al. 1999).

In this paper we describe research related to three objectives of the project, which were to:
i) Develop an understanding of soil-water dynamics in the rooting zone of rehabilitated residue, and its response to residue treatment and vegetation growth.
ii) Develop an understanding of pedogenesis in the topsoil/subsoil/residue profiles, especially in relation to the role of shrinkage cracks, the evolution of structure, and the capacity of roots to explore the residue.
iii) Determine and model changes in water balance on the residue areas as a whole. This will include the effect of vegetation on water balance and leachate production in the medium and longer term.

Materials and Methods

Site description and characterization

Boddington has a Mediterranean climate with winter rainfall (760mm annually) and hot dry summers. The majority of gold ore at both mine sites was extracted from the oxide clay/saprolite layer approximately 15 to 60 meters in depth. Gold was recovered from the ore by the carbon-in-leach process and the refining residue was deposited into purpose-built RSAs as a tailing comprising approximately 38% solids in process water. The solids are predominantly silt to clay-sized material and after consolidation and evaporation, make up about 60% (w/v) of the residue's bulk. Vertical shrinkage cracks occur at the residue surface as it consolidates and dries. These cracks may be up to 4 cm wide at the surface, and generally reach to a depth of 1 to 2 meters, but erosion and slumping tends to cause the cracks to fill in with loose material over time.

In order to define the most appropriate arrangement of plots and treatments, variability in residue physical and chemical characteristics over the field area was defined. The physical and chemical characteristics of the residue examined included field texture, % water content, depth, critical shear strength, pH, and electrical conductivity (EC). The sampling program examined the top 50 cm of residue, with the most intensive sampling in the top 10 cm. Depth and shear strength was measured using a Dynamic Cone Penetrometer (DCP), to a maximum depth of 2 m.

The residue was alkaline (average pH (1:5 water) of 9.6). The salinity of the residue varied with depth and position from the RSA beach. $EC_{1:5}$ (1:5 soil-water extract) was typically between 2.5 and 5 dS/m (TDS 12,000 and 23,000 mg/L) in the surface 10 cm layer of residue, but was much less below this depth, decreasing to around 1.0 – 1.5 dS/m (4700 to 7000 mg/L TDS) 30 cm below the surface. The nutrient concentrations of residue did not vary across the field experiment site but did tend to differ with depth (Table 1). Surface residue (24% (w/w) water) was slightly drier than underlying layers (29% water), which increased progressively in water content with depth. Shear strength of the residue decreased with depth and increasing distance from the edge of the RSA.

Treatments applied

The main treatments examined were three depths of gravel-rich subsoil, (referred to as "gravel") (0, 15, and 30 cm) overlying the residue. These were applied after gypsum (30 tonnes ha^{-1}) was broadcast, and all were followed by a final layer of topsoil (10 cm). The different gravel treatments were designated Treatments 1, 2, and 3, respectively. The field experiment also included two secondary treatments of additional gypsum (total of 60 t ha^{-1}) or an application of compost (50 m^3 ha^{-1}) to the residue surface. The topsoil and gravel materials had been stockpiled separately for approximately 10 years, after being removed from the base of the RSA before residue deposition. The topsoil is a sandy gravel soil with some organic matter, while the gravel is made up principally of ferruginous gravel and sand. The treatments were replicated four times in a randomized block design, with the blocks located according to the patterns of surface residue texture, and each block being at least 45m by 30m.

Table 1. Chemical analysis of gold residue at 0-10 cm and 20-30 cm depth, sampled Jan/Feb 1999, in comparison to previous analysis (Bell et al., 1997), and to topsoil and gravel sampled at field experiment in May 1999. (± s.e., n=4)

