Tyndrum Site Survey

Introduction

The village of Tyndrum has a legacy of sporadic and uncontrolled mining for over 200 years, resulting in visible scarring to the landscape and pollution events that have impacted environments up to 25 km away (Mills, Simpson and Adderley, 2014). The mine tailings to the west and south-east of the village (Fig.1) have been derelict for approximately 87 years, with minimal ecological recovery and vegetative presence in this time. There have been a few studies on the soil characteristics and related pollution from the historic mining on the site, mainly focusing on the atmospheric and fluvial depositions of lead to the surrounding environment. However, aside from the unsuccessful replanting of native trees by the Forestry Commission (FC) there have been no attempts for remediation of the mining site and conversion back to productive land.

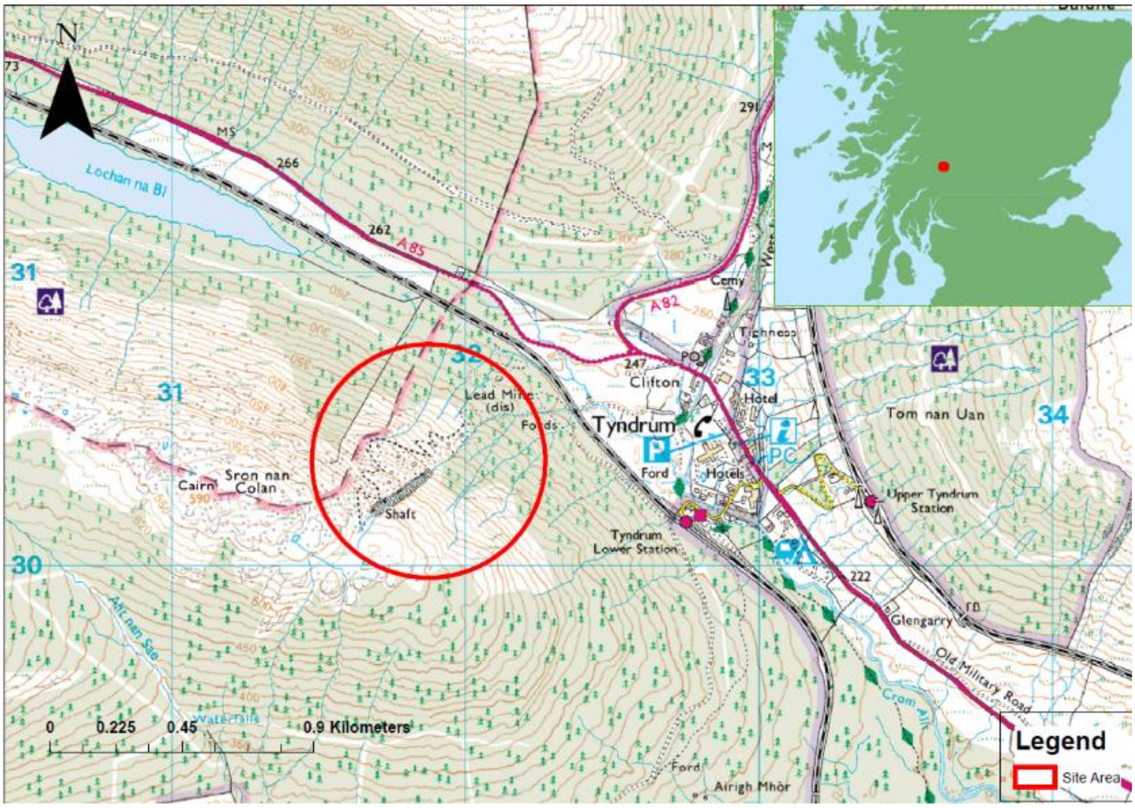

Figure 1. Site Overview of the Tyndrum Pb/Zn mine.

Pollution considerations

Whilst previous studies suggest that airborne risks to the local community remain low (Nurlidia, 2006), the mine tailings have been identified as a source of lead pollution to downstream waterbodies, particularly Loch Tay (Farmer *et al.*, 1997). Pressures from fluvial action and the subsequent erosion of the tailings will likely continue to deposit lead and zinc rich sediments to the downstream watercourses, potentially disrupting the sensitive ecosystems within the Loch Lomond and Trossachs National Park.

