A chronosequence of bauxite residue sand: weathering and vegetation response

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Abstract

We aimed to identify the edaphic characteristics limiting vegetation performance on rehabilitated bauxite residue storage areas. A chronosequence (up to 25 y) of rehabilitation sites was investigated at Alcoa of Australia's residue storage areas at Kwinana and Pinjarra, Western Australia, where gypsum-amended residue sand has been rehabilitated with native vegetation or pasture. Vegetation diversity and biomass were assessed within 6-m squares from which soil samples from different depths in the residue profile were taken for analysis. An exponential decline with time in maximum electrical conductivity (EC) was demonstrated using quantile regression while a progressive reduction in spatial variability of EC with time was also evident. Vegetation biomass index was more strongly related to age of residue than to period since establishment, indicating a diminishing limitation with time of some edaphic factor such as salinity. Additional sites will allow identification of such factors systematically through the environmental envelope approach using quantile regression. The present data, in confirming that simple parameters for assessing rehabilitation progress show consistent trends with time, indicate the potential value of these sites for providing additional more complex chronosequences such as evolution of secondary minerals, accumulation and humification of organic matter, and the development of complex microbial communities, all of which probably have an effect on ecosystem stability.

Key Words

Bauxite residue, chronosequence, weathering, rehabilitation vegetation, pedogenesis

Introduction

Bauxite refining produces considerable volumes of residue, which is generally managed by establishing a vegetation cover for visual amenity, dust and erosion control, and water management purposes. Vegetation has been established on bauxite residue with varying degrees of success due to the high pH and sodicity of the 'soil' medium. Assessments of vegetation success on bauxite residue have received attention (Wehr *et al*. 2006) and although some general factors governing the success are widely applicable, other factors are site specific owing to the varied elemental content of bauxite residue at different locations worldwide and the influence of climate.

In Western Australia, Alcoa's bauxite residue is separated into sand and mud fractions, with the sand fraction (> 150 µm) being used for constructing embankments within which the mud is dry-stacked. The embankments are ameliorated with gypsum to reduce sodicity and sequester alkalinity before vegetation is established – either a grass pasture or native species from a scrub/woodland ecosystem that occurs locally.

Measuring the establishment and long-term resilience of the vegetation in relation to residue properties is needed to demonstrate adherence to environmental standards as well as to reveal the soil factors exerting most influence on vegetation performance as the bauxite residue undergoes pedogenic alteration through natural weathering and leaching. To measure the success of vegetation establishment a chronosequence of sites is required for which accurate records are available of bauxite residue deposition and amendment history and of vegetation establishment. In this study we describe the establishment of such a database of rehabilitation sites from which the progress of vegetation establishment is assessed in relation to soil development in the bauxite residue.

Methods

Site selection and soil sampling

Seventeen sites at Alcoa of Australia's Kwinana and Pinjarra residue storage areas, of various ages of deposition and vegetation, were selected with the aid of a GIS database of botanical monitoring plots. These 6 × 6-m plots were originally made to monitor the establishment success of the rehabilitation vegetation since 2003. Additional plots were made in older and more recent areas where no botanical monitoring had been conducted.

Samples of the litter layer and the 0–2 cm mineral layer were collected with a trowel, and the 2–10 cm, 10–20 cm, 20–50 cm, and 50–80 cm layers were collected by driving a 9-cm PVC pipe into the soil, then extruding and dividing the cored sample into the abovementioned profile layers. Eight such samples were taken on each 6 x 6 m plot, spaced evenly over the site, and these were mixed to obtain a composite sample for each layer. At four sites, the eight samples of six layers were kept separate for an assessment of spatial variability. Samples were air-dried and passed through a 2 mm screen.

Vegetation assessment

Individual plants rooted within the 6 × 6-m plots were identified by species and measured at their widest extent in two perpendicular directions as well as a measurement of their height. An index of vegetation performance was calculated from width × width and width × width × height. Such indices of shrubby vegetation correlate very closely with total plant biomass (Raison *et al.* 2003). Ephemeral weedy vegetation was measured by height and % cover of the plot, and analogous indices of vegetation performance were calculated from these measurements.

Chemical analyses

Electrical conductivity (EC) of a 1:5 soil:water extract was measured according to Rayment and Higginson (1992). pH_{water} and pH_{KCl} were measured on 1:2.5 soil:solution extracts according to Gautheyrou and Pansu (2006).

Results and discussion

The sites show a distinct trend of reducing EC over time as seen in the raw values of EC for all depths, with the upper boundary of EC values, represented by the 95th quantile, very closely following an exponential decay with time (Figure 1). This is consistent with the leaching of soluble salts (probably mostly sodium sulfate) from the gypsum-amended residue sand. (About 50 Mg/ha gypsum had been mechanically incorporated to a depth of 1–1.5 m on all sites prior to vegetation establishment).

