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Coal mine tailings: development after revegetation with salt-tolerant tree species

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Abstract

Coal mine tailings are often hostile media in which to grow plants. This paper reports selected physical and chemical properties of alkaline saline-sodic tailings 1.4 and 9.4 years after deposition in three experimental tailings storage facilities (TSFs). This study included the effects on the tailings of three moderately salt-tolerant tree species grown on their surfaces during the last 7.6 years of this period.

Few changes occurred to the physical properties of the vegetated or unvegetated tailings over this period apart from strength increases associated with drying and settling. Chemical changes over this period included lower salinity (as EC), Na and S concentrations beneath the tree canopies which were associated with reduced site irradiance. No pedologically meaningful changes to properties reflecting soil organic matter or the concentrations of other elements were apparent. It is concluded that meaningful pedological development in these wastes is likely to require lengthy periods.

The tailings materials of a seasonal wetland studied in one of the TSFs showed materials differences due to deposition of non-tailings materials eroded from upslope. Salinity was substantially reduced in the near-surface materials due to extensive leaching and lower C and N concentrations indicated a reduced organic matter content; further, the lower C:N ratio may indicate a different type of organic matter associated with the wetland vegetation present.

It is concluded that for successful direct rehabilitation of tailings, careful evaluation is required of the physical, chemical and biological properties that potentially limit plant growth. The plant species to be initially established must be chosen for their tolerance of potentially growth limiting properties, particularly extremes of pH and salinity. Where tailings properties exceed tolerance limits of the species to be established or plant nutrient element supply limits growth, the materials may need to be ameliorated. In the field, particular attention to drainage of these fine-textured materials is critical to plant success. Pedological development of these fine-textured wastes is considered to require extended time periods, even under optimal conditions.

1 Introduction

Coal tailings are most commonly disposed of as aqueous slurries into tailings storage facilities (TSFs), where they have potential to cause safety and environmental problems. When first deposited into TSFs, such tailings have very low surface bearing strengths and may remain hazardous to humans, domestic stock and wildlife for lengthy periods (Chapman et al., 1995; Fourie, 2009). Percolation of associated waters may lead to contamination of aquifers and surface waters and extended drying times have been estimated on the basis of laboratory tests. On drying, dust may be generated from their surfaces (Kon et al., 2007) and they may also be subject to spontaneous combustion (see, for example, DERM, 1995).

Coal tailings are difficult to rehabilitate directly since they are fine-textured materials and may possess physical and chemical properties inimical to the growth and development of plants and their associated beneficial micro-organisms. Rehabilitation solutions therefore necessitate control of drainage and commonly dictate covers of various types and thicknesses (see, for example, Fourie and Tibbett, 2007).

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The post-depositional evolution of tailings landforms and their materials properties appears to be poorly known, even over relatively short time frames. If landforms constructed of processing wastes and other geological materials are to be developed as self-sustaining ecosystems, there is a need to understand their long-term evolution in relation to materials properties and the combined effects of pedological-biological influences on their development and spatial organisation, particularly on the near-surface materials. These influences include the physical and chemical activities associated with weathering and related processes but include organisms, particularly plants (see, for example, Binkley and Menyailo, 2005; Hobbie et al., 2007) and their symbiotic micro-organisms. They also include free-living micro-organisms and the soil fauna, particularly the activities of the larger soil organisms responsible for the formation of structure and the incorporation of organic materials (Lavelle and Spain, 2001).

This paper reports changes in fine-textured coal tailings placed in three experimental TSFs at Ebenezer Mine for 3,450 days (c. 9.4 years), including 2,791 days (c. 7.6 years) of tree growth. As part of a wider study of rehabilitation at this mine site (Spain et al., 2010a, 2010b; Tibbett et al., 2010), it poses the question ‘can self-sustaining ecosystems be successfully established directly on fine-textured coal tailings materials?’ This paper specifically asks ‘what changes occur to coal tailings landforms during this period and to the properties of the near-surface materials through the presence of a vegetation cover of trees over this period?’.