Aims of the Survey

1. To characterise the extent of heavy metal pollution on the Tyndrum lead mine spoil.
2. To investigate the vegetation that have successfully colonised on the mine
3. To identify the overarching barriers to the potential vegetation of the site.
4. To consider the remedial actions that could be applied to reduce metal transportation from the mine into the wider environment.

Sampling Methodology

Mine tailings are rarely reported to have a homogenous distribution of chemical characteristics which can be problematic when describing the environmental burdens of the site. To provide an output which could aid in informing future decisions a geo-statistical approach to site sampling was taken (Fig.2). The geographical information software ArcGIS was used to design the sampling regime and provide pre-determined sampling locations.

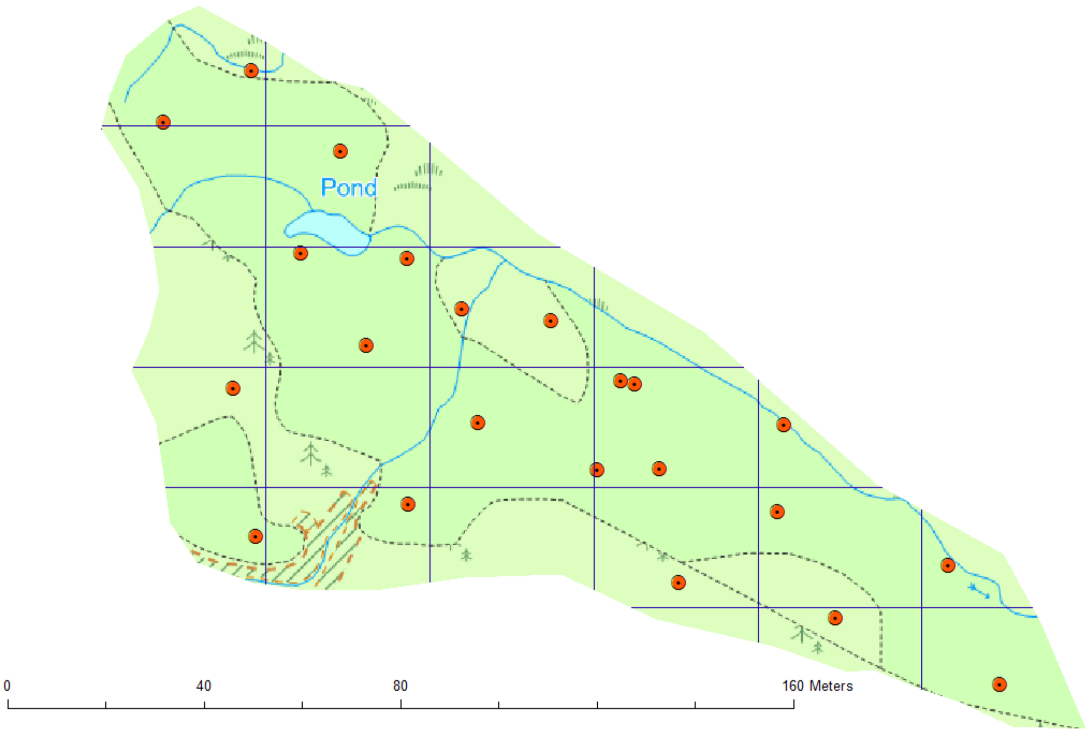

Figure 2. Sampling regime at the Tyndrum lead mine.

A Garmin etrek was used to locate the sampling sites with an accuracy of ±3m. Soil samples (approx. 50g) were taken at each point and the vegetation was recorded using three randomly placed 30cm^2 quadrats. A profile of the mine was taken using a coring auger to gain an understanding of the tailing profile and the vertical extent of the mine spoil.

Analytical procedures and data processing

Briefly, spoil samples were analysed for total elemental concentrations (Al, As, Ca, Cd, Co, Cr, Cu, Fe, Mg, Mn, Ni, P, Pb, S, Sb, Ti and Zn) using HNO_3 – HF microwave assisted digestions (EPA 3052) and plant available concentrations were measured using $CaCl_2$ extractions (Houba *et al.*, 2000). Elemental concentrations were analysed using inductively coupled plasma optical emission spectrometry (ICP-OES). Total carbon and nitrogen content of the spoil was assessed using a CN elemental analyser. Other spoil characteristics (e.g. pH, electrical conductivity organic matter and moisture content) were also recorded.

