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Enhancing ecosystem services at urban brownfield sites – what value does contaminated soil have in the built environment?

P Drenning*[1,2], J Norrman[1], S Chowdhury[1], L Rosén[1], Y Volchko[1] and Y Andersson-Sköld[1,3]

[1]Department of Architecture and Civil Engineering, Chalmers University of Technology, 41296 Gothenburg, Sweden
[2]Water & Environment West, COWI AB, 41458 Gothenburg, Sweden
[3]National Road and Transport Research Institute, VTI, 58195 Linköping, Sweden
*Author to whom correspondence should be addressed: drenning@chalmers.se

Urban environments are challenged with a plethora of wicked problems in the face of rapid urbanization and land use change, not least natural capital degradation and widespread land and water contamination. Brownfields, under-used sites with real or perceived contamination, are significant urban and peri-urban land resources which, with well-designed remediation and management strategies can address these concerns. Gentle remediation options (GRO) are scalable nature-based techniques which provide significant opportunities for multi-functionality: managing risks posed by contaminants and at the same time enhance ecosystem services (ES) by improving the soil ecosystem in a low-impact, cost-effective manner. GRO align with an increasing interest in taking a holistic view on soil and land management to protect and improve the soil ecosystem for direct human benefit in the form of ES as well as for its indirect, intrinsic value as a haven for biodiversity. This short review aims to present a synthesis of ideas to raise awareness for urban planners about GRO techniques as nature-based solutions which can promote green infrastructure in the urban environment.

1. Introduction

1.1. *Remediation of today*

In Europe, there are more than 2.5 million potentially contaminated sites caused by anthropogenic activity, of which approximately 85 000 are in Sweden [1]. Brownfields are typically defined as underused or derelict areas with, in many cases, real or perceived, soil and groundwater pollution that require intervention to bring them back into beneficial use [2]. These sites often face a barrier to redevelopment due to investment risks, ownership constraints, risk of future liability claims and public stigma [3]. Global perceptions, regulations, policies and challenges associated with brownfields differ depending local context; however, market and exploitation pressures and stakeholders' perception of uncertainties in time, costs, efficiency of alternative remediation options, and future liabilities have a crucial impact on the selection of treatment solutions at contaminated sites regardless of location [4]. Commonly today, contaminated masses are excavated and landfilled due to time constraints, low disposal fees and well-established effectiveness in removing the source of the contamination, which is readily accepted by regulatory authorities [4]. Perhaps most importantly, this quick conventional method is feasible for rapid redevelopment in urban areas with high land value. However, excavation entails many disadvantages, including the negative effects caused by transportation (use of fossil fuels, emissions and accident risks), use of virgin material for refilling at the sites, the production of nonrecyclable waste for landfilling as well as significant economic and social costs [5,6]. In general, conventional remediation techniques like excavation, where soil is viewed as a disposable waste, are often resource intensive and entail multiple environmental externalities. In addition, it often destroys the soil ecosystem thus making it unfit for 'soft' end uses like green spaces, which require ecological functioning [7–9]. There is an international consensus on promoting increased use of alternative, more sustainable remediation methods [5–7,10–13]. Indeed, new practices are crucial, because a significant amount of brownfield land area remains derelict or underutilized due to restoration being uneconomic or unsustainable using conventional methods [11]. This problem is of particular concern for larger land areas or smaller, marginal sites where contamination inhibits immediate development, but economic return post-remediation does not justify the costs [11]. Alternative methods should ideally enable soft land uses by incorporating alternative low-cost, low-impact in situ remedial measures which may be viable to manage low and moderate risks posed by contaminants to human health and the environment while providing societal benefits and improving soil quality [11,14,15]. A promising field of innovative remediation technologies which have received much attention in recent years are those involving amendment-, plant- (phyto-), fungi- (myco-) and/or bacteria- (bio-) based methods, i.e. gentle remediation options (GRO). This review aims to discuss the potential of GROs as an alternative remediation strategy in urban environments to mitigate the abovementioned problems and improve human well-being by restoring soil functioning.

