Soil physical properties affecting root growth in rehabilitated gold mine tailings

Selva Kumar Arunachalam, **Christoph Hinz** and Graham Aylmore

School of Earth and Geographical Sciences, Faculty of Natural and Agricultural Sciences,
The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australiua. Email: sarunach@agric.uwa.edu.au chinz@agric.uwa.edu.au , aylmore@cyllene.uwa.edu.au

Abstract

Fine gold mine tailings from Boddington Mine, Western Australia are characterised by their extreme physical and chemical properties such as massive clay structure, desiccation cracks, high penetration resistance when dry, low hydraulic conductivity, high pH and salinity. The physical factors affecting root growth in rehabilitated residue materials have not been widely understood and there is a need for further research on the mechanisms of root exploitation in heterogeneous residue layers especially in relation to texture and the development of shrinkage cracks. A trench profile method was used to map the roots of *Eucalyptus camaldulnesis and E.gomphocephala* along with visible cracks within a residue profile. The maps were digitised and interpreted in ArcView GIS. The basic physical and chemical properties of residue layers were measured both in situ and in the laboratory for 476 soil samples. The results indicate that the roots in tailings exploited the low resistance paths (usually along the cracks) first and then grew laterally along the sandy loam soil layers and bedding surfaces of the residue. Abundant lateral roots were found in sandy loam layers and extended to 25 cm distance away from the nearest cracks. Several residue layers were found to have bulk densities exceeding the threshold values for restriction of root growth estimated from the texture. Root distributions away from cracks were mainly determined by the texture of residue layer and the combination of >18% clay and <30% of sand found to be the main contributing factor to limit root growth in tailings. Penetration resistance, size of the roots and moisture content conformed to linear relationships.

Key Words

Mining residue, root growth, root distribution, crack intensity, Electrical conductivity, Growth Limiting Bulk Density (GLDB),

Introduction

The adverse physical properties of soils that affect root growth include texture (Dexter, 2004), bulk density (Glinski and Lipiec, 1990; Lipiec et al, 2003), moisture content (Laclau et al, 2001) and penetration resistance (Bengough and Mullins, 1990; Bengough et al, 2001; Lipiec et al, 2003) and have been reported in the past for various naturally occurring soils. Similar studies on physical factors affecting root growth in rehabilitated gold mine residue materials have not been widely published and hence there is a need for further understanding of root exploitation in heterogeneous residue layers especially in relation to the shrinkage cracks and texture. The specific objectives of the present study were (a) to assess the soil physical properties affecting root growth in gold mine residue and (b) to map the root distribution in different layers of residue in relation to crack distribution and basic soil physical characteristics of the layers. In this respect mine residues have the virtue of providing well defined but hostile media, which have not been modified by any gross biological activity before rehabilitation.

Materials and Methods

Study area

Based on the results of several experiments carried out at Murdoch University (WA), a field trial area was established during the year 1999 on 5 ha of land in one of the residual storage areas (RSAs) (NW corner of R4) of Boddington Gold Mines (BGM), located 125 km Southwest of Perth, Western Australia. Parts of the residue areas were treated with different thickness of soil/subsoil, gypsum application and with or without gravel to evaluate the most successful rehabilitation process for RSA. The trial involves the planting of species endemic to adjoining Jarrah forest and known salt and water logged species. Measurements were carried out in 3 trenches during April-June 2002 and in another 3 trenches in March-April 2003, excavated by backhoe in and around the rehabilitated residue area. Four trenches (T1, T2, T4 and T6) were located in the bare residue plots with only gypsum treatment (30/60 tons/ha gypsum) and two trenches (T2 and T5) were located in a plot with gravel treatment (30 cm gravel, 10 cm topsoil and 60 t/ha gypsum).

Soil sampling
Both undisturbed and disturbed residue samples were collected from all visually distinguishable layers (10 to 15 layers along a profile) to determine the basic physical and chemical properties and the variation in salinity with reference to root distribution and cracks.

