

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

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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, 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 km² 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., 2016^{a,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., 1995^a, 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 sector on remediation for critical risks or to rapidly return smaller urban brownfield sites to productive use (Cundy et al., 2013). This focus has tended to exclude GROs, which are perceived as slow and more suited to large area problems (Puschenreiter et al., 2009). A lack of convincing pilot applications, and legal frameworks which predicate removal or destruction of contaminants to reach generic soil concentration targets, also pose significant barriers (Puschenreiter et al., 2009; Vangronsveld et al., 2009; Cundy et al., 2013). Stakeholders (site owners, planners, consultants, regulators, local community, investors, insurers etc) may also lack awareness of and/or confidence in the application of GROs (Onwubuya et al., 2009). In particular:

- There is uncertainty relating to the required time-scales for GROs, and their long-term effectiveness as risk management methods (*e.g.* Puschenreiter et al., 2009).
- (Within Europe at least) GROs services are offered by relatively few consultants and contractors, which has limited their availability (Cundy et al., 2013).
- There is limited awareness of the role of GROs as practical site solutions.

A questionnaire-based survey of stakeholder perceptions of GROs, carried out in the EU SUMATECS (Sustainable management of trace element contaminated soils) project in 2008, assessed reasons for hindrance in the wider uptake of gentle remediation options (Puschenreiter et al., 2009). The 130 participants of the survey were drawn from more than 10 European countries, and included representatives from university/research institutions, regional authority/government,

environmental consultancies, remediation contractors, and other key stakeholder groups (including land owners, investors, and pressure groups). While gentle remediation technologies were known to most respondents (87% of respondents) they were rarely applied, with perceived disadvantages in the need for long-term monitoring and a lack of applicability for some types of sites and contaminants. Lack of knowledge, experience and convincing pilot projects were considered the main obstacles for more general application of gentle remediation technologies. Kennen and Kirkwood (2015) note similar obstacles, and discuss further (historical) issues whereby a huge surge of interest in phytotechnologies in the 1990s was followed by mixed performances in the field (due to application at unsuitable sites, or that implementation occurred before the supporting science was substantiated), causing a crash in stakeholder confidence in GROs which is only slowly being recovered.

3. The GREENLAND project – overcoming the impediments to practical application.

The GREENLAND project has adopted a transparent and simple plan of action to address these impediments. It has co-ordinated data collection from a range of long-duration GRO pilot projects at contaminated sites across Europe, evaluated standard protocols and methods for site monitoring, and developed a set of specific design aids (for use when GRO appear to be a viable option) to promote the appropriate use of gentle remediation options and encourage participation of (and inform) stakeholders. The specific aims of the project were to:

1. Assess the efficiency of GRO via long-term (> 5 year duration) field trials;
2. Test the possibilities for biomass valorisation at trace element contaminated sites;
3. Evaluate a set of soil tests to assess GRO performance or “success”;
4. Enhance the efficiency of GRO (*e.g.* by selection of the most effective plants, microbes, and soil amendments, and by improving agronomic practices);
5. Develop a decision support system, stakeholder engagement guidance, and a guide for practical application of GRO.

The project made use of existing long-term (greater than 5 years) GRO field experiments in Europe (Belgium, France, Sweden, Switzerland, Poland, Austria, Germany, and Spain, Table 2, <http://www.greenland-project.eu/>), coupled with laboratory and industrial trials, stakeholder discussions, and desk reviews. These were used to provide: operational data on the effectiveness of GRO under different contaminant and site scenarios; pilot case studies/applications for different GRO types; high-level GRO technical applicability guides; assessment and decision support tools (including an economic cost calculator tool); and technical guidance to support the design, implementation and assessment / monitoring of GRO strategies on a site specific level.