Data were assessed using Genstat® and ArcGIS® packages. Kriging was used for graphical representations of metal concentrations. Descriptive and multivariate statistics were employed to describe the mine spoil characteristics.

Spoil structure and characteristics

The lower mine site comprises a layer of fine sandy tailings (approximately 65cm deep) that have the physical characteristics of a loamy sand. In this layer there was no indication of organic matter or biological activity. The soil core provided details on the tailing horizons (Table 1). The core revealed that the mine tailing is approximately 60-70 cm in depth with a deep layer of partially decomposed organic matter beneath it. Several layers consisted of grey and orange material, suggesting anaerobic conditions and gleying. No macro invertebrates or root systems were noted throughout the soil profile in exception from samples taken directly below vegetation.

Table 1. Physical profile of the Tyndrum mine tailings.

Horizons	Depth (cm)	Structure	Munsell Rating	Texture	Notes
1	0-50cm	(1) Single grain, very fine, very loose	5Y6-2	Loamy sand	No visible biological activity
2	50 - 65	friable	5Y6-2	Sandy loam	May have translocated clays
3	65 – 75	Coarse, sub angular blocks, 1b^{t}, weathered horizon	7.5 YR5-6	Sandy loam	Prominent orange colours
3(2)	65 – 75	Single grain, friable, granular	5Y4-2	Loam	Visibly grey/gleying
4	75 - 90	Coarse, angular, blocky, friable	5Y2.5-1	Sandy clay loam	Considered a 2A horizon
5	90-104	(1) medium, angular blocky, friable	Dark black colour – not on scale	Silty clay	Soil is very high in OM

The spoil shows evidence of hydrological erosion (Fig.3) most of which is created by the small streams running through the mine.

Figure 3. Hydrological erosion of the Tyndrum mine tailing.

The spoil is acidic (pH = 5.5 (±0.9)) with low total nitrogen content (0.17% (±0.28), relatively high moisture content (30.8% (±21.2) and a range in organic matter presence (0.8 – 80%). Spatial agreements exist between vegetative cover, OM and N concentrations (Fig.4)

