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# Amelioration of soil chemical constraints for revegetation on gold oxide processing residues☆

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ABSTRACT

Gold oxide processing residues are highly alkaline, sodic and saline and initially require amelioration for plant establishment. The aim of this study was to determine the efficacy of soil covers and residue ameliorants in alleviating chemical constraints for revegetation. The effects of residue covers (10 cm topsoil plus 0, 15 or 30 cm gravelly sub-soil referred to as gravel), combined with gypsum (30 and 60 t $ha^{-1}$), and compost (0 and 50 $m^3$ $ha^{-1}$) on chemical properties (pH, electrical conductivity (EC), exchangeable Na percentage (ESP), cation exchange capacity (CEC), total N, extractable N, P, K, S, cations and micronutrients) of gold oxide processing residue were studied in a large-scale field trial at Boddington, Western Australia in a Mediterranean climate. After the first season's rainfall, the $EC_{1:5}$ decreased substantially (from 4.5–5.0 to about 1.0 dS $m^{-1}$) across all treatments in the 0–10 cm residue layer (RES1), while topsoil and gravel materials which had low initial salinity (0.04–0.07 dS $m^{-1}$) increased their $EC_{1:5}$ to 0.40–0.45 dS $m^{-1}$ in the 10 cm above the residue interface in the 2nd hot-dry summer season. pH of both RES1 and the 10–20 cm layer of residue (RES2) dropped from 9.0 to 8.0 over the trial period but topsoil pH remained at 5.2–5.5, regardless of treatments. Exchangeable Na percentage in RES1 and RES2 decreased, but increased from 17 to 70% in topsoil placed directly on the residue surface, compared with no increase in topsoil where there was a gravel layer separating topsoil from residue. Fertiliser added to topsoil raised extractable nutrients to levels adequate for plant growth. Nutrient elements did not differ with gypsum rate and compost amendment except for S, on account of the gypsum applied, and extractable P and Mn, which were elevated by compost. These findings indicate the efficacy of gravel plus fertilised topsoil cover on residue treated with surface broadcast gypsum to alleviate the adverse properties of alkaline, saline, sodic gold oxide processing residue as a medium for plant establishment and early growth.



## 1. Introduction

Ore processing residues are often inhospitable to plant growth, due to alkalinity or acidity, saline–sodic conditions, elevated contents of metals, low nutrient availability, low plant available water, negligible soil microbial activity, coarse or excessively fine texture and poor structure (Hossner and Shahandeh, 2002). Phytostabilisation or revegetation is often an effective means of remediating residues but field investigations are needed to understand the key chemical constraints of the residue (Mendez and Maier, 2008). Typical constraints in gold processing residues were reported by Hossner and Shahandeh (2002). However, the processing residue on most gold mine residue disposal areas (RDA) is typically sourced from crushed rock. By contrast, during the previous operating phase at the Boddington Gold Mine (now Newmont Boddington Gold), processing residues were generated from regolith ore comprising mainly non-swelling kaolinitic clays (Rayner et al., 1996).

Revegetation on gold oxide processing residue requires the reconstruction of a soil profile that will support both establishment and longer term survival of vegetation. Initially, processing residue consists of 60–70% saline liquor and 30–40% milled ore. Following consolidation and drying (to about 70% solids), the residue lacks many of the characteristics of soil, as it dries to form massive apedal blocks with low hydraulic conductivity, separated by relatively wide cracks that are open to approximately 2 m below the residue surface (Ho et al., 1999). It is also characterised by

☆ A preliminary account of the results was presented in McGrath et al. (2003).
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chemical properties that are not conducive to soil biological activity or plant growth as a result of contact with the saline process water, and treatment with sodium hydroxide (NaOH) and sodium cyanide (NaCN) during processing (Ho et al., 1999).

Salinity of the pore water of gold oxide processing residue at Boddington could be as much as 10,000 mg of total dissolved salts $L^{-1}$ (TDS) (equivalent to electrical conductivity ECe[3] 8.7–17.0 dS $m^{-1}$ or $EC_{1:5}$ of 1.45–2.83 dS $m^{-1}$) (Rayner et al., 1996). A higher $EC_{1:5}$ in the residue surface (>3 dS $m^{-1}$) is expected due to surface evaporation and subsequent capillary rise of pore water transporting salts to the surface. The concentrated salt layer may restrict seed germination and root growth if not removed or dissipated during rehabilitation.

Below the surface layer, the recorded $EC_{1:5}$ is still likely to be at levels that will limit growth of most species (between 1.4 and 2.8 dS $m^{-1}$: see Ho et al., 1999). For agricultural crops and pasture, the residue would be regarded as very saline to highly saline and only very salt tolerant crops would be likely to yield satisfactorily (Shaw, 1999). According to Moore (1998), an $EC_{1:5}$ of 1.4–3.5 dS $m^{-1}$ severely limits the growth of most plants.

Processing of ore uses NaOH to extract gold, resulting in a residue pH of approximately 9–9.5. Generally, a pH above 8.5 is considered to severely limit the growth of most plants (Purdie, 1998) due directly to high pH or to induced nutrient deficiencies by immobilising nutrients such as zinc (Zn), manganese (Mn) and iron (Fe). Gypsum can reduce soil pH by removing bicarbonates and carbonates from soil solution as insoluble calcium carbonate (Barrow, 1982). Earlier research with gold oxide processing residue indicated that gypsum at 30 t $ha^{-1}$, when well incorporated into residue (to 30 cm depth), increased plant growth (Ho et al., 1999).