The work reported here forms part of studies of pedogenetic development of the upper tailings profile (Spain et al., 2010b). Worrall et al. (2008) presented the results of studies of the growth of the three evergreen salt-tolerant tree species studied here (*Casuarina glauca*, *Eucalyptus camaldulensis*, *Melaleuca quinquenervia*) over 2,791 days (c. 7.6 years) on the currently described tailings.

2 Methods

The studies reported here were carried out at Ebenezer Mine, located at 27°40’S, 152°40’E, c. 44 km south-west of Brisbane. The climate is described as subtropical, with no dry season (Bureau of Meteorology, 2012). Mean rainfall is approximately 864 mm per year with a summer maximum: mean monthly rainfall exceeds 100 mm for the months of December to February, declines to a minimum of 29.4 mm in August and increases subsequently. Estimated actual evapotranspiration follows the same pattern and ranges from 90–110 mm per month in December to February, declining to 20–30 mm per month between June and August (Bureau of Meteorology, 2012).

The three experimental TSFs (Worrall et al., 2008) were constructed in early January 1998 and ranged in size from 960 to 2,070 m^2; they were filled with an aqueous slurry of fine-textured tailings in the same month. They were excavated to maximum depths of 4.5 m within a landform constructed of mixed saline-sodic overburden spoil (‘waste rock’) (Spain and Tibbett, 2011); because of their angled internal batters, the TSFs were shallower towards the edges. Low above-grade walls were built of the same materials. These TSFs virtually comprise their own catchments, with only small contributions from their surrounds. All three TSFs retained input rainwater for periods during the wet season: TSFs 1 and 3 hold water for extended periods and have developed seasonal wetland plant communities dominated by *Typha* sp. (Typhaceae) while TSF 2 holds water for lesser periods and has no wetland community.

Areas of TSFs 1 and 3 were planted (mostly at a 3m by 3m spacing) to three salt-tolerant native tree species on 29 October 1999 (Worrall et al., 2008). Of these three species, *C. glauca* has high salt tolerance (root zone ECe 8–16 dS m^{-1}; *E. camaldulensis* and *M. quinquenervia*, both have moderate salt tolerance (root zone ECe 4–8 dS m^{-1}) (Marcar and Crawford, 2004). Ineffective drainage led to extensive mortality in trees planted in the lower parts of these TSFs (Worrall et al., 2008) and while these areas were subsequently used to infer potential changes in unvegetated tailings, it is likely that they experienced greater leaching than those more elevated.

Initial sampling of the tailings (0–0.10 m) was based on sampling conducted in June 1999, 1.42 years (519 days) after tailings deposition and these were subsequently analysed for selected chemical and particle size properties. On 19 June 2007, near-surface (0–3 cm depth) tailings associated with the trees in TSFs 1 and 3 were sampled in relationship to their distances from three individuals of the three tree species listed above: 0–0.25 m from the stem, the 0.25 m lateral interval located mid-way between the stem and the canopy margin, the 0.25 m immediately inside the canopy margin and from 0.50–0.75 m beyond the canopy margin. Further samples (0–3 cm) were taken in unvegetated areas where tree mortality had occurred due to insufficient drainage. On 14 September 2007, three near-surface (0–2 cm) tailings samples were taken from the seasonal wetland at the lowest point of TSF 3. At this time, four pits in TSF 1 were sampled; information from samples taken between 0.75 and 1.50 m deep was used to permit comparison of the properties of the sub-surface materials with those near the surface.

Particle size distributions were measured by sieving for the sand fractions and by the pipette and sieve method for those finer (Coventry and Fett, 1979). The following were measured using procedures described in Rayment and Higginson (1992): pH (in 0.01M $CaCl_2$, at a 1:5 soil-solution ratio), salinity was measured as EC at a 1:5 soil-solution ratio (EC 1:5). Saturated paste equivalent (ECe) was estimated from EC 1:5 using a multiplier (8.5) based on the light clay field texture (Hazleton and Murphy, 2007). Cation exchange capacity (CEC) and exchangeable basic cation concentrations were measured using the compulsive exchange method with a pre-washing to remove soluble salts (Rayment and Higginson, 1992). Mineralogy of the <2 mm fraction was determined by X-ray diffraction analysis. Free swell was measured using the American Colloid Company procedure (Kajita, 1997). Total C and total N were determined using a Leco furnace. Concentrations of other total elements were determined using XRF analysis, neutron activation analysis (NAA) or by ICP-AES determination following acid digestion and appropriate dilution.

