AMENDING BAUXITE RESIDUE SANDS WITH RESIDUE FINES TO ENHANCE GROWTH POTENTIAL[1]

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Abstract: Long term success of rehabilitation on bauxite-processed residue storage areas is dependant on establishing a capping stratum which will satisfy water use and nutrient cycling requirements of the intended plant community. Bauxite residue sand is the primary growth media for rehabilitating residue disposal areas (RDAs) in Western Australia however; the sustainability of the vegetation cover can be compromised by the poor water-retention and nutrient cycling properties of the residue sand. This glasshouse study was conducted to determine if adding untreated or altered residue fines (< 150 µm) to residue sand (> 150 µm) would improve the characteristics of the final storage capping layer for sustained plant growth. Residue sand was amended by adding increments (1, 2, 3, 5, 10, 20 % w/w) of untreated or treated (carbonated or seawater washed) residue fines to determine whether these materials affected the chemical and physical properties of the growth media, and their ability to support vegetative growth (*Acacia saligna*), compared with the current practice of using only residue sand. Addition of residue fines increased water retention and extractable nutrient concentrations relative to untreated residue sand. However, the addition of residue fines increased both the electrical conductivity and exchangeable sodium percentage. Vegetative growth over a 3-month growing period varied with rate of residue fines addition, and residue fines pre-treatment (seawater > carbonated = unaltered). However, the addition of residue fines did not yield greater growth when compared with unamended residue sand. The importance of differences found in water retention and nutrient concentrations among residue treatments for plant growth need to be investigated in a water-limited field environment.

Additional Key Words: *Acacia saligna*, carbonation, nutrient concentrations, seawater treatment, water retention, Western Australia

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Introduction

As one of the world's largest alumina producers, Alcoa World Alumina Australia (Alcoa) processed 40.6 million tons of bauxite for aluminum production in 2004. Over this period, bauxite processing produced 20 - 30 million tons of residue sand and residue fines, which requires long term storage in impoundments. In Western Australian bauxite, sand is a significant proportion of the residue (~50%), and has traditionally been used as the growth medium to cap residue storage piles because it is more easily leached than residue fines and thus revegetation has proven more successful.

Successful rehabilitation of residue sands embankments poses many challenges due to the inherent high pH, alkalinity, sodicity, salinity and the low water holding capacity associated with freshly deposited residue sands. In addition to poor conditions that exist prior to leaching, the sands are also low or deficient in many necessary plant nutrients including N, P, Mg, Mn and Zn (Bell et al., 1997; Eastham and Morald, 2006; Eastham et al., 2006; Fuller and Richardson, 1986; Gherardi and Rengal, 2003; Gherardi and Rengel, 2001; Meecham and Bell, 1977). Many studies have developed partial solutions to these problems such as gypsum additions to correct pH and sodicity (Eastman and Mullins, 2004; Gupta and Singh, 1988; Kopittke et al., 2004; Wong and Ho, 1988; Wong and Ho, 1991; Wong and Ho, 1993); leaching to adjust alkalinity and salinity; and fertilizers which are applied at high rates alone or with organic amendments to increase plant available nutrients (Bell et al., 1997; Courtney and Timpson, 2004; Eastham et al., 2006; Fuller et al., 1982; Gherardi and Rengal, 2003; Jasper et al., 2000; Marschner, 1983; Williams and Hamdy, 1982; Wong and Ho, 1991). Although these manipulations have been successful to varying degrees, low water holding capacity and the poor nutrient retention of sands still remain major constraints to long-term self-sustaining vegetation.

Revegetation is a key component for long-term rehabilitation of residue storage areas in terms of erosion control, site stability, water balance, pollution control and aesthetics. These issues will only be successfully managed if self-sustaining vegetation is established. Successful revegetation of RDA's in the mediterranean type climatic region of south-western Western Australia is in turn dependant on a capping stratum which will satisfy water use and nutrient cycling requirements of the vegetation. Currently a diverse native flora community is the preferred vegetation for rehabilitation.

Until recently the other by-product of bauxite refining, residue fines, was mostly ignored as a soil amendment for on-site capping of the residue piles due to its caustic nature and slow leaching characteristics. Residue fines has been used successfully as an amendment on sandy, acidic soils both in agriculture and mine spoils due to its neutralizing capacity and increased water holding capacity (Barrow, 1982; Browner, 1995; Koch and Bell, 1983; Summers et al., 2001; Summers et al., 1993; Summers et al., 1996; Summers and Pech, 1997; Ward, 1983). The only previous attempt to use residue fines to amend bauxite residue sands showed very high rates of addition of unaltered residue fines only compounded the adverse caustic characteristics (Meecham and Bell, 1977). Recently research has developed techniques to alter the residue fines to reduce its pH and remove excessive amounts of Na, thus reducing the adverse caustic nature (Cooling et al., 2002; Menzies et al., 2004). As an on-site amendment of residue capping sands, altered residue fines could be useful to increase water holding capacity, reduce overall pH and sodicity, while improving the medium's ability to retain nutrients and increase essential plant nutrients.

