Journal of Environmental Management 184 (2016) 67–77

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Brownfields to green fields: Realising wider benefits from practical contaminant phytomanagement strategies

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ARTICLE INFO

Article history:
Received 31 January 2016
Received in revised form 16 March 2016
Accepted 19 March 2016
Available online 5 April 2016

Keywords:
Contaminated land
Brownfields
Gentle remediation options
Phytoremediation
Phytomanagement
Heavy metals
Decision support tools

ABSTRACT

Gentle remediation options (GROs) are risk management strategies or technologies involving plant (phyto-), fungi (myco-), and/or bacteria-based methods that result in a net gain (or at least no gross reduction) in soil function as well as effective risk management. GRO strategies can be customised along contaminant linkages, and can generate a range of wider economic, environmental and societal benefits in contaminated land management (and in brownfields management more widely). The application of GROs as practical on-site remedial solutions is still limited however, particularly in Europe and at trace element (typically metal and metalloid) contaminated sites. This paper discusses challenges to the practical adoption of GROs in contaminated land management, and outlines the decision support tools and best practice guidance developed in the European Commission FP7-funded GREENLAND project aimed at overcoming these challenges. The GREENLAND guidance promotes a refocus from phytoremediation to wider GROs- or phyto-management based approaches which place realisation of wider benefits at the core of site design, and where gentle remediation technologies can be applied as part of integrated, mixed, site risk management solutions or as part of "holding strategies" for vacant sites. The combination of GROs with renewables, both in terms of biomass generation but also with green technologies such as wind and solar power, can provide a range of economic and other benefits and can potentially support the return of low-level contaminated sites to productive usage, while combining GROs with urban design and landscape architecture, and integrating GRO strategies with sustainable urban drainage systems and community gardens/parkland (particularly for health and leisure benefits), has large potential for triggering GRO application and in realising wider benefits in urban and suburban systems. Quantifying these wider benefits and value (above standard economic returns) will be important in leveraging funding for GRO application and soft site end-use more widely at vacant or underutilized sites.

1. Introduction

Large areas of land around the world have been impacted by former industrial and other anthropogenic activities. These include urban brownfield sites, former mining or resource extraction sites,

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http://dx.doi.org/10.1016/j.jenvman.2016.03.028

and urban and rural areas affected by diffuse contamination. For example, there are estimated to be close to one million (or more) potential brownfield sites across the European Union (Oliver et al., 2005), a considerable fraction of which may have real or perceived contamination problems (Panagos et al., 2013). The German register of contaminated sites lists about 300,000 potentially contaminated sites (UBA, 2015), while the French Basol database references 6319 polluted sites requiring government action, mainly located in Rhone-Alpes (17%), Nord-Pas-de-Calais (10.5%), Aquitaine (9%) and Ile de France (8.6%) (Commissariat Général au Développement Durable, 2013; Basol, 2016). Although the extent of diffuse contamination is less well-known thousands of square kilometres of land are potentially affected (Bardos et al., 2011). In Belgium and the Netherlands alone, two moderate-sized countries which share a similar history of industrial development and subsequent partial industrial decline with much of western Europe, diffuse contamination by metals affects approximately 700 km^2 of land (Witters et al., 2009). While a number of impacted sites have been remediated or restored to productive use a significant land area remains derelict or underutilized because its restoration is uneconomic or unsustainable using conventional methods. This dereliction and underutilization is a particular problem for large land areas where contamination may be causing concern but is not present at highly elevated levels (such as areas impacted by diffuse metal smelter contamination), or where smaller sites are economically marginal for hard redevelopment (*e.g.* where economic returns from site redevelopment for housing are insufficient to cover conventional remediation or rehabilitation costs). An expanding body of work since the 1990s however indicates that management and re-utilisation of these sites is possible through use of low input longer term remediation approaches (*e.g.* ITRC, 2009), particularly through so-called gentle remediation options (GROs) (Mench et al., 2010; Kidd et al., 2015).