Air-dried coal tailings sampled from TSFs 1 and 3 were subjected to a modified 'Toxicity Characteristic Leaching Procedure' (TCLP) test (EPA, 1986). The test involved leaching 100 g of tailings material in 2 litres of an acetic acid solution (5.7 ml glacial acetic acid per litre water, pH 2.88) by tumbling in a rotary extractor device for 18 hours at 30 rpm. This was followed by filtration (0.45 µm) and measurement of elemental concentrations by ICP-AES.

Observations were made during 2007 of erosion of the TSF walls, deposition of transported materials and the surface properties of the tailings materials. Structural phenomena in the upper tailings profiles were described from four pits dug in TSF 1 to maximum depths of c. 1.50 m, from surface observations made in the three TSFs and in the adjacent main mine TSF.

Where statistical comparisons were made using analysis of variance, appropriate data transformations were applied. Mann–Whitney non-parametric tests were used where data properties did not conform to the requirements of parametric methods.

3 Results and discussion

3.1 Materials properties

Based on a sampling of the near-surface materials, physical and chemical properties of the tailings are presented from the two sampling occasions, from unvegetated and vegetated sites, from the wetland in TSF 3 and from the four pits dug in TSF 1.

3.1.1 Selected tailings properties determined 1.4 years post deposition

Based on three near-surface (0–0.10 m) samples taken from each TSF in June 1999, the mean mass of the <2 mm fraction was 82.2% of total sample weight (se 6.6, n = 9). The mean particle size distribution of the <2 mm fraction is presented in Table 1. The field texture of the materials approximates to a light clay (McDonald and Isbell, 1998).

The mineral composition of the <2 mm fraction of the tailings is dominated by smectite (34–49%) and kaolinite (31–34%) with substantial quartz (18–20%) also present. Despite the appreciable smectite present, the tailings materials swelled on hydration by only 10 to 20% of a standard smectite sample.

Table 1 Proportions by weight (means and standard errors) of the components of the <2 mm fraction of the tailings (n = 9)

	Coarse Sand 200–2,000 μm	Fine Sand 20–200 μm	Silt 2–20 μm	Clay <2 μm
Mean	12.4	27.5	25.8	34.4
se	2.4	2.6	2.0	1.7

The tailings materials are strongly alkaline (Table 2). The mean equivalent saturated paste EC (ECe) was estimated to be 15 dS m^{-1}, which indicates that plants require a high salinity adaptation to succeed on these tailings plants (Marcar and Crawford, 2004). The high salinity of the near-surface tailings may partially reflect the elevated values of the near-surface capillary fringe. Consistent with the substantial presence of fine coal particles noted, total C and N concentrations in tailings were higher than occur in most Australian predominantly mineral soils (Spain et al., 1983). Mean tailings C:N ratio is also high in this situation because of the presence of an unknown proportion of non-reactive carbon. Mean bicarbonate-extractable P (Olsen P) concentrations were all less than 5 mg kg^{-1}.

Table 2 pH, EC 1:5, total C, total N and the C:N ratio of near-surface (0–0.10 m) tailings materials (means and standard errors) from three experimental TSFs, June 1999

Statistic	pH 1:5 $CaCl_2$	EC 1:5 dS m^{-1}	Total C (%)	Total N (%)	C:N
Mean	8.22	1.74	**19.7**	0.38	51
se	0.14	0.10	1.1	0.03	1
n	9	9	14	14	14

The cation exchange capacity (CEC), of the tailings (measured as the effective CEC, or ECEC) (Table 3), is moderate and perhaps lower than expected, given the dominant smectites. By soil standards (Hazleton and Murphy, 2007), exchangeable Ca^{2+} is moderate and less than exchangeable Mg^{2+}, which is high; exchangeable K^+ is low and exchangeable Na^+ is very high. The exchangeable Na^+ percentage (ESP, or exchangeable Na^+ expressed as a % of ECEC) was also high and variable (range 13 to 38) and all materials analysed were strongly sodic.