Parameter[1]	**Residue 0-10cm depth (25/01/99)**	**Residue 20-30cm depth (15/02/99)**	**Residue treated with gypsum and then leached**[2]	**Topsoil (26/05/99)**	**Gravel (26/05/99)**
$NO_3 + NH_4$ (mg/kg)	25 ± 4	16 ± 6	2 ± 0	10 ± 1	8 ± 0.2
Total N (%)	0.01 ± 0	0.04 ± 0.01	N/A[5]	0.16 ± 0.03	0.09 ± 0.02
Colwell P[3] (mg/kg)	10 ± 0.6	5.8 ± 1.5	29 ± 1	2.8 ± 0.2	3.2 ± 0.9
Colwell K[3] (mg/kg)	520 ± 30	500 ± 50	260 ± 20	83 ± 7	46 ± 5
Sulphur[4] (mg/kg)	640 ± 24	310 ± 49	N/A	15 ± 2	66 ± 21
Organic Carbon (%)	0.14 ± 0.01	0.13 ± 0.01	1.8 ± 1.2	1.6 ± 0.1	0.87 ± .13
Reactive Fe (mg/kg)	430 ± 10	510 ± 60	N/A	1940 ± 250	1450 ± 190
Exchangeable cations (cmol/kg)					
Ca	1.00 ± .03	1.01 ± 0.14	1.4 ± 0.1	2.5 ± 0.16	2.2 ± 0.2
Mg	0.91 ± 0.02	1.01 ± 0.07	1.2 ± 0.1	0.85 ± 0.05	0.71 ± 0.06
Na	24.4 ± 1.0	8.1 ± 0.9	17.3 ± 0.1	0.3 ± 0.06	0.2 ± 0.03
K	0.2 ± 0.01	0.2 ± 0.01	0.3 ± 0.02	0.2 ± 0.02	0.1 ± 0.01
EDTA extractable micronutrients (mg/kg)					
Fe	30 ± 1	34 ± 5	N/A	210 ± 40	130 ± 20
Cu	25 ± 2	22 ± 3	11 ± 0.1	1 ± 0.1	1 ± 0.1
Zn	1 ± 0.1	1 ± 0.1	1 ± 0.1	0.3 ± 0.1	0.4 ± 0.3
Mn	4 ± 0.2	5 ± 1.2	2 ± 0.1	11 ± 1.0	8 ± 1.5

[1] Page et al., (1995) unless otherwise stated. [2] From Bell *et al*. (1997) [3] Colwell (1963).
[4] Anderson et al. (1992), [5] Not available

After spreading topsoil, the plots were cultivated by tynes to a depth of 10 cm. The plots were seeded in early May, 1999, initially at a rate of 1.5 kg ha^{-1}, and a 'top-up' seeding of 0.6 kg/ha two weeks later. The seed mix was a blend of species known to occur in the jarrah forest that surrounds the site, together with selected salt- and waterlogging-tolerant Australian native species. In addition, twenty-nine plant species were transplanted into plots in mid-July 1999. The eight month-old nursery grown seedlings comprised selected species from the seed mix list, and were included to allow early observations of plant survival and vigor. In early September

1999, seven further species were selected from remaining seedling stock and planted along side the earlier planted seedlings. Inorganic fertilizer was broadcast over the entire field experiment (5 ha approximately) in late August 1999 using a helicopter and suspended hopper to distribute the dry mix evenly (Table 2).

Table 2. Constituents and rate of inorganic fertilizer application, 28th August, 1999.

Fertilizer Constituents	Target Application Rate (kg/ha)
Urea	150
Super phosphate with Cu Mo Zn	400
Superphosphate	400
Muriate of Potash	60
$MnSO_4$	24
TOTAL	1034

<u>Analyses and monitoring</u>

From October 1999 to March 2001, the topsoil, gravel and residue (to 30 cm depth), were sampled five times. Generally, three sub-samples were taken from each plot, separated according to depth (Figure 1), and then sub-samples from each section were bulked to provide a sample for each specific part of the profile in each plot. Data from the four replicate plots of each treatment, were then used for statistical comparisons between treatments. In bare residue, only two sub-samples were taken from each of the four plots in which the residue was sampled at 10 cm intervals to a depth of 30 cm.

In late March 2000, six trenches (3 m long x 1.2 m wide) were excavated by a backhoe to a depth of approximately 1.5 m, in one plot, of each of treatments 1 and 2 (3 trenches in each). Samples were taken from the trench face at the residue interface and at 15, 40, and 80 cm depths. Samples from each of these depths were extracted at the edge of a vertical crack, 15 cm away (in a horizontal plane approximately at right angles to the crack), and 30 cm away from this crack. Three crack sites were sampled for each trench. Sample grids were also established on the trench walls for more detailed residue sampling and root density examination.