The aim of this study was to determine the optimal proportion of altered residue fines to residue sand by measuring the growth of *Acacia saligna* and the resulting chemical and physical properties of the ameliorated residue. Additionally, we assessed the relationship between aboveground and belowground biomass of *Acacia saligna* by depth increments within the different growth media.

Methods

Column Preparation

Three types of residue fines were tested as amendments to residue sand: unaltered, carbonated, and seawater washed. Proportions of added residue fines were: 0 (control), 1, 2, 3, 5, 10, 20 % (w/w) residue fines. All treatment columns were replicated three times.

Residue sand was amended with gypsum and fertilizer to reflect the operational protocol in RDA rehabilitation. This treatment (i.e. no residue fines addition) was used as the control for comparisons. Residue sand and industrial waste gypsum were dried and sieved to < 2 mm. Dried residue fines were pulverized in rock crushers to ensure all aggregates larger than 200 μm were dispersed. Sand, residue fines, gypsum and fertilizer were analysed individually prior to column preparation for extractable nutrients (NO_3, NH_4, P, K, and S), exchangeable Ca, K, Mg, Na (pre-washed with 70% ethanol to remove water-soluble forms), and pH and EC on a 1:5 soil to water extract (see Table 1). All treatment columns received industry standard equivalent gypsum 2% (w/w) and the industry standard equivalent fertilizer additions (current practice applied in the field). Pre-determined portions of sand, fines, gypsum and fertilizer were combined and thoroughly mixed in a concrete mixer. Once mixed the growth medium was placed into 50 cm tall PVC columns of 13 cm diameter that where able to be split vertically. Growth medium was packed into columns in 10 cm increments to ensure a uniform bulk density and growth medium texture throughout the 45 cm profiles. Columns were then leached with 340 mm rainfall equivalent (6000 ml or 2.4-3.4 pore volumes) as distilled water in 14.15 mm increments (250 ml) prior to seedling transplanting to ensure adequate plant growth conditions. The extent of leaching is considered plausible under field conditions in the rainy winter season of the south-west of Western Australia which averages 400-600 mm of rainfall in events typically of 5-20 mm.

Botanical

Acacia saligna "Coojong" variante cyanophylla (Labill.) H.L.Wendl (orange wattle) was chosen as the biological indicator because it is a semi-salt tolerant legume native to the coastal south-west of Western Australia. Seedlings were produced from seeds grown in 3 cm^3 of inert sand for two weeks. The seedlings reached a height of approximately 5 cm and possessed two leaflets prior to transplanting at a density of four plants per column with three columns per treatment for a total of 12 plants per treatment. To ensure adequate growth, moisture content within each column was adjusted every three days to 85 % water holding capacity by reweighing each column and correcting water content. Every two weeks columns were randomly relocated within the greenhouse to limit any variability in temperature and sunlight received. After the 12 week duration of the experiment, plants were harvested at the growth medium surface, gently washed with distilled water, dried at 60 ^oC for 48 hours and aboveground biomass dry weights were recorded. Columns were split open vertically and roots where separated by depths of 0-10, 10-20 and > 20 cm. Roots were separated from growth medium by a series of seivings and root material greater than 125 µm was recovered and dried at 60 °C for 48 hours and below ground biomass dry weights were recorded.

Growth Medium

After packing and leaching the columns, initial growth medium samples were collected from the 0-10 cm depth and analysed for electrical conductivity (EC) (Rhoades, 1996) and pH (Thomas, 1996) in a 1:5 soil to water extract, available nutrients (NO_3, NH_4, P, K, and S), and exchangeable Ca, K, Mg, Na to identify possible nutrient deficiencies which may limit plant growth.

At harvest the growth medium was separated into depth increments of 0-10, 10-20, 20-30 and 30-40 cm. The 0-10 cm depth was analysed for EC, pH, extractable nutrients (NO_3, NH_4, P, K, and S), and exchangeable cations as outlined above. As 75% (ranging from 45-100 %) of roots were limited to 0-10 cm depth, nutrient analysis of the growth medium was only assessed for this portion. EC and pH were determined for the 0-10 and 10-20 cm depth increments. Water retention characteristics (Dane and Hopmans, 2002) at 0.033 and 1.5 MPa were determined for the growth medium sampled at 20-30 cm depth. Bulk density (Grossman and Reinsch, 2002) was determined from the 30-40 cm depth.

