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Earthworm community development in soils of a reclaimed steelworks

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ABSTRACT

Long-term studies are essential to learn earthworm community development and soil formation post reclamation. Investigations were undertaken at a former steelworks site at Hallside, near Glasgow, UK, reclaimed in the 1990s using a mixture of colliery spoil and sewage sludge. The site was largely planted for production of short rotation coppice willow (*Salix* spp.). Earthworm inoculation formed a part of the restoration process. Minimal monitoring occurred in the interim, but some records of earthworm sampling existed in 2000 and 2005. This study focused on monitoring earthworms and soil properties across the site, drawing comparisons with adjacent unspoiled soil. Results showed that after 22 years, a species-rich community of earthworms ($n = 16$) colonized the site, with endogeic *Aporrectodea caliginosa* being dominant by number and anecic *A. longa* by mass. Across the site, earthworm community density and biomass were 208 individuals m^{-2} and 71 g m^{-2}, respectively. The Shannon diversity index for earthworms was 1.89, with an evenness of 0.68. The sewage sludge increased the soil organic matter, but the stone content of the colliery spoil prevented digging in some locations. Soil chemistry had no negative effect on earthworms, but the compacted substrate did hinder water infiltration. Earthworms colonized the reclaimed site from adjacent areas, and community structure and density below well-drained, scrub-free willow, birch, and grassland were not significantly different ($P > 0.05$) from those of the adjacent unspoiled areas. The results show that the historical earthworm inoculation was unnecessary and badly timed. Future reclamations of similar sites can learn from this investigation.

Key Words: colliery spoil, colonization, inoculation, land reclamation, pedogenesis, rehabilitation, sewage sludge, willow

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INTRODUCTION

In the sphere of restoration ecology, long-term studies relating to soil development and the development of a functioning earthworm community are relatively uncommon (Pigott, 1989; Butt, 2017), which may be surprising, given the expected timeframes for pedogenesis, under natural conditions (Jenny, 1941) or in a reclamation context (Bradshaw, 1983). Finance is often the driver of projects and science plays a secondary role, but to understand such soil-related processes, thinking that extends to decades and beyond is necessary. To address this, it is essential to return to documented reclamation sites and develop a lengthy chronology that may need to extend beyond the careers of individual researchers. The current work is a step in this direction, spanning two decades and taking heed of remarks on earthworms used in reclamation (Butt, 1999).

This investigation concerned a 35-ha reclaimed steelworks site at Hallside (55°48′59″ N, 4°07′41″ W), 13 km to the southeast of Glasgow, Scotland, UK. The site was reclaimed from dereliction by the Scottish Greenbelt Company during the 1990s. All contaminated soil was removed from the site, and a rudimentary soil was formed by spreading stone-rich material from enormous heaps of colliery spoil and locally-derived sewage sludge (biosolids) to create a growing medium 2 m in depth. Trees, mainly willow (*Salix* spp.), were planted for Short Rotation Coppice by the Forestry Commission (Craven, 1995). To potentially assist tree growth and pedogenesis, earthworms were added to the site using two techniques: i) the earthworm inoculation unit (EIU) technique, using *Lumbricus terrestris* (Butt *et al*., 1995) and ii) earthworm-rich turf discs (supplied commercially but also investigated for earthworm species at the time by the lead author). The success of the earthworm inoculation was investigated over the first two years, with indications that both techniques had been poorly implemented and very few, if any, earthworms had persisted (Bain *et al*., 1999; Butt, 2008). After a period of less than a decade, a project initially given support by the West of Scotland Water Authority, Scottish Enterprise, the Forestry Commission, and Scottish Natural Heritage, and considered a model study for reclamation of contaminated steelworks, was largely abandoned.