Two key outputs from the project were (1) a (multi-lingual) best practice guidance, designed to encourage wider consideration and use of GROs as part of effective risk management strategies within Europe and in other geographic regions, and (2) a practical decision support tool (DST), presented as a simple MS-Excel based workbook and designed to support stakeholder engagement, site options appraisal and decision making. Both outputs are available for download from the GREENLAND project website (www.greenland-project.eu). The overall structure and content of the DST have already been described by Cundy et al., (2015). This paper focuses on aspects of the best

practice guidance and DST (and the GREENLAND project more widely) which develop ideas around the use of GROs in achieving effective risk management along contaminant linkages, and which assess economic, social and environmental benefits of GRO application (*i.e.* wider benefits related to sustainable remediation principles and concepts). We also discuss emerging ideas around a shift in practice from phytoremediation to phytomanagement approaches, in which a long term combination of profitable site use with gentle remediation options (GRO) leads gradually to the reduction of pollutant linkages and the restoration or generation of wider site services.

4. Customising GROs along contaminant linkages, and wider GRO-based site management strategies.

Gentle remediation options, specifically those using plants and their associated soil microbial systems, can be applied 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 stabilize or immobilize contaminants in the subsurface (*e.g.*, phytostabilization, *in-situ* immobilization/phytoexclusion) (*e.g.*, Vangronsveld et al., 2009; Mench et al., 2010; Cundy et al., 2015, Table 1). A number of studies have shown the potential of GROs to provide rapid risk management via pathway control coupled with a longer term removal or immobilization/isolation of contaminants (*e.g.*, Bert et al., 2009, 2012a; Friesl-Hanl et al., 2009; Kolbas et al., 2011; Cundy et al., 2013; Herzig et al., 2014; Kennen and Kirkwood., 2015; Janssen 2015). For example, within the GREENLAND network of sites (Table 2):

Phytoextraction (using tobacco variants and sunflower mutants selected for their metal tolerance and phytoextraction properties) was applied to Zn-contaminated soils at a former hot dip Zn factory at Bettwiesen in eastern Switzerland. The overall results of a 5-year time series experiment showed a lowering of the labile Zn pool in the soils by 45–70%, indicating the feasibility of bioavailable zinc stripping at the site within a few years (Herzig et al, 2014). In the northeast of Belgium (the Campine region), an area of more than 280 km² is historically contaminated with mainly Cd, Zn and Pb. Biomass production and metal accumulation of pre-selected tobacco clones (*Nicotiana tabacum* L.), pre-selected sunflower mutants (*Helianthus annuus* L.) and a commercial hemp (*Cannabis sativa* L.) were determined over 2-4 years while the phytoextraction potentials of more than 200 different commercially available and experimental (designed by the Institute of Nature and Forest Research, INBO) poplar (*Populus*) and willow (*Salix*) clones in short rotation coppice (SRC) were assessed at the end of the first cutting cycle (after 4 growing seasons). The tobacco clones and the sunflower mutants were shown to be efficient extractors of Cd and Zn respectively, while the highest simultaneous extraction of Cd and Zn was observed using woody species in SRC. Phytoextraction of Pb was limited using the crops tested but this was not considered to be a major problem given the low bioavailability and activity of Pb at the site. The estimated long remediation times (> 60 years to reduce total Cd contents to Flemish guideline values) however indicated that, in this case, additional value generated from economic and (other) environmental benefits will be crucial for large-scale implementation of metal phytoextraction (Janssen 2015).

In France, aided phytostabilisation was applied over a 6 year period on a 1ha site used for on-land disposal of Zn, Pb and Cd contaminated sediments at Fresnes-sur-Escaut in northern France.

Following initial site clearance (mainly of the invasive plant Japanese knotweed), a basic mineral amendment (Optiscor™) was applied to the soil, which was then planted at high density with a commercial cultivar of grass (*Deschampsia cespitosa*) (Bert et al., 2009, 2012b). The trial showed stabilisation of contaminants with effectively 100% vegetation cover (reducing soil – human contaminant linkages via direct soil exposure and dust inhalation) and a reduction in plant-metal uptake and transfer (foliar element concentration in cover grass was reduced by 60 % (for Zn) and 20% (for Cd)). Metal values in plant biomass were sufficiently low to allow subsequent biomass use as compost.

