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Planting woody crops on dredged contaminated sediment provides both positive and negative effects in terms of remediation

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ABSTRACT

There is currently a requirement for studies focusing on the long-term sustainability of phytoremediation technologies. Trace element uptake by *Salix*, *Populus* and *Alnus* species planted in dredged contaminated canal sediment and concentrations in sediment and pore waters were investigated, eight years after a phytoremediation trial was initiated in NW England. Soil biological activity was also measured using invertebrate and microbial assays to determine soil quality improvements. Zinc was the dominant trace metal in foliage and woody stems, and the most mobile trace element in sediment pore water ($\sim 14\ mg\ l^{-1}$). Biological activity had improved; earthworm numbers had increased from 5 to 24, and the QBS index (an index of microarthropod groups in soil) had increased from 70 to 88. It is concluded that biological conditions had improved and natural processes appear to be enhancing soil quality, but there remains a potential risk of trace element transfer to the wider environment.

1. Introduction

Current problems associated with reclamation of brownfield land include, (i) disposal of existing contaminated soil and (ii) import of new topsoil; both are prohibitively expensive and lack environmental sensitivity (Dickinson et al., 2002). When soils are contaminated with metal(loid)s and/or organic xenobiotics, there are no simple alternatives to the traditional dig and dump approach; in these instances green technologies are more suitable. It is therefore more cost-effective to work *in situ* with the existing contaminated soil/sediment and restore its health. Natural attenuation is often the favoured approach especially for low value brownfield land, and phytoremediation through tree planting may also be suited to this task (Lepp and Dickinson, 1998; Dickinson, 2000). Phytotechnologies involve the use of plants in pollution control and can be used in combination with other traditional remediation technologies (Prasad et al., 2010). The key plant-based processes variously may involve phytoextraction, phytodegradation or phytostabilisation of contaminants (Garbisu and Alkorta, 2001).

Phytoextraction exploits the ability of metal-accumulating plants to extract metals from the soil with their roots and concentrate them in their above ground parts (Kamal et al., 2004). In comparison to other methods such as excavation and the removal of soil, the technology is not as effective, but can reduce the total remedial costs (Prasad et al., 2010). Nevertheless, although extensive research has been carried out over the last decade, successful phytoextraction field trials remain very scarce (Robinson et al., 2006). Phytostabilisation is however more applicable to metal-contaminated soils and sediments, reducing the risk presented by non- or sparsely-vegetated contaminated soil; the technology, by the establishment of a vegetation cover, reduces re-entrainment of toxic particulates (Vandenhove, 2006).

In early 2002 a short rotation coppice (SRC) phytoremediation trial was set up on dredged contaminated sediment from a derelict and neglected canal (New Cut Canal) with falling water levels, located in Warrington, NW England. The criteria for selection of the tree species followed Punshon et al., (1996) who suggested that characteristics including the ability to grow on nutrient-poor soil develop deep root systems and fast growth rates were all beneficial to growing trees on metal-contaminated land. Species, such as *Salix caprea* and *S. cinerea*, and the hybrid *S. viminalis*, are known to colonise edaphically extreme soils (Dickinson et al., 1994) and willows and poplars rapidly accumulate biomass whilst alders are hardy pioneer species and are associated with riparian vegetation. The trial was carried out over a three year period, the results of which are well documented in the literature (Dickinson et al., 1994;

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King et al., 2006). This on-site phytoremediation trial was used to investigate whether a healthy soil environment could be restored without extensive removal of sediment from the site.

It was concluded from the initial study that the trees provided little benefit in terms of sediment remediation, contaminant concentrations in foliage were high enough to potentially pose a risk to herbivores and the increased hazard of re-entrained particulates from wind-blown dust following exposure and drying of the sediment caused concern (King et al., 2006). However, the success of phytoremediation trials can also be evaluated not only in terms of the reduction of bioavailable trace elements (TE) but also by soil biological quality improvements that can demonstrate restored multifunctionality to contaminated soil. An assessment of biological indicators of soil quality was carried out at the site during early 2005, as part of an urban regeneration and community forestry programme around Liverpool U.K. (Dickinson et al., 2005); biological activity was extremely low and out of ten UK brownfield sites tested during this period, the New Cut Canal phytoremediated sediment ranked the lowest in terms of soil quality (Hartley and Lepp, 2008; Hartley et al., 2008).