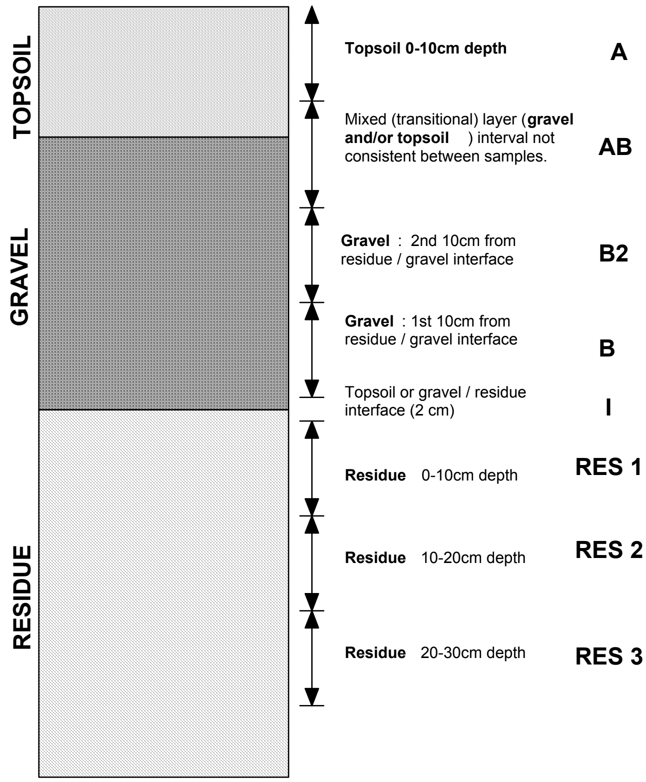


Figure 1. Sectioning of soil core samples. Treatment 1 (10 cm topsoil only) did not have an AB, B2, or B section. RES 3 was not sampled for Treatment 2 and 3.

Detailed soil analyses included nitrate, ammonium, and total N, Colwell P, Colwell K, KCl-40 S, organic C, exchangeable Ca, Mg, Na, and K (see Table 1 for methods). DTPA or EDTA extractable Cu, Zn, Mn, and Fe were also measured for selected samples from these batches. Samples taken during the trench excavations were analyzed by Barnes (2000) for cations in soil solution (Ca, Mg, and Na) by saturating samples, vacuum filtering, and analysing the leachate using ICP. Exchangeable cations (Ca, Mg, and Na) and cation exchange capacity (CEC) were also measured, and SAR and ESP were calculated from this data. The distribution of salts across the trench face was measured as changes in apparent EC by Boyle (2000) using a hand-held conductivity probe, with particular emphasis on areas adjacent to cracks. Salt distribution data was mapped using the Spatial Analyst module of ArcView.

Gravimetric water content was determined for residue samples taken in February 1999, February 2000, and March 2001, at 10 cm depth intervals to at least 20 cm. Samples were taken from each replicate plot at 3 sample locations at increasing distances from the edge (A, B, and C respectively). Difficulties were encountered when attempting to sample residue underlying the thicker gravel treatment (Treatment 3) in March 2001, as the sampling equipment could not penetrate the gravel layer. Neutron probe measurements of volumetric water content were conducted every 2-3 months from November 1999 to July 2001 in four plots at intervals of 0.2 m to a depth of 3 m.

Identification of emerged seedlings

The term 'emerged seedlings' is used here to identify seedlings recruited from seed present in the topsoil and from hand broadcasting in May 1999 and distinguish them from transplanted seedlings. The monitoring of establishment and growth of emerged seedling was done by sampling four 4 x 4 m quadrats arranged systematically in each of the four replicate plots for the three gravel treatments. Monthly vegetation assessments of emergence and seedling density were conducted from August 1999 to March 2000, again in October 2000, and finally in April 2001.

The October 2000 and April 2001 assessments were more intensive flora surveys, in which the majority of seedlings were identified to species level (McGrath, 2001). These were the main data sets used to characterize species diversity and composition. Within each quadrat, the following data was recorded in October 2000 and April 2001:

- Overall % live foliage cover;
- Number of individuals of each species present (separated into live and dead);

Individuals that were not rooted inside the quadrat were not included in the count of individuals, although overhanging foliage was included in the assessment of live cover.

Results and Discussion

Plant establishment

On cultivated, gypsum-treated, bare residue, recruitment from broadcast seeding was limited to a few halophytic species. However, 21 out of 30 species survived when transplanted as seedlings in the bare, cultivated, gypsum-treated residue. These included five species from the neighboring jarrah forest. Topsoil spread on residue substantially increased seedling recruitment and survival of plants (Figure 2). However, recruitment from seed in the stockpiled topsoil was minimal. Of the species with > 75% survival, 31 % were jarrah forest species in Treatment 1 (with 10 cm of topsoil only on residue), and 39-48 % in Treatments 2 and 3 (with 15 or 30 cm of gravel between topsoil and residue). Plant diversity levels after 2 years were comparable to that achieved in rehabilitation of jarrah forest after bauxite mining in this region (Nichols, 1998).