In Austria, *in-situ immobilisation / phytoexclusion* was applied over a 13 year period at Arnoldstein (south Austria) on arable land impacted by Pb/Zn smelter emissions. Gravel sludge and iron bearing materials (red mud, 3 % (w/w) = 9 kg/m² = 90 t/ha) were applied as soil amendments and Cd-excluding cultivars of commercial food crops (barley, maize, and potatoes) grown, with the aim of reducing contaminant transfer from soil to plants and groundwater (Friesl-Hanl et al., 2009). Amendment addition generated a significant reduction in the labile contaminant pool in the soils (Cd could be reduced by >80%; Zn >90% and Pb >90%), while Cd uptake into barley could be reduced by >75 % (compared to an accumulating cultivar). Uptake into maize silage was reduced by up to 50% for Cd, 60% for Pb, and 70% for Zn.

Site risk management by GROs can be summarised in an approach which customises or tailors GROs along contaminant linkages to manage site risk (Figure 1), discussed previously in Cundy et al., (2013). Here, methods such as phytoextraction can be used to remove the bioavailable contaminant pool at a site, or methods such as *in-situ* stabilisation immobilise the contaminants within the soil, and so reduce the mass flux of contaminants to the receptor. Pathway management can also be applied through rhizofiltration or phytovolatilisation options, which reduce contaminant transfer to groundwater and surrounding water bodies, while plants (as ground cover) can be used to manage receptor access to the subsurface. Application of soil amendments (such as lime, red mud, zeolites, cyclonic ashes, iron grits and slags, or composts, biochar and other organic amendments) can reduce the bioavailability of a wide range of contaminants while simultaneously enhancing revegetation success and, thereby, protect against offsite movement of contaminants by wind and water (Vangronsveld et al., 1995a,b,, 2009; Bes and Mench 2008; Kumpiene et al., 2008; Puschenreiter et al., 2009; Bolan et al., 2014; Jones et al., 2016). Building further on this contaminant linkages approach, the design and implementation guidance from the GREENLAND project focuses on the concept of phytomanagement (*i.e.* the long term combination of profitable site use with GROs which leads gradually to the reduction of contaminant linkages and the restoration of ecosystem and other site services), rather than phytoremediation *per se*. The latter has been often associated in the contaminated land sector with phytoextraction, which is perhaps the most well-known GRO, and which has been widely tested at demonstration scale (*e.g.* Vangronsveld et al., 2009; Mench et al., 2010). Phytoextraction has generally been seen as a source management strategy which aims to gradually remove trace elements from soil over time into above-ground biomass. It has poor acceptance as an effective source management tool amongst many contaminated land practitioners as contaminant removal may take decades, source removal effectiveness depends strongly on contaminant bioavailability, early phytoextraction-based site trials met with mixed success, and there may be concerns over presence of contaminants in harvested biomass (*e.g.* Van Slycken et al., 2013a,b; Cundy et al., 2013; Delplanque et al., 2013; Cao et al., 2015; Janssen 2015; Kennen and Kirkwood, 2015). Phytomanagement refers to a wider design and management strategy which,

alongside risk management, places realisation of wider (including economic) benefits at the core of site design, and uses GRO as part of integrated site management strategies rather than applying plant monocultures over extensive areas to gradually extract the bioavailable contaminant pool (although this latter approach still has clear merits under some site circumstances, *e.g.* Herzig et al., 2014). Phytomanagement approaches allow the use of plant-based systems as a “holding strategy” (*i.e.* reducing contaminant transfer and site risk on vacant sites, while providing other benefits such as biomass generation, amenity and leisure, site value uplift of surroundings, urban climate management, ecosystem services etc., prior to development of favourable economic conditions for hard redevelopment or other site regeneration), or as part of a zoned, mixed site use, approach where GRO are applied (in combination with “hard” cover systems or conventional remediation technologies) on less contaminated areas within a site, which may better reflect site (and contaminant) heterogeneity (Neu and Müller 2014). The large potential for GRO incorporation into urban design and landscape architecture via wetlands, riparian buffers, stabilisation mats, air flow buffers, stormwater filters, interception hedgerows etc., has been extensively discussed in Kennen and Kirkwood (2015), while a number of European examples exist which show the potential for use of GRO in site “greening” and for realisation of wider site benefits as part of general site regeneration strategies (*e.g.* www.thelandtrust.org.uk). GRO design and successful application will however be strongly site and contaminant specific: *e.g.* for phytoextraction to be successful, metal(loid)s must be present in chemical forms/solubilities which plants can absorb and translocate to shoots. Conversely, phytostabilization requires that these metal(loid)s can be either converted to unavailable forms for plant uptake and remain retained in the soil matrix preventing leaching losses, or captured and retained in the root systems. Given this site and contaminant specificity, it is always recommended to implement and monitor field trials after the selection of feasible GRO before deploying the selected GRO at full implementation scale. The best conventional remediation option should also be compared in parallel to have an alternative in case of GRO failure or underperformance. GRO application may also require additional technical input from agronomists and plant specialists, institutional or planning controls to avoid shifts in land-use or land management, and a supportive local/regional regulatory framework (in cases where contaminants are stabilised in the ground, rather than removed (*e.g.* phytostabilization, *in-situ* immobilization/phytoexclusion) or where only the bioavailable contaminant fraction is removed (*e.g.* in phytoextraction)).

