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Developing effective decision support for the application of “gentle” remediation options: The GREENLAND project

Andy Cundy, Paul Bardos, Markus Puschenreiter, Nele Witters, Michel Mench, Valerie Bert, Wolfgang Friesl-Hanl, Ingo Müller, Nele Weyens and Jaco Vangronsveld.

ABSTRACT / SUMMARY

Gentle remediation options (GRO) are risk management strategies/technologies that result in a net gain (or at least no gross reduction) in soil function as well as risk management. They encompass a number of technologies which include the use of plant (phyto-), fungi (myco-) and/or bacteria-based methods, with or without chemical soil additives or amendments, for reducing contaminant transfer to local receptors by in situ stabilisation, or extraction, transformation or degradation of contaminants. Despite offering strong benefits in terms of risk management, deployment costs and sustainability for a range of site problems, the application of GRO as practical on-site remedial solutions is still in its relative infancy, particularly for metal(loid)-contaminated sites. A key barrier to wider adoption of GRO relates to general uncertainties and lack of stakeholder confidence in (and indeed knowledge of) the feasibility or reliability of GRO as practical risk management solutions. The GREENLAND project has therefore developed a simple and transparent decision support framework for promoting the appropriate use of gentle remediation options and encouraging participation of stakeholders, supplemented by a set of specific design aids for use when GRO appear to be a viable option. The framework is presented as a three phased model or Decision Support Tool (DST), in the form of a Microsoft Excel-based workbook, designed to inform decision-making and options appraisal during the selection of remedial approaches for contaminated sites. The DST acts as a simple decision support and stakeholder engagement tool for the application of GRO, providing a context for GRO application (particularly where “soft” end-use of remediated land is envisaged), quick reference tables (including an outline economic cost calculator), and supporting information and technical guidance drawing on practical examples of effective GRO application at trace metal(loid) contaminated sites across Europe. This article introduces the decision support framework.

INTRODUCTION

Conventional approaches to contaminated land risk management have focussed mainly on containment, cover and removal to landfill (or “dig and dump”). From the late 1990s onwards there has been a move towards treatment-based remediation strategies, using *in situ* and *ex situ* treatment technologies such as soil washing, “pump and treat” of contaminated groundwater *etc.* (*e.g.* Dermont et al., 2008), coupled with the widespread adoption of a risk-based approach to contaminated land management. Recently, building on earlier ideas on so-called “extensive” technologies (which sought to distinguish low input longer term remediation approaches from energy, resource and labour intensive strategies, Bardos and van Veen, 1996), the concept of Gentle Remediation Options (GRO) has emerged. GRO are defined (e.g. Cundy et al., 2013) as risk management strategies/technologies that result in a net gain (or at least no gross reduction) in soil function as well as risk management. This emphasis on maintenance and improvement of soil function means that they have particular usefulness for maintaining biologically productive soils, which is important where a “soft” end use for a site (such as urban parkland, biomass/biofuels production *etc.*) is being considered. GRO encompass a number of technologies which include the use of plant (phyto-), fungi (myco-) and/or bacteria-based methods, with or without chemical additives or amendments, for reducing contaminant transfer to local receptors by *in situ* stabilisation (using biological and/or chemical processes), or extraction, transformation or degradation of contaminants (Exhibit 1).

There have been a number of active *in situ* tests of a range of plant (phyto)-based risk management techniques from the 1990s onwards (e.g. Bardos et al., 2010), as well as widespread use of “green” technologies such as landscaping, application of green covers, reedbeds and constructed wetlands in remediation or industrial/urban regeneration projects. Nevertheless, the application of GRO as practical on-site remedial solutions is still in its relative infancy, particularly (a) in Europe, and (b) for trace element contaminated sites. In order to overcome some of the impediments to practical GRO application within Europe, the GREENLAND (Gentle Remediation of Trace Element Contaminated Land) project was initiated in 2010, funded by the European Commission FP7 programme. The project brought together a range of academic institutes, regulators and industry bodies, focusing on practical application of GRO at European sites contaminated with metals and metalloids. It made use of a network of long-term (>5 years) GRO field experiments in Europe (from Belgium, France, Sweden, Switzerland, Austria, Germany and Spain), to provide data, case studies, operating windows, assessment and decision support tools, and practical guidance for the application of GRO at contaminated or brownfield sites across Europe. In this paper, we describe the decision support framework developed during the project.