Statistical Analyses

Difference between residue fines treatments and additions were analysed by general linear models with Tukeys' post hoc test (alpha = 0.05) using SPSS 14.0 (SPSS, 2005).

Results

Initial materials

Chemical analysis of the residue sand, residue sand after gypsum and fertilizer was added (control), unaltered residue fines, seawater-washed residue fines and the carbonated residue fines are shown in Tables 1 and 2. Residue sand exhibited an extremely alkaline pH, was classified as sodic and contained negligible concentrations of essential plant nutrients. Adding gypsum and fertilizer lowered sodicity and increased nutrients concentrations of the residue sand but also increased EC. Seawater-washed residue fines had significantly lower pH but higher EC and greater concentrations of nutrients than the control. Carbonated residue fines had similar pH but greater EC, ESP and greater concentrations of nutrients, except S, than the control. Unaltered residue fines had greater pH, EC and ESP and greater concentrations of nutrients, but was also lower in S when compared with the control.

Construction of the columns after mixing the materials resulted in profiles with bulk densities that were not significantly different (1613 kg m^{-3} ± 6 kg m^{-3}, n = 57) ranging from 1666 kg m^{-3} to 1544 kg m^{-3}. Columns where leached with 340 mm rainfall equivalent reducing EC in leachate (soil solution) from an initial range of 74.6 to 291 dS m^{-1} to a final range of 4.4 to 9.0 dS m^{-1}.

Table 1. Chemical analysis of the initial residue sand and residue fines materials prior to column construction. Means (n = 3) ± standard errors are shown.

	pH (1:5)		Electrical Conductivity ($dS\ m^{-1}$) 1:5		Exchangeable Sodium Percentage		Calcium Carbonate %	
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
Residue Sand	10.5	0.04	2.00	0.05	81.9	0.50	0.97	0.01
Residue Sand with Gypsum and Fertilizer	10.3	0.07	3.40	0.25	60.4	1.16	0.68	0.01
Seawater Residue fines	8.5	0.12	24.2	0.50	74.1	1.62	4.78	0.31
Carbonated Residue fines	10.6	0.01	5.67	0.27	96.2	0.12	11.3	0.32
Unaltered Residue fines	12.0	0.08	9.60	0.26	89.5	2.25	8.28	0.69

Table 2. Extractable nutrient levels within the initial residue and residue fines materials prior to column construction. Means (n = 3) and standard errors are shown.

	Phosphorus (mg/kg)		Potassium (mg/kg)		Sulphur (mg/kg)		*Exchangeable Calcium (cmol/kg)		*Exchangeable Magnesium (cmol/kg)		*Exchangeable Sodium (cmol/kg)		*Exchangeable Potassium (cmol/kg)	
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
Residue Sand	5.00	1.00	15.0	0	120	39.9	1.79	0.10	0.05	0.01	5.60	0.13	0.10	0
Residue Sand with Gypsum and Fertilizer	36.3	2.33	90.7	8.41	2432	116	6.55	0.28	0.07	0.01	2.57	0.18	0.10	0
Seawater Residue fines	57.0	1.53	1203	34.4	1819	74.4	17.9	1.40	3.81	1.86	10.2	5.02	0.40	0.16
Carbonated Residue fines	356	4.91	37.3	2.19	465	53.1	6.72	0.34	0.68	0.03	33.8	0.12	0.10	0
Unaltered Residue fines	217	5.49	34.7	0.67	406	38.4	18.6	3.64	0.33	0.04	26.8	0.46	0.10	0

* Exchangeable concentrations were measured after samples were pre-washed to remove soluble salts.

Growth medium

Chemical characteristics of the residue fines treatments, taken prior to transplanting *A. saligna* seedlings "initial" and after harvesting biomass "final", are shown in Tables 3 and 4. The pH increased in all treatments between initial and final sampling, except for treatments that received 10 and 20 % of the seawater-washed residue fines (Table 3). Electrical conductivity and ESP decreased significantly in all treatments. NH_4 and NO_3 concentrations were measured, but NH_4 was only detected at levels < 1 mg/kg throughout the study. NO_3 concentrations initially were measured only below < 1 mg/kg with a slight increase in the final sampling ranging from 2-4 mg/kg, but with no discernible trend. Although these concentrations are very low, *A. saligna* is a legume and benefits from the symbiotic relationship with rhizobium which fixes atmospheric nitrogen. Initial samples taken prior to transplanting *Acacia saligna* seedlings showed that adding seawater residue fines increased extractable P, K, S, and exchangeable Ca, Mg, and Na (Table 4). Adding carbonated residue fines increased extractable P, K, S, and exchangeable Mg, and Na, particularly at the 10 and 20 % addition rate. Adding unaltered residue fines also increased extractable P, K, S, and exchangeable Ca, Mg, and Na particularly at the 10 and 20 % additions.