Earthworms have a positive effect on soil formation, so it was anticipated that these ecosystem engineers would advance pedogenesis in the anthropogenic soils at Hallside (Edwards and Bohlen, 1996; Blouin *et al*., 2013). Small scale investigations (Mitchell, 2001; Butt and Lowe, 2005) showed the earthworm communities had started to develop, so a major

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survey was undertaken in 2018. Previous investigations, personal knowledge of the lead author from the 1990s, and desk-based studies revealed that the west region of the site was the focus of reclamation, compared with some non-industrial areas (former farmland) to the north-east, south of the railway. The latter, planted with aspen (*Populus tremula*), were considered as control sites and as potential soils from which earthworm colonization may have occurred, as seen in other reclaimed industrial sites (Butt and Briones, 2017). In addition to the willow, small areas of the reclaimed site had been planted with stands of various tree species. These included birch (*Betula* spp.), cherry (*Prunus* spp.), Scots pine (*Pinus sylvestris*), and Norway spruce (*Picea abies*). The soils below these trees were also investigated due to differing rates of leaf degradation and known effects of leaf material on earthworms, hence soil development (Wittich, 1943; Ashwood *et al*., 2017).

This investigation aimed to gather information on the development of soil and earthworm communities in an anthropogenic soil after a period of more than two decades. Specific objectives were to determine the earthworm species present and draw comparisons with previous records, measure community density and biomass, calculate community diversity, compare effects of vegetation on earthworms, draw comparisons with adjacent, unspoiled soils, and assess relevant soil parameters.

MATERIALS AND METHODS

During spring (April and May, 2018), stratified sampling was carried out across the site, based on the proportion of vegetation cover (various tree species and grassland) and knowledge of where (aspects of) reclamation had occurred. The site was predominantly willow-covered, from which 12 sampling sites were selected (Fig. 1). A further five sampling sites were randomly allocated within the grassland of the non-tree-covered central section, two to separate birch stands and one each below cherry, Norway spruce, and Scots pine in the central northern part of the site. In addition, two sites were identified as controls in unspoiled soils over 150 m to the north-east of the reclaimed site, within an aspen plantation. At each of the 24 sampling sites, earthworms and soil were collected with three replicates. Additional soil measurements were undertaken as outlined below.

The collection of earthworms was achieved through hand-sorting of soil, dug from plots of 0.1 m^2 to a depth of 25 cm, where possible. To extract earthworms from below this depth, a vermifuge (expellant) of mustard powder and water (5 g L^{-1}) was applied to encourage any deep burrowing worms to the surface (Butt and Grigoropoulou, 2010). Earthworms were preserved in 4% formaldehyde and returned to the laboratory for identification using the nomenclature of Sherlock (2018). Furthermore, the earthworms' masses were determined and the specimens were assigned to one of three ecological categories: epigeic (surface living), endogeic (shallow burrowing), and anecic (deep burrowing) (Bouché, 1972).

Soils at 0–10 cm were collected from each sampling point and placed in sealed polyethylene bags to prevent moisture loss. These were returned to the laboratory for analysis. The following variables were determined using methods described by Rowell (1994): pH, moisture content, organic matter content by loss on ignition (LOI), texture, soil