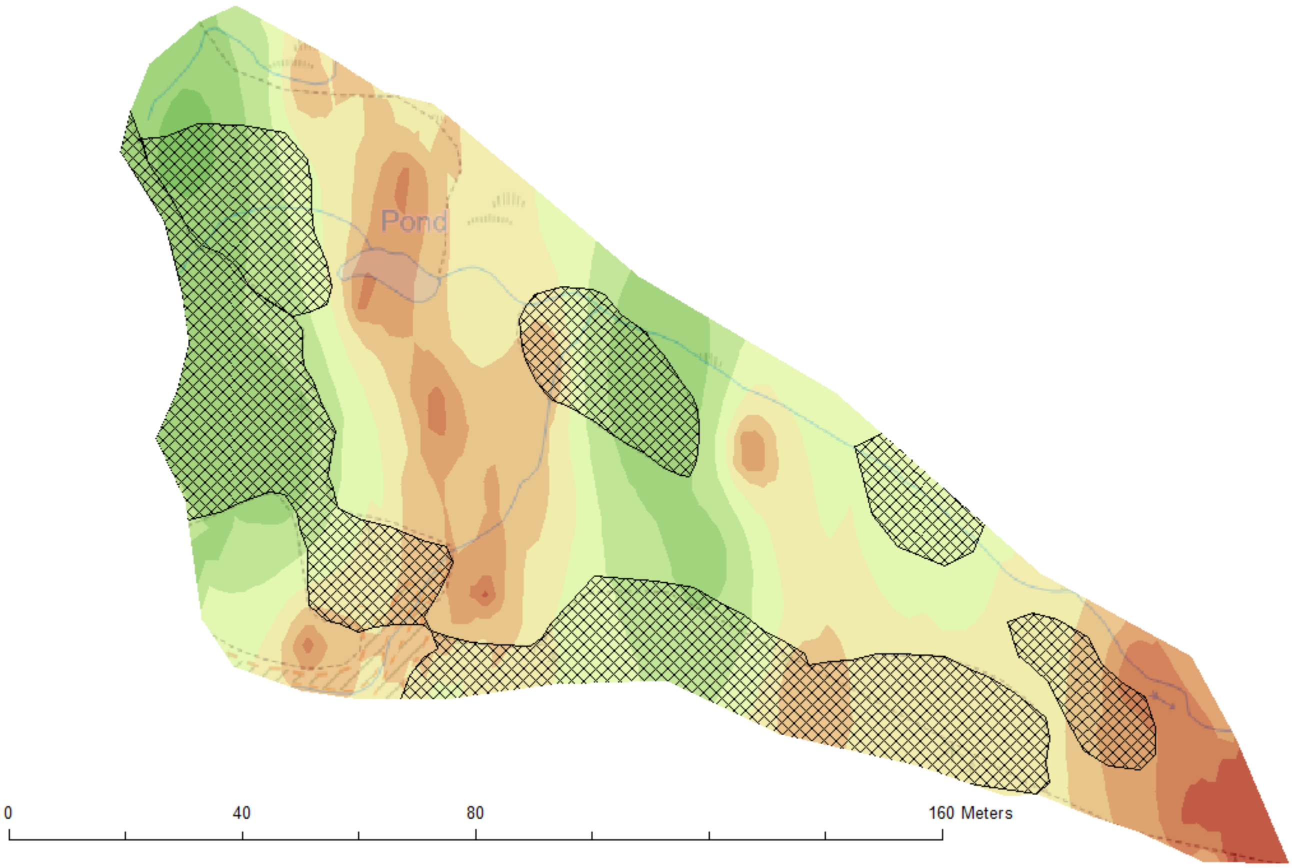

Figure 4. Vegetation (hatched) and nitrogen/OM concentration on the Tyndrum spoil. Green areas indicate higher OM and N concentrations, red represent a deficit.

Vegetation

The vegetation throughout the site survey was limited in terms of diversity (Table 2). Vegetation cover for identified genera were found to be highly variable with ranges between 0-90% coverage depending on the species and the area sampled.

Table 2. Identified vegetation on the Tyndrum Pb/Zn mine spoil.

Species	
Calluna vulgaris	*Picea sitchensis*
Cardamine hirsuta	*Larix decidua*
Agrostis capillaris	*Larix kaempferi*
Agrostis vinealis	*Pinus contorta*
Capsella bursa-pastoris	*Picea abies*
Pinus sylvestris L	*Sphagnum capillifolium*

Potentially toxic elements

Table 3 describes the total concentrations of selected metals within the mine spoil matrix. Element concentrations were found to be in the order of Pb>Zn>Cu>Cr>Ni>As>Cd>Co>Sb. Lead concentrations were significantly higher than any other element ($p=<0.001$). Plant available metals gave evidence for significantly elevated Pb and Zn concentrations.

Table 3. Concentrations of potentially toxic metals in the Tyndrum spoil matrix. All values in mg/kg. n=24. Limit of detection is <0.1 mg/kg

Element	Mean (StDev)	Minimum	Maximum	$CaCl_2$ Extractions
As	19.37 (20.09)	<detection	66.96	<0.01
Cd	14.04 (19.09)	<detection	37.94	<0.01
Co	5.77 (6.59)	<detection	17.7	<0.01
Cu	536.4 (373)	<detection	1,725	<0.01
Cr	99.61 (126.)	<detection	336.7	<0.01
Ni	30.3 (40.5)	14.8	156.4	<0.01
Pb	12,261 (10,153)	545.5	40,872.1	203.3
Sb	3.92 (3.4)	<detection	10.472	<0.01
Zn	3,966 (3,495)	129	17,031	142.3

The distributions of Pb and Zn are shown in Figs. 5 and 6. Zinc and lead were not found to be spatially similar or associated with each other.