The GREENLAND best practice guidance and DST summarise conceptual site models and supporting data for a series of longer-term trial sites drawn from the GREENLAND network, which have shown effective risk management for different metal(loid) contaminants under contrasting site conditions. Such pilot-scale applications of effective GRO strategies (*i.e.* “success stories”) are key in providing robust technical and practical data for GRO implementation and in engendering confidence in stakeholders, both in terms of illustrating the long-term risk management potential of GRO but also in showing how wider economic, environmental and societal benefits can be realised. Pilot sites can also be pivotal in education and training as demonstrator sites, both for specialists (*e.g.* regulators, contaminated land consultants) and non-specialists. For example, the BIOGECO phytoremediation platform is a large Cu-contaminated wood preservation site located in the Gironde, SW France (and part of the GREENLAND site network) which has been used as a pilot site since 2006 for phytostabilisation, aided phytostabilisation (combining *in situ* stabilisation and phytostabilisation), (aided) phytoextraction, and PAH phytodegradation. The platform provides site training in

phytoremediation and risk assessment (and related topics) to University students and engineers, and is supported by the Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME) to act as a demonstrator site to train consultants and other stakeholders in effective GRO application. Other French pilot sites are included in the SAFIR network supported by ADEME (<http://www.safir-network.com/>)

5. Realisation of wider benefits.

A diverse range of wider benefits can be realised when applying phyto- and other GRO –based risk management strategies. For example, application of phytoremediation or use of soil amendments (as part of, or independently of, *in-situ* immobilisation and phytostabilisation applications) may generate “core” benefits or services in the form of risk mitigation of contaminated land and groundwater, but also other benefits such as soil improvement, water resource improvement, provision of green space, renewable energy and material generation, greenhouse gas mitigation, and amenity and economic assets. Table 3 draws on data from the GREENLAND project, and from the EU FP7 HOMBRE project (www.zerobrownfields.eu) to classify these wider benefits and give specific examples, drawn from field and pilot trial GRO sites, where these benefits have been evidenced. Examples are shown from sites contaminated with metal(loid)s or with other contaminants of concern. Many individual sites show multiple benefits. For example, the Betteshanger site is a former coal-mining site located in East Kent, southeast U.K., which was regenerated between 2002 and 2011 with financial support from UK national government (BBP Regeneration, 2008). Gentle remediation strategies applied at Betteshanger involved landscaping and green cover, and the construction of a Sustainable Urban Drainage System (SUDS) which incorporated reed beds for treatment of surface run-off and foul water from new and existing built developments. In addition to risk management and water resource protection benefits, the regenerated site provides economic and amenity assets, and enhances the local environment: the major Fowlmead Country Park on its former waste tip site includes provision for walking, cycling, horse-riding and wildlife observation, while the smaller former coal-mine site accommodates a local park and up to 35,000 m² of warehousing, industrial and office space (BBP Regeneration, 2008, Cundy et al., 2013). In Belgium, research at the Lommel site in the Campine region has targeted the repurposing of Cd and Zn-contaminated agricultural land for biomass and energy crops (using silage maize (*Zea mays*), rapeseed (*Brassica napus*), willow (*Salix spp.*) and poplar (*Populus spp.*), the latter two in short rotation coppice systems), rather than food crops (Meers et al., 2010; Ruttens et al., 2011; Witters et al., 2012, reviewed also in Kennen and Kirkwood, 2015). The soils in the region are characterized by a sandy texture and relatively low pH which gives an enhanced risk for uptake of these metals in crops and leaching to groundwater, resulting in food and fodder crops that often exceed European and Belgian legal threshold values for Cd in particular (Witters et al., 2012). By transitioning from food crops to biomass and energy species, the agricultural lands remain profitable to farmers (*i.e.* through renewable energy and materials generation and economic benefits), and contaminant linkages (*e.g.* soil – food pathways) are reduced, with long-term source remediation. Taking into account the marginal impact of the metals in the biomass on the energy conversion efficiency and on the potential use of the biomass and its residual (metal-enriched) products after conversion, clear carbon abatement benefits are seen with up to 14,000 kg CO₂ ha⁻¹ y⁻¹ net CO₂ avoidance for silage maize crops grown at the site (Witters et al, 2012).