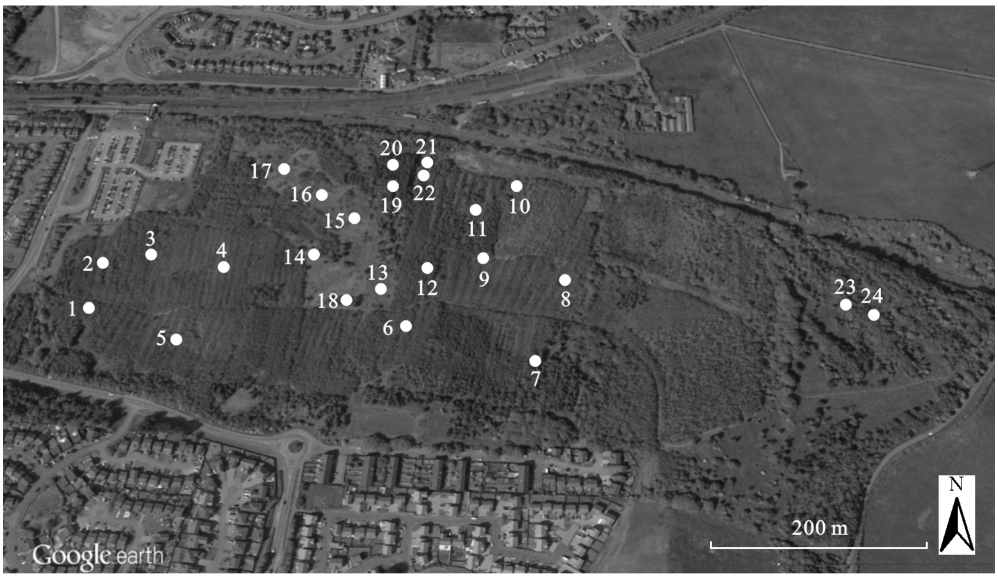

Fig. 1 Aerial view of the reclaimed Hallside steelworks in UK, bounded to the north by a railway and to other sides by roads. A total of 24 sampling points under different vegetation cover in 2018 are shown (Source: Google Earth), with Nos. 1–12 under willow, Nos. 13–17 under grass, Nos. 18–19 under birch, No. 20 under Norway spruce, No. 21 under cherry, No. 22 under Scots pine, and Nos. 23–24 in unspoiled soils within an aspen plantation (control).

chemistry, and C:N ratio. Heavy metal concentrations were analyzed using an inductively coupled plasma mass spectrometer (ICP-MS) (Thermo Scientific X Series 1, Thermo Fisher, USA). Each soil sample was oven-dried at 80 °C for 24 h.

Penetration resistance was measured at selected sampling points using a 06.01 Eijkelkamp penetrometer (Eijkelkamp Soil & Water, The Netherlands). Measurements were recorded when a uniform pressure allowed cone penetration (base area 3.3 cm^2) at a constant rate of 2 cm s^{-1}. If stones were struck, readings were aborted. Resistance was read in N and converted using: cone resistance = manometer reading/base area of the cone. Infiltration rate was measured within the selected habitats, using a plastic cylinder (void area 95 cm^2) hammered into the soil, into which we poured water (1 L) to a depth of 10.5 cm (adapted from Lassabatère *et al*. (2006)). Then, infiltration time was recorded, or, if water remained after 5 min, the remaining depth was measured, with calculations made to give the infiltration rate. Three replicates were performed at each sampling location. A small cylinder was necessary to permit measurements in the very stony soils. Soil pits were excavated to expose the soil profile and obtain information on the development of soil horizons. However, this was rarely possible due to the compacted and stone-rich nature of the reclaimed soils. In the reclaimed areas, pits were excavated to 45 cm at best, whereas a pit to 1 m was possible in the unspoiled area.

The data were subjected to the appropriate statistical analyses depending on normality and variance, using Minitab 17 software. One-way analysis of variance (ANOVA) compared, for example, the effects of vegetation cover on earthworm community density and community biomass. Earthworm data were also used to determine the diversity of the community on site using the Shannon-Wiener calculation. Comparisons were drawn with data relating to unpublished earthworm monitoring previously undertaken at Hallside (Mitchell, 2001; Butt and Lowe, 2005).

RESULTS

A total of 1 499 individuals from 16 earthworm species were collected (Table I). This equates to a mean community density across the site of 208 ± 18.1 individuals m^{-2}, with a mean mass of 71 ± 6.1 g m^{-2}. Seven of the species were present in high numbers at the adjacent control site where natural soils were present. Two additional species were of those inoculated to the site using turf discs in 1996. Only two species (*Murchieona muldali* and *Octolasion lacteum*) were previously unrecorded in Hallside.