CONTEXT: GENTLE REMEDIATION OPTIONS (GRO)

Gentle remediation options are best deployed to remove the labile (or bioavailable) pool of inorganic contaminants from a site (phytoextraction), remove or degrade organic contaminants (*e.g.* phytodegradation), protect water resources (*e.g.* rhizofiltration), or stabilise or immobilise contaminants in the subsurface (*e.g.* phytostabilisation, *in situ* immobilisation/phytoexclusion) (*e.g*. Vangronsveld et al., 2009; Mench et al., 2010). GRO approaches can be tailored along contaminant linkages (Cundy et al., 2013, Exhibit 2). Intelligently applied GRO can provide rapid risk management via pathway control, through containment and stabilisation, coupled with a longer term removal or immobilisation/isolation of contaminants. Additionally GRO can provide a broad range of wider economic (*e.g.* biomass generation), social (*e.g.* leisure and recreation) and environmental (*e.g.* C sequestration, water filtration and drainage management, restoration of plant, microbial and animal communities) benefits. These benefits have often been only superficially considered during remediation options appraisal in the past, but present a potentially very important wider value proposition for use of GRO, especially for areas with a soft (i.e. non-built) end-use, such as for renewables, habitat or parkland. Benefits may be in the form of direct revenue generating opportunities (*e.g.* biomass revenues), an increase in natural or cultural capital in an area (*e.g.* soil and water improvement, provision of green infrastructure, amenity space etc.), or provision of tangible economic benefits (*e.g.* increase in property values, job generation etc.) or intangibles such as reputational benefits. Deployment costs can also be significantly lower than more invasive techniques, particularly where large land areas require treatment (Vangronsveld et al., 2009; Witters et al., 2012a,b).

Hence while the potential application of GRO may be limited in scope at sites requiring rapid redevelopment, or removal or destruction of contaminants to reach generic soil concentration targets, there are a number of site circumstances which may be highly amenable to GRO-based risk management methods (Cundy et al., 2013). These include:

- Large treatment areas, particularly where contamination may be causing concern but is not at strongly elevated levels
- Where biological functionality of the soil is required after site treatment
- Where other environmental services related to soil quality (*e.g.* biodiversity, carbon sequestration) are valued highly
- Where there is a need to restore marginal land to produce non-food crops and avoid major land use changes
- Where there are budgetary constraints
- Where there are deployment constraints for land remediation process plants (*e.g.* as a function of area and location).

CURRENT BARRIERS TO GRO APPLICATION, AND DECISION SUPPORT NEEDS

Gentle remediation options can offer great benefits in terms of risk management, deployment costs and sustainability for a range of site problems, however, awareness and take up is low, at least in a European context. The barriers to wider adoption of GRO, especially in Europe, arise both from the nature of GRO as remediation techniques, and market and stakeholder perceptions of uncertainties over whether these methods can achieve effective risk management in the long term (Cundy et al., 2013). The majority of remediation work in Europe has been carried out as a result of regulatory demand for critical risks and/or to stimulate the re-use or re-development of brownfield land, and so is often constrained by pressures on time scale, and focused on relatively limited site areas. Both of these factors have tended to exclude consideration of GRO which are perceived as slow and more suited to large area problems. Onwubuya et al., (2009) note additionally that general uncertainties and lack of stakeholder confidence in (and indeed knowledge of) the feasibility or reliability of GRO as practical risk management solutions (*e.g.* phytoextraction, Van Nevel et al., 2007) has limited their uptake. Practical, well disseminated guidance and decision support tools (DST) which incorporate GRO could help in this respect, but the take up and acceptance of bespoke systems, such as specialist softwares, by stakeholders is low. Previous work under the EU ERA-net SNOWMAN SUMATECS project published by Onwubuya et al., (2009) reviewed available decision support tools and systems for GRO, and stakeholder perceptions of the fitness for purpose of these systems. It argued that a simple, tiered DST model, which linked to well-established national decision frameworks and provided links to more detailed information to support practical GRO implementation, was the most effective format to promote wider use and uptake both of GRO and of GRO-based decision support. The GREENLAND project has adopted and expanded on these recommendations to produce a simple and transparent framework for promoting the appropriate use of GRO and encouraging participation of stakeholders, supplemented by a set of specific design aids for use when GRO appear to be a viable option. This decision support framework is discussed below.