1.2. Soil as a resource

A series of agenda-setting reports by the European commission (e.g. Vision for a Resource Efficient Europe, European Biodiversity Strategy to 2020) have raised awareness of the widespread degradation of soil ecosystems by over-exploitation, land-use change, contamination, sealing, compaction, erosion, neglect, etc. [16–18]. These stressors have led to rapid losses in biodiversity and diminished total provided ecosystem services (ES), defined as *the direct and indirect contributions of ecosystems to human well-being* [19], by approximately 60% worldwide in the past 50 years alone. Urgent action is mandated by the European Commission and United Nations to curb the loss of biodiversity, resource degradation, and land take by transitioning to a more sustainable development pattern where soil and land are viewed as a resource. Soil and its functions have been raised to a position of critical importance for our common future through the (currently revisited) *Thematic Strategy on Soil Protection* [18]. From this report, seven essential soil functions have been established: (i) biomass production, including agriculture and forestry; (ii) storing, filtering and transforming nutrients, substances and water; (iii) biodiversity pool, such as habitats, species and genes: (iv) physical and cultural environment for humans and human activities; (v) source of raw materials; (vi) acting as a carbon pool; (vii) archive of geological and archaeological heritage. Soil functions are here defined as *what the soil has the capability to do in its natural (undisturbed) state as a result of the (bundles of) soil processes (e.g. soil formation, nutrient cycling, etc.) arising out of the complex interaction between biotic and abiotic components in the soil environment* [20,21]. Soil functions thus can be viewed as a subset of wider ecosystem functions which underpin the delivery of ecosystem services [20,21]. *Soil quality* is another key concept when discussing restoration. Soil quality has an agreed upon definition broadly meaning *the capacity of a soil to perform its functions necessary for its intended end use* [22]. This inherently anthropocentric term has alternatively been defined to include soil functioning 'within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health' [23]. This expanded definition reflects more the concept of 'soil health', in terms of ecological functioning while under productive use and supports the multi-functionality of soils [21].

1.3. Alignment with international goals – connecting to the SDGs

The concept proposed in this review (as well as the larger ongoing project) of utilising GRO for brownfield remediation and soil restoration to enhance SF and ES primarily supports achieving four of the declared UN Sustainable Development Goals (SDGs) within the context of the built environment: 15 – Life on land, 13 – Climate action , and 11 – Sustainable cities and communities.

- **SDG 15**: Many ecosystem services and soil functions are connected to this goal, e.g. nutrient cycling, habitat provisioning, biodiversity, and biomass production. Utilising GRO supports the rehabilitation of ecological soil functions, making soils more resilient and increasing the provision of ecosystem services in areas where those currently are low due to contamination or other forms of degradation. Increased provision of ES can further contribute to human wellbeing and social sustainability. Improving biodiversity is a key theme of this goal since soil is a major reservoir of the Earth's total biodiversity, which underpins ecosystem functioning, as is reflected in the milestones established in the EU Biodiversity Strategy [17].
- **SDG 13**: The soil function of carbon sequestration directly contributes to the climate targets to mitigate carbon emissions. Soil has the capability to sequester large amounts of carbon if well-managed. This storage potential will be instrumental in the achieving the 4‰ annual growth rate of the soil carbon stock to halt atmospheric CO2 increases established at COP 21 of the UNFCCC. Furthermore, GRO can be included in cities as green infrastructure that can increase the resilience of cities for adapting to climate-related hazards like erosion and flooding due to soil's innate capacity to regulate water.
- **SDG 11**: The ES concept as a part of land use planning can promote the consideration of soil aspects in early planning phases and by doing so, support more informed and sustainable management of brownfields and the surroundings. Also, GRO as a nature-based solution can be designed for accessibility as a greenspace, which provides ES like local climate regulation, with due consideration to the risks posed by potential contamination.

Soil science and management is essential in achieving the SDGs as many of them have a strong connection to land and water management [24]. Keesstra et al. [24] link specific soil functions and ecosystem services to the SDGs that ultimately call for sustainable use of resources, ecosystem restoration, biodiversity, carbon sequestration, and sustainable catchment management for which enhanced ecosystem services are essential to realize [24,25]. Furthermore, a shift from predominantly grey, 'hard' built infrastructure to 'soft' nature-based solutions [25] or green infrastructure [26], terms used to stress the multi-functionality offered by green spaces and natural processes, is essential to meet the abovementioned goals [7,27,28].