Comparisons between areas dominated by different vegetation types showed a significant effect ($P < 0.05$) of habitat on both earthworm community density and biomass (Fig. 2). On the reclaimed site, more earthworms were located where willow (height 10–12 m) and birch (height 12–15 m) were present and where grassland had developed, with community densities of 240 ± 23, 274 ± 52, and 295 ± 49 individuals m^{-2} and biomasses of 86.1 ± 10.8, 103.8 ± 20.3, and 75.3 ± 11.9 g m^{-2}, respectively. These areas

TABLE I

Details of current (2018) and historical earthworm records from a former steelworks site at Hallside, UK, reclaimed in the 1990s using a mixture of colliery spoil and sewage sludge

Species	Common name	Category[a)]	Inoculated (1996)	Present in the reclaimed site						Present in natural area (2018)
				1998	2000	2005	2018	Percentage (2018)		
								In number	In mass	
								%	%	
Allolobophora chlorotica (green morph)	Green	En	Yes	No	Yes	Yes	Yes	4	2	No
Allolobophora chlorotica (pink morph)	Pink-green	En	No	No	No	Yes	Yes	1	< 1	No
Aporrectodea caliginosa	Grey	En	No	No	Yes	Yes	Yes	34	24	Yes
Aporrectodea longa	Black-headed	A	No	No	Yes	Yes	Yes	13	33	Yes
Aporrectodea nocturna	NA[b)]	A	No	No	No	Yes	Yes	< 1	2	No
Aporrectodea rosea	Rose-tip	En	Yes	No	No	Yes	Yes	27	10	Yes
Dendrobaena octaedra	Octagonal	Ep	No	No	Yes	No	Yes	4	1	No
Dendrodrilus rubidus	Bank/tree	Ep	Yes	No	Yes	No	Yes	1	< 1	No
Eiseniella tetraedra	Square-tailed	Ep	No	No	Yes	Yes	Yes	2	< 1	No
Lumbricus castaneus	Chestnut	Ep	No	No	Yes	Yes	Yes	3	1	Yes
Lumbricus rubellus	Red	Ep	No	No	Yes	Yes	Yes	2	2	Yes
Lumbricus terrestris	Lob/dew	A	Yes	No	Yes	Yes	Yes	3	12	Yes
Murchieona muldali	NA	Ep	No	No	No	No	Yes	< 1	< 1	No
Octolasion cyaneum	Steel-blue	En	No	No	No	Yes	Yes	8	12	Yes
Octolasion lacteum	NA	En	No	No	No	No	Yes	< 1	< 1	No
Satchellius mammalis	Little tree	Ep	No	No	No	Yes	Yes	< 1	< 1	No

a) A = anecic; En = endogeic; Ep = epigeic.

b) Not applicable.