Table 3 Exchange properties (cmol kg^{-1}) (means and standard errors) of near-surface tailings samples (n = 9)

Statistic	Exchangeable Basic Cations				ECEC	ESP	CEC
	Ca^{2+}	Mg^{2+}	K^+	Na^+			
Mean	4.55	5.69	0.23	2.57	13.0	26	16
se	1.31	1.60	0.05	0.45	3.3	3	1

The total concentrations of 30 elements in tailings of the three experimental TSFs are presented in Table 4. Concentrations of Al and Na are high in terms of world soils (non-saline soils only) although P and Si are low (Kabata-Pendias and Mukherjee, 2007; Kabata-Pendias, 2011). Concentrations of the remaining elements all fell within the ranges reported for world soils. The concentrations in the tailings of some contaminant elements present in the waters of the main mine TSF, notably Se and Mo, were less than detection limits of the analytical methods used.

Table 4 Total element concentrations (mg kg^{-1}, unless otherwise indicated) in tailings samples taken from the three experimental TSFs and from the main mine TSF (Chapman et al., 1995)

Element	Mean	se	Element	Mean	Std Dev.
Concentrations Determined By ICP AES (n = 5)					
Ca (%)	†1.45	–	**Cu**	†33	–
K (%)	0.55	0.04	**Mg (%)**	†0.58	–
Na (%)	0.50	0.04			
Concentrations Determined By NAA (n = 5)					
As	2.45	0.25	**Ba**	228	29
Br	6.67	0.86	**Ce**	47.4	1.8
Co	5.94	0.55	**Cr**	13.48	1.00
Cs	4.87	0.38	**Eu**	1.05	0.08
Fe (%)	1.18	0.31	**Hf**	4.08	0.20
La	20.70	0.84	**Lu**	0.27	0.01
Rb	25.30	3.22	**Sb**	0.44	0.08
Sc	12.44	0.21	**Sm**	4.88	0.18
Th	8.58	0.32	**U**	†1.37	–
Yb	1.82	0.06	**Zn**	†82.8	–
Single Sample Values From Main TSF					
Al (%)	10.1	–	**Mn**	30	–
P	110	–	**S**	580	–
Si (%)	20.9	–			

Note: Values in the 'Means' column prefixed with an † are medians and indicate that some sample values were less than the detection limit.

3.1.2 Properties of the near-surface materials 9.4 years after deposition

Near-surface (0–3 cm) tailings materials were re-evaluated c. 8 years after the initial sampling, following c. 7.6 years of tree growth on the surfaces. Properties were compared with those of unvegetated areas of the TSFs, the seasonal wetland located at the lowest part of TSF 3 and from the walls of pits dug in TSF 1 (Table 5).

3.1.2.1 Below and beyond-canopy locations

Data from the vegetated areas, including samples taken from 0.50–0.75 m beyond the canopy margins, were subjected to nested analysis of variance to test for significant differences between species and between locations, nested within species. Significant differences ($P<0.05$) among species means were limited to concentrations of total Al and Mn; significant ($P<0.05$) differences between locations within species were limited to EC 1:5, the C:N ratio and total S concentrations.

The range in mean Al concentrations among tailings associated with the three species was less than 1%, with means varying from 6.95% in those associated with *M. quinquenervia* to 7.94% in those associated with *C. glauca*. For Mn, the opposite situation pertained with mean values varying from 90 mg kg^{-1} associated with *C. glauca* up to 155 mg kg^{-1} in tailings associated with *M. quinquenervia*. Because of these differences are minor, Table 5 presents mean values calculated over all species.

Posterior tests indicated that small differences in mean EC 1:5 (range 0.18 to 0.96 dS m^{-1}) were present among sampling locations beneath the canopy although these were significant (P<0.05) only in tailings associated with *M. quinquenervia*. As indicated in Table 5, the mean EC 1:5 value for the three below-canopy locations over all species was substantially less than the mean value (1.49 dS m^{-1}, se 0.31, n = 9) for sites located 0.50–0.75 m beyond the canopy margins, which ranged from 1.41 to 1.58 dS m^{-1}. The mean C:N ratios ranged from 41 to 49 over all species and locations; slightly greater values occurred in the half-canopy and within-canopy-margin locations.