THE GREENLAND DECISION SUPPORT FRAMEWORK

The GREENLAND DST is a simple Microsoft Excel-based workbook. It has a phased (or tiered) structure, designed to inform decision-making and options appraisal during the selection of remedial approaches for contaminated sites. It is presented alongside an accompanying best practice guidance document (provided (initially) in English, German and French languages), which summarises the key information in the DST, and provides a context for GRO application, an overview of its current state of development and risk management capability, potential wider (sustainability) benefits, and high-level GRO "operating windows" (*i.e.* the combination of contaminant, environmental and site circumstance in which a given remediation technology will almost certainly achieve project remedial objectives, Scott and Nathanail, 2004) based on field data from the GREENLAND site network. The DST is designed to interface with existing national guidance at the options appraisal stage, although we recognise that the DST may have equal applicability at earlier (site planning) stages. The DST has a three phase structure, summarised in Exhibit 3, with each phase terminating in a decision point (Yes = proceed to next phase; No = return to options appraisal), and increasing in complexity and time investment from phase 1 to 3. The worksheets for each phase of the tool can be found by navigating via the worksheet titles at the base of the user's screen, or by selecting the highlighted buttons on the left of the flow diagram. A full user's guide for the tool can be accessed by selecting the "User Guide" tab at the base of the user's screen.

The tool is aimed at planners, consultants, regulators, practitioners, scientists, and other brownfields or contaminated land stakeholders, and is intended to provide practical decision support when appraising various options for contaminated site management.

In phase 1 of the model (***initial concepts / feasibility***), the user is referred to a series of worksheets outlining:

- Definitions of GRO;
- GRO scope and risk management capability (or High Level Operating Windows), and a quick reference on GRO applicability ("Are GRO applicable at your site?" (Exhibit 4));
- Examples of cases where application of phytomanagement strategies have led to demonstrable source removal, pathway management or receptor protection ("success stories", drawn from the GREENLAND site network and presented as a simplified 2 page

summary including site details and site conceptual model, main contaminant linkages, technology applied, measures of remediation success, supporting data and contact details);

- An outline contaminant matrix to assess the applicability of various GRO options to different metal(loid) contaminants (or combinations of these).

The user can navigate between these pages, and on to phase 2 or back to the overview page, by selecting the hyperlinks given in the lower part of each worksheet.

In phase 2 of the model (***exploratory stages / confirmation***), the user is referred to a series of worksheets outlining:

- Stakeholder engagement guidelines, including general principles of stakeholder engagement when applying GRO (published in Cundy et al., 2013), criteria for the identification of different stakeholders profiles/categories, and example lists of stakeholders;
- A wider sustainability benefits identification and assessment module. While economic, social and environmental benefits will clearly be site and project specific, a number of more generic qualitative, semi-quantitative and fully quantitative tools and systems are available to enable identification and quantification of wider benefits arising from application of GRO. Within this tool, we provide links to three matrices/modules: The European Union FP7 HOMBRE project (grant 265097, www.zerobrownfields.eu) Brownfield Opportunity Matrix (BOM) - an Excel-based qualitative screening tool to help decision makers identify which services they can obtain from “soft reuse” interventions (including GRO) at a site, and how these services interact; The SuRF-UK indicator sets (with further links to external analysis software resources), which provide a semi-quantitative ranking system based on key economic, environmental and social indicators (Bardos et al., 2011), and an outline cost calculator, developed within the GREENLAND project, which incorporates user-entered cost data to estimate the economic value proposition of GRO at a particular site (discussed further below).

The user can again navigate between these pages, and on to phase 3 or back to the overview page, by selecting the hyperlinks given in the lower part of each worksheet.

In phase 3 of the model (***design stages***), the user is referred to a series of worksheets outlining:

- Outline operating windows for GRO. Here, we provide three MS Excel-based operating window matrices (Exhibit 5), which allow the user to check the outline applicability of GRO (grouped as phytoextraction, phytostabilisation, and immobilisation/phytoexclusion) to a specific site, in terms of local soil pH, site plant toxicity, climate, soil type, and depth of contamination. The purpose of these matrices is to highlight the potential applicability of GRO at a site, not to confirm that GRO will be a successful risk management tool at the site. Further technical and design input and expertise will be required to determine site specific operating windows, and to effectively design and implement a GRO strategy for an individual site that effectively manages contaminant risk, and delivers wider benefit.
- Technical reference sheets on: design and implementation; selection of plant species, cultivars and soil amendments; safe biomass usage; indicators of success and methods; and stakeholder engagement.
- Further reference sources.