Sodium accumulates as the dominant cation in processing water from the brackish source water, and is increased by direct addition of NaOH and NaCN in the refining process. The exchangeable sodium percentage (ESP) of the residue has been previously recorded at 62% (Ho et al., 1999), while an ESP of 5% is sufficient to cause the dispersion of clay particles (Rengasamy and Churchman, 1999). Hence the high concentrations of exchangeable Na contribute to the lack of pedality in the residue and poor infiltration of water. Problems arising from these effects can include waterlogging, low plant-available water storage (Shaw et al., 1994), poor aeration and hence poor root development (Naidu and Rengasamy, 1993). Gypsum is commonly added to soils to reduce sodicity, as it is a source of $Ca^{2+}$ ions which replace $Na^{+}$ ions on soil exchange sites, reducing the ESP of the residue (Qadir et al., 2001; Walker and Bernal, 2008; Lakhdar et al., 2008).

Residues may have levels of nutrients that cause deficiencies or toxicities in plants. Nutrient disorders potentially affecting revegetation of residue include: low levels of phosphorus (P), although jarrah forest vegetation has adapted to these conditions (Handreck, 1997); zinc, manganese (Mn) and iron deficiency (Fe) due to high pH causing elements to transform to unavailable forms; and elevated copper (Cu) due to Cu mineralisation together with gold (Rayner et al., 1996) that may cause Cu toxicity reactions in susceptible plants (Jones et al., 2010).

The adverse properties of residue mean that a cover of topsoil, sub-soil or other benign substrate may improve plant establishment and growth on residue storage areas. However, topsoil and sub-soil may be in short supply at the sites of residue disposal, and in any case generally have been in long term storage stockpiles which is not optimal for plant growth (Carrick and Krüger, 2007). A risk from placement of topsoil or sub-soil over residue is that over time migration of salts from residue into the cover compromises its suitability for plant growth unless the cover forms an effective capillary break for saline pore water in residue. Hence there is a need to determine the optimum thickness of cover and its properties over time following placement. Considering the value and availability of topsoil or gravel covering, the reconstructed soil profile was predicted at Boddington to consist of a 10–40 cm layer of topsoil and/or sub-soil to act as a seed bed, rooting medium and capillary break, overlying residue that had been solar dried for 2–3 years after deposition and treated with 30–60 t of gypsum $ha^{-1}$ incorporated to 30 cm depth (Ho et al., 1999).

Application of gypsum to the residue to increase both flocculation of clay particles and hydraulic conductivity should encourage leaching of salts from the residue surface enhancing the prospects for plant growth. The effectiveness of gypsum when incorporated into residue has been previously demonstrated by improved plant growth (Ho et al., 1999) but the efficacy of surface broadcast application has not. Broadcasting of compost on the residue surface was also investigated in this trial as an additional organic form of nutrient supply.

In this study, we investigated the effects of gravel thickness, two rates of gypsum application, and the addition of organic material on amelioration of adverse chemical properties of the underlying residue over time. The aim of the study was to determine the effect of soil cover thickness (comprising topsoil alone with or without underlying gravel) and broadcasting of gypsum or compost on the residue on the edaphic properties of the reconstructed soil profile, and its likely suitability for plant growth and ecosystem function. A companion paper examines the consequences of these properties for vegetation establishment, vigour and diversity (Ni et al., 2014).

## 2. Materials and methods

### 2.1. Site location

The study was conducted at Newmont Boddington Gold (NBG) mine near Boddington, 125 km south-east of Perth, Western Australia (Rayner et al., 1996; McGrath et al., 2004). The climate of the southwest of Western Australia is typically Mediterranean, with cool wet winters (June–August) and hot dry summers (December–February). Mean annual rainfall at the nearby Marradong station (32.86° S 116.45° E) is 724 mm with 88% falling between April and October while mean maximum/minimum temperatures in January and July at Wandering station are 32/14.2 and 15.8/3.8 °C, respectively (Bureau of Meteorology, 2001)>. The monthly rainfall of 1999–2000 and the rainfall minus evaporation are shown in Fig. 1 for the weather station at Wandering (Bureau of Meteorology, 2001).

### 2.2. Experimental design and sample collection

For site characterisation, the residue was sampled in January 1999 and then in more detail in February 1999, prior to the application of treatments (Table 1). Initially, a 15 m × 15 m grid was established over the 4.5 ha area and the surface 10 cm of residue sampled from 200 points on the grid. In February 1999, the residue was sampled at 10 cm intervals to a depth of 50 cm at 21 sampling points, distributed evenly over the site. The layout of replicate plots was designed to ensure uniformity of surface texture within each block, based on residue textural gradients determined from the January 1999 sampling on a grid pattern (McGrath, 2001).

[3] ECe is the electrical conductivity in a water extract of saturated residue. A conversion ratio of 6 determined by Prasodjo (1996) for gold oxide processing residue was used to convert these units to EC in a soil to water extract of 1:5 [$EC_{1:5}$], i.e. ECe = 6.0 × $EC_{1:5}$. $EC_{1:5}$ will be the unit generally used to quantify salinity in this article.