Final compared against initial residue concentrations showed that extractable P had increased in the control only. Potassium had decreased in the control and seawater treatments, while concentrations of S had increased in the control and seawater treatments compared with initial samplings. Concentrations of exchangeable Ca in the final samples remained similar to the initial samples in all treatments, while exchangeable Mg decreased in the seawater and unaltered residue fines treatments. Exchangeable Na concentrations in the final sampling decreased in all treatments while exchangeable K increased in all treatments compared with initial sampling.

Comparisons between treatments and the control in the final sampling showed concentrations of K, S, exchangeable Ca and Na within the seawater treatments remained greater when compared against control, while P and exchangeable Mg were no longer different, and exchangeable K had increased to being significantly greater than the control. Concentrations of total K within the carbonated treatments remained greater than in the control, while P, S and exchangeable Mg, Na were no longer different, and exchangeable K had increased to being significantly greater than the control. Concentrations of K, S within the unaltered treatments remained greater when compared against the control, while P was only greater at the 10 and 20 % treatments, and exchangeable Ca, Mg, Na were no longer different, but exchangeable K had increased to being significantly greater than the control.

Water retention characteristics.

Water retention capacity increased with additions of residues fines (Fig. 1). Soil water content at 0.033 MPa ranged from 6.26 - 13.2 %. At 1.5 MPa, soil water content ranged from 4.20 - 8.54 %. Plant available soil water content ranged from 1.74 - 5.17 %. All treatments had similar increases in water retention as percentage of fines increased. All treatments with 5 % addition or greater of residue fines had greater plant available water than the control.

Table 3. Basic chemical characteristics in the residue fines treatments.

			pH		EC (dS m^{-1})		ESP	
			Mean	S.E.	Mean	S.E.	Mean	S.E.
Control	0 %	Initial	8.28	0.01	0.76	0.14	7.38	0.65
		Final	8.72	0.09	0.58	0.14	0.64	0.37
Seawater	1 %	Initial	8.36	0.04	0.81	0.13	8.67	1.52
		Final	8.65	0.12	0.62	0.13	1.30	0.38
	2 %	Initial	8.27	0.07	0.98	0.19	11.1	1.38
		Final	8.68	0.05	0.71	0.06	2.03	0.25
	3 %	Initial	8.38	0.04	0.78	0.12	9.88	0.97
		Final	8.86	0.11	0.50	0.05	3.30	0.31
	5 %	Initial	8.48	0.07	1.29	0.10	10.5	1.02
		Final	8.58	0.11	0.97	0.15	4.01	0.44
	10 %	Initial	8.73	0.04	1.11	0.09	11.2	0.27
		Final	8.63	0.04	0.83	0.03	5.56	0.53
	20 %	Initial	8.61	0.08	1.42	0.32	15.2	0.52
		Final	8.60	0.03	1.06	0.03	9.21	0.97
Carbonated	1 %	Initial	8.40	0.15	0.98	0.30	11.7	1.59
		Final	8.97	0.09	0.51	0.05	0.48	0.10
	2 %	Initial	8.36	0.05	0.95	0.17	10.8	3.05
		Final	9.07	0.07	0.47	0.07	0.45	0.30
	3 %	Initial	8.64	0.08	0.96	0.18	14.6	1.17
		Final	8.85	0.15	0.59	0.05	0.48	0.31
	5 %	Initial	8.67	0.08	0.90	0.09	15.8	0.91
		Final	9.00	0.03	0.49	0.02	0.63	0.23
	10 %	Initial	8.62	0.14	1.11	0.14	25.9	1.84
		Final	9.07	0.05	0.59	0.12	1.18	0.30
	20 %	Initial	8.49	0.03	1.84	0.18	34.5	0.44
		Final	8.73	0.22	0.85	0.05	0.79	0.38
Unaltered	1 %	Initial	8.30	0.04	1.02	0.11	10.9	0.65
		Final	8.80	0.05	0.56	0.06	0.51	0.24
	2 %	Initial	8.46	0.06	1.16	0.21	13.5	0.88
		Final	8.81	0.07	0.59	0.08	0.87	0.25
	3 %	Initial	8.63	0.01	0.90	0.03	14.1	0.80
		Final	8.76	0.03	0.66	0.03	0.67	0.40
	5 %	Initial	8.54	0.03	0.94	0.14	13.8	0.74
		Final	8.70	0.10	0.57	0.10	0.55	0.13
	10 %	Initial	8.47	0.10	0.92	0.17	18.1	0.45
		Final	8.91	0.03	0.58	0.06	0.99	0.10
	20 %	Initial	8.70	0.18	1.60	0.19	22.0	4.19
		Final	9.11	0.08	0.55	0.07	1.09	0.14

"initial" samples were taken prior to *Acacia saligna* seedling transplanting and "final" samples were taken at harvest after 13 weeks of vegetative growth. Means (n = 3) ± standard errors of samples taken from the 0-10 cm depth.