Physical and chemical properties
Penetration resistance of residue layers at locations with and without roots and cracks were recorded in all trenches. A detailed survey (259 locations in a grid) was carried out in a trench with gravel treatment on the top (T5) to assess the variations in soil strength. The basic soil physical and chemical properties measured in the laboratory for the soil samples collected from all the trenches were gravimetric water content, bulk density, texture analysis, water retention, pH and EC. The water retention properties of the first six layers from ground level in T1 and six representative layers at different depths in T4 were determined at various water potentials (0, -10, -100, -1500 kPa) by using a pressure plate method.

Root Mapping
The trench profile wall method (van Noordwijk et al, 2000) was used for root mapping in 5 trenches except in T4 where there was no plant growth. Two methods were adopted for recording roots along a profile wall:(a) root counting in 1 m^2 grid (10 cm^2 grids) and (b) tracing the roots and structures on a polythene sheet (transparent polythene sheet, 100 μm thick). These tracings (maps) of roots with other observable features (cracks) were used for point pattern analysis in geographical information systems. In trench T1, root occurrences were recorded by overlying a 1 m^2 grid on the pit wall. Both vertical and horizontal distributions of roots of a tree (Eucalyptus camaldulnesis) located in a bare residue plot were mapped in a 10.5 m^2 grid area (1050 of 10 cm^2 squares). The roots were counted at the point of appearance on the plane of observation and the abundance of roots and their sizes were recorded in the manner described by McDonald, 1990.The spatial distribution of roots of 5 different species (Eucalyptus camaldulnesis, E.rudis, E.gomphocephala, Melaleuca incana, M.armillaris, Atriplex amnicola and Acacia saligna) in two trenches (T2 and T5) and the roots of Eucalyptus trees (Eucalyptus camaldulnesis and E.rudis) in 2 trenches (T3 and T6) respectively were recorded by using polythene overlay. The tracings were photographed in 1m^2 grid (containing 100 cm^2 squares) and the presence or absence and size of the roots in each grid were mapped from the images. The roots observed in the top 30 to 40 cm thick gravel layers in two trenches (T2 and T5) could not be recorded due to their abundance and the rugged surface of the profile wall.

Data Analysis
The measured physical and chemical properties of the residue layers in the 6 trenches were compared layer wise and with depth of their occurrence. A comparative statistical analysis was carried out using *Analyse-It* software (version 1.68, Analyse-It Software, Ltd. Leeds LS27 7WZ, UK) to assess the differences between the physical properties of samples collected from various residue layers. In addition, a regression tree model (*S-Plus* software) was used to predict the factors (texture, depth) controlling the root growth limiting bulk density (GLBD). The regression tree is a non- parametric and recursive-partitioning method to group dependent variables on the basis of independent variables (Lapen et al, 2001) and the application of regression tree in spatial data analysis is to uncover the predictive structure of the problem (Breiman et al, 1984). For this study, a regression tree model was generated with the particle size fractions and depth of residue layers as predictor variables and GLBD-BD values as response variables.

Spatial analysis of roots and cracks data
Two methods were adopted to record root distributions from the images. First, the root distribution and the distances to a crack were visually recorded for each 10 cm^2 grid area. Secondly, in order to get the exact spatial relationship between roots and cracks and various textures of residue layers, a detailed digitization was carried out for every image. The roots and cracks were digitized using *WinDIG 2.5* (Lovy, 2002) and converted as vector data after defining 3 reference points (x, y) in each image for recording the spatial coordinates for roots and cracks in a residue layer. The digitizing process converts the spatial features (points, lines, areas) of a map (a physical model of reality) into a digital format (i.e., into a series of x, y coordinates). The digitizing error was estimated to be within the limit of 0.1 to 0.5 cm. The digitized points were imported as x, y point data in ArcView (both 3x and 8.3) and the point themes of cracks and roots were merged for all residue layers in a profile. The merged roots and cracks themes were then spatially joined in ArcView to visualise the spatial relationship between cracks and root distribution. The distance between each root and the nearest crack is automatically assigned to a table. The number of cracks along a profile wall and

distances between the cracks in different residue layers and with depth were also measured to assess the variation in crack distribution.