ECONOMIC BENEFITS: THE GREENLAND COST CALCULATOR

The GREENLAND cost calculator, presented in phase 2 of the DST, was based initially on published literature and data from the Lommel (Belgium) GREENLAND site (*e.g.* Ruttens et al., 2011; Van Slycken et al., 2013; Witters et al., 2012a,b), and was extended and validated by testing the model on further GREENLAND sites (n = 16). The model was elaborated so that it is an easy to understand and easy to use tool for practitioners, with no additional data gathering required. Also, the model does not elaborate on who performs the on-site work (*e.g.* harvest by hand by site workers or by professional agency). Therefore, the model should be used more as a guidance rather than for decision making and full project cost quantification. It is a simplified model that focuses on easily quantifiable costs and benefits, and assumes that the main revenue from the site is from sale of produced biomass (it does not attempt to quantify wider benefits and value, which are assessed qualitatively, in the form of service interactions, elsewhere in phase 2 of the DST via a link to the HOMBRE project Brownfield Opportunity Matrix).

The cost calculator consists of two parts: data provision (two tabs) and a discounted cost calculation (one tab). In the first tab the user provides general information regarding the site (*e.g.* use, soil density, distances to suppliers and buyers), the contamination (*e.g.* depth, element, concentration, project risk management goal *i.e.* extraction or stabilisation) and the plant (*e.g.* rotation, density, biomass per part). In the second tab the user provides cost data as well as a timing estimate regarding the preparation (*e.g.* license, ground levelling), start-up (*e.g.* purchase of plants and seeds), maintenance (*e.g.* replacement of crops), harvest (*e.g.* type of machine, transport) and monitoring (during and after the project) of the remediation or containment project. There is also an opportunity to indicate potential revenues from the biomass produced. In the third tab the duration of the project is calculated as well as detailed yearly costs throughout the project, the contribution of each cost type and a discounted total project cost.

DISCUSSION

The GREENLAND DST is designed to act as a simple decision support and stakeholder engagement tool for the application of GRO, providing a context for GRO application (particularly where "soft" end-use of remediated land is envisaged), quick reference tables, and supporting information and guidance drawing on practical site examples of effective GRO application at trace metal(loid) contaminated sites across Europe. As indicated by the GREENLAND sites and in published literature, GRO show clear potential for practical risk management at a range of site types (*e.g.* Bert et al., 2009, Friesl-Hanl et al., 2009, Herzig et al., 2014). GRO may indeed be used to trigger land regeneration in circumstances where the case for intervention is economically marginal by virtue of their lower cost and also, potentially, by their linkage to other project services such as biomass, public green space provision, recovery of land values *etc.* (*e.g.* Bardos et al., 2011, Andersson-Skold et al., 2014). Technical information from the GREENLAND demonstration sites provides evidence of the effectiveness of GRO in the medium to longer term under varying site contexts and conditions throughout Europe, and data for economic and other assessments, which are included in this DST to help regulators, consultants, site managers and planners develop practical strategies for GRO application across Europe.

The DST includes a dedicated module on stakeholder engagement strategies. As noted by Cundy et al., (2013) the application of GRO may raise significant long term site stewardship issues beyond those of more conventional remediation methods, and so effective and sustained engagement strategies will be required to ensure that site risk is effectively managed over the longer-term, and that full potential benefits of GRO (*e.g.* CO_2 sequestration, economic returns from biomass generation and "leverage" of marginal land, amenity and educational value, ecosystem services *etc.*) are realised and communicated to stakeholders. Given stakeholder uncertainties (and scepticism) over the feasibility, reliability or limitations of GRO as practical site solutions (see discussion in Onwubuya et al., 2009), the information and modular tools provided in the DST and the linked best practice guidance documentation also have an informing and communicating role during engagement with site decision makers, regulators, consultants and the wider public, to encourage wider consideration of GRO as a potentially effective risk management strategy within Europe and in other geographic regions. While the DST and accompanying guidance are focused on the European context, much of the material is readily transferable to other geographic regions, although further validation under different regulatory and environmental management frameworks will be required.