Table 4. Extractable nutrient concentrations in the residue fines treatments.

			Phosphorus (mg/kg)		Potassium (mg/kg)		Sulfur (mg/kg)		Exchangeable Calcium (cmol/kg)		Exchangeable Magnesium (cmol/kg)		Exchangeable Sodium (cmol/kg)		Exchangeable Potassium (cmol/kg)	
			Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
Control	0 %	Initial	18.7	7.17	41.0	3.51	291	58.9	7.53	0.15	0.04	0.01	0.61	0.05	0.10	0
		Final	37.3	2.91	24.3	1.45	404	15.0	8.08	0.16	0.03	0	0.05	0.03	0.37	0.01
Seawater	1 %	Initial	34.0	6.56	41.0	4.16	490	74.0	7.54	0.14	0.10	0.01	0.74	0.13	0.14	0.02
		Final	44.7	7.31	31.3	3.53	698	20.2	8.61	0.35	0.02	0	0.12	0.03	0.40	0.06
	2 %	Initial	31.0	5.51	48.0	4.73	505	168	7.14	0.21	0.20	0.06	0.94	0.15	0.13	0.03
		Final	32.0	2.08	34.0	2.00	579	67.0	8.55	0.60	0.03	0	0.19	0.01	0.57	0.04
	3 %	Initial	31.7	5.93	62.0	8.62	515	94.9	8.49	0.47	0.30	0.04	0.97	0.08	0.10	0
		Final	27.3	3.84	50.7	4.10	565	97.7	8.38	0.35	0.05	0.01	0.31	0.02	0.63	0.05
	5 %	Initial	25.3	4.41	71.0	9.07	631	100	8.32	0.30	0.47	0.03	1.05	0.11	0.10	0
		Final	33.3	5.33	62.0	3.79	828	82.2	9.02	0.38	0.04	0.01	0.40	0.03	0.68	0.04
	10 %	Initial	39.7	10.4	95.3	2.33	701	84.8	9.37	0.04	0.75	0.03	1.29	0.04	0.10	0
		Final	36.0	4.36	85.7	5.70	810	37.5	10.4	0.49	0.05	0	0.66	0.04	0.90	0.02
	20 %	Initial	43.7	4.06	115	15.1	1020	252	11.0	1.64	1.34	0.09	2.25	0.33	0.10	0
		Final	36.3	2.96	111	4.00	1240	21.0	10.5	0.62	0.06	0	1.20	0.09	1.35	0.05
Carbonated	1 %	Initial	16.7	3.18	48.0	7.23	431	107	7.16	0.54	0.04	0.01	0.96	0.11	0.10	0
		Final	21.0	3.79	54.0	1.00	463	101	7.52	0.51	0.04	0.01	0.04	0.01	0.71	0.05
	2 %	Initial	31.7	12.2	51.3	2.73	368	76.5	9.90	2.87	0.04	0.02	1.04	0.13	0.10	0
		Final	20.3	3.48	46.0	1.15	381	39.5	7.31	0.37	0.05	0	0.03	0.02	0.68	0.04
	3 %	Initial	45.3	6.89	76.7	9.82	456	53.1	7.47	0.21	0.05	0.01	1.31	0.10	0.10	0
		Final	39.7	4.33	67.7	10.7	499	64.8	7.87	0.51	0.06	0.01	0.04	0.03	1.05	0.10
	5 %	Initial	17.0	2.00	61.3	8.41	300	27.3	8.11	0.01	0.04	0.01	1.55	0.11	0.10	0
		Final	28.7	4.18	57.3	4.33	526	94.0	9.11	0.76	0.09	0.04	0.06	0.02	1.07	0.03
	10 %	Initial	31.0	7.02	56.7	5.17	560	90.5	8.57	0.30	0.10	0.01	3.08	0.25	0.10	0
		Final	32.7	1.45	57.0	5.03	462	49.3	7.70	0.04	0.05	0	0.12	0.03	1.93	0.13
	20 %	Initial	42.7	3.18	61.7	5.17	999	71.7	8.34	0.45	0.14	0.01	4.54	0.32	0.10	0
		Final	49.3	4.98	73.7	3.18	993	118	11.3	0.42	0.06	0.01	0.11	0.05	3.12	0.19
Unaltered	1 %	Initial	21.7	2.19	42.0	1.53	460	41.5	7.31	0.16	0.05	0	0.92	0.08	0.10	0
		Final	24.3	5.36	42.0	4.16	814	55.2	8.07	0.26	0.04	0.01	0.05	0.02	0.58	0.06
	2 %	Initial	23.7	3.84	59.0	9.54	537	75.2	7.48	0.33	0.07	0.01	1.19	0.05	0.10	0
		Final	27.7	2.19	58.7	4.84	729	73.9	8.00	0.70	0.06	0.01	0.08	0.03	1.22	0.46
	3 %	Initial	23.7	2.96	52.7	6.06	411	96.1	7.64	0.03	0.08	0	1.29	0.09	0.10	0
		Final	35.0	5.69	54.3	4.91	840	153	8.35	0.17	0.06	0.01	0.06	0.04	0.86	0.03
	5 %	Initial	26.7	3.18	43.7	3.28	427	33.4	8.33	0.07	0.11	0.01	1.37	0.08	0.10	0
		Final	41.7	9.68	45.0	6.43	786	229	9.37	0.52	0.05	0	0.06	0.01	0.80	0.11
	10 %	Initial	47.0	3.46	62.0	7.94	615	112	8.57	0.40	0.12	0.01	1.95	0.14	0.10	0
		Final	57.3	8.95	63.0	6.24	747	69.7	10.3	0.12	0.07	0	0.12	0.01	1.70	0.08
	20 %	Initial	63.7	7.36	62.0	13.0	1250	629	11.9	1.96	0.17	0.02	3.28	0.39	0.10	0
		Final	60.3	2.96	69.0	6.81	485	83.1	9.68	0.72	0.06	0.01	0.13	0.01	2.28	0.19