Unfortunately, experimental trials often lack long-term funding to deliver crucial assessments (Mench et al., 2006) and it has been recognised that there is an urgent need for demonstration field trials on contaminated land, to assess the sustainability in the longer term of plant-based remediation technologies (Nan et al., 2002; Vervaeke et al., 2003). Following termination of the initial project in 2004, and due to a lack of further funding, management ceased at the site and the trial was abandoned. The aim of the present study was to return to this site and evaluate whether the unmanaged trees had provided any remedial effect on soil quality. The objectives of this work were: (i) to evaluate trace element mobility in the sediment and subsequent accumulation in the woody crop stand and (ii) to determine if soil quality in terms of biological activity had improved in the plant-remediated sediment-derived soil, eight years after the trial had been set up.

2. Materials and methods

2.1. Study site

The site is a 150 m section of canal located in Warrington, NW England (53° 23′N, 2° 33′W). Sediment had been dredged from the canal beneath the water and deposited on one side of the exposed canal basin to form a planting platform 150 m × 3 m × 0.5 m (length × breadth × depth). Following dredging, the planting platform was subsequently planted with a randomised block of *Salix* (willow) including, *S. atrocinerea, S. caprea* × *cinerea* × *viminalis* (Calodendron) and *S. viminalis* L. (Jorunn), *Populus* (poplar) including *P. deltoids* × *nigra* (Ghoy) and *P. trichocarpa* (Trichobel) and *Alnus* (alder) including *A. cordata* Lois and *A. glutinosa* L. SRC species. For further details of the site and its history see Dickinson et al., 2004, King et al., 2006 and Hartley and Dickinson, 2010.

2.2. Determination of trace elements in sediment

2.2.1. Sediment sampling

Sediment samples ($n = 30$) were collected to a depth of 10 cm following ISO 10381-1 and -2 guidelines. Sampling was conducted using a non-systematic pattern (W formation) along the planting platform to account for any spatial variability. Samples were temporarily stored in sealed polyethylene containers until they were transferred to the laboratory. Subsequently these samples were thoroughly mixed by hand and 5 representative samples were used for pseudo-total trace element (TE) determination. For determination of pseudo-total As and heavy metal (μg l^{-1}) concentrations samples were air-dried (20 ± 2 °C), sieved (<4 mm diameter) and aliquots (0.2 g) pressure digested with Analar grade 15.55 M HNO_3 (10 ml) using a CEM Mars Xpress microwave (Programme; 1600w 100% power 10 min; hold @ 160 °C 20 min). Solutions were analysed by ICP-MS (XSERIES 2 ICP-MS; Thermo Scientific, MA, USA). For Quality Assurance reference to international certified standards (NWRI-TMDA-62) and NCS DC73310 (GBW07312) were used.

2.2.2. In situ pore water sampling

A trial pit was excavated at the planting platform and on one face of the pit 'Rhizon' soil moisture samplers (Eijkelkamp Agrisearch Equipment, The Netherlands) were inserted horizontally into the soil profile, in triplicate, at depths of 5, 15 and 30 cm. The overlying soil was then gently compressed. The samplers were left for a 2 week period in which time the soil surrounding the samplers could equilibrate. After this period soil pore water samples were collected weekly over a two month period. Solutions were analysed by Inductively Coupled Plasma-Mass Spectrometry (XSERIES 2 ICP-MS; Thermo Scientific, MA, USA) for trace elements and TOC-VE for dissolved organic carbon (Shimadzu, Tokyo, Japan). For Quality Assurance reference to international certified standards of water (NWRI-TMDA-62) and sediment NCS DC73310 (GBW07312) were used.