Despite the relatively detailed site information and implementation guidance provided, it is important to note that the tool itself should not replace expert input – in common with many remediation strategies GRO are not “off-the-shelf” tools, and a site specific assessment and testing is required prior to implementation if site risk is to be effectively managed. The tools provided are for decision support, not decision making, and do not attempt a ranking of GRO against alternative remediation or site management techniques. It is clear though that intelligently applied GRO can provide rapid risk management via pathway control, through containment and stabilisation, coupled with a longer-term removal or immobilisation of the contaminant source term. GRO can be durable solutions as long as land use and land management practice does not undergo substantive changes causing shifts in pH, Eh, plant cover, *etc*. suggesting that some form of institutional or planning control may be required. However, the use of institutional controls over land use is part-and-parcel of urban remediation using conventional technologies (*e.g.* limitation of use for food production), so any requirement for institutional control and management with GRO continues a long established precedent.

ACKNOWLEDGEMENTS

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Exhibit 1: Examples of Gentle Remediation Options used to remediate soils contaminated by either trace elements or mixed contamination (after Peuke and Rennenberg, 2005, Mench et al., 2010).

GRO	**Description**
Phytoextraction	The removal of metal(loid)s or organics from soils by accumulating them in the harvestable biomass of plants. When aided by use of soil amendments, 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 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 by plant roots and associated microorganisms.
Phytostabilisation	Reduction in the bioavailability of pollutants by immobilisation in root systems and / or living or dead biomass in the rhizosphere soil – creating a substrate which enables the growth of a vegetation cover. When aided by use of soil amendments, this is termed "aided phytostabilisation".
Phytovolatilisation	Use of plants to remove pollutants from the growth matrix, transform them and disperse them (or their derived products) into the atmosphere.
In situ immobilisation / 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 excluder plants which do not accumulate contaminants in the harvestable plant biomass can be combined with *in situ* immobilisation.

Exhibit 2: Example GRO-based risk management strategy, tailored along contaminant linkage model

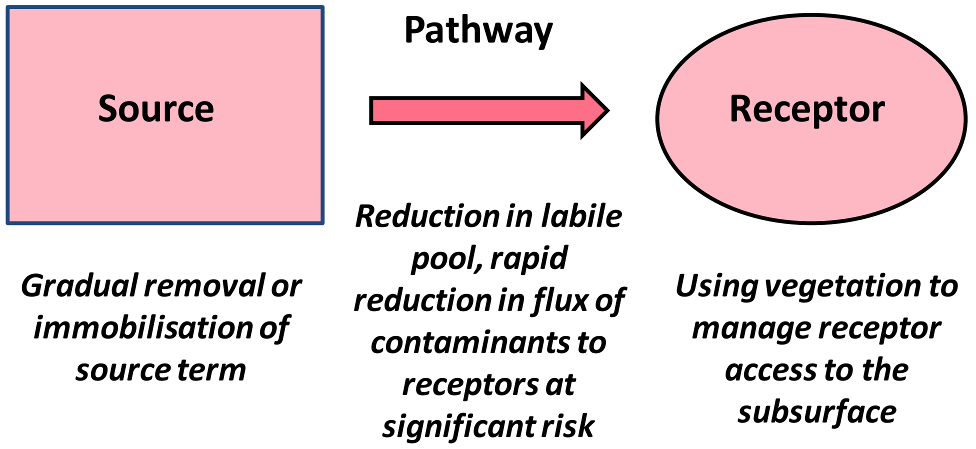
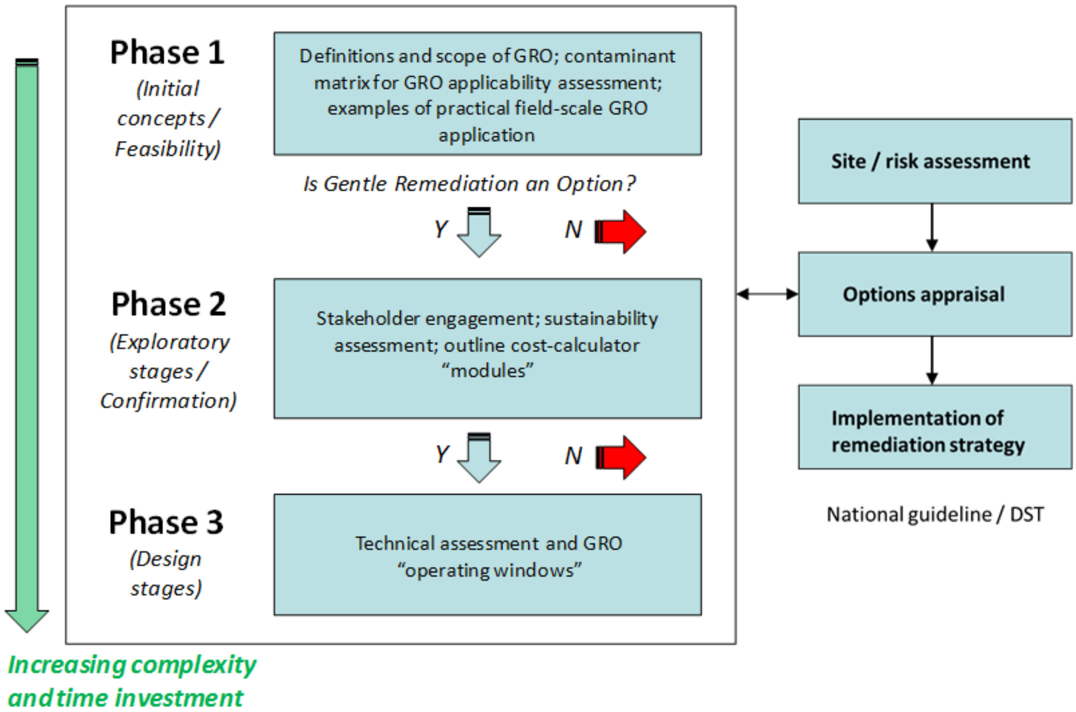