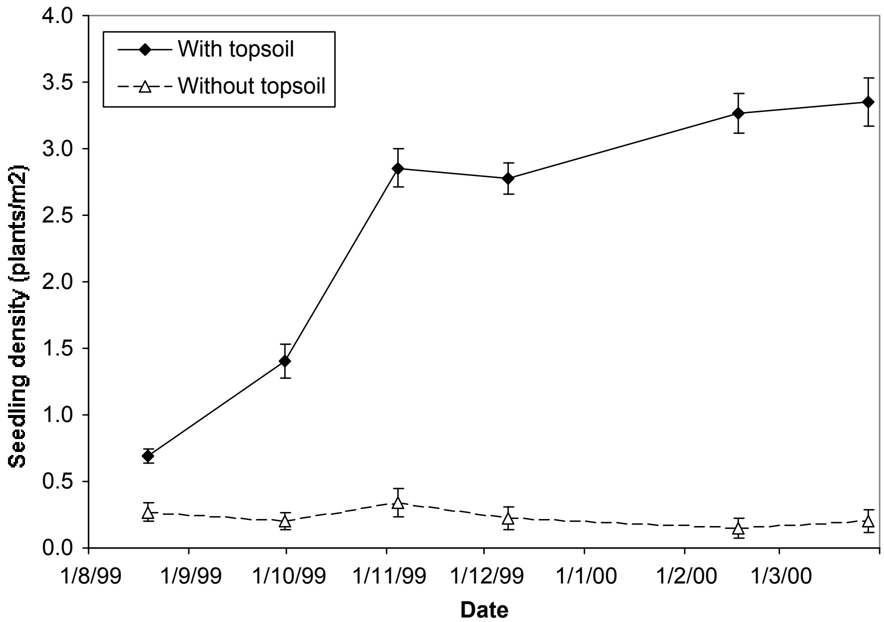


Figure 2. Plant density in field experiment on replicate plots (4) with topsoil and bare residue (BR) plots without topsoil from August 1999 to March 2000. Means of 48 quadrats across 3 gravel treatments for replicate plots and of 12 quadrats across two gypsum treatments for BR plots. Vertical bars indicate standard errors (adapted from Brion, 2000).

Plant growth response to the gravel subsoil treatments

In the first two years, plant growth was substantially more vigorous with 10 cm of topsoil only on residue (Treatment 1), and significantly retarded with 15 or 30 cm of gravel between topsoil and residue. Above-ground biomass production increased from 4 t/ha/yr (Treatments 2 & 3) to 8.5 t/ha/yr (Treatment 1) (Huggins et al., 2002). This growth difference was also reflected in cover values for each treatment (Figure 3). The improved growth with 10 cm topsoil only was attributed in part to improved access to water and nutrients stored in the residue, and in part to inhibited root growth in the gravel due to low water and nutrients, and possibly compaction. Analysis of *Eucalyptus camuldulensis* in June 2000, found that the N concentration in young leaves was significantly higher in those seedlings sampled from the no gravel treatment (T1) compared to with 15 cm gravel (T2) (data not shown). After 18 months of growth, it appeared the increased vigor and cover of plants in plots with 10 cm of topsoil only had begun to suppress species richness and species diversity (data not shown).

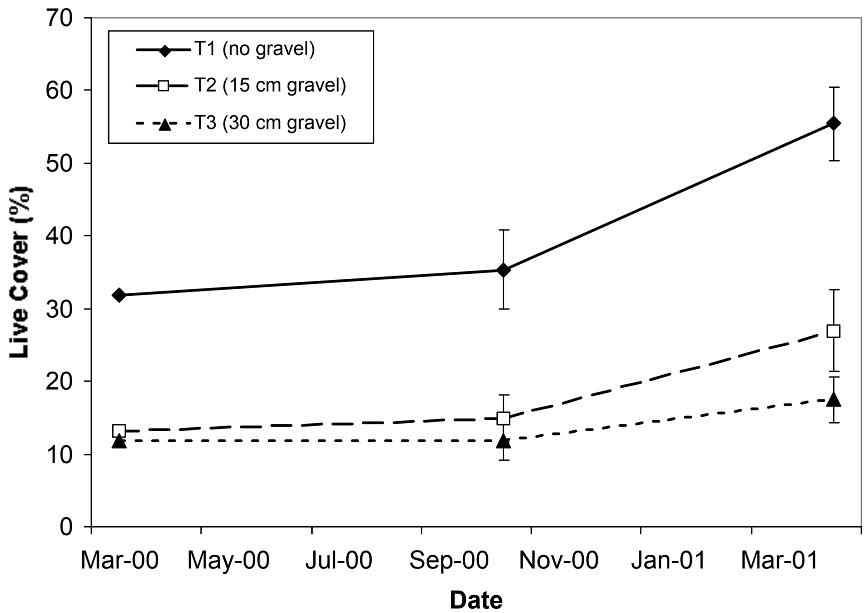


Figure 3. Live cover of foliage recorded for 3 gravel treatments from March 2000 to April 2001. Mean of four replicates. Bars indicate standard error.

Compaction may have been a factor in the poorer performance of treatments with a gravel layer. During site preparation, the gravel layer was trafficked repeatedly and there is evidence from the penetrometer measurements that increased compaction occurred in the gravel layer but the implications of this for root growth, and hence water and nutrient uptake have not been clearly determined. Assuming that ripping would be conducted in future rehabilitation operations, the poorer performance of the treatments with gravel layers compared to those with only topsoil, is likely to be less marked. Growth on gravel-treated areas would also be increased by the provision of sufficient nutrient sources, such as compost, to compensate for the low nutrient status of the gravel.