'initial" samples were taken prior to *Acacia saligna* seedling transplanting and "final" samples were taken at harvest after 3 months vegetative growth. Means (n = 3) ± standard errors of samples taken from the 0-10 cm depth.

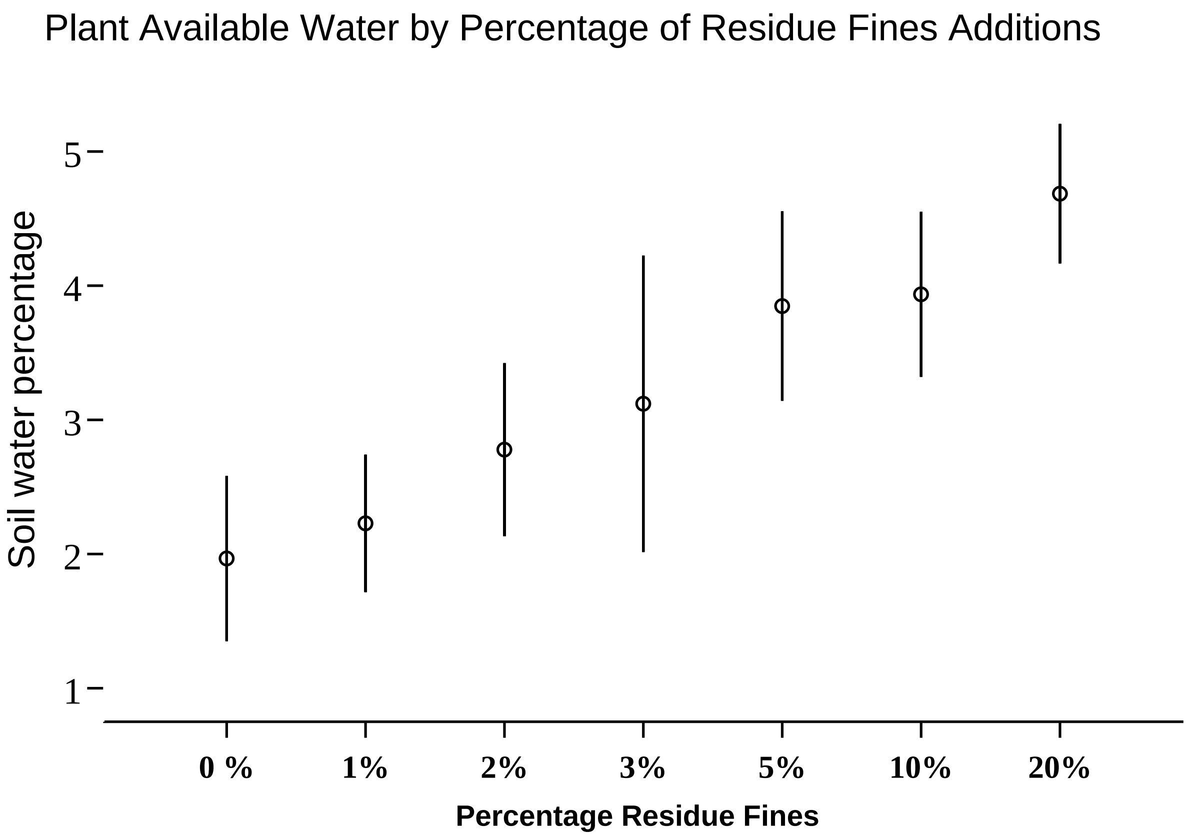

Figure 1. Increases in plant available water as percentage of residue fines additions increase. Circles are sample means (n = 3) and bars are standard errors of the means.

<u>Vegetation</u>

Aboveground biomass of *Acacia saligna* under various residue fines treatments are shown in Table 5. Aboveground biomass ranged from 1.39 g per column to 0.15 g per column and tended to decrease with increasing fines percentage added. In seawater treatments, aboveground biomass tended to be greater than either the carbonated or unaltered treatments at all percentages of residue fines addition. Overall the carbonated treatments resulted in the least vegetative growth, never exceeding 50 % of the control. The unaltered residue fines treatments were not significantly different than the growth of the carbonated treatments.

Overall belowground biomass was on average 45 % (1 to 96 %) greater than the aboveground biomass as shown in Table 5. Total belowground biomass ranged from 2.06 g per column to 0.27 g per column.

Table 5. *Acacia saligna* above and belowground biomass from 13 weeks growth in residue fines addition treatments. Means (n = 3) and standard errors of the means.

		Acacia saligna Aboveground Biomass (g column^{-1})		*Acacia saligna* Belowground Biomass (g column^{-1})	
		Mean	S.E.	Mean	S.E.
Control	0 %	1.21	0.17	1.86	0.30
Seawater	1 %	1.19	0.22	1.61	0.38
	2 %	0.72	0.18	0.99	0.39
	3 %	0.84	0.22	1.18	0.37
	5 %	1.39	0.18	2.06	0.10
	10 %	0.48	0.15	0.59	0.16
	20 %	0.45	0.15	0.65	0.22
Carbonated	1 %	0.45	0.15	0.54	0.18
	2 %	0.59	0.08	0.67	0.06
	3 %	0.34	0.07	0.34	0.05
	5 %	0.47	0.07	0.55	0.08
	10 %	0.20	0.08	0.27	0.10
	20 %	0.32	0.09	0.34	0.11
Unaltered	1 %	0.96	0.16	1.55	0.27
	2 %	0.61	0.09	0.95	0.03
	3 %	0.70	0.14	0.86	0.18
	5 %	0.51	0.05	1.00	0.09
	10 %	0.21	0.05	0.40	0.07