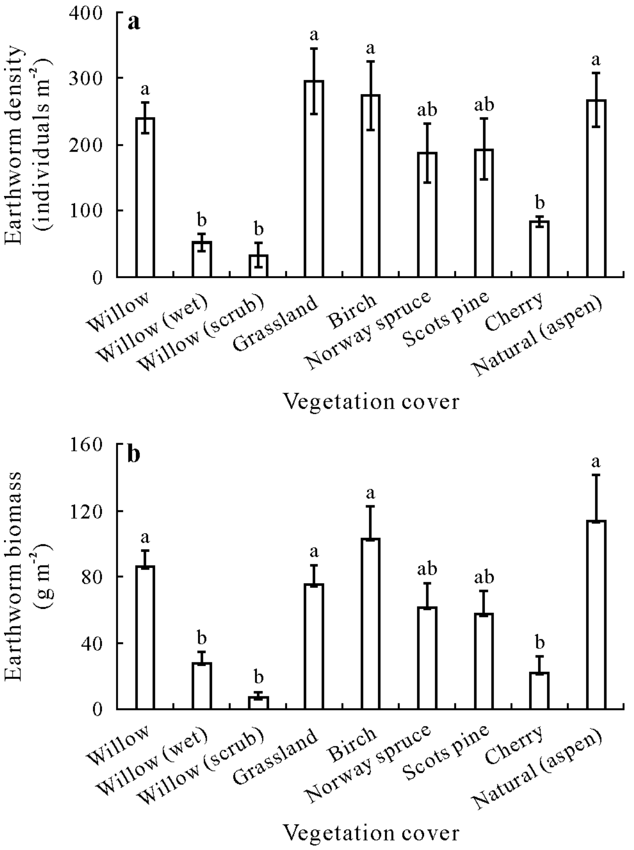

Fig. 2 Effect of major vegetation cover at a reclaimed steelworks on earthworm community density (a) and biomass (b). The site is at Hallside, UK and was reclaimed in the 1990s using a mixture of colliery spoil and sewage sludge. Bars represent standard errors of the means ($n = 3$). Different letters indicate significant differences ($P < 0.05$).

compared favorably with the unspoiled control (natural), where aspen was planted, with 267 ± 40 individuals m^{-2} and biomass of 114.4 ± 27.1 g m^{-2}. Areas of wet reclaimed soil, where willow was present but had grown poorly (height 3–5 m), had a negative effect on both earthworm density and biomass (52 ± 12 individuals m^{-2} and 28 ± 7 g m^{-2}, respectively), leading to a reduction by more than a quarter compared with willow stands. Similar negative results were obtained from willow scrub, co-dominated by bramble (*Rubus fruticosus*), and where cherry was planted. Reclaimed areas supporting two coniferous tree species (Norway spruce and Scots pine) were intermediate for both earthworm number and biomass. In those areas, a mat of needles covered the soil surface, which was particularly dense below spruce.

Of the earthworms collected in 2018, endogeics accounted for 74%, with *Aporrectodea caliginosa*, *Aporrectodea rosea*, *Octolasion cyaneum*, and *Allolobophora chlorotica* (green and pink morphs combined) equating to 34%, 27%, 8%, and 5%, respectively (Table I). The most abundant anecic species was *Aporrectodea longa* (13%). Epigeics accounted for only 5% of all earthworms and were dominated by *Dendrobaena octaedra* (4%). Earthworm diversity across the site was characterized by a Simpson's index of 0.789 and a Shannon index (H) of 1.89, with an evenness of 0.68. Diversity increased after nine years, with greater evenness of the 12 species. Of the additional species recorded in 2018, most were found in very low numbers. Species richness had increased over time with monitoring after 4, 9, and 22 years, and was at its greatest in 2018 with 16 earthworm species present.

Table II shows the results of selected physical and chemical properties from the Hallside soil samples. With respect to pH, results are relatively consistent, within a range of only 1.5 units across the whole of the site, including slightly more acidic conifer-influenced soils. Nevertheless, the control soil below aspen also had a pH close to 5.

The organic matter content of the soil was high, with values of 180–273 g kg^{-1} in the reclaimed areas. This increase could in part be attributed to the original sewage sludge content and coal particles present in the spoil were another source of combustible material. More recent additions would also have come from the leaf litter of the trees. Where control soil was sampled, organic matter content of 61 g kg^{-1} was recorded.

Nitrogen values within the reclaimed soils gave C:N ratios of 3–10. Sewage sludge certainly had promoted these

TABLE II

Selected physical and chemical properties of soils under different vegetation cover in 2018 at a former steelworks in Hallside, UK reclaimed in the 1990s using a mixture of colliery spoil and sewage sludge