Increased plant growth, in Treatment 1 (no gravel) has caused the residue (16% w/w water) to dry out to a greater extent compared to that in treatments with thicker gravel layers (21% moisture) (Treatments 2 and 3 (15 and 30 cm gravel respectively)). However, there were generally minimal differences between plants in these treatments as measured by plant water potential (data not shown). There were no discernible differences between the plant growth in plots with 30 t gypsum/ha applied to the residue and subplots with twice as much gypsum applied (60 t/ha) based on % live cover, seedling heights, and seedling densities (data not shown).

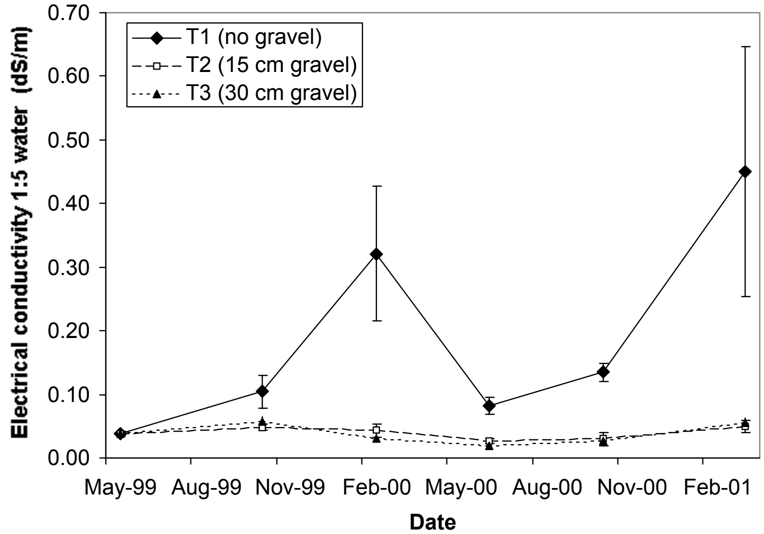
Changes in salinity and pH

The topsoil/gravel layers reduced salt accumulation in the soil surface in proportion to their thickness, preventing a typical salt build up in summer that occurred prior to the experiment. Nevertheless, salt levels increased in topsoil or gravel layers that were immediately above residue (Figure 4). The levels of salt tended to oscillate with increases during summer and early autumn followed by decreases under winter rainfall. Whilst salt accumulation was greater in the topsoil and gravel in summer of the second year, this was attributed to the very low rainfall. Concentration of salts in the surface 10 cm of residue decreased significantly each winter, presumably due to migration of salts into overlying soil layers, lateral flow and runoff, throughflow into cracks, and leaching through profile (Figure 5).

Salinity in topsoil (without gravel) and subsoil (with gravel) will need to be monitored, as rises in summer 2001 were a concern. Continued increases in salinity over time may impact on plant growth and survival. By March 2001, the topsoil salinity of Treatment 1 (no gravel) was an order of magnitude greater than that of Treatment 2 and 3 (15 cm and 30 cm gravel) (Figure 4).

The favorable conclusions regarding the topsoil-only treatment need to be tempered in light of the increasing salinity levels in topsoil overlying residue, particularly when spring and summer rainfall is low. The first year was favorable for leaching of salts from the topsoil during summer as several atypical heavy rainfall events occurred. In a more typical summer, there may well be enough salt accumulation in the topsoil in the first year to inhibit plant growth or decrease plant survival. There is evidence that salt sensitive species from the local jarrah forest were less abundant with topsoil only and exhibited symptoms of salt injury. Hence the prospects of achieving significant establishment and survival of these species were diminished by omitting the gravel, even though overall early vigor was enhanced.

