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A risk management framework for Gentle Remediation Options (GRO)

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