Despite a significant (P<0.05) overall effect of location for the total S concentrations, posterior tests did not indicate any significant differences (P<0.05) between locations within species. However, as for EC 1:5, the mean value for total S over the three below-canopy locations was substantially lower (2,431 mg kg^{-1}) than the mean value for all sampling sites from 0.50–0.75 m beyond the canopy margin (3,928 mg kg^{-1}, se 747, n = 9).

3.1.2.2 Comparisons of vegetated and unvegetated areas

Table 5 presents the properties of tailings sampled at locations distant from the direct effects of vegetation and contrasts these with those taken at the vegetated sites. Where no significant differences (P<0.05) were apparent among the three TSFs, combined values are presented. Where significant differences occurred among the TSFs, the ranges of mean values among the individual TSFs are presented.

Mean pH $CaCl_2$ differed by only c. 0.71 units among TSFs, while EC 1:5 differed more markedly. TSF 1 had a significantly higher mean value and was more variable than the remaining two TSFs. TSF 1 also had the highest concentrations of Na and S, two elements that contribute to salinity. The concentrations of Ca and K differed slightly among unvegetated sites although concentrations of the remaining elements did not.

The major differences evident between the vegetated and unvegetated areas were those related to salinity. Site median EC 1:5 values declined in the order: unvegetated areas, areas 0.50 to 0.75 m beyond the canopy margins, areas below tree canopies; differences between these three groups were all significantly different (P<0.05, Mann–Whitney tests). Mean total Na and S concentrations were lowest in below canopy areas and the remaining properties determined were either similar or little different.

3.1.2.3 Seasonal wetland at the lowest point of TSF 3

The wetland materials differed in a number of respects from those upslope due partially to acquisition of TSF wall and other materials and to extended leaching. No particle size information was available for the <2 mm size fraction of the materials of this site although the mass percentage of this fraction was 78.3 (se 6.39, n = 3), slightly lower than the tailings materials from upslope locations; this is ascribed to acquisition of coarser-textured TSF wall materials. The pH $CaCl_2$ value differed little from upslope sites while EC 1:5 was markedly lower in the wetland materials. Lower total C and total N concentrations indicated lesser organic matter concentrations in the latter materials and the lower C:N ratio may indicate qualitatively different organic matter, associated with contributions from the *Typha* sp. Concentrations of K, P and Si were higher than in upslope locations, those of Al, Ca, Fe, Mg and Mn were similar and those of Na and, particularly S, were lower.

3.1.3. Estimated salinities in five groupings of sites

Estimated ECe values are presented (Figure 1) for five groupings of sites, including values from tailings sampled within four pits at depths below 0.75 m (n = 7). The approximate minimum salinity tolerances required by plants to grow satisfactorily in media of differing salinities are also presented (Marcar and Crawford, 2004).

Substantial salinity differences existed between the low values of the seasonal wetland and the remaining sites. Among the near-surface sites sampled, salinity increased markedly with increasing site surface irradiance in the order: below-canopy sites to the sites 0.50–0.75 m beyond the canopy margins to the extremely saline values of the unvegetated tailings. Estimated ECe values in the pits at depths greater than 0.75 m were similar to sites 0.50–0.75 m beyond the canopy margins.

Table 5 Descriptive statistics for pH ($CaCl_2$), EC 1:5, the concentrations of total C, total N, the C:N ratio, and total concentrations of selected other elements in vegetated, near-surface (0–3 cm) tailings from TSFs 1 and 3, unvegetated sites in TSFs 1–3 and a wetland site in TSF 3 9.4 years after deposition (concentrations % unless otherwise indicated) (vegetated sites, n = 36; unvegetated sites, n = 18; wetland site n = 2)