GROs may be particularly valuable in combination with renewables generation (through biomass and biomaterials production but also through use with solar and wind power on brownfields or marginal land, USEPA, 2015; Gonsalvesh et al., in press) and with urban flood management strategies, providing rainfall interception, surface and groundwater flow management, soil erosion prevention and reduced impermeable surface area, which allows their effective integration with sustainable urban drainage (SUDS) strategies (e.g. Kennen and Kirkwood, 2015). “Greened” urban areas may also play an important role in reducing urban contaminant transfer to water bodies (e.g. recent studies in Manchester, U.K. indicate that zinc and hydrocarbon delivery to urban drainage systems could be reduced by expanding green infrastructure, Rothwell et al., 2015).

Although GROs may be seen as “green” or more environmentally-friendly remediation options, particularly by local stakeholders (e.g. Hesske et al., 1998; Glass 1999), they are not however automatically sustainable – the overall economic, environmental and societal benefits depend on local site circumstances (such as the need for irrigation, fertilizers, fencing, etc.), the presence of local conversion chains for the produced biomass, and the site design (e.g. a monoculture option vs. encouragement of a diverse site ecosystem, use of non-native or genetically modified species etc.). It is therefore important to identify and ideally quantify the full wider value that GRO strategies may provide, so that a balanced judgement of costs and benefits can be derived. A number of studies have proposed the use of GROs to trigger land regeneration in circumstances where the economic case for intervention is marginal due to their lower deployment cost (e.g. Vangronsveld et al., 2009; Kuppusamy et al., 2016^{a,b}) and, potentially, also by their linkage to other project services such as renewable material generation, public green space or amenity land provision, recovery of land values, etc. (e.g. Bardos et al., 2011; Andersson-Sköld et al., 2014). While some of the benefits from these services may be relatively readily quantified (e.g. economic return from biomass generation, uplift in surrounding land and housing values, and flood management value) others related to environmental and societal value may be much more difficult to monetise (e.g. Bardos et al., 2016). A number of recent studies have highlighted the potential health and societal benefits from urban parks and green space (e.g. Parks Victoria, 2015), which are highly compatible with GRO, and 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.

6. Concluding remarks.

Gentle remediation options (GROs) show clear potential for practical risk management at a range of site types, coupled with wider economic, environmental and societal benefits. The GREENLAND project decision support tool (DST) and best practice guidance have been designed to provide a context and technical support for GROs application (focussed on metal(loid)-contaminated sites), an overview of their current state of development, risk management capability, and potential wider (sustainability) benefits, quick reference guides, high-level GRO technical applicability guides, and details of convincing pilot GRO applications within Europe. The guidance can be used to support site planning, options appraisal, stakeholder engagement and consideration of initial design scenarios, and wider education of the potential risk management capacity and economic, environmental and societal benefits of GROs. The guidance, and the GREENLAND project more widely, promotes a

refocus from phytoremediation to phytomanagement-based approaches, which places realisation of wider benefits at the core of site design and where gentle remediation technologies can be used 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.

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Table and figure captions.

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).

Table 2: The GREENLAND site network of GRO pilot trials at metal(loid) contaminated sites in Europe.