2. Method

This review paper is intended to specifically raise the question of *'What value does contaminated soil have in the built environment?'* The aim is to elucidate the potential value brownfields offer in urban environments as a resource for meeting environmental goals that can be leveraged by considering alternative land management strategies using innovative techniques. In the following sections, this paper presents a brief compilation of best practices and ideas utilising GROs, with references to other reviews for further reading, that can be taken into consideration during the early phases of urban planning to enable green infrastructure. The main points of discussion include: 1) reviewing the potential of GRO to manage risks posed by contaminants via degradation, extraction and stabilisation mechanisms, 2) reviewing the added value of GRO in providing a range of wider benefits to enhance ES and SF, including how these strategies can promote green infrastructure for sustainable living environments, 3) comparing to conventional remediation techniques, and 4) showing how applying GROs intersects with urban planning and design.

3. Results

3.1. Gentle remediation options

GRO 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* [11,29]. The most common of these techniques is plant-based phytoremediation; however, the term includes also fungal and microbial-based methods, with or without chemical additives or soil amendments [11,29,30]. Monitored natural attenuation (i.e. long-term self-cleaning via natural processes) could also technically be included within GRO [29], but it will be not be covered in this review. In terms of technical applicability for risk management, GROs are primarily applied on contaminated soils to reduce contaminant transfer to local receptors by removing the bioavailable pool of inorganic contaminants (*phytoextraction*), removing or degrading organic contaminants (*phyto- and rhizodegradation*), filtering contaminants from water (*rhizofiltration*), and stabilising or immobilising contaminants in the soil matrix (*phytostabilisation, in-situ immobilization or phytoexclusion*), see Table 1. The degradation, extraction and stabilisation mechanisms will be briefly discussed in this review; however, for more technical reviews the reader is referred to previously conducted reviews and research [9,11,31,32] and best practice guides for implementation [30,33–35].

Table 1. List of definitions for GROs used to remediate soils contaminated by either trace elements or mixed contamination, summarized from Greenland [30].

GRO	Definition
Phytoextraction	The removal of metal(loids) or organics from soils by accumulating them in the harvestable biomass of plants.
Phytodegradation/ phytotransformation	The use of plants (and associated microorganisms like endophytic bacteria) to uptake, store and degrade pollutants.
Rhizodegradation	The use of plants and rhizospheric (in root zone) microorganisms to degrade organic pollutants.
Rhizofiltration	The removal of pollutants from aqueous sources by plant roots and associated microorganisms.
Phytostabilisation	Reduction in the bioavailability of pollutants by immobilisation in root systems and/or living dead biomass in the rhizosphere soil.
Phytovolatilisation	The use of plants to remove pollutants from the growth matrix, transform them to less toxic forms and disperse them (or their degradation products) into the atmosphere.
In-situ immobilisation/ phytoexclusion	Reduction in the bioavailability of pollutants by immobilisation or binding them to the soil matrix through the incorporation into the soil of organic or inorganic compounds to prevent excessive uptake of contaminants.

3.1.1. *Degradation.* Breaking down organic contaminants into carbon dioxide, water, microbial biomass, bioenergy and/or less harmful by-products via endophytic and rhizospheric bacteria has seen definitive success in multiple studies and is one of the most promising areas for applying GRO as a remediation strategy [9,31,32]. The key to effective degradation is the presence of biologically active microorganisms, though microorganisms are potentially impaired by contaminants and poor soil quality. Plants themselves enable microbial activity by supplying oxygen, water and a variety of rhizodeposits (i.e. residual photosynthesis products like sugars) into the root zone that are critical for a rich microbial life as well as inducing breakdown of organic compounds by bacteria [32,34,36]. Two promising strategies to improve the effectiveness of organic degradation can be broadly classified into those based on *biostimulation* (improving the existing microbiome using additives) and/or *bioaugmentation* (introducing external microbes which may be better suited for degrading specific contaminants) to promote plant growth and tolerance and increase degradation rates [31,32,34].