Exhibit 3: Three phase structure of the GREENLAND DST.

Go to Phase 1 information

Go to Phase 2 information

Go to Phase 3 information



User guide

Exhibit 4: Quick reference table on GRO outline applicability, from phase 1 of the GREENLAND DST.

Quick reference: Are GRO applicable to your site?	
Key questions:	**If YES, are GRO potentially applicable?**
Does the site require immediate redevelopment?	**Unlikely** (except immobilisation / phytoexclusion which can show immediate positive effects)
Are your local regulatory guidelines based on total soil concentration values?	**Unlikely** for phytoextraction but possibly for some other GRO
Is the site under hard-standing, or has buildings under active use?	**Unlikely** (there is a need to remove the hard-standing or buildings and to establish a soil layer enabling plant growth).
Do you require biological functionality of the soil during and after site treatment?	**YES**
Is the treatment area large, and contaminants are present but not at strongly elevated levels?	**YES** (even where soil ecotoxicity is high, use of soil pretreatments and amendments may enable GRO application)
Are the contaminants of concern present at depths within 5 – 10m of the soil surface?	**YES** (depending on soil porosity, if contamination is present within 1m of the soil surface then treatment is possible by most plants. Deeper contamination may be addressed using trees, with interventions as necessary to promote deeper rooting).
Is the economic case for intervention and use of "hard" remediation strategies marginal?	**YES**
Are you redeveloping the site for soft end-use (biomass generation, urban parkland etc)?	**YES**

Exhibit 5: Example outline operating window matrix (phytoextraction example) from Phase 3 of the GREENLAND DST. Recommendation is based on data from the GREENLAND site network and Best Practice Guidance, and reviews of published literature.

For each category, choose only 1 of the 3 options by writing "Yes". Examples are shown

What is the typical soil pH range at your site?	pH
5 - 8	
4 - 5 / 8 - 9	
2 - 4 / 9 - 11	yes

What is the relative diversity and density of current plant species present on your site?	Plant Community
Diversity and density of plant species are similar to surrounding areas (on non-contaminated soil)	
Diversity and density of plant species is visibly less/different to surroundings (non-contaminated soil)	yes
No plant species are growing on the contaminated site	

What is the overall climate of the region in which your site is located?	Climate
Arid	
Semi-Arid	
Humid/Temperate	yes

What is the typical soil type / composition on your site?	Soil Type
Clay	
Loam	yes
Sand	

What is the typical soil depth to which contaminants of concern are present?	Depth of contamination
Top Soil (0-30 cm)	yes
Sub Soil (30-90 cm)	
Deep Soil (> 90 cm)	

Recommendation

Expert advice and plant toxicity tests are recommended

BIOGRAPHICAL SKETCH OF LEAD AUTHOR

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