Property	Vegetated Sites		Unvegetated Sites		Wetland Site	
	Mean	se	Mean	se	Mean	se
pH ($CaCl_2$)	7.36	0.08	*7.03–7.74	–	7.55	0.04
EC (dS m^{-1})	†0.58	0.07	*1.92–4.28	–	0.12	0.02
C	24.90	0.95	23.00	1.49	7.83	0.72
N	0.55	0.02	0.48	0.03	0.22	0.02
C:N	45	1	48	1	35	1
Al	7.53	0.15	8.06	0.34	10.47	0.18
Ca	1.05	0.11	*0.40–3.21	–	0.49	0.03
Fe	1.59	0.07	1.31	0.05	1.46	0.03
K	0.68	0.03	*0.592–0.809	–	1.03	0.01
Mg	0.48	0.02	0.50	0.02	0.70	0.02
Mn mg kg^{-1}	123	8	99	10	129	26
Na	0.28	0.01	*0.349–0.644	–	0.19	0.01
P mg kg^{-1}	187	5	149	7	227	9
S mg kg^{-1}	†2,431	118	*2,283–3,338	–	677	39
Si	17.33	0.40	17.83	0.64	24.32	0.16

*Ranges of means in the three TSFs.
† excludes samples taken 0.50–0.75 m beyond the canopy margins, n = 27

3.1.4 Compositions of leachates from the tailings materials

Table 6 presents the concentrations of 17 elements in weak acid tailings leachates. In decreasing order of concentrations, the dominant elements were Sr, Br, Na, Cl, Ba, B and S and those most likely to be available from leaching of the current tailings. Chloride was present in elevated concentrations in the two leachates indicating its probable physiological importance of this ion in waters associated with the tailings in situ. Present at lower concentrations were Br, B, Ba, Mo, Se, As, Cd, and Cs. The important contaminant elements Se and Mo were present in notable concentrations in the waters of the main mine TSF.

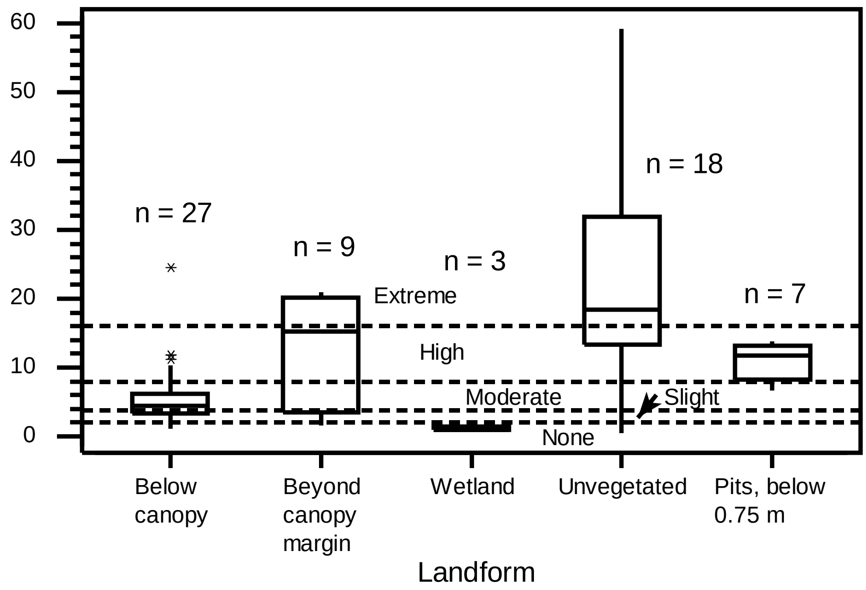

Figure 1 Box and whisker plots of ECe values in five groupings of tailings materials in the experimental TSFs, together with the degree of salinity tolerance necessary for satisfactory growth (see text for explanation)

Table 6 Elemental compositions of weak acid leachates from coal tailings samples from two experimental tailings dams (June 1999) (units µg L-1, unless otherwise indicated)

Element	Sample Location		Element	Sample Location	
	TSF 1	TSF 3		TSF 1	TSF 3
As	6.4	8.4	**K (mg L^{-1})**	8.8	5.5
B	220	140	**Mg (mg L^{-1})**	14	7
Ba	220	140	**Mo**	130	61
Br	670	250	**Na (mg L^{-1})**	500	300
Ca (mg L^{-1})	12	6.6	**S (mg L^{-1})**	113	54
Cd	1.3	0.6	**Se**	22	69
Cl (mg L^{-1})	440	290	**Sr (mg L^{-1})**	850	330
Cs	0.2	<0.1			