Table 3: Examples of wider benefits from the use of GROs. Adapted and expanded from the HOMBRE project Brownfield Opportunity Matrix (BOM, <http://www.zerobrownfields.eu>), a qualitative MS Excel-based screening tool which identifies potential services from soft re-use land regeneration strategies, Bardos et al., (2016).

Figure 1: Example risk management strategy using GROs customised along contaminant linkages. Out-facing arrows link to illustrative wider environmental, economic and societal benefits that may be realised from GRO application. After Cundy et al., (2013) and www.greenland-project.eu. See Section 4 for discussion.

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 immobilisation 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.
<i>In situ</i> 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 <i>in situ</i> immobilization.

Table 2: The GREENLAND site network of GRO pilot trials at metal(loid) contaminated sites in Europe.

Location	Site type	Contaminants	GRO strategy	Plant species	Selected references
Austria	Agricultural soils	Cd, Pb, Zn (As, Cu)	<i>In situ</i> stabilisation / phytoexclusion	Crops (barley, maize)	Friessl et al., 2006; 2009
Belgium	Agricultural soils	Cd, Zn, Pb	Phytoextraction	Poplars, willows, maize, rapeseed, tobacco, sunflower, hemp	Meers et al., 2010; Ruttens et al., 2011; Witters et al., 2012; Janssen, 2015
France	Industrial soil in urban area	Cd, Zn, Pb	Phytoextraction	<i>Arabidopsis halleri</i> , willows	Bert et al., 2012a; Huguet et al., 2012
France	Dredged sediment landfill	Cd, Zn, Pb, As, Cu	Aided phytostabilisation	Tufted hair grass, willows	Bert et al., 2009, 2012a, 2012b
France	Industrial soils	Cu and Cu/PAHs	Phytoextraction; phytostabilisation and rhizodegradation	Sunflower, tobacco, sorghum, poplars, willows, grasses, vetiver	Bes and Mench, 2008; Cundy et al., 2013; Hattab et al., 2014, 2016
Germany	Agricultural soils	Cd, Zn, Pb	Phytoextraction; <i>in situ</i> stabilisation/phytoexclusion	Poplars, willows, crops, grassland	Dietzsch, 2011; Cundy et al., 2013
Poland	Post-industrial soils	Cd, Zn, Pb	<i>In situ</i> stabilisation / phytoexclusion	Grassland	Siebielec et al., 2006; Wójcik et al., 2014
Spain	Tailings	Cd, Zn	Phytoextraction	<i>Noccaea caerulea</i>	Becerra-Castro et al., 2012; Monterroso et al., 2014
Spain	Tailings	Cu	Phytostabilisation	Poplars, willows	Kidd et al., 2014; 2015
Sweden	Commercial sludge-amended fields	Cd, Zn (Cu, Ni, Cr, Pb)	Phytoextraction	Willows	Heinsoo and Dimitriou (2014); Dimitriou and Rutz (2015)
Switzerland	Agricultural soil on former landfill	Zn (with some Cd, Cr and Cu contamination)	Phytoextraction	Sunflower, tobacco	Herzig et al., 2008; 2009; 2014

