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Research paper

Indicators of soil formation in restored bauxite residues

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ABSTRACT

Increasingly, the aim of mine residue rehabilitation is moving towards ecosystem reconstruction rather than vegetation establishment. In an unamended state, mine residues exhibit degraded soil structure as well as other chemical and biological characteristics which are inhibitory to long-term plant growth. At a bauxite residue disposal area in South-west Ireland, a series of restoration treatments were investigated for evidence of soil development. Unamended residue has high pH, sodicity, salinity, dominance of fine fraction and poor aggregate stability as well as low carbon content. Within one year, amended and vegetated sites exhibited improved physico-chemical properties and increased aggregate stability. Further improvement of these properties in subsequent years and evidence of non-labile carbon and nitrogen accumulation indicate that development of root systems and soil communities drive pedogenesis in restored industrial sites.

1. Introduction

Mine tailings and mineral processing residues are the fine-grained (<2.0 mm) by-products resulting from the ore extraction processes and these are often disposed on land in large residue disposal areas. The potential pollution risk from uncovered tailings is well reported and it is generally accepted that revegetation is the most suitable method for effectively stabilising the residue surface, decreasing wind and air erosion and improving aesthetics (e.g. Tordoff et al., 2000; Ye et al., 2000).

Bauxite residues are a sodic-alkaline by-product from the extraction of alumina from bauxite ore. Global production is estimated at 120 Mt and understanding of the processes involved in the successful restoration of these wastes are a recognised concern (Jones and Haynes, 2011). Plant growth on bauxite residues can be inhibited as they typically exhibit high pH and exchangeable sodium (ESP) content (Jones and Haynes, 2011) as well as characteristics typical of other mine wastes such as low soil organic matter (SOM) content, low fertility, and poor physico-chemical and biological properties (Bradshaw, 2000). Gypsum amendment of bauxite residue is widely used in its rehabilitation to effectively reduce the pH and ESP (Jones and Haynes, 2011) whilst organic amendment of mine tailings and bauxite residues is recognised as a source of nutrients (e.g. Ye et al., 2000; Courtney and Harrington, 2012).

The success of bauxite residue restoration has largely been assessed by soil chemical analyses and short term vegetation growth trials (Courtney et al., 2009a; Jones and Haynes, 2011 and references therein). Increasingly it is recognised that for successful cover systems on mine residues the formation of soil and a greater understanding of the processes in soil development are crucial (Shu et al., 2005; Biederman et al., 2008). The restoration of functional ecosystems on mine waste sites can be manipulated by introducing vegetation (revegetation) which can accelerate the stabilisation and development of the soil surface (Bradshaw, 1997). Widely used parameters for assessing soil physical quality such as bulk density, porosity, and water stable aggregates (AI) and are becoming more widespread in assessing restoration on mine wastes (Shukla et al., 2004; Asensio et al., 2013).

The current study was carried out under field conditions where bauxite residues had been amended with gypsum and organic matter to support vegetation cover but varied in their physico-chemical composition and/or time since amendment and seeding. The hypothesis of this work is that the oldest revegetated residue amended with organic matter and gypsum will exhibit the highest physical quality compared to more recently amended sites or those with less gypsum.

2. Methodology

2.1. Materials and methods

2.1.1. Soil sampling

The sampling area is located at the Aughinish alumina refinery, Limerick, South-west Ireland. The climate of the experimental

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site is temperate maritime, with average precipitation reaching 1180 mm per year and a mean annual daily temperature of 10.5 °C.

In alumina refineries, bauxite ore is processed by the Bayer process in which Al-containing minerals are dissolved in NaOH under high temperatures and pressures. Generally, for each tonne of alumina, 1–2 tonnes of insoluble solids (bauxite processing residue) are produced (Jones and Haynes, 2011). At Aughinish the residues are separated during the process into a fine fraction 'red mud' and coarse fraction 'residue sand' and deposited separately in an adjacent 180 ha engineered bauxite residue disposal area (BRDA). The principal residue, red mud, is produced at a rate of approximately 1.05 million tonnes per annum and about 0.15 million tonnes of process sand is also produced. The mud fraction is pumped (c. 60% solids) to the BRDA where it is discharged, spread and allowed to consolidate. The sand fraction (<10% of residue) is trucked to the BRDA and deposited.

In order to evaluate the evidence for soil formation on restored residue, five treatment areas were selected representing residue of varying properties and/or restoration history (e.g. amount of gypsum added, time since seeding). The soil samples are described in greater detail below. The soil was sampled to a depth of 15 cm at five randomly chosen points in each site. Samples were stored in polyethylene bags, dried at room temperature and sieved to <2.0 mm prior to being analysed.

2.1.2. Bauxite residue treatments

Restoration trials were initiated in 1998 to investigate methods for amending the sodic and alkaline bauxite residues to support vegetation establishment (e.g. Courtney et al., 2009a). Residue disposal and management is within a series of raises (upstream method) and the BRDA is operational. Consequently, available space for restoration work is restricted to terraced areas between raises. All study sites were located on the same BRDA terrace height with similar distances from surrounding vegetation. Study sites were approximately 10 m × 20 m.

The control site for the bauxite residue (BR1) was in an untreated area of the BRDA, and is devoid of vegetation.

