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An ecological assessment of rehabilitated bauxite residue

R. Courtney, E. Feeney, A. O'Grady *

Department of Life Sciences, University of Limerick, Limerick, Ireland

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ABSTRACT

Assessment of soil biological communities and activity may be a valuable indicator of ecological stress and ecosystem function in rehabilitated bauxite residues. Establishment of keystone species and evidence of processes such as decomposition have been demonstrated on a number of mine spoil types but not on alkaline, sodic bauxite residue.

Using the litterbag technique the spatial and temporal variation in decomposition rates was examined in a residue rehabilitation series; site A (not rehabilitated), site B (1yr), site C (10yr) and site D (12yrs). Soil arthropods were extracted by Tullgren and species and enzyme activities (β-glucosidase and dehydrogenase) were related to residue properties. The natural establishment of large invertebrates such as earthworms and ants show that sites C and D are in late succession while site B had a large quantity of springtails and Dipteran larvae which typify early succession. The ten year old site showed 'best' soil quality and this was attributed to the lower Na and exchangeable sodium percentage exhibited.

The combination of improved physico-chemical properties, increased vegetation diversity, greater biological activity and invertebrate establishment indicate that the alkaline and sodic residues can be rehabilitated to a semi-natural soil quality.

1. Introduction

In Europe, an excess of 1.2 billion tonnes of mine tailings are currently in storage in tailings facilities (BRGM, 2001). The environmental risk of mine wastes and tailings is long recognised and establishment of vegetation is seen as a cost effective and environmentally sustainable method for reclamation and stabilization of such sites (Tordoff et al., 2000). Amendment procedures to promote vegetation growth on tailings and wastes will vary with specifics of tailings type, climatic conditions, resources available and land-use envisaged. Bauxite residue tailings are a sodic–alkaline by-product from the extraction of alumina from bauxite ore and recent research has highlighted the ability of amended residues to support plant growth (Jones et al., 2011; Courtney and Kirwan, 2012; Goloran et al., 2014).

It is now recognised that ecosystem reconstruction leading to self-sustaining systems is the necessary goal of mine waste restoration (Van Hamburg et al., 2004). Soil enzymes provide a rapid and reliable source of information on ecological processes and soil health and have been used for a variety of mine waste types such as brown coal waste (Baldrian et al., 2008) and copper tailings (Zhan and Sun, 2014). Knowledge about the invertebrate recolonization of mine wastes is essential as they are major drivers in the processes of soil development and formation and ecosystem functions (Frouz et al., 2007; Majer et al., 2007). Evidence of ecosystem functions, such as nutrient cycling, has been assessed on rehabilitated mine wastes and have demonstrated the effects of various soil biota groups in the processes (Frouz et al., 2006).

Although several researchers have investigated ecosystem recovery of bauxite mine sites with emphasis on terrestrial invertebrate activity (Majer et al., 2007; Koch et al., 2010) relatively few studies have transferred to the restoration of the bauxite processing residues (Courtney et al., 2010, 2011).

To date, evidence of ecological function in rehabilitated bauxite residues is limited with the majority of published work examining methodologies for improving soil properties and/or plant growth. Here, soil arthropod communities were compared and plant litter decomposition rates from bauxite residues at different restoration stages.

2. Materials and methods

The study area is located at Aughinish Alumina Ltd., Askeaton, Co., Limerick in the south west of Ireland (52°37′06″N, 9°04′19″W). The study site is a bauxite residue disposal area (BRDA) with fine fraction bauxite residue (red mud) spread across an area of 104 ha. This is an active site and residue disposal from the refinery is still occurring.

* Corresponding author. Tel.:+353 61 202903.
E-mail address: audrey.ogrady@ul.ie (A. O'Grady).

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Table 1
Description of the study sites investigated.

	Treatment			
	A	B	C	D
Amendment history				
Gypsum addition (t/ha)	0	90	90	45
Compost addition (t/ha)	0	120	120	120
Years since seeding	0	1	10	12
Vegetation ground cover (%)	0	100	100	100
Size (m^2)	80	60	60	60

2.1. Study sites

Four study sites were investigated (Table 1). The years since seeding and amendment refer to the number of years since the sites were originally amended with gypsum and organic matter and then seeded (Courtney et al., 2013). The ecological status of each site was assessed seasonally during 2012 using litterbag decomposition, enzyme activity and faunal assemblages. Additional samples were taken to characterise the physico-chemical properties of each treatment.

The litterbag method was used to measure plant litter decomposition in each site, using nylon mesh of 0.5 cm by 0.5 cm aperture fixed to polythene frames (10 cm by 10 cm). This mesh allows the entry of macrofauna. Litterbags were filled with 3.6 ± 0.01 g of dried (oven dried at 70 °C) *Lolium perenne* leaves that was grown in the University field biology facility. This allowed for consistency in litter quality. For each sampling period a total of 10 litter bags were placed at sites B, C and D: 5 on the soil surface, and 5 belowground at 8–10 cm depth. Due to poor soil structure, no belowground litterbags were placed at site A. Litterbags were retrieved after 28 days and oven-dried at 70 °C to a constant dry weight and decomposition was expressed as mass loss (g) per day. Mass loss from the bags is referred to as "decomposition" as per Smith and Bradford (2003) who acknowledge mass loss asthe result of both the physical process of "breakdown" and the catabolic process of "decomposition".