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A. Phyto-Remediation

General benefit		Examples	Case Studies / citations
Risk Mitigation of Contaminated Land and Groundwater	Biosphere (including human health)	15 full scale project examples are listed on the CLU-IN website which highlight the effectiveness of phytoremediation for human health / ecological risk management. Oregon Poplar site, J-field at Aberdeen Proving Ground. Risk mitigation at trace element contaminated sites using different phytoremediation interventions.	www.clu-in.org/products/phyto/search/phyto_list.cfm EPA, 2015. Herzig et al., 2014; Friesl-Hanl et al., 2009; Hattab et al., 2014.
	Water Resources (hydrosphere)	15 full scale project examples are listed on the CLU-IN website, which show examples of the use of phytoremediation for water resource protection. Oregon Poplar site, J-field at Aberdeen Proving Ground. Risk mitigation at trace element contaminated sites using different phytoremediation interventions.	www.clu-in.org/products/phyto/search/phyto_list.cfm EPA, 2015. Herzig et al., 2014; Friesl-Hanl et al., 2009; Bert et al. 2012; Hattab et al., 2014, 2016; Janssen, 2015.
Soil Improvement	Fertility and soil structure	Maintenance or improvement in soil fertility and structure can occur directly through vegetation and rhizosphere development, or through amendment addition.	Herzig et al., 2014; Friesl-Hanl et al., 2009; Nsanganwimana et al., 2014; Hattab et al., 2014, 2016; Kidd et al., 2015; Evangelou et al., 2015.
Water Resource Improvement	Water resource efficiency and quality	Improvements in local water resources arising from phytoremediation application are illustrated by an integrated phytoremediation system at Murdock, Nebraska, USA. Phytoremediation-based water treatment systems in Sweden.	ANL, 2008; EPA, 2007. Dimitriou and Aronsson, 2005.
	Flood and capacity management	Potential of phytoremediation systems for hydraulic control. An integrated phytomanagement system at Murdock, Nebraska, USA illustrates how system design can be used to control infiltration and water residence time and decrease flood risk.	Pivetz, 2001. ANL, 2008.
	Rehabilitation of water	Rehabilitation of water opportunities are illustrated by an integrated phytoremediation system at Murdock, Nebraska, USA.	ANL, 2008.
		Potential for waste water treatment is illustrated by various rhizofiltration approaches. Phytoremediation-based water treatment systems in Sweden.	Pivetz, 2001. Dimitriou and Aronsson, 2005.

Provision of Green Space	Enhancing ecosystem services	<p>Potential for phytoremediation in enhancing ecosystem services is illustrated by the integrated phytoremediation treatment system at Murdock, Nebraska, USA, which utilises co-planting of trees for phytovolatilisation with native prairie grasses and wildflowers.</p> <p>Potential for phytoremediation in enhancing ecosystem services is illustrated by the vegetated landfill cover at the BASF Rensselaer Landfill, NY, USA, with phytoremediation planting designed to maximize ecological value, providing wildlife habitat.</p>	<p>ANL, 2008.</p> <p>Kennen and Kirkwood, 2015.</p>
	Enhancing local environment	<p>Potential for local environment enhancement is illustrated in Cundy et al., (2013) for the Betteshanger site, SE England, where GRO application was part of a regeneration initiative to develop a country park involving provision for walking, cycling, horse-riding and wildlife observation.</p>	<p>Cundy et al., 2013; GREENLAND.</p>
Mitigation of Human Induced Climate Change (global warming)	Renewable energy generation	<p>A number of projects and field applications have shown the potential of phytoremediation to generate usable biomass.</p>	<p>Delplanque et al., 2013; Van Slycken et al., 2013b; Cundy et al., 2013; Marchand et al., 2015; GREENLAND.</p>
	Renewable material generation	<p>Usable biomass production from phytoremediation approaches is shown in the listed case studies.</p> <p>Usable biomass production from phytoremediation for metal recovery with biomass reuse.</p>	<p>Delplanque et al., 2013; Witters et al., 2012; Cundy et al., 2013; Gonsalvesh et al., 2016; GREENLAND.</p> <p>Anderson et al., 1999; Escande et al., 2015.</p>
	Greenhouse gas mitigation	<p>Carbon abatement potential for a willow, maize and rapeseed-planted phytoremediation site at Lommel, Belgium.</p>	<p>Witters et al., 2012.</p>
Socio-Economic Benefits	Amenity	<p>Potential for amenity provision is illustrated in Cundy et al., (2013) for the Betteshanger site, SE England, where GRO application was part of a regeneration initiative to develop a country park involving provision for walking, cycling, horse-riding and wildlife observation.</p>	<p>Cundy et al., 2013; GREENLAND.</p>
		<p>Potential for amenity provision is illustrated by the vegetated landfill cover at the BASF Rensselaer Landfill, NY, USA, which contains an environmental education centre, walking trails and an amphitheatre.</p>	<p>Kennen and Kirkwood, 2015.</p>

	Economic assets	Economic development opportunities are illustrated in Cundy et al., (2013) for the Betteshanger site, SE England, where GRO application was part of a regeneration initiative to develop a country park involving provision for walking, cycling, horse-riding and wildlife observation. Use of biomass options to leverage re-use of economically marginal land is evaluated by the REJUVENATE project.	Cundy et al., 2013; GREENLAND. Andersson-Sköld et al., 2013.
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B. Amendment Addition