Results

Physical and Chemical properties

(a) Texture and bulk density

The depth and thickness of residue layers are not uniformly distributed in the tailing dams due to differences in the composition of the processing ore and pumping strategy adopted during the deposition of slurry. The field texture ranges from loam to silty clay soils. Most of the surface layer over the study area up to 20 cm depth is silty clay loam. The bulk density (ρ_b) measured in different residue layers varied between 1.32 and 1.57 g/cm^3 in TBR and from 1.25 to 1.61 in TGR. Higher bulk densities were observed in the top few residue layers. The threshold bulk density *(Growth Limiting Bulk Density)* for restriction of root growth was estimated from the texture of residue layers as suggested by Daddow et al, 1983 (Appendix Table 1).

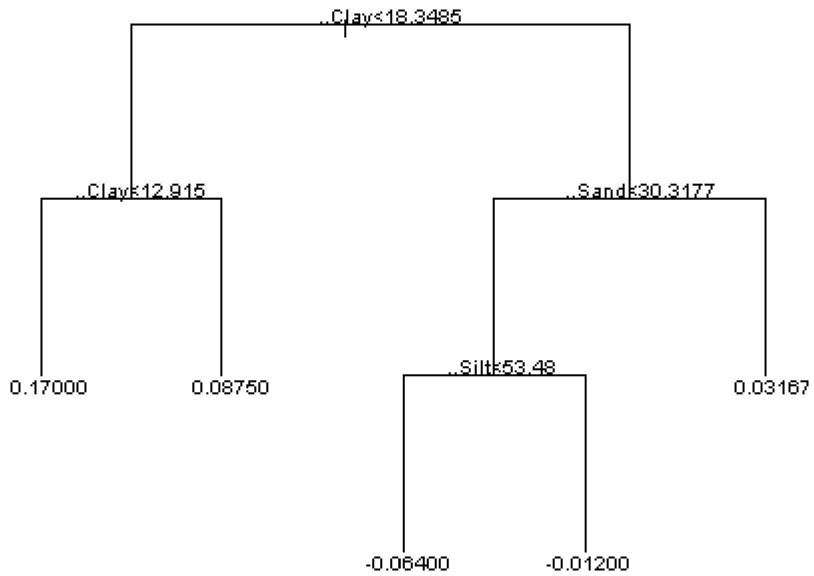

Figure 1.Correlation matrix of different textures and GLBD-BD

A few residue layers have higher measured bulk densities than the GLBD based on their texture and the root growth in these layers appears to be more restricted than in other layers. The correlation matrix of textures and the difference between GLBD and BD (GLBD-BD) values indicate a negative correlation with increased clay content and positive correlation with increased sand content in the residue layers (Figure 1). The regression tree model (Figure 2) demonstrates the influence of clay content over the growth limiting bulk density (GLBD) for root growth. Whenever the clay content of the layer is more than 18.3 % with a combination of <30.3 % of sand and <53.5 % of silt the root growth (GLBD = –0.06400) is limited.

Figure 2. Regression tree model generated with texture and depth of residue layers as predictor variables and GLBD-BD as response variable

(b) Field water contents (θ_g):

The gravimetric water content depended largely on the texture of a residue layer and the water content varied at short distances within the same residue layer. The silty clay to silty clay loam soils had higher moisture contents (20 to 25%) than the silty loam to loamy soils (6 to18%). When compared to the TGR area, the TBR plots had higher moisture contents. A lower moisture content (5 to 9%) was observed in the residue layer located just below the thick gravel treatment (30-40 cm). The moisture contents measured in different layers in T1 (TBR) at various depths in continuous sampling at every 2.5 cm horizontal distance indicates that the silty clay layers were wetter than the silty loam residue layers at depth. In general, the moisture content increased with increasing depth except in the silty/sandy loam soil layers and along the wider cracks.