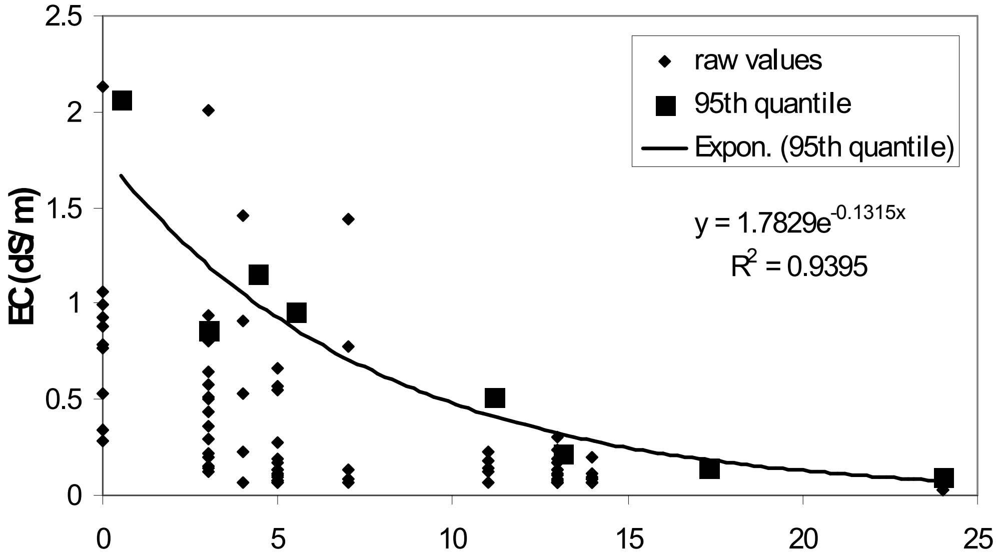

Figure 1. The decline in EC (individual values for different depths at each site and the 95th quantile) with increasing age of bauxite residue sand. .

Besides the general decline in EC with time, the spatial variability of EC within sites also decreased substantially with age regardless of the vegetation type established on the site (Figure 2). These data confirm the expectation of a progressive decline in salinity through seasonal leaching. The large spatial variability shown at the youngest rehab site in Figure 3 is probably because gypsum incorporation was achieved mechanically and thorough mixing was difficult to achieve.