The second sampled area (BR2) was amended with process sand (25%), gypsum (90 t ha^{-1}) and compost (100 t ha^{-1}) and seeded with ryegrass (*Lolium perenne* L.), red fescue (*Festuca rubra* L.) and clover (*Trifolium* sp.), one year previously.

The third and fourth areas sampled (BR3 and BR4) were restored nine years previously with process sand addition (25%, w/w) and compost at 100 t ha^{-1} and seeded as per BR2. Treatment BR4 also received gypsum amendment at 90 t ha^{-1}, BR3 received no gypsum. At the time of sampling the vegetation dynamics had changed and the sites were dominated by Yorkshire Fog (*Holcus lanatus* L.), red fescue (*F. rubra*), red clover (*Trifolium pratense* L.) as well as willow (*Salix* sp.).

The fifth area sampled (BR5) was amended as per BR4 but with 45 t ha^{-1} of gypsum and vegetated 11 years previously. Similarly to BR3 and BR4, vegetation was dominated by Yorkshire Fog, red fescue and clover. In addition to willow encroachment there were also some birch (*Betula* sp.) and Common Alder (*Alnus glutinosa* L. (Gaertn.)). For all restored sites amendments were surface spread and incorporated to ~0.2 m depth using standard agronomic rotavating and harrowing machinery.

In addition, soil from an adjacent unmanaged grassland was sampled to provide a potential analogue for site comparisons.

2.1.3. Analytical methodology

Bulk density (ρ_b) was determined from undisturbed soil cores using bulk density rings (Eijkelkamp) and oven dried. Values are reported on a soil oven-dry mass basis. Core samples were then ground and passed through a 2 mm sieve and the particle density (ρ_d) determined using the pycnometer method, where the soil particles were dispersed in water and the air expelled from the suspension through boiling (Rowell, 1994). Total porosity (St) was calculated as the difference between both densities expressed as a percentage.

Additional soil samples (0–15 cm) were air dried and passed through a 2-mm sieve prior to physico-chemical analysis. Soil pH and electrical conductivity (EC) were measured in an aqueous extract (soil to water, 1:5, v/v). Available cations (sodium, calcium, potassium and magnesium) were determined following extraction with 1 M ammonium acetate and ESP determined using the method of Qadir and Schubert (2002).

The proportion of water-stable aggregates larger than 250 μm (macroaggregates) was established using an Eijkelkamp (Agrisearch Equipment, The Netherlands) wet sieving apparatus. In this method, residue samples were sieved and 4 g of 1–2 mm aggregates were placed in each sieve. Samples were pre-moistened with a fine mist spray and the samples lowered into the sample cans containing bi-distilled water and subjected to a regular up-and-down motion with a vertical distance of 1.3 cm and a rate of 34 cycles/min for 3 min. Sieves were then raised to allow excess water to drain and the remaining material dispersed using sodium hexametaphosphate (2 g l^{-1}) until only sand and root fragments remained on the sieve. Cans containing residue were dried at 105 °C and the dried residue was weighed. The stable fraction was determined as:

$$A : I = 100 \times \frac{\text{weight of dispersed aggregates}}{\text{weight of dispersed and water dispersed aggregates}}$$

Soil carbon fractionation procedure followed the method of George et al. (2010) as follows. The soil sample (~10 g) was first disaggregated on an end-over-end shaker with 80 ml of 25 g l^{-1} sodium hexametaphosphate for a period of 16 h. This disaggregated soil was then passed through 200 μm pore size sieve followed by a 53 μm pore size sieve. The sediment, consisting of sand and particulate organic matter, was gently worked with a spatula to ensure that no aggregates were retained in the particulate fractions.

This procedure divided the soil into three size classes: (1) 200 μm; (2) 200–53 μm; and (3) <53 μm fractions. The 200 μm (highly labile carbon pool) and 200–53 μm (moderately labile carbon pool) fractions represent particulate organic carbon (POC) and were dried at 90 °C and ground to a fine homogenous powder using a ball mill grinder. The <53 μm fraction (representing the recalcitrant fractions of the soil—formed after various SOM conversions and/or structurally unaltered SOM stabilised by various processes) was collected in a measuring cylinder (1-L) after passing through both sieves in de-ionised water. The samples were allowed to settle before the supernatant was discarded. The solid fractions were then weighed and analysed for total *C* and *N* by the dry combustion gas method using a Thermo FlashEA 1112 Elemental Analyser.

The microaggregate stability residue treatments were determined using the method previously described by Courtney et al. (2009b). Briefly, soil samples were dispersed by shaking in DI water and the suspension passed through a 53 μm aperture sieve. Particle size analysis was assessed using a Malvern Mastersizer 20001 (Malvern Instruments Ltd., UK) and values reported are (i) the mean diameter of particles in suspension [$d(4,3)$], with large values indicating the presence of more stable aggregates and (ii) the $d(0,10)$ values, which represent 10% of the total particles enumerated in the soil suspension. This value is illustrative of clay dispersion, with low values representing an increase in dispersible clay.

Following the implementation of Kolmogorov–Smirnov normality tests the data generated were analysed statistically using analysis of variance, descriptive measures and Pearson's bivariate correlations on SPSS, version 19.0. Differences between the