General benefit		Examples	Case Studies / citations
Risk Mitigation of Contaminated Land and Groundwater	Biosphere (including human health)	A number of studies examine the effects of compost on contaminant bioavailability. Risk mitigation using carbon amendments (activated carbon, bone char and biochar), which impact the bioavailability of contaminants in soils. The effectiveness of several amendments (limestone, red mud, and furnace slag) on availability of metal(loid)s, microbial activities, and phytoavailability of soil metals is evaluated.	CL:AIRE 2008; Tandy et al., 2008. Denyes et al., 2013; Chen et al., 2006; Jones et al., 2016. Lee et al., 2009; Gray et al., 2006; Marschner et al., 2010, 2011; Bert et al., 2012 ^b .
	Water Resources (hydrosphere)	The effectiveness of three different brownfield soils amended with green waste compost or biochar is examined in the context of increasing dissolved carbon concentrations in soil pore water and reducing As leaching to groundwater. The effects of a range of biochar products and chars amendment on heavy metal immobilization are examined with respect to water resource protection.	Hartley et al., 2009. Uchimiy et al., 2010 ; HOMBRE, 2014; Yang et al., 2016.
Soil Improvement	Fertility	A range of amendments such as lime, furnace slag, compost and red mud are applied at contaminated sites to generate improvements in soil fertility.	Lord et al., 2010; Gandolfi et al., 2010; Lee et al., 2009; Bert et al. 2012 ^b ; Dadrasnia and Agamuthu, 2013; Lagomarsino et al., 2011; Xiong et al., 2015; WRAP (various refs); Jones et al., 2016.
	Soil Structure	Composted organic wastes are applied to improve soil structure and plant biomass yield. Compost can function as, e.g., soil conditioner, topsoil improver and mulch to improve plant growth and support soft re-use of sites.	Lord et al., 2010; CL:AIRE, 2008; TWIRLS. WRAP, 2012; ECL and CL:AIRE, 2006.
Water Resource Improvement	Water resource efficiency and quality	The effectiveness of biochar as a sorbent in removing metal(loid)s (Pb, Cd, Cu, Zn, As) and U(VI) from groundwater and aqueous solutions is tested in various case studies.	Hartley et al., 2009; Kumar, 2011; Xu et al., 2013; Liang et al., 2014.

Provision of Green Space	Enhancing ecosystem services	Services provided by green space and soft re-use strategies involving amendment addition (such as wildlife habitat protection, regional trail links and renewable energy production) are outlined.	LfULG, 2008; Lord, 2010; USEPA, 2010.
	Enhancing local environment	Rehabilitated sites (open spaces, parks, woodland and wildlife habitat) generate a range of enhancements including amenity trails, air quality and water quality improvement.	LRUG; USEPA, 2010.
Mitigation of Human Induced Climate Change (global warming)	Renewable energy generation	Generation of energy crops (sunflower, <i>miscanthus</i> and SRC willow) and renewable materials on brownfield land following amendment-based strategies.	ECL and CL:AIRE, 2006; WRAP, 2007; Hartley et al., 2009; Kolbas et al., 2011; Qantas et al., 2013; HOMBRE, 2014.
	Renewable material generation	Promoting material use and reusing waste are considered as environmental indicators of sustainability in a Cluster project.	CL:AIRE, 2012.
	Greenhouse gas mitigation	Carbon storage and sequestration benefits are determined following soil amendment with green waste compost and biochar.	Beesley, 2012; HOMBRE, 2014.
Socio-Economic Benefits	Amenity	Potential for amenity provision along with other benefits by plant growth or woodland are examined at various sites. Four cases are summarized to show that compost can help to restore wetlands, forests and revitalize habitats by providing an excellent growing medium for young seedlings.	Palmer and Davies, 2008; HOMBRE, 2013; LRUG. USEPA and SWER, 1997.
	Economic assets	The possibility of income generation, employment opportunities and other economic return in land regeneration are qualified in several case studies.	Paulson et al., 2003; Wilczek, 2004; WRAP, 2009; LRUG.

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