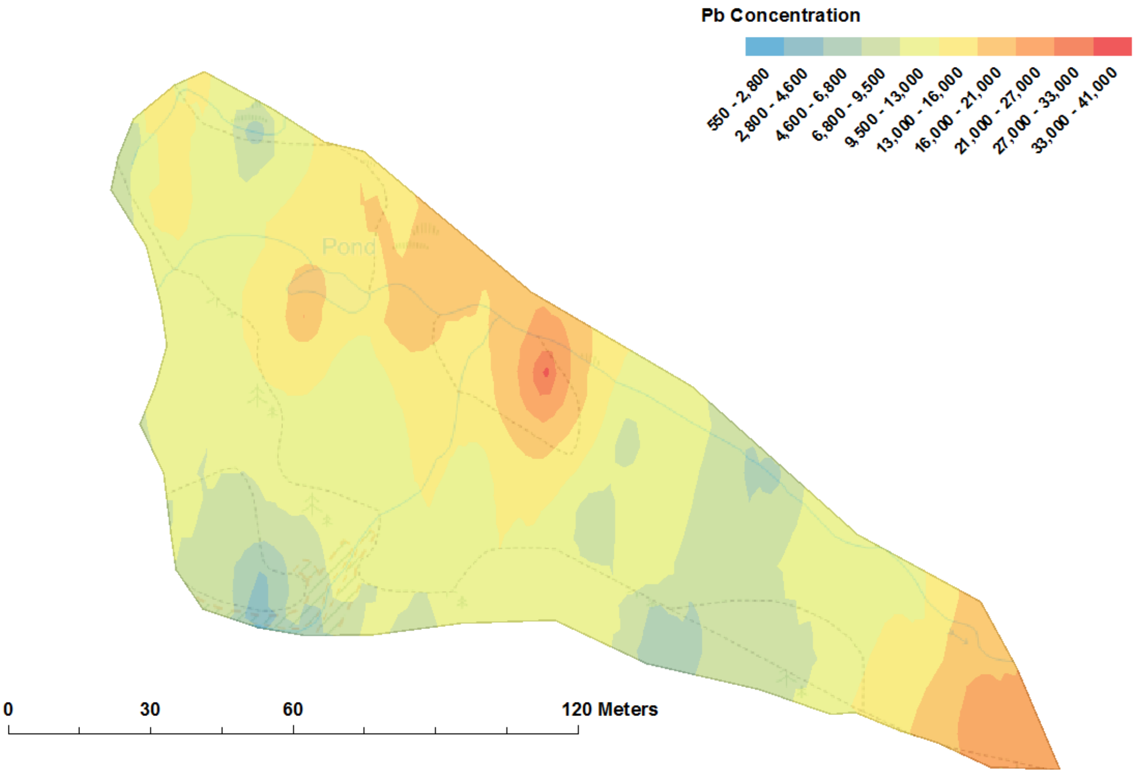

Figure 5. Spatial distribution of total Pb at Tyndrum

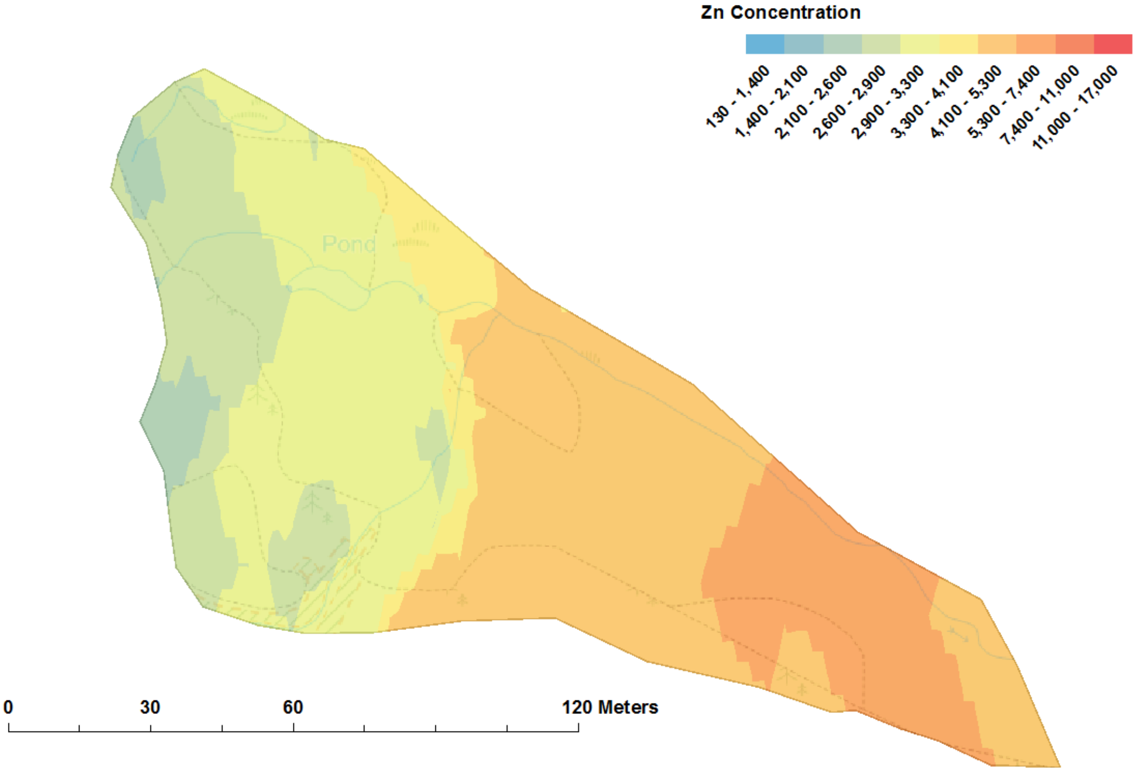

Figure 6. Spatial distribution of total Zn at Tyndrum

Discussion

The mine at Tyndrum has previously attracted attention by researchers, with concentrations of up to 120,000 mg/kg of Pb reported (Mills, Simpson and Adderley, 2014) signifying significant pollution. Such high concentrations were not found in the survey, although the variation in concentrations across a relatively small site (1.3 ha^{-1}) is considerable. It was also noted that the concentration of biologically available Pb was substantial, creating a direct toxicity issue to vegetation and soil biota. In addition to the elevated Pb levels, Zn concentrations were similarly high, although the biologically available fraction was less significant. The presence of other potentially toxic elements such as As, Cd and Cu provide evidence for a more complex, multi-elemental contamination issue than previously identified.

Lead and zinc pollution from the tailings have been strongly linked to spoil erosion (Farmer *et al.*, 1997; Nurlidia, 2006) with other transportation routes such as aerial deposition and dissolution in water courses identified as a minimal risk. The priority for any remedial action therefore would be in the reduction of erosive pressures and the binding of the tailing material to vegetation. The skeletal nature of the mine spoil is possibly exacerbating the problems surrounding biologically available metals in the tailings. The lack of complexity in terms of structure, texture, organic matter and soil constituents produce a deficit in potential binding sites where metals could be sequestered (J. Rieuwerts *et al.*, 1998; J. S. Rieuwerts *et al.*, 1998). This then likely causes greater concentrations of elements such as Pb and Zn to exist in the more exchangeable fractions of the spoil since other adsorption surfaces are already saturated.