(a) Topsoil



(b) Gravel

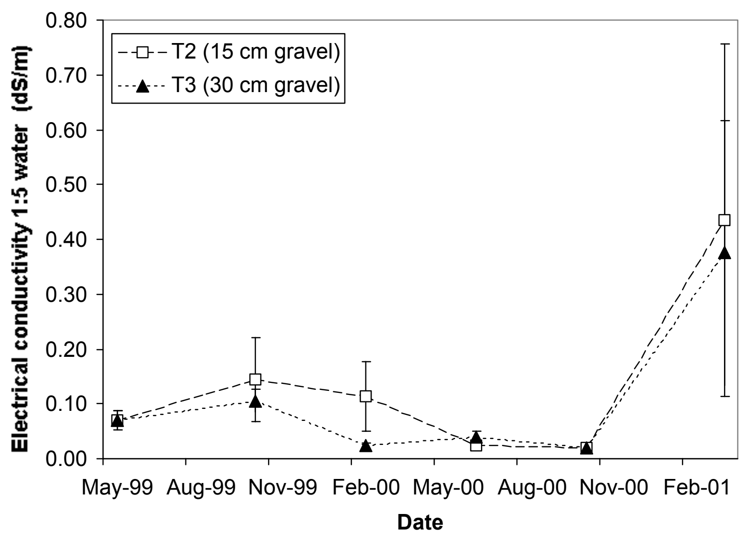
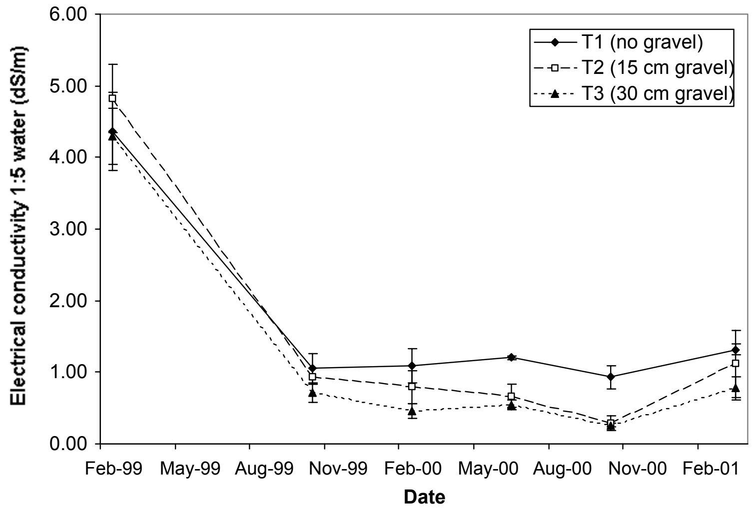


Figure 4. Electrical conductivity in a 1:5 extract with water of (a) topsoil (0-10 cm) and (b) gravel (first 10 cm above residue interface), for three gravel treatments, from Feb 1999 to March 2001. Bars indicate standard error.

(a) Surface residue (0 – 10cm)



(b) Residue at 10-20 cm depth

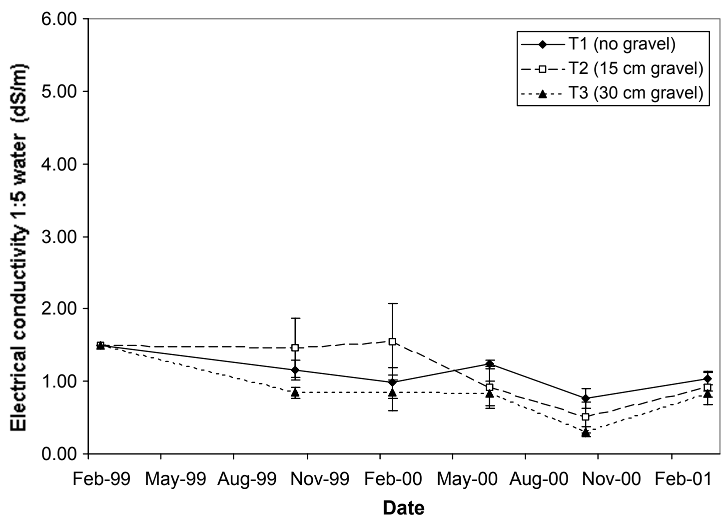


Figure 5. Electrical conductivity in a 1:5 extract with water of (a) surface 10 cm of residue (RES 1) and (b) residue 10-20 cm depth (RES 2), for 3 gravel treatments from February 1999 to March 2001. Means of 4 replicates except February 1999, which were calculated from corresponding data in the site characterization sampling grid.

The residue layers contained vertical shrinkage cracks formed as the residue dried, and excavations revealed that there were numerous finer cracks running vertically and laterally through the residue, connecting the larger cracks. The EC at the face of major cracks (>0.5 cm wide) was higher than that 15 and 30 cm into the body of residue (Boyle, 2000) (Figure 6). It was also found that minor crack faces had higher salt levels than within the residue blocks, with the salinity increasing with crack width and depth. In large cracks, increased evaporation due to faster water vapor transport to the ground surface is likely to lead to greater EC. Higher salt levels at the crack surface could also be related to the high density of roots in and around these cracks. As plant roots take up water, salts may be excluded, and the drying of the surrounding residue causes more soil solution to migrate to replace the absorbed water, consequently transporting more salts with it.