Vegetation cover	C:N	pH	Moisture	Organic matter	Infiltration	Penetration resistance	Cr	Mn	Co	Ni	Cu	Zn	Cd	Pb
			%	g kg^{-1}	L min^{-1}	N cm^{-2}	mg kg^{-1}							
Willow	9.55	6.13	31.7 ± 2.0[a]	246 ± 18	0.90 ± 0.26	72.4 ± 3.6	102.38	1 261.28	32.80	83.25	166.27	1 723.78	6.62	419.25
Grassland	4.83	6.63	32.4 ± 3.6	273 ± 69	0.52 ± 0.23	72.1 ± 4.7	72.06	932.57	27.77	70.13	125.95	560.01	1.74	316.18
Birch	8.71	6.12	32.3 ± 2.0	248 ± 27	0.32 ± 0.12	64.1 ± 4.6	67.61	968.26	25.04	58.69	45.54	473.97	0.61	109.22
Norway spruce	2.99	5.13	28.5 ± 0.9	180 ± 10	1.20 ± 0.13	72.1 ± 6.9	62.52	1 248.29	22.78	57.29	47.34	122.57	0.64	80.83
Cherry	3.90	5.83	34.7 ± 0.6	204 ± 8	NR[b]	NR	68.84	738.43	26.69	77.97	73.79	247.24	0.93	152.50
Scots pine	5.80	5.43	33.2 ± 3.0	259 ± 26	0.32 ± 0.03	93.1 ± 16.5	65.60	687.25	23.70	63.25	70.58	439.77	1.57	172.38
Natural (aspen)	1.91	5.06	24.8 ± 2.9	61 ± 10	0.10 ± 0.01	62.1 ± 2.0	83.50	777.06	33.53	90.37	206.40	675.15	3.02	513.92

[a] Mean ± standard error ($n = 3$).
[b] Not recorded.

relatively high nitrogen levels and the growth of vegetation across the site. Willow trees, which ought to have been coppiced after 4–7 years (an abandoned scheme), reached heights of 12 m in some locations. However, where drainage was poor, willow trees survived but showed reduced growth. Soil moisture was 28%–35% in the reclaimed soils, compared with 25% in the natural areas. Water infiltration varied across sites but was influenced by habitat type. Some areas of the site had standing water at certain times of the year but were covered in terrestrial vegetation, further suggesting poorly draining soils. These results are summarised in Table II alongside levels of heavy metals.

The digging of soil pits where colliery spoil and sewage amendments had been added proved difficult due to the very stony/rocky nature of the soil. Pits could only be dug to maximum depths of 40–45 cm. A developing A horizon (5–10 cm thick) was recognized, but material below was very compacted with little distinct structure. The soil was more easily excavated within the natural area, where soil pits were dug to 1 m and displayed two distinct horizons. A grey, sandy clay loam was recorded from 0–35 cm, and a yellow sand was observed below (both classified from finger texturing). This natural soil supported the highest earthworm biomass recorded.

DISCUSSION

When the Hallside site was sampled for earthworms, over a two-year period in the late 1990s, post-reclamation and post-earthworm inoculation, no earthworms were recovered (Bain *et al.*, 1999). Considering historical data and current monitoring (Table I), earthworm colonization of the reclaimed site has occurred and community density and biomass (208 individuals m^{-2} and 71 g m^{-2}, respectively) are now equivalent to records from numerous UK pasture and woodland sites (Edwards and Bohlen, 1996). The Hallside records are also equivalent to values (203 individuals m^{-2} and 56 g m^{-2}) obtained by Scullion and Mohammed (1991) from rehabilitated (sub-soiled and fertilized) grasslands on an opencast mining site, where soils can be considered similar. By comparison, at a reclaimed colliery site at Chisnall Hall (Lancashire), where waste organic matter was experimentally added in excess (up to 3 000 t ha^{-1}), earthworm community values up to 638 individuals m^{-2} and 215 g m^{-2} were recorded (Butt and Putwain, 2017). However, these were obtained relatively early (2–3 years) after organic inputs, and it is envisaged that these numbers will markedly reduce with time as the material is exhausted and a more stable earthworm community develops.

The differences in earthworm community density and biomass that have developed below different stands of trees and on grassland can be directly attributed to the quality of the leaf litter produced. Although not an objective of this investigation, previous research has shown that leaf litter is incorporated into the soil at different rates depending on species (Wittich, 1943), and laboratory experimentation has demonstrated that earthworms show preferences for specific types of leaf litter from trees that are used in land reclamation (Ashwood *et al.*, 2017) and in short rotation forestry (Rajapaksha *et al.*, 2013). Willow, whilst supporting fewer earthworms, was planted to dominate this site for coppice production, and the low lying (wet) soils seem to have favoured this tree species. However, where planted, seemingly to gather data on growth rates and survival, other tree species (particularly birch) have survived. Future work could investigate these trees for growth parameters and associated soil macro-, meso-, and micro-fauna.