Five soil samples were randomly collected, using a soil corer (0–15 cm depth) across each site. Enzyme activity was determined for soil samples that were field sieved and then stored at 4 °C (Paul and Clark, 1996). Samples for physico-chemical analysis were oven dried at 70 °C for 48 h and sieved (<2 mm). Undisturbed soil clods were returned to the laboratory for arthropod extraction and determination. Bulk density (ρb) was determined from undisturbed soil cores using bulk density rings (Eijkelkamp) and oven dried. Values are reported on a soil oven-dry mass basis. Soil temperature was recorded in-situ using a temperature probe. Field moist soil was returned to the laboratory and oven dried at 70 °C for 72 h and loss in weight expressed as soil moisture. Soil pH and EC were measured in an aqueous extract (1:5). Organic matter content was determined by loss on ignition at 500 °C for 24 h Total available cations were determined following extraction with 1 M ammonium acetate at pH 7 (Thomas, 1982) and exchangeable sodium percentage expressed as ESP = 100(Na_{exch})/CEC. Available phosphorous was determined using UV spectrophotometry following extraction with sodium bicarbonate, and total nitrogen content by the Kjeldahl method (Bremner and Mulvaney, 1982).

Field-moist soil samples were sieved (2 mm) and stored at 4 °C (Paul and Clark, 1996) prior to enzyme determination. β-glucosidase activity was measured as described by Alef and Nannipieri (1995). In brief, 1 g samples of moist-sieved soil were incubated for 1 h at 37 °C with *p*-nitrophenyl-β-d-glucoside and toluene in a pH 6.0 modified universal buffer. Following addition of $CaCl_2$ and Tris buffer (pH 12) the product was determined colorimetrically at 400 nm. Dehydrogenase activity was estimated by the addition of triphenyltetrazolium chloride (TTC) to 5 g soil followed by incubation at 30 °C for 24 h. The triphenyl formazan (TPF) was then extracted with acetone and determined colorimetrically at 546 nm (Thalmann 1968).

Tullgren extraction was used to determine soil faunal assemblages from each study site. All invertebrates collected in traps were sorted to class, order, family, genus and species when possible, and otherwise assigned to morphospecies. The Shannon–Wiener diversity index (H') was calculated for pitfall trap samples using Multivariate Statistical Package (MVSP) version 3.1 (Kovach, 1998) where

$$H' = -\sum_{i-1}^{s} \text{pilogpi}$$

pi = proportion of species in the community, s = no. of species.

2.2. Statistical analysis

Tests of normality and homogeneity were carried out in SPSS version 19 before two-way analysis of variance. Duncan's post hoc test ($P < 0.05$) were used to determine if there was any significant differences between sites and seasons. Pearsons correlations were carried out to determine if there was any linear dependence between soil variables. Multivariate analysis was carried out using CANOCO version 4.5. All graphs were created in GraphPad Prism version 5. Species that occurred in only one season or had less than five individuals were excluded from multivariate ordination. Canonical correspondence analysis (CCA) using Canoco for Windows version 4.5 (ter Braak and Smilauer, 1998) was carried out, as follows: the species data were log transformed, ln (x + 1). The sites were input as treatments (environmental variables) and

Table 2
Selected soil physico-chemical characteristics of the four study sites (0–15 cm) and recommended values for success.

	Site A	Site B	Site C	Site D	Rehabilitation goal
pH (H_2O)	10.2 ± 0.06a	8.3 ± 0.18b	8.1 ± 0.13b	8.2 ± 0.07b	5.5–9.0[a]
EC (mS/cm)	0.9 ± 0.1a	0.5 ± 0.01b	0.2 ± 0.01c	0.17 ± 0.01c	<4[a]
Na (mg/kg)	1800 ± 267a	957 ± 160b	213 ± 15c	229 ± 42c	
ESP (%)	65 ± 13a	18 ± 2.0b	4.9 ± 0.32c	11.8 ± 3.4 d	<9.5[a]
OM (LOI) (%)	6.8 ± 0.01a	11.5 ± 1.3b	12.1 ± 1.7b	11.2 ± 0.69b	
TKN (%)	N.D.	0.26 ± 0.04a	0.30 ± 0.03a	0.28 ± 0.04a	0.1–0.15[b]
P (%)	N.D.	3.8 ± 0.02a	2.9 ± 0.02a	1.4 ± 0.03b	
BD ($g\,cm^{-3}$)	1.4 ± 0.03a	1.06 ± 0.03a	1.1 ± 0.02a	1.09 ± 0.01a	≤1.5[a]

Values expressed are mean ($n = 5$) followed by S.E.
Means within a row followed by the same letters are not significantly different at $P = <0.05$.
ESP = exchangeable sodium percentage; OM (LOI) = organic matter (loss on ignition); TKN = total kjedahl nitrogen; BD = bulk density
[a] Gräfe and Klauber, 2011.
[b] Asensio et al. 2013.