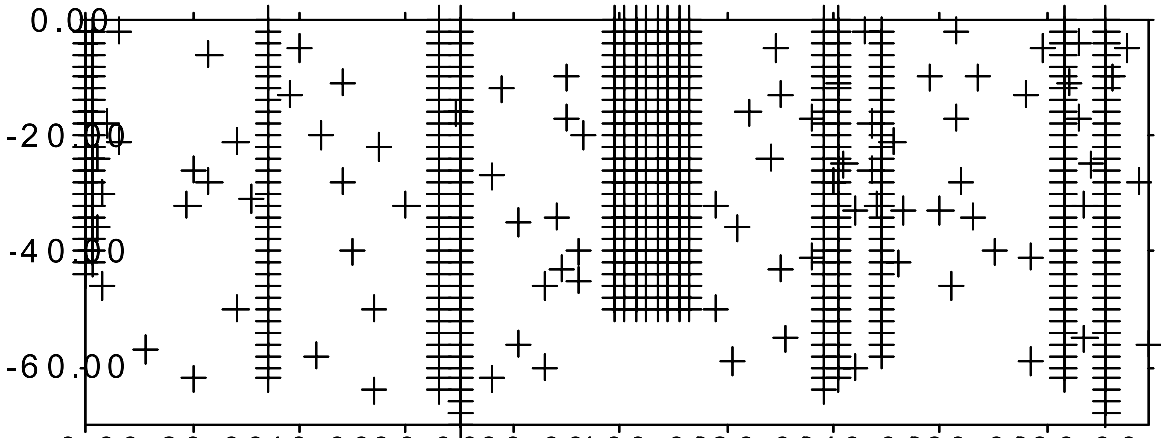
Following gypsum application and spreading of topsoil and gravel over residue, pH decreased by one unit (pH 9 to pH 8) (data not shown). After two years, there are no indications that pH was returning to original levels. Effects of gypsum application decreased with depth, but despite no cultivation to incorporate gypsum, a pH decrease occurred to at least 20 cm. Vertical shrinkage cracks appeared to provide a pathway for localized amelioration of pH by gypsum to a depth of 50-100 cm. Two years after application, there were no obvious effects of doubling the gypsum application rate from 30 to 60 t/ha on residue pH or sodicity.

<u>Root growth in the reconstructed profile</u>

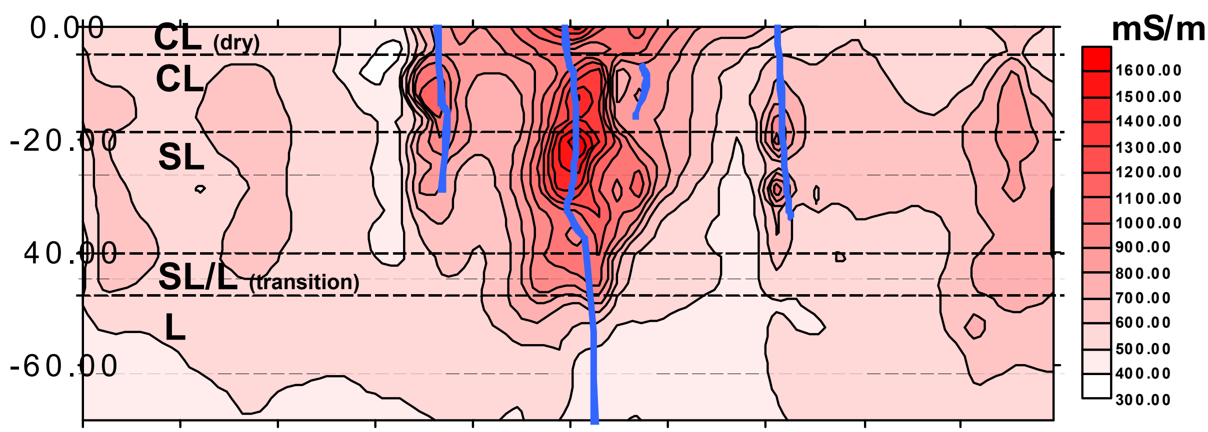
Excavations in March 2000 revealed that plant roots (plant species not identified) were growing into the residue profile to depths greater than 1.2 m below the residue surface. Roots were in abundance in the topsoil in all trenches but less dense in the gravel layer in the 15 cm gravel plot. Large numbers of tap roots and small feeder roots were found growing horizontally across the residue surface at the soil / residue interface. Roots were found to extend horizontally up to 5 m through the residue layers (Mr S. Kumar (University of W.A.), personal communication).

The majority of large roots found in the residue were growing along the faces of the vertical cracks, particularly if the crack was filled with loose soil / gravel. Roots were found to be exploring these cracks preferentially throughout the profile. This correlates with visual and physical evidence that the cracks are also pathways for water flow. Layers of coarser-textured residue appeared to have some structure, with aggregation of particles and improved porosity, and roots were observed growing preferentially into this layer presumably by exploiting the increased macropore space.