(c) Water retention

The water retention properties of the residue layers measured in the laboratory have shown that the field capacity and wilting point increases with increasing clay and silt content and the amount of plant available water ranged between 14.8 and 26.8% in the silty clay loam to silty clay soils and from 36 to 45% in the silty/sandy loam soils.

(d) Penetration Resistance

Penetration resistance measurements depend significantly on the moisture content and bulk density of a residue layer and varied over short distances within layers. The residue layer located beneath the gravel treatment showed higher penetration resistance (9 to 11 MPa) than that measured at depth (Figure3). Higher Penetration resistances were also recorded in the coarser sandy/silty loam soils when dry. No direct relationship between the root distribution and penetration resistance in residue layers could be established due to the growth of the majority of roots along the macropores. However a decrease in penetration resistance with increasing root size was recorded in a silty loam soil layer in T6.

Figure 3. Inverse Distance Weighted map of penetrometer resistance with cracks and roots along a profile wall (T5)(TGR) (20 cm grid; 259 locations).

(e) Electrical conductivity ($EC_{1:5}$)

High EC values were observed in samples collected along some crack surfaces and in wet silty clay loam to silty clay layers .In general, higher EC values were observed in TGR plots than in TBR except in trench T6 where EC values ranged between 3 and 9 dS/m. Any relationship between the spatial distribution of roots and salinity along the profile wall could not be clearly demonstrated due to the coarser sampling locations at 10 to 20 cm grids.

(f) pH

The pH values observed within the residue layers were in the range of 7.2 to 10 and were mostly consistent along each of the residue layers except in a few locations and was found to increase with depth.

Crack distribution

The desiccation cracks developed due to shrinkage of clayey soils play an important role in root growth in tailings. In order to assess the pattern in cracks along the profile wall, the horizontal and vertical distribution of cracks (recorded on the polythene overlay) were manually counted. The distances between the cracks increased with depth and in the silty loamy soil layers .The number of cracks decreases with depth and the vertical cracks extend to more than 1.5 m depth. The intensity of cracks is greater at shallow depths in the bare residue plots than in the gravel treated area and it appears that the initial desiccation cracking pattern was preserved under the gravel treatment.

Root Distribution

The roots pertaining to a Eucalyptus tree in T1 (TBR), classified according to the size of the roots are illustrated in figure 8. The roots in the residue layers had preferentially grown along the cracks and abundant roots were also found along the bedding surfaces of the residue layers. High root abundance was observed at depth in the sandy/silty loam soils. The lateral distribution of roots had extended to more than 4 m and 5.5 m distance from the centre of the tree in T3 and T1 respectively. Root abundance decreased with increasing depth and with distance from the tree.

Spatial relationship between cracks and roots
Macropores (cracks) facilitate the unrestricted passage of roots and help to avoid the areas of higher mechanical impedance during their growth. The spatial relationship between the cracks and roots in trench T2 were established from the interpretation of digitised data in ArcView as shown in Figure 4.