GROs have been defined as risk management strategies or technologies that result in a net gain (or at least no gross reduction) in soil function as well as achieving effective risk management (Cundy et al., 2013). They encompass many technologies, including the use of plant (phyto-), fungi (myco-), and/or bacteria-based methods, with or without chemical additives or soil amendments, for reducing contaminant transfer to local receptors by extraction, transformation, or degradation of contaminants, or by *in-situ* stabilization (using biological and/or chemical processes). Plant (phyto)-based GROs are described in Table 1. As the treated soil remains unsealed, GROs are highly applicable to soft-end use for a site, *e.g.* for urban or community park-land, biomass generation etc. (Mench et al., 2009; Fässler et al., 2010; Bert et al., 2012a; Evangelou et al., 2012, 2015; HOMBRE, 2013; Kidd et al., 2015; Marchand et al., 2015; Robinson et al., 2015). Furthermore, depending on the specific site situation GROs can have significantly lower deployment costs than conventional remediation technologies (Vangronsveld et al., 2009; Kuppusamy et al., 2016a, b). GROs can also contribute strongly to sustainable remediation strategies, by providing a broad range of wider economic, social and environmental benefits (*e.g.* economic returns through biomass production; restoration of plant, microbial, and animal communities; water filtration and run-off and drainage management; amenity and recreation (Vangronsveld et al., 1995a, 2009; Witters et al., 2012; Cundy et al., 2013, 2015)).

Despite these benefits the application of GROs as practical on-site remediation strategies is still limited, particularly in Europe and for trace element (typically metal and metalloid) contaminated sites (Vangronsveld et al., 2009; Mench et al., 2010). This is due to a number of perceived (or actual) barriers or impediments related to technical issues and stakeholder perceptions, and which are further discussed in section 2. In order to overcome some of the barriers to practical application of GROs within Europe, the 17 partner GREENLAND (Gentle Remediation of Trace Element Contaminated Land) project was initiated in 2010 (with funding from the European Commission FP7 Programme). This project involved a network of academic institutes, regulators and industry bodies, and practical field applications of GROs, and has developed practical case studies, assessment and decision support tools and practical guidance for the application of GROs at sites contaminated with metals and metalloids.

This paper reviews emerging ideas about the use of GROs in achieving effective risk management along contaminant linkages, and the wider benefits that GROs have to offer contaminated land (and brownfield) restoration, for soft reuses in particular. It discusses challenges to the practical adoption of GROs in contaminated land management, and summarises the decision support tools and best practice guidance developed in the GREENLAND project aimed at overcoming these challenges. The wider possibilities for implementation of GROs as practical contaminated site management strategies, particularly for metal and metalloid contaminated sites, and their potential role in sustainable site management strategies are also discussed, in particular how GROs can be applied to "leverage" wider economic, environmental and societal benefits at contaminated sites.

2. Challenges to the adoption of GROs in contaminated land management

The main barriers to widespread GROs application, in Europe and more widely, derive from a general focus of the remediation

Table 1
Examples of Gentle Remediation Options used to remediate soils contaminated by either metal(loid)s or mixed contamination (after Peuke and Rennenberg, 2005; Mench et al., 2010; Cundy et al., 2015).

GRO	Description
Phytoextraction	The removal of metal(loid)s or organics from soils by accumulation in the harvestable biomass of plants. When aided by use of soil amendments (*e.g.* EDTA or other mobilising agents), this is termed "aided phytoextraction".
Phytodegradation/ phytotransformation	The use of plants (and associated microorganisms such as rhizosphere and endophytic bacteria) to uptake, store and degrade or transform organic pollutants.
Rhizodegradation	The use of plant roots and rhizosphere microorganisms to degrade organic pollutants.
Rhizofiltration	The removal of metal(loid)s or organics from aqueous sources (including groundwater) by plant roots and associated microorganisms.
Phytostabilization	Reduction in the bioavailability of pollutants by immobilization in root systems and/or living or dead biomass in the rhizosphere soil. When aided by use of soil amendments, this is termed "aided phytostabilization".
Phytovolatilization	Use of plants to remove pollutants from the growth matrix, transform them and disperse them (or their derived products) into the atmosphere.
In situ immobilization/ phytoexclusion	Reduction in the bioavailability of pollutants by immobilizing or binding them to the soil matrix through the incorporation into the soil of organic or inorganic compounds, singly or in combination, to prevent the excessive uptake of essential elements and non-essential contaminants into the food chain. Phytoexclusion, the implementation of a stable vegetation cover using so-called excluder plants which do not accumulate contaminants in the harvestable plant biomass, can be combined with *in situ* immobilization.