	20 %	0.15	0.02	0.31	0.04

Overall belowground biomass of *Acacia saligna* was closely related to the aboveground biomass as was the 0-10 and 10-20 cm depth increments (Table 6).

Table 6. Relationships between belowground biomass and aboveground biomass of *Acacia saligna* after 13 weeks growth.

Depth	Relationship	p-value	r^2
All depths	Below = -0.0144 + 1.4456*above	< 0.001	0.895
0-10	Below = 0.169 + 0.744*above	<0.001	0.829
10-20	Below = -0.177 + 0.507*above	<0.001	0.786

Discussion

Although residue fines have adverse characteristics, after mixing with residue sand that had been treated with gypsum and fertilizer, the leached products showed positive changes in characteristics when compared with residue sand alone. The improvements in amended residue characteristics included both greater concentrations of plant nutrients and greater water retention. Even with these improved growth medium characteristics, the resulting *Acacia saligna* biomass did not show significant increases with additions of residue fines compared with residue sand alone. Vegetative growth over the 3-month growing period varied with rate of residue fines addition (tending to decrease with increased fines additions), and residue fines pre-treatment (seawater > carbonated = unaltered) but, none of the residue fines additions increased growth when compared with the residue sand.

Initially increases in all plant nutrients were evident with residue fines additions and with increased residue fines percentage. Seawater residue fines treatments showed the greatest increases in plant nutrients initially mostly due to increased levels of Mg, Ca, and K introduced from the seawater during the fines processing, but carbonated and unaltered treatments also had significant improvements in nutrient concentrations, particularly in the 10 and 20 % treatments.

Residue fines treatments did increase essential nutrient levels, although four out of the six essential nutrients measured may still be marginally deficient for healthy plant growth of many species (Table 7).

