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Amendment of bauxite residue sand can alleviate constraints to plant establishment and nutrient cycling capacity in a water-limited environment☆

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ABSTRACT

Improving below-ground physical, chemical and biological properties is crucial to developing sustainable vegetation cover on mine tailings or mineral processing residues. This study evaluated amendments with the potential to alleviate constraints to plant growth in residue generated from the refining of bauxite to produce alumina. The effects of textural (carbonated residue mud or soil-derived clay), organic (raw-state or mature compost) or combined textural–organic amendment of the bauxite residue sand fraction on key physical, chemical and microbial properties and growth of annual ryegrass were studied in a glasshouse trial. Two watering treatments were utilised to assess the efficacy of amendments under predominantly nutrient-limited or water-limited growth environments. Amendment of residue sand with carbonated residue mud, although able to improve water retention, was detrimental to plant growth as a result of added alkalinity, salinity and sodicity. Amendment with a kaolinitic clay did not improve water retention and was also detrimental to plant growth, most likely due to increased micro-nutrient cation sorption, which was not overcome by combining with organic amendment. Organic amendment significantly increased the organic C and N content, inorganic nutrient availability (P and K) in residue sand with up to 20-fold increases in the size of the microbial biomass (depending on compost type and amendment rate). When organic amendment was used in addition to an initial inorganic nutrient application, plant growth increased. The optimal organic amendment rate (field relevant rates of 2 and 5% by weight were tested) for rapid plant establishment was dependant on whether nutrient-limitation or water-limitation was the dominant growth constraint. Under a regular rainfall scenario, root and shoot growth was maximised with the lower organic amendment rate. A negative correlation between plant growth and microbial biomass or activity suggested that plant–microbial nutrient competition slowed plant growth at the higher organic amendment rate. Conversely under a drought stress scenario, the higher organic amendment rate maximised plant growth, the result of significantly improved water retention capacity. In conclusion, organic amendment was able to alleviate nutrient and water availability constraints to plant establishment that could not be achieved through fine-fraction textural amendment.

1. Introduction

The refining of bauxite ore to produce alumina involves the dissolution of Al-containing minerals in hot concentrated NaOH *via* the Bayer process. The insoluble solids remaining after digestion are described as bauxite residue. Globally, there is an estimated 2.7 billion tonnes of bauxite residue in storage areas and the quantity is increasing each year (Grafe and Klauber, 2011). The future management and environmental legacy of this residue is of increasing concern. While there are re-use opportunities, the vast majority of residue is placed in long-term storage (Power et al., 2011). One management option is to remediate residue *in situ* by establishing vegetation and developing a more ‘soil-like’ below ground ecology to drive microbially-mediated organic matter turnover and nutrient cycling for the long-term provision of plant nutrients (Banning et al., 2011b). The primary constraints to vegetation establishment

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on bauxite residues include high alkalinity, sodicity and salinity coupled with a lack of organic matter, mineral nutrients and microorganisms. Further physical constraints may include high bulk density or low water retention capacity depending on the textural characteristics of the residue (Grafe and Klauber, 2011). Successful rehabilitation of bauxite residues relies on amendments that can improve one or more of the physical, chemical or biological characteristics of the residue (Courtney et al., 2009).

In Western Australia, which produces almost one-third of the world's bauxite (US Geological Survey, 2010), sand is a significant proportion of the bauxite residue and is typically separated from residue fines during refining. The bauxite residue sand (BRS) fraction is primarily used as the growth medium for rehabilitation as it is more easily leached than the fine ('mud') fraction and has had better revegetation success (Anderson et al., 2011). Despite some success with the growth of native coastal sand dune plant species or grasses, rehabilitation outcomes and sustainability are constrained by the poor water retention capacity of BRS and a lack of below-ground organic matter, microbial biomass and nutrient availability (Banning et al., 2011b).

The re-introduction of residue mud and organic amendment of BRS from Western Australian refineries has been examined previously for their potential to improve physical, chemical and biological properties of BRS and to enhance seed germination (Jones et al., 2010, 2011) or plant growth (Anderson et al., 2011; Jones et al., 2012). However, effects of BRS amendment on both early plant establishment and microbial characteristics under a water-limited scenario have not been investigated. South-western Australia has a Mediterranean-type climate in which water availability is the main driver of net primary productivity. The region has experienced declining rainfall for the previous 10 years and the future climate is predicted to become drier with more variable rainfall patterns (Banning et al., 2011a; Matusick et al., 2013). Irrigation of residue rehabilitation has been trialled in the past but in-field monitoring has shown little benefit to plant performance unless high irrigation intensities are employed.