4 Conclusions

From their initial state as a low-bearing-strength aqueous slurry, the fine-textured Ebenezer coal tailings have, over c. 9.4 years, undergone substantial strength increases with drying, crusting and consolidation to the point where they no longer pose a threat to humans or animals and can support vehicular traffic when dry. This increase in strength has been accompanied by substantial structural and landform changes leading to the development of concave landforms with seasonal wetlands forming at their lowest points (Worrall et al., 2008; Spain et al., 2010b). Erosional and transportational processes have lead to modification of materials at the lowest part of the tailings landforms to form wetland substrates of different physical and chemical properties. The remaining tailings materials showed a limited number of changes in chemical properties consistent with their short period of exposure to soil-forming influences.

4.1 Materials properties

The present tailings materials may be classified as fine-textured, moderately to highly alkaline, moderately to highly saline (Marcar and Crawford, 2004) and strongly sodic (Hazleton and Murphy, 2007), which confirms them as a hostile growing medium for unadapted plants. Nonetheless, largely unfertilised, moderately to highly salt-tolerant tree species have grown adequately on these materials, reaching heights greater than 10 m in c. 7.6 years of growth and largely stabilising their associated tailings with a combination of near-surface plant litter and roots (Worrall et al., 2008).

Tailings alkalinity implies that some nutrient elements, notably the critical element P, will be less available to plants while high salinity substantially limits the survival and growth of unadapted higher plants (Marcar and Crawford, 2004). Salinity levels reported here are extreme in the near-surface evaporative fringe occurring in unvegetated tailings although much lower values occur beneath the substantial litter layers that occur under the tree canopies. Below the surface capillary layer, moderately elevated ECe values indicate that plant species to be grown in these materials must be at least moderately salt tolerant (Marcar and Crawford, 2004). Salinity may be overestimated in the current situation since water soluble and readily-leachable elements present in the tailings may contribute to EC and therefore salinity calculations. The strongly sodic character of the tailings implies instability, dispersion of clays and pore blockage; it also implies the presence of potentially phytotoxic Na^+ ions.

The present tailings differ in elemental composition from normal soils (Kabata and Mukherjee, 2007; Kabata-Pendias, 2011). The C concentration lies between those of mineral and organic soils although an unknown proportion of the C present in these tails occurs as fine coal and is unavailable to normal soil-based biological processes. Nitrogen concentrations are in the upper part of the range for Australian mineral soils (Spain et al., 1983) and the C:N ratio also falls between values typical of these two groups of soils. The concentrations of Al are greater than those typical of world soils while, consistent with their highly saline status, total concentrations of both Na and S are elevated by the standards of world non-saline soils. Concentrations of Fe are in the lower part of this range and those of Si are slightly lower than normally found in world soils. Concentrations of the biologically important nutrient element P are particularly low: less than one third of the value considered typical of the globally-low P concentrations occurring in Australian soils (Norrish and Rosser, 1983). This implies that planted species are likely to respond positively to P addition, at least.

The compositions of leachates derived from the tailings indicates that they may be contributing to contaminant loading in the main tailings dam waters, although mine spoils and other materials are further potential sources (Spain and Hettipathirana, 2000a). In particular, Mo and Se concentrations were substantial in the leachates and were also high (respectively, 46 to 100 $\mu g\ L^{-1}$ and 5.6 to 11.6 $\mu g\ L^{-1}$) in TSF waters (Spain and Hettipathirana, 2000b) and have the potential to cause significant food chain effects (Smith, 1998).

Apart from strength increases associated with drying and settling, differentiation of the lower parts of two of the TSFs to form seasonal wetlands may represent the greatest change in tailings properties that has occurred during the c. 9.4 year period since deposition. The substantially lower C:N ratio of the wetland indicates the presence of a qualitatively different organic matter in this area and the P concentration was also slightly higher than in the surrounding tailings. Other reported changes in the tailings over the period following deposition and tree growth are relatively minor or of little ecological significance.