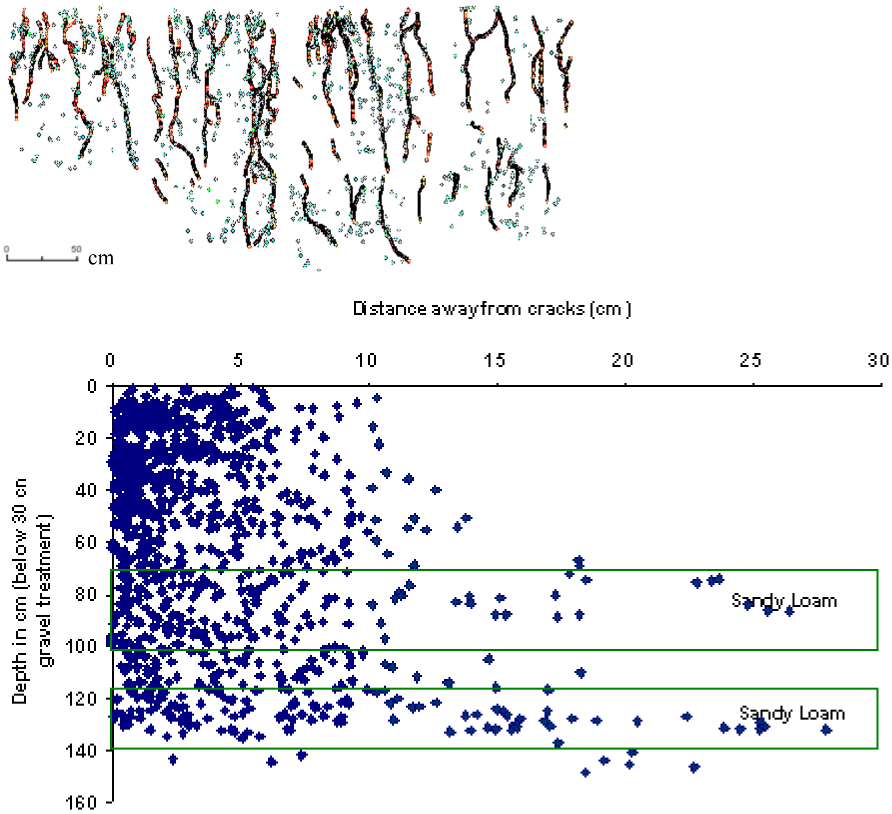

Figure 4. Spatial distribution of cracks and roots observed on the profile wall of a trench (T2) (imported from ArcView after merging two themes).

Similar pattern were observed in the other trenches (T5 and T3). The results clearly indicate that the root distribution mainly occurs along the macropores and extended more than 25 cm distance from the nearest crack in the sandy loamy textured soils (shown in boxes).

Conclusions
In this study we have demonstrated the physical properties affecting root growth in a rehabilitated gold mining residue and quantification of the spatial relationship between the roots and macropores along with the influence of texture through the combined method of root mapping in profile walls, digitisation and interpretation in GIS. The results of this study reveal that the roots had preferentially grown along the macropores (cracks) and in sandy/silty loamy soils at depth due to the availability of soil water at high Ψ_m. The roots of an isolated Eucalyptus tree have laterally extended more than 5.5 m distances from the centre of the tree and root density decreased with increasing depth. The texture of the residue plays an important role in defining the root distribution away from cracks and the combination of clay >18.3% with sand <30% may be the main contributing factor to limit root growth. The observed spatially heterogeneous physical properties such as penetration resistance, EC and pH could not directly be related to the root distribution along the profile wall due to the coarse sampling strategy adopted. However, a linear relationship between penetration resistance and size of the roots and water content is indicated.

References

Bengough, A. G., Campbell, D.J., O'Sullivan, M.F. (2001). Penetrometer Techniques in Relation to Soil Compaction and Root Growth. Soil and Environmental Analysis: Physical Methods. K. A. Smith, Mullins, C.E., Marcel Dekker, Inc., NY 10016.

Bengough, A. G. M., C.E. (1990). "Mechanical impedance to root growth: a review of experimental techniques and root growth responses." J. Soil Sci.(41): 341– 358.

Breiman, L., Friedman,J.H.,Olshen,R.A.,Stone,C.J. (1984). Classification and Regression Trees, Wadsworth, Belmont, CA.

Daddow, R. L., Warrington, G.E. (1983). Growth-Limiting Soil Bulk Densities as Influenced by Soil Texture, Watershed Development Group, USDA Forest Service, Colorado 80524**:** 17.