Furthermore, there is a significant knowledge gap in how to apply amendments in way that is most beneficial to the establishment of both plants and a functional below-ground microbial community (Jones and Haynes, 2011). In many ecosystems, plants and microbes compete for limiting nutrients such as N (Bardgett, 2005; Jones et al., 2013). Given the severe nutrient limitation of bauxite residues and its nascent non-equilibrium ecological state, there is potential for organic amendments to enhance microbial competitive ability to the detriment of plant nutrient uptake. The objectives of this study were to examine plant and microbial responses to textural and organic amendment of BRS in a glasshouse trial under a realistic winter rainfall scenario involving wet-dry cycles and a drought stress scenario.

2. Materials and methods

2.1. Bauxite residue sand description and pre-treatment

BRS was collected from the top 10 cm of an embankment at Alcoa's Kwinana Residue Storage Area approximately 40 km south of Perth, Western Australia (32°12′ S, 115°49′ E). The BRS had been placed there less than 6 months previously and covered in wood mulch for dust suppression (which was removed for BRS sampling) but was otherwise unamended. The particle size distribution of the residue sand was 96.5% sand, 2.2% silt and 1.3% clay. The mineralogical composition of BRS from the Kwinana refinery is predominantly quartz (around 67%) with significant amounts of hematite (around 14%) and goethite (around 14%). Gibbsite (around 2%), maghemite (around 2%) and desilication products (sodalite; less than 1%) are also present (Jones et al., 2012). After collection and transport of the BRS to the laboratory, phospho-gypsum (a waste product from superphosphate fertiliser production) was incorporated at a rate of 1.2% (w/w basis); equivalent to the Alcoa's field application rate of 225 t ha^{-1} to 1.5 m depth. Bulk leaching of 600 kg of phospho-gypsum amended BRS was carried out to remove excess soluble salts (primarily sodium sulphate) until the EC of the leachate stabilised at 2.5 mS cm^{-1}. This process altered the pH (1:5 water) of unamended BRS from 10.0 to 8.1 and the EC from 0.24 to 1.3 mS cm^{-1}. The phospho-gypsum amended, leached BRS was air-dried prior to further use and without further amendment was used as the control BRS material.

2.2. Trial amendments

Two fine textured materials were selected: carbonated red mud which is the residue mud fraction that has been reacted with CO_2 by a direct carbonation process (Power et al., 2011), and a locally-sourced kaolinitic clay. Both materials were air-dried and crushed prior to use. Organic amendments included a green-waste derived raw state compost ('compost A') and animal and plant derived mature state compost ('compost B'). Compost B was higher in organic C, N, P and K with a lower C:N ratio than compost A. Field-relevant application rates of 0, 5 and 10% (w/w) of red mud or clay and 0, 2 and 5% (w/w) of composts were tested. Combination amendments were tested at a single application rate of 5% (w/w) red mud of clay with 2% (w/w) of compost.

All BRS amendments were tested with the addition of inorganic basal nutrients as pre-trials demonstrated ryegrass is not able to grow in BRS without a nutrient addition. Nutrients were supplied at rates similar to that of Damon and Rengel (2007) with concentrations (in mg kg^{-1} of BRS) of N (33), P (20), K (88), Mg (4), Mn (3), Zn (2), Mo (0.1), Cu (0.5), B (0.1). These concentrations are 2- to 10-fold lower than the rates typically applied *via* granular fertilisation of BRS embankments in the field. However, a more readily-available solution form of nutrient delivery was utilised for the trial and the application rates were found sufficient for growth of ryegrass during pre-trials. As organic amendment is also a nutrient supply mechanism, all compost amended treatments were also tested without inorganic nutrient solution addition.

2.3. Water retention characteristics

The water content of control and amended BRS samples was determined (prior to plant growth trial) at 0 kPa (equilibrated at normal air pressure), −5 kPa (field capacity), −100 kPa and −1500 kPa (wilting point) using pressure plate apparatus as described by Rayment and Higginson (1992). Plant available water content was calculated from the difference between the water content at −5 kPa and that at −1500 kPa.

2.4. Plant growth trial design and watering treatments

One hundred and thirty two mesh-lined, free-draining pots containing six replicates of 3 kg of BRS ± amendments were laid out in a randomised block design in an evaporative cooled glasshouse. Average maximum/minimum temperatures were 24 °C/11 °C with average day length of 12 h. Annual Wimmera ryegrass (*Lolium rigidum*) cv. Winter Star, was sown at a rate of 20 seeds per pot. Watering was carried out to simulate winter rainfall conditions in the south-west region of Western Australia. This region has a Mediterranean-type climate with hot dry summers and cooler wet