3.1.2. *Extraction.* Extraction is the primary mechanism for managing inorganic contaminants (e.g. metals), and phytoextraction is arguably the most well-known and thoroughly tested GRO technique. Typically, hyperaccumulator plants (those that can store an inordinate amount of metals in their tissue) and fast-growing, high biomass producing plants would be used as 'bio-pumps' to take up metals from the soil and store in their biomass [37]. The plants would then be harvested and processed by e.g. incineration, landfilling, etc. to eventually reduce concentrations to acceptable thresholds after successive cropping [36,37]. However, due to several failures to perform as expected [11,35], the exceedingly long timeframe required [38] and other significant obstacles phytoextraction has seen limited full-scale application [39]. Phytoextraction with the narrow focus of exclusively taking up metals as a stand-alone technology may indeed rarely be suitable for strictly remediation purposes [36,38]. However, alternate extraction strategies like *soil polishing* (reducing marginally elevated

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concentrations to threshold levels) or *bioavailable contaminant stripping* (reducing the soluble, plant-available fraction of metals thereby reducing environmental risk) are viable niche-solutions which could be more widely applicable at various scales [36,38–40]. A promising new direction in this field is the development of *phytomanagement* as a long-term land management strategy that incorporates such techniques as phytoextraction and stabilisation to maximise the wider benefits offered by GRO like provisioning ecosystem services [9,11,30,40].

3.1.3. *Stabilisation.* Stabilisation mechanisms to decrease mobility and bioavailability of contaminants with (i.e. 'aided') or without amendments is promising both as a stopgap remediation strategy and for enabling synergies to garner wider benefits at a site as in phytomanagement. For example, the *Rejuvenate project* [41] was created to develop a methodology for designing and implementing profitable biomass production on marginal land while effectively managing risks by stabilising the contaminants using plants. These 'crop-based' systems for risk-based land management have successfully demonstrated the benefits of vegetation-, energy crop-, or generally nature-based solutions for both managing risks and providing wider value at contaminated sites including ES provisioning [14,15,30]. Stabilisation, rather than uptake of contaminants, is well-suited to this type of strategy where the future usage and economic return of the produced biomass can be dependent upon contaminant concentrations in the various plant tissue [41].

3.2. Comparison to conventional techniques
Potentially, several low- and moderate-risk contaminated sites can be treated within a budget for excavation and disposal of one high-risk site, increasing the overall remediation progress at national level in the long-run. GROs are low-cost, low-impact in situ remediation technologies which could be stand-alone or a part of treatment trains (i.e. combined with conventional techniques like when excavations are unavoidable because of hotspots or construction of foundations) and are estimated to cost at least 50% less than excavation in total [9,31,32,42]. A few life cycle assessments (LCA) have been performed to evaluate GRO (often phytoremediation with productive biomass use) as a standalone technology or in comparison with excavation. The studies show that GROs are indeed low-cost, low-impact solutions with a small or even positive environmental footprint [43] that also offer substantial socio-economic benefits like an attractive landscape and resilience to climate change impacts (e.g. sea level rise) [44], profitable and sustainable bioenergy production provided the biomass is valorised as a product and not as a waste [45], and marginal carbon abatement costs of between €55-501/ha when used as biomass for renewable energy [46]. For further reference on cost estimates and comparison with other technologies, see [34,35].

3.3. Accounting for soil functions and ecosystem services
Integrating key concepts of soil science like soil quality, soil functions, and soil parameters into contaminated site investigation and management is a significant step in the right direction towards sustainable soil and land management. By using such tools as the Soil Function Box tool [47], accounting for soil parameters in addition to contamination levels will enable soil being managed in accordance with the soil's capability to its best condition [48]. Means of enhancing SF and ES are many and varied, but much research interest has focused on the set of land and soil management strategies included under the umbrella term of nature-based solutions (NBS), e.g. [25]. A growing body of research has shown that GRO, often included within NBS, can provide both effective risk management and result in a net gain in ecological soil function at contaminated sites [11,31,32,49]. Many researchers argue that it is exactly these wider benefits offered by GRO, as shown in the *Brownfield Opportunity Matrix* [7,50], that should lie at the core of site design and will provide added value [11,50]. Also, the ultimate goal must be not only to manage the contamination but also to restore soil health, functioning and thus delivery of ES [51]. Therefore, the restoration of soil to provide ecosystem services should be a central feature in evaluating the success of any GRO endeavour. For doing such an evaluation at micro-scale, a series of 'bio-indicators' have been created to measure

microbial health linking directly to soil functioning (thus ecosystem services) to directly measure the improvement in soil health that can result from GRO [22,52]. Taking a different approach, as part of the *Balance 4P* project [53] an 'ecosystem services mapping' method was developed for decision-support in selecting remediation techniques. By applying a semi-quantitative approach (i.e. evaluating on a point scale between 1-5 using indicators), the changes in ecosystem services resulting from various remediation alternatives could be evaluated [54]. The value in this method is that it brings urban and soil ES, to the forefront of the decision-making process in a clear, scalable way by providing indicators (or proxy indicators) for quantifying and evaluating the expected change in the services for each alternative (Table 2). For a more recent application and evaluation of the ES mapping methodology paired with cost-benefit analysis as part of the *Applicera* project for improving ecological risk assessment in Sweden, see [55].