Glinski, J., Lipiec, J. (1990). Soil Physical Conditions and Plant Roots, CRC Press, Inc., Florida.

Laclau, J. P., M. Arnaud, et al. (2001). "Spatial distribution of Eucalyptus roots in a deep sandy soil in the Congo: relationships with the ability of the stand to take up water and nutrients." Tree Physiology **21**(2-3): 129-136.

Lapen, D. R. T., G.C., Gregorich, E.G., Hayhoe, H.N., Curnoe, W.E. (2001). "Divisive field-scale associations between corn yields, management, and soil information." Soil and Tillage Research **58**: 193-206.

Lipiec, J. and R. Hatano (2003). "Quantification of compaction effects on soil physical properties and crop growth." Geoderma **116**(1-2): 107-136.

Lovy, D. (2002). WinDIG 2.5 http://www.unige.ch/sciences/chifi/cpb/windig.html

van Noordwijk, M., Brouwer.G.,Meijboom.F.,do Rosario G.Oliveira.M.,Bengough.A.G. (2000). Trench Profile Techniques and Core Break Methods. Root Methods A Handbook., Eds. Smit, A.L., Bengough, A.G., Engels, C., van Noordwijk, M., Pellerin,S.,van de Geijn,S.C., Springer**:** 211-233.

Appendix

Table 1. Texture, bulk density and GLBD of residue layers in 4 trenches

Depth (cm)	Clay %	Silt %	Sand %	Bulk Density (g/cm^3)	GLBD (g/cm^3)	GLBD-BD (g/cm^3)
			Trench 1			
21.0	22.30	54.74	22.96	1.50	1.46	-0.04
31.0	40.83	46.95	12.22	1.54	1.42	-0.12
42.0	8.23	66.71	25.06	1.32	1.44	0.12
48.0	23.29	55.22	21.49	1.37	1.45	0.08
65.0	9.96	42.51	47.54	1.33	1.57	0.24
87.0	20.33	68.50	11.17	1.39	1.43	0.04
93.0	14.24	58.56	27.21	1.43	1.46	0.03
104.0	30.07	59.50	10.43	1.45	1.43	-0.02
115.0	12.66	39.98	47.36	1.32	1.57	0.25
			Trench 2			
19.0	14.86	33.59	51.55	1.55	1.60	0.05
30.0	21.66	46.25	32.08	1.56	1.49	-0.07
54.0	17.42	32.31	50.26	1.43	1.59	0.16
67.5	19.99	47.86	32.16	1.46	1.49	0.03
93.5	19.63	48.93	31.44	1.40	1.48	0.08
114.5	22.13	57.03	20.83	1.57	1.45	-0.12
138.0	18.45	36.61	44.94	1.61	1.56	-0.05
			Trench 3			
18.0	13.17	35.66	51.18	1.57	1.60	0.03
20.0	16.39	38.24	45.38	1.41	1.56	0.15
32.0	34.02	45.04	20.94	1.47	1.45	-0.02
51.0	28.50	48.30	23.20	1.55	1.47	-0.08
88.0	6.42	21.67	71.91	1.58	1.73	0.15
100.0	18.59	52.22	29.20	1.62	1.48	-0.14
			Trench 4			
9.0	18.25	43.25	38.51	1.44	1.52	0.08
30.0	24.42	34.48	41.10	1.43	1.54	0.11
63.0	11.56	34.17	54.27	1.53	1.62	0.09
96.0	24.72	40.36	34.93	1.43	1.52	0.09
154.0	17.07	40.17	42.76	1.44	1.54	0.10
214.0	13.58	44.50	41.92	1.43	1.53	0.10

	Clay	Silt	Sand	GLBD-BD
Clay	1.00	0.27	-0.75	-0.53
Silt	0.27	1.00	-0.84	-0.37
Sand	-0.75	-0.84	1.00	0.56
GLBD-BD	-0.53	-0.37	0.56	1.00