Aside from the elevated concentrations of potentially toxic elements the spoil structure provides limited support for soil biota and vegetation. The lack of organic material, nutrients, compaction and a reducing environment in the tailings present a difficult growth media for vegetation and other soil organisms to establish. Although there is some evidence of natural succession and re-vegetation of the tailings on the fringes, without intervention and the introduction of soil conditioning materials it may take several centuries for the mine tailings to provide vegetative support.

The majority of species were from the *Brassicaceae* and *Poaceae* families, species that are aligned with metalifferous and nutrient poor landscapes. The site displays species such as *A. capillaris* and *A. vinealis*, suggesting that these specific species are well adapted to surviving on these harsh landscapes. Furthermore, there is some evidence that the surveyed species have been investigated previously in the wider literature of metal contaminated soils e.g. (Baker and Proctor, 1990; Huang and Cunningham, 1996) Particularly, has been evidence of the rare metallophyte moss (*Ditrichum plumbicola*) which is only found on temperate lead mines (Carfrae J, 2014).

Vegetation was spatially aligned with nitrogen concentration and organic matter hotspots, explaining that either vegetation established on fertile pockets of the mine spoil or more likely, that pioneer species improved the immediate spoil environment around the plant, promoting further vegetative expansion. Interestingly vegetation was not strongly associated with either the absence or presence of elevated metal concentrations. This suggests that the species had a substantial tolerance to metal toxicity, or that the metals were in a form unavailable for biological interaction. This may highlight that the re-vegetation of the mines may not necessarily be connected to metal alleviation, but rather to the improvement of the spoil material as a supporting medium.

Conclusions

The lower tailing area at the bottom of the mine spoil heap would be a suitable site for developing remediation plots if it is deemed appropriate. The crusher site at Glengarry is an established point of cultural interest despite the potential risks for HM pollution, and so may not be an ideal choice for a remediation project. The lower mine tailings however are less trafficked and have lower value to the local community and walkers, making this an ideal site for trials.