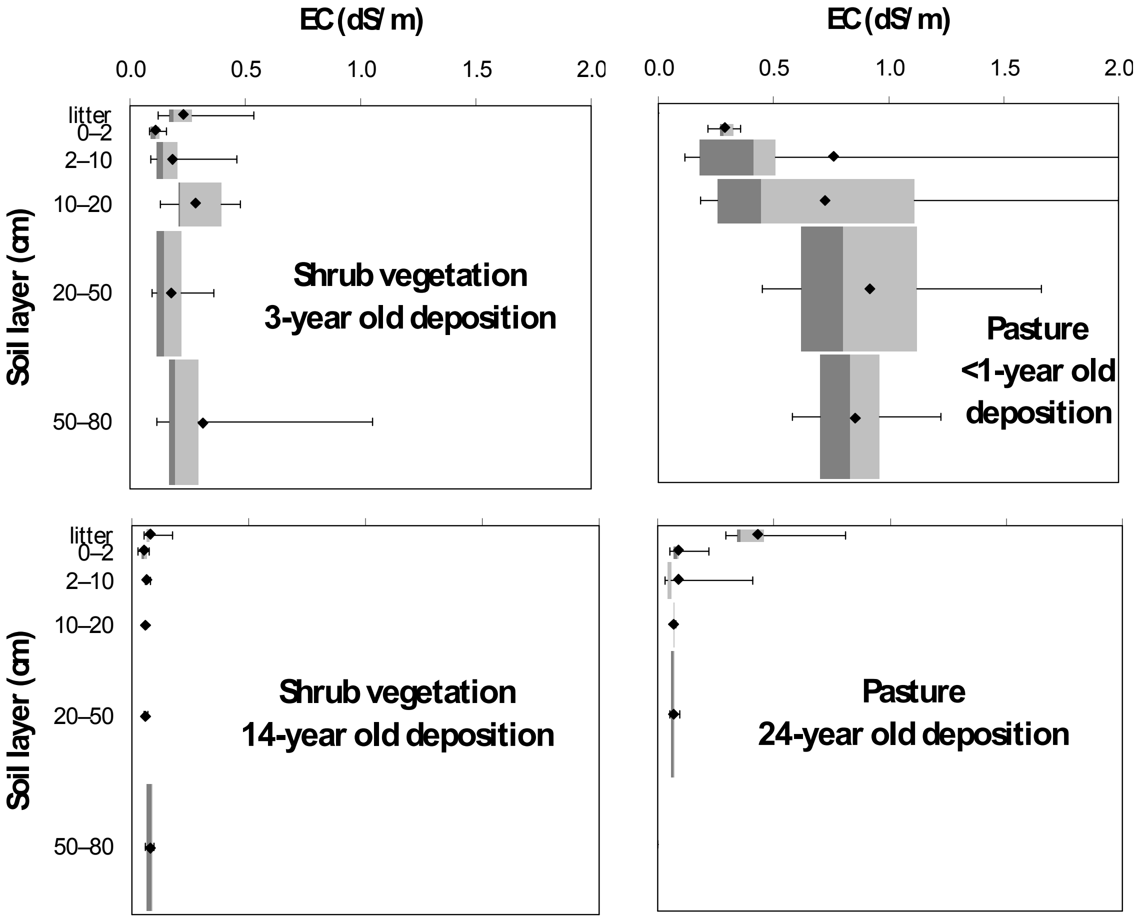

Figure 2. The spatial variability of soil layer EC within 6 × 6-m plots of scrub/woodland or pasture vegetation on different ages of deposition of bauxite residue sand. Data are represented as box and whisker plots, with boxes delineating the 25th, 50th, and 75th quantiles, and whiskers showing the range. Points show the mean.

The index of vegetation biomass was positively correlated with the age of deposition of the bauxite residue but not correlated with the age of the vegetation itself, when assessed on those sites that had been planted with the same suite of native species (Figure 3). This indicates that plant productivity is limited by some edaphic factor(s) given its lack of correlation with vegetation age. The pH data (ranging between values of about 6 at the surface and 8 at depth) did not show any clear trend with time, probably as a result of buffering by calcium carbonate formed through reaction of applied gypsum with residual alkalinity and CO_2. We have sampled too few sites at this stage to enable the use of an environmental envelope approach for identifying limiting factors (Fey and Mills 2009) and additional sites will be examined for which a wider variety of soil properties will be determined. Other researchers have emphasised the importance of leaching bauxite residue prior to the successful establishment of vegetation (Meecham and Bell 1977; Woodard *et al*. 2008). Once salinity has largely been removed, however, it is probable that the relatively high pH levels will result in deficiencies of one or more trace elements. Low availability of Mg is also potentially limiting in amended bauxite residue, although the key factors limiting vegetation growth after gypsum amendment and leaching remain to be identified.

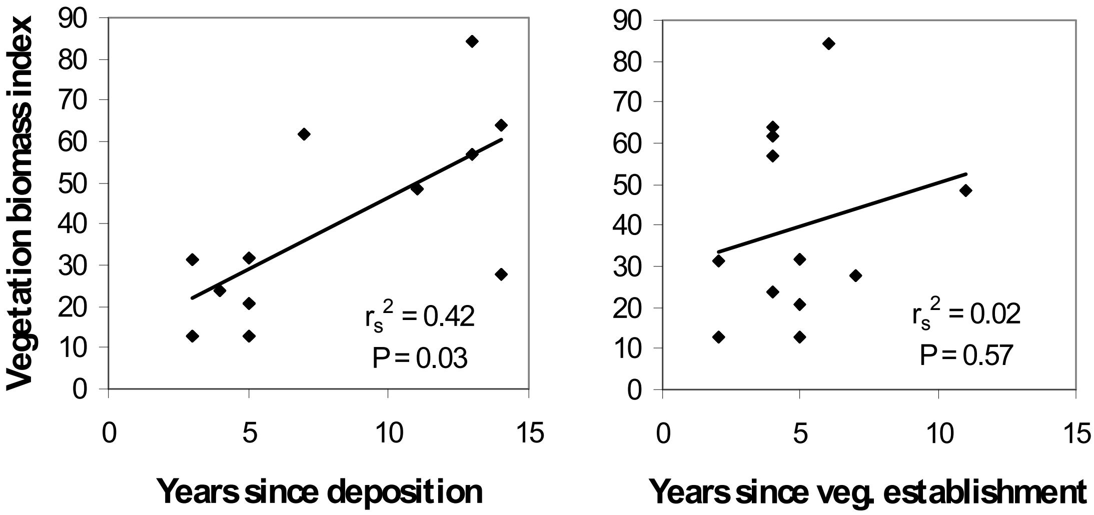

Figure 3. The correlation (Spearman rank correlation) of vegetation biomass index at each site versus years since the deposition of the bauxite residue sand and years since the vegetation was established. Only comparable sites that were vegetated with native scrub/woodland species are included in this analysis; pastured sites have been excluded.

Conclusions

The results confirm an expected pattern over time of both improved vegetation cover and ameliorated soil chemical status due to leaching of soluble salts. The study will now be expanded to include more soil properties and assessment at more sites. The chronosequence should also prove useful for examining microbiological processes affecting nutrient cycling. Ultimately it may be developed as a model of how ecosystem sustainability can be verified through temporal monitoring to reveal the parallel development of soil quality and vegetation.

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