Table 7. Nutrient concentrations in residue fines treatments compared to soil critical concentrations for crop growth.

Nutrient	Concentration range	Level	Critical range for crop growth	Reference:
P	19 - 63 mg kg^{-1}	Marginal	5 - 76 mg kg^{-1}	(Moody and Bolland, 1999)
K	24 - 115 mg kg^{-1}	Marginal	5 - 350 mg kg^{-1}	(Gourley, 1999)
S	291 - 1250 mg kg^{-1}	Adequate	< 1-12 mg kg^{-1}	(Lewis, 1999)
Ex Ca	7.14 – 11.9 cmol kg^{-1}	Adequate	0.44 – 5 cmol kg^{-1}	(Bruce, 1999)
Ex Mg	0.02 - 1.34 cmol kg^{-1}	Marginal	0.1 - 0.44 cmol kg^{-1}	(Aitken and Scott, 1999)
Ex K	0.1 - 2.28 cmol kg^{-1}	Marginal	0.07 – 0.75 cmol kg^{-1}	(Gourley, 1999)

These findings of essential nutrient deficiencies are in agreement with past studies with residue sand which have found similar deficiencies even after heavy fertilizer additions (Courtney and Timpson, 2004; Eastham and Morald, 2006). In particular, exchangeable Mg may be a limiting nutrient with concentrations mostly being inadequate with only the higher seawater residue fines treatments (5-20 %) showing adequate concentrations compared with the critical limits for crops. These significantly higher concentrations of initial exchangeable Mg may explain the greater overall biomass resulting in the seawater treatments.

Water retention characteristics were also greatly improved by additions of residue fines. There was more than a doubling in plant available water (from 1.97 to 3.85 %) in the 5 % addition of residue fines over the unamended residue sand; and a marginally greater than double increase (from 1.97 to 4.69 % water content) in the 20 % residue fines additions. The improvement in water retention increased steadily with increasing percentage of residue fines. Even with this increase in PAW, the negative chemical properties of the initial growth medium with elevated exchangeable Na, EC and ESP, likely limited growth in the fines treatments thus overriding the benefits of the PAW increase. Additionally although residue fines treatments showed greater concentration of nutrients, and the controls had greater vegetative biomass, all *Acacia saligna* plants showed signs of nutrient deficiencies or sodium toxicity to some extent. Very low biomass of *Acacia saligna* in the 10 and 20 % residue fines treatments is likely due to retarded growth from high exchangeable Na present. With initial ESP values ranging from 7 to 34, all treatments would be considered at least marginally sodic and would compound problems for the vegetation and may be enough to limit growth even further. Vegetation establishment and growth is already greatly restricted in these materials due to a very low level of organic carbon (0.08 - 0.17%). Without this nutrient pool from organic matter there is probably very little microbial biomass to mineralize nutrients in the growth medium (Hamdy and Williams, 2001).

Soil moisture was kept constant and adequate for plant growth to focus on treatment effects on nutrient deficiencies or toxicities. Clearly in the field, limited soil water availability is likely in the Mediterranean climate of south-west Australia, and would combine with the osmotic stress of ions and salts in the soil solution to restrict plant growth. On the other hand, in the field the low plant available water storage of the residue sand may limit plant growth compared with the residue fines additions. Considering the adverse increases in exchangeable Na at 10 % residue fines and above; it appears 5 % residue fines may give an optimal increase in water retention while limiting the additional inputs in Na, and thus may be the optimal proportion of fines addition. In a climatic regime where available water would be limited to a short cool rainy season, with sparse water throughout the summer with very high evapotransporation, we expect the difference in water retention characteristics to play a much greater role in determining long term vegetation success than was expressed in the present short term glasshouse trial.

Also of interest in the present findings was the strong relationship of aboveground biomass of *A. saligna* to the belowground biomass. This data will be useful in the future to predict belowground biomass of juvenile *A. saligna* plants from aboveground biomass measurements.

A long term field experiment has been initiated to assess the potential growth medium characteristics of residue fines at 3 and 8 % additions to a 1.5 m depth. These percentages were selected to increase water retention and nutrient availability while limiting increases in exchangeable Na and ESP. The field study will focus on vegetative growth of a native coastal plain (Western Australia) flora community and the chemical and physical properties of the growth medium. Of particular interest will be the nutrient retention capacity of the growth medium over a two year period.

Conclusion

In the past, residue fines has been a problem substrate for revegetation due to its caustic nature but the present results suggest that it may be a beneficial addition to residue sand to produce a more efficient growth medium. Benefits recognized in this study from adding altered residue fines to residue sand include: reduced pH, greater water retention and increased plant nutrients.

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