Variation in most properties was substantial at a range of scales. The three TSFs differed in a number of properties and sample variability was high at all locations in nearly all of the measured properties. Because of this, many of the small changes that occurred in the chemical properties of the tailings materials that could be ascribed to the presence of the trees must be regarded as indicative: pedologically and ecologically meaningful changes to materials properties are expected to take a substantially longer period to emerge.

4.2 Implications for rehabilitation

Phytoremediation has been shown to be an ecologically sound and cost-effective way to rehabilitate a wide range of post-mining landforms (Weiersbye, 2007; Mendez and Maier, 2008). It may be used as a way to rehabilitate sites prior to relinquishment or, particularly where trees are used, as a technique to accelerate substrate drying, to protect ground and surface waters and perhaps in suppress dust. However, careful control of drainage is required to avoid extended periods of inundation and therefore hypoxia-related mortality (Worrall et al., 2008), especially where fine-textured materials are present.

Since many tailings possess properties that are likely to cause stress in unadapted plants, detailed evaluation of properties important to successful plant growth is necessary and, for rehabilitation purposes, careful species selection is required in relation to such properties. Further, appropriate fertilisation (notably with P) is likely to be required and, where substrate conditions are extreme, other forms of amelioration such as pH adjustment considered. The use of deep-rooting tree species (notably eucalypts) has advantages over grasses in terms of deeper and more rapid drying and probably dust suppression. As judged by their capacity to stabilise slopes (see, for example, Gray, 1995), where strongly rooting trees are successfully grown their roots are likely to provide stronger mechanical reinforcement of substrates than grasses. Nonetheless, depending on their growth habits, certain grasses are offer an effective stabilisation of surface materials and some are also known to be deep rooted (Fisher et al., 1994).

A longer-term problem with fine-textured materials such as the present tailings is that seasonal saturation from flooding during and for a variable interval after the higher summer rainfall season will lead to extended periods of low oxygen concentrations (hypoxia) in near-surface materials. This will be prolonged at least during the initial part of seasonal drying. During this latter period, high capillary rise in these fine-textured materials will lead to extended periods of low oxygen concentrations and elevated solute concentrations in near-surface materials. In these and other flooded saline materials, hypoxia interacts with salinity to create greater stress in the existing vegetation beyond that due to either effect alone (Barrett-Lennard, 2003). Such conditions also lead to poor recruitment from seeds both of plant species be sown by man and those spread to the sites by wind or animals and may make the recruitment of future generations of trees from seed problematic. Provision of a partial or complete layer of coarse-textured materials may serve to create a more favourable environment for the establishment of volunteer plants although such a layer need not be thick.

While substantial physical change was clear in the increased strength and structural formation that occurred with drying, minimal chemical change to the upper tailings materials was apparent following c. 7.5 years of tree growth. Measured chemical changes in the tailings that could be ascribed to the presence of vegetation appear largely limited to reduction of the saline capillary fringe beneath the tree canopies. This may also be reflected in the composition of salts present in the near-surface layer. Other limitations to plant growth may be addressed through substrate amelioration (especially of growth limiting pH conditions) and nutrient deficiencies addressed through experimental determination of fertiliser requirements.

No meaningful changes in C or N concentrations (or in the C:N ratio) were apparent, despite the 7.5 years of successful tree growth and the formation of substantial litter layers (Worrall et al., 2008). While fungal hyphae were abundant in the litter layers, there was little indication of the biologically mediated incorporation of litter into the surface tailings material that occurs in normal soils. Changes to tailings properties that would reveal incipient pedogenesis seem more likely to be reflected in properties reflecting microbiological activity.

Although longer term changes to substrate properties following from on-going ecosystem and pedogenetic development appear inevitable (Fourie and Tibbett, 2007; Fourie et al., 2012), pedogenetic development in these materials as reflected in the present suite of chemical properties must be regarded as minimal and considerable time periods will be required for meaningful substrate development to emerge. This contrasts with the situation in coarser-textured, free-draining materials where ecologically and pedologically significant substrate changes can emerge within a few years (see, for example, Spain et al., 2006).

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