As earthworm community density has increased, so has species richness at Hallside. However, this is something that can only be learned from long-term monitoring of a site. Investigations are usually short-term, *i.e.*, 3–5 years, but lengthier monitoring can prove to be invaluable, as not only do numbers change but the proportions of species (community composition) can also be dynamic. Results of the major species recorded at Hallside (Table I) show a steady increase in endogeic species and a decrease in the epigeics, exemplified by *Eiseniella tetraedra*, which Mitchell (2001) reported as dominant but had reduced to a minor component of the earthworm community in 2018. This species is semi-aquatic (Sims and Gerard, 1999) and its decrease may be attributed to changes in soil moisture dynamics on the site. Similar changes have been previously recorded at restored sites, *e.g.*, during a long-term (20 years) study following the construction of a second runway at Manchester Airport (Butt, 2017). In addition, the presence of other soil organisms, such as aerobic bacteria and vesicular-arbuscular endophytes (fungi), can be influential (Scullion, 1992). A recent study (Morriën *et al.*, 2017) has suggested that (on restored arable land) the relationships between soil bacteria and soil fungi are complex and have a major influence on carbon dynamics. Such relationships of microbes could be broadened to incorporate soil ecosystem engineers (earthworms) and above ground organisms (plants) and warrant further investigation of carbon dynamics on reclaimed sites, for example at Hallside.

Monitoring has shown that the soils at Hallside are compacted, have a high stone content, and are resistant to water infiltration. The presence of deep burrowing earthworm species, such as *L. terrestris*, which create large burrows (diameter 7 mm, depth $>$ 1 m) as a part of their everyday existence (Butt and Grigoropoulou, 2010), would probably help. This species was inoculated to site by managers in 1996, but soils were too embryonic and incapable of offering support at that stage. Some 20 years on, an inoculation of this nature might still be inappropriate despite the colonization by some species, as *L. terrestris* would struggle to produce deep burrows in these compacted, stone-rich soils.

It appears that the physical challenges associated with the Hallside soils now outweigh any chemical problems that may once have existed. The chemical nature of the soils is such that soil fauna, represented specifically by earthworms, can survive with no adverse effects. Recorded levels of chromium (Cr) (Table II) fall within UK soil guideline values for residential use and allotments (DEFRA, 2018). Mean cadmium (Cd) levels are raised within the willow plantations but also fall within the soil guideline values for residential use. Mean lead (Pb) levels vary across the site, but no soil guide values are available for this element. Most soil contaminants were removed from the Hallside steelworks site before reclamation, but some metal contaminants must have been introduced with the spoil and sludge (Craven, 1995). In addition to providing a useful product, use of willow was also seen as a potential way to bring about phytoremediation of the site (Witters *et al*., 2009), although this was not mentioned as one of the primary objectives at the time of reclamation.

The combination of colliery spoil and sewage sludge has created a substrate that supports life and represents an improvement on the contaminated soils which were removed before reclamation. However, to overcome some of the challenges, greater thought could have been given to the site preparation before tree planting. Although the trees have performed reasonably well in most areas, sub-soiling may have alleviated the compaction problems, as seen at colliery sites (Scullion and Mohammed, 1991), and would certainly have overcome some of the problems associated with water pooling at the soil surface.

After more than two decades, reclamation at the Hallside steelworks can be viewed mainly as a success. It has replaced a contaminated site and a large colliery waste heap with a green space in an urban landscape. The current investigation has addressed the proposed objectives regarding earthworm community development and soil reclamation at Hallside. Nevertheless, further research on the biological aspects (*e.g*., microbial development) of these soils could be undertaken and reveal more information on the services that such soils can offer.

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