Although the risk of a pollution event is currently low the metal concentrations of the mine tailings will not diminish with time, continuing a problem that has already lasted some 200 years. The site is in need of restoration and would benefit from increased vegetation cover to stabilise the mine tailings to ensure pollution mitigation.

Future investigations should focus on the identification of suitable plant species and organic matters than can be used for remediation purposes as well as pinpointing sites for pilot studies and field trials. Once these components can be established it would be possible to conduct research into the exploration of different treatment systems to identify which ones could then be generalised to the whole site.

References

Baker, A. J. M. and Proctor, J. (1990) 'The influence of cadmium, copper, lead, and zinc on the distribution and evolution of metallophytes in the British Isles', *Plant Systematics and Evolution*. Springer-Verlag, 173(1-2), pp. 91–108. doi: 10.1007/BF00937765.

Carfrae J (2014) 'Tyndrum Lead Mine Field Trip.' Edited by A. Innes. Tyndrum.

Farmer, J. G., MacKenzie, A. B., Eades, L. J., Kirika, A. and BaileyWatts, A. E. (1997) 'Influences on the extent and record of heavy metal pollution in sediment cores from Loch Tay in a mineralised area of Scotland', *Journal of Geochemical Exploration*, 58(2-3), pp. 195–202. Available at: http://ezproxy.lib.ed.ac.uk/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=A1997XB38400011&site=eds-live.

Houba, V. J. G., Temminghoff, E. J. M., Gaikhorst, G. A. and van Vark, W. (2000) 'Soil analysis procedures using 0.01 M calcium chloride as extraction reagent', *Communications in Soil Science and Plant Analysis*. Taylor & Francis, 31(9-10), pp. 1299–1396. doi: 10.1080/00103620009370514.

Huang, J. W. and Cunningham, S. D. (1996) 'Lead phytoextraction: species variation in lead uptake and translocation', *New Phytologist*. Wiley-Blackwell, 134(1), pp. 75–84. Available at: http://ezproxy.lib.ed.ac.uk/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=eih&AN=12572620&site=eds-live.

Mills, C., Simpson, I. and Adderley, W. P. (2014) 'The lead legacy: the relationship between historical mining, pollution and the postmining landscape', *Landscape History*, 35(1), pp. 47–72. Available at: http://ezproxy.lib.ed.ac.uk/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=hia&AN=96280274&site=eds-live.

Nurlidia, M. I. (2006) 'Investigation of lead and zinc dispersion from an abandoned mine site at Tyndrum, Scotland, using tree bark measurements', *ä¸å›½åœ°çfåŒ–å¦å¦æŠ¥ï+šè‹±æ–‡ç‰ˆ / Chinese Journal of Geochemistry*, (B08), p. 23. Available at: http://ezproxy.lib.ed.ac.uk/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=edscqv&AN=edscqv.23006611&site=eds-live.

Park, J. H., Lamb, D., Paneerselvam, P., Choppala, G., Bolan, N. and Chung, J.-W. (2011) ‘Review: Role of organic amendments on enhanced bioremediation of heavy metal(loid) contaminated soils’, *Journal of Hazardous Materials*. Elsevier B.V., 185, pp. 549–574. doi: 10.1016/j.jhazmat.2010.09.082.

Prasad, M. N. V, Freitas, H., Fraenzle, S., Wuenschmann, S. and Markert, B. (2010) ‘Knowledge explosion in phytotechnologies for environmental solutions.’, *Environmental pollution (Barking, Essex : 1987)*, 158(1), pp. 18–23. doi: 10.1016/j.envpol.2009.07.038.

Rieuwerts, J. S., Thornton, I., Farago, M. E. and Ashmore, M. R. (1998) ‘Factors influencing metal bioavailability in soils: preliminary investigations for the development of a critical loads approach for metals’, *Chemical Speciation & Bioavailability*. Taylor & Francis. Available at: http://www.tandfonline.com/doi/abs/10.3184/095422998782775835 (Accessed: 16 February 2016).

Rieuwerts, J., Thornton, I., Farago, M. and Ashmore, M. (1998) ‘Quantifying the influence of soil properties on the solubility of metals by predictive modelling of secondary data’, *Chemical Speciation & Bioavailability*. Taylor & Francis. Available at: http://www.tandfonline.com/doi/abs/10.3184/095422998782775817 (Accessed: 16 February 2016).