2.3. Determination of trace elements in vegetation

Trace element concentrations in leaves and woody stems were determined at the end of the growing season in September, 2010. Leaves and woody stems were collected in accordance with the original study by King et al. (2006). All plant material was washed with deionised water to remove any residues, blotted with tissue paper until dry, weighed fresh then oven dried at 35 °C for five days. Dried biomass was re-weighed then ground in a stainless steel Foss Cyclotec mill (1093). Ground samples were stored in polyethylene containers prior to analysis. Plant samples were digested using a CEM Mars Xpress microwave digestion instrument. Dry, finely ground plant material was weighed (0.2 g) into a digestion vessel (120 ml) to which Analar grade 14 M HNO3 (10 ml) was added. Digests were carried out in triplicate and analysed using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) (XSERIES 2 ICP-MS; Thermo Scientific, MA, USA). Bowens Kale powder (Bowen, 1974; Katz, 2002) was used as a standard reference plant material for QA purposes.

2.4. Biological assays

The descriptors selected for this study were selected from a range of assays tested on 10 brownfield sites during 2005 (Hartley et al., 2008). These were considered to provide the most accurate assessment of soil biological quality.

Three assays were selected to measure invertebrate activity, with all analyses being performed in triplicate. Firstly, Bait Lamina Strips were used to provide a simple and straightforward descriptor that measures the overall feeding activity of soil invertebrates (Von Torne, 1990). The strips are used to assess soil functional integrity. These were left *in situ* for 7 d then carefully removed for evaluation. After removal, a low powered microscope was used to count the number of piercings in each strip; this was carried out immediately on return to the laboratory with feeding activity classed as either pierced or non-pierced (Hartley et al., 2008).

The second invertebrate assay was a measure of earthworm numbers. Numbers and functional groupings, i.e. epigeics, (small size, litter dweller/feeder, pigmented, no burrows), endogeics (medium size, surface soil feeders (A horizon), no pigmentation, horizontal burrows) and anecics (large size, soil dweller, dorsally pigmented, vertical burrows) (Bouché, 1977) were determined within a 0.25 m^2 quadrat at three randomly selected locations along the planting platform; the area delineated by the quadrat was excavated until there was no further evidence of earthworm activity. Sediment was then carefully hand-sorted for earthworms, which were counted and returned to the laboratory for identification and classification into functional groups (Hartley et al., 2008).

The Biological Index of Soil Quality (QBS; Qualità Biologica del Suolo) (Parisi et al., 2005) which allocates scores (1–20) to soil microarthropods according to an EMI (Eco-Morphological Index) was used for the third assay. Microarthropods were extracted using standard Tullgren funnels (Burkard Scientific Ltd). Cores were extracted using the Tullgren chamber as a corer and then transferred to the extractor and left for 7 d (Hartley et al., 2008). Microarthropods move away from heat generated by a light bulb (25 W) placed above the core, through the soil into a preservative solution (50% ethanol). Organisms were counted and placed into broad groupings based on easily recognisable morphological features and the QBS index scores applied. Higher QBS scores reflect soil microarthropod groups better adapted to the soil conditions.

For determination of microbial activity, Adenosine 5 − triphosphate (ATP) was used. The method of analysis used luciferine-luciferase, which breaks down ATP, releasing light which is measured using luminometery. This was carried out on the sediment following the protocol of Horiuchi et al., (2003). A portable ATP luminometer (Uni-Lite Xcel) with reagent test kits (Aqua-Trace™) from Biotrace International (Cheshire, UK) was used to analyse ATP (Hartley et al., 2008).

2.5. Analytical methods

Sediment pH was determined in 20 g (fresh and air-dried) samples mixed to form a slurry with deionised water (50 ml) (Allen, 1989). Phosphorus (P), iron (Fe) and sulphur (S) concentrations were determined by Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES; Thermo Scientific, MA, USA). Dissolved organic carbon in leachates was determined using a TOC-VE Shimadzu analyser (Shimadzu, Tokyo, Japan). Particle size analysis of the air-dried sediment was determined using a laser diffraction particle size analyser (LS 13320). Water stable aggregates were determined using a variation of the method of Kemper and Rosenau (Kemper and Rosenau, 1986). Soil strength was determined using Pilcon