Table 2. Urban and soil ecosystem services, adapted from [54].

Type	Category	Ecosystem Service
Urban	Provisioning	Food, fresh water
	Regulatory	air quality, climate (global), climate (local), water, noise reduction, water purification and waste treatment, pollination and seed dispersal, maintaining nursery populations and habitats, natural hazard regulation
	Cultural	Knowledge systems, aesthetic values, cultural heritage, recreation
Soil	Provisioning	Food, biomass
	Regulatory	Water purification, climate regulation (global), water regulation, erosion regulation, waste treatment

3.4. *Intersection with urban planning*

As brownfields are primarily located in urban areas, they have the potential to be considered as opportunities for further development in dense urban areas [56]. Since they are numerous and possess the potential threat of contamination, efficient strategies such as screening processes will enable planners to better integrate brownfields in urban land management process and leverage this important land resource. More holistic approaches, e.g. [7,53], to brownfield redevelopment consider sustainability, soil and groundwater quality and are better implemented in the early phases of a redevelopment project. There are numerous ways to improve integration of the sustainable soil perspective into urban planning, e.g. the hierarchical approach for 'planner-oriented' soil functions suggested by Lehmann et al. [57], but a prerequisite is to plan according to a 'longer time-horizon' to allow for more proactive remediation [3]. In general, a longer time-horizon would enable alternative land management and remediation approaches other than the typical quick and intensive remediation solutions which are dominant today. Pairing such strategies with brownfields characterisation processes, e.g. by market land value [2] and/or according to time and level of intervention required for future green land use [58], would ensure that more sustainable solutions are not excluded due to time shortages and redevelopment urgency in later stages. Also, brownfields could be screened far in advance of the planned redevelopment to identify sites amenable to GRO or determine GRO feasibility at a particular site. Examples of screening criteria which do not favour traditional remediation, but may be suitable for GRO, include [11,29,30]:

- Where there are budgetary and deployment constraints (e.g. large areas with diffuse contamination not causing immediate concern such as abandoned rail tracks);
- Where biological functioning is desired post remediation (e.g. greenspaces, bioswale);
- Where ecosystem services are highly valued (e.g. riverbank greens, urban wilderness);
- Where there is a need to restore land and a potential to produce non-food crops (e.g. for biofuels);

Typically, these constraints describe a site where a 'soft' end use is envisaged [30], which are well-suited for provisioning greenspace, green infrastructure, or other similar land uses which require a functioning soil ecosystem [7,50]. This kind of land use can be readily incorporated into urban design and landscape architecture either on a long-term basis as a 'self-funding land management regime' [59] or as an interim 'holding strategy' at vacant sites [11]. Also, landscape design strategies incorporating GRO, 'phytotypologies', have been extensively covered from a landscape architecture perspective [35].

4. Conclusion

- Brownfield sites present a significant opportunity for exploiting the latent potential of soil and land resources in and around cities to meet national and international environmental goals, including Sustainable Development Goals 11, 13 and 15.
- Given land shortages, increased demand for land resources, the EU no net land take goal, and the challenge of climate change, brownfield sites form an important resource for urban development and should be viewed as a societal resource.
- In suitable situations, well-designed GRO-based remediation strategies have the potential to play a significant role in long-term, holistic management and decontamination of brownfield land as well as promoting green infrastructure to restore soil functioning and enhance ecosystem services.
- GRO are highly applicable for large land areas and peri-urban areas which tend to not be economically beneficial for 'hard' redevelopment and lie abandoned as traditional remediation techniques are unreasonably expensive or undesirable. GRO's inherent multi-functionality can be utilised to manage the risks posed by contaminants, provision ecosystem services as well as serve as long- or short-term land management strategies for proactively restoring brownfield sites to productive 'soft' use or in expectation of future redevelopment.

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