(a)



(b)



------ **Boundaries of residue layers with differing texture**

Major cracks

Figure 6. (a) Sampling distribution on the vertical section of residue used for apparent EC measurements by Sigma Probe and (b) resulting salinity (mS/m) contour map of west face of Trench 2 (Plot 13) measured in April 2000. Layers of differing texture identified by CL – Clay Loam (27 % clay), SL – Sandy Loam (13 % clay), and L – Loam (16 % clay).

Roots were observed to be growing in greater abundance and at greater depth in Treatment 1, compared to that in the 15 cm gravel plot. There were also some indications that root penetration through the soil / residue interface into the residue may have been greater in the subplots with 60 t gypsum/ha.

Water balance modeling

Investigation for water balance modeling revealed that the water balance behavior of the residue profile is dominated by the capacity and connectivity of residue shrinkage cracks. Shrinkage cracks were dominant in the near-surface residue, due to exposure to evaporative drying. Rainfall upon the residue surface is readily infiltrated into the fracture network, percolating downward to the base of cracks, or until the crack becomes blocked. Downward percolation into the underlying residue matrix is very limited, while lateral movement along the interface of coarse residue lenses may occur. The result of this is that the ability of the near-surface residue to infiltrate and percolate water from the surface greatly exceeds the ability of the deeper residue profile to receive and percolate water. This can result in perched water and run-off.

In the center of the RSA, residue texture becomes finer due to the spigotting method of deposition used, and a pond overlies the residue surface, preventing drying and consolidation. This region therefore is expected to have no cracking which, along with having the finest residue texture within the RSA, makes vertical and lateral conductivity extremely slow.

The rehabilitation treatments have had several direct impacts upon the water balance behavior of the residue profile. Firstly, the application of topsoil and gravel allowed this material to fill residue shrinkage cracks that are open at the residue surface. This stabilized these cracks, which otherwise would tend to fill with residue sediment over time. The topsoil and gravel layers also act as an additional store for water; percolation into the residue profile in winter only occurred once the soil moisture deficit of the topsoil and gravel layers had been satisfied. However, the topsoil and gravel layers also acted to insulate the residue from evaporation, reducing the extent of drying in the residue over summer. The topsoil and gravel layers tended to retard infiltration into the residue profile, possibly by restricting lateral flow towards cracks at the residue surface.

A final, important impact of topsoil and gravel addition relates to their differing ability to support vegetation growth. Improved vegetation growth is directly associated with increased plant water usage, which minimizes the amount of excess water available for seepage and runoff. The long-term sustainability of this improved vegetation growth is an important issue requiring investigation.

A relatively simple capacitance modeling approach has exhibited a reasonable ability to simulate these water balance behaviors at an individual plot scale. A laterally-connected areal model, which uses the plot-scale (cell) model as a 'building block', has also been shown to capture basic patterns in the spatial variability in hydrological response in the sub-surface of the RSA. Further refinement is being carried out to accurately reflect the hydrological conditions over the whole RSA.

Conclusions

This detailed rehabilitation experiment examining soil replacement and residue amendment strategies for gold residues has demonstrated that successful rehabilitation with native species appears likely. Generally, the growth of plants exceeded expectations and a wide range of species have proved suitable for use in rehabilitation of these residue storage areas, including many from the adjacent jarrah forest. The requirements for optimum vegetation establishment appear to be: treating the residue with gypsum to assist in the reduction of salinity, sodicity, and alkalinity; using 10 cm of a sandy gravel topsoil covering on residue to maximize the survival and establishment of seedlings over the first year, and; providing adequate nutrient sources for plant growth.

If growth on treatments with gravel layers can be improved by loosening the layers following spreading and applying compost, Treatments 2 (15 cm gravel) and 3 (30 cm gravel) may therefore be preferable to Treatment 1 (no gravel). The soil surface salinity may still increase, but the effect will be delayed greatly by the provision of a thicker layer, and this may give the plants sufficient time to establish to such densities that they will restrict the amount of capillary rise occurring. The plants would ideally be using all water from the residue as it rises from deeper layers into the root zone and prevent saline pore water from reaching the soil layers.

The long-term salt balance is difficult to predict, but providing current levels of plant biomass and water use are maintained, then the profile may be expected to become drier, and experience a net leaching of salts with annual winter rainfall. Residue salinity levels do appear to have stabilized, and may be declining, but this requires on-going monitoring. The monitoring of vegetation for symptoms of salt stress is also recommended.

Vegetation was well established and had diversity comparable to other jarrah forest rehabilitation. Species diversity was very dependent on an appropriate seed mix and favorable seedbed conditions plus transplants. Topsoil had little value as seed source. The necessity for storing topsoil on site means that little can be done to overcome this limitation in the value of topsoil, apart from continuing to maintain vegetation on heaps, and exploring the options for decreasing the height of future stockpiles. Successful establishment of many local jarrah forest species suggests the desirability of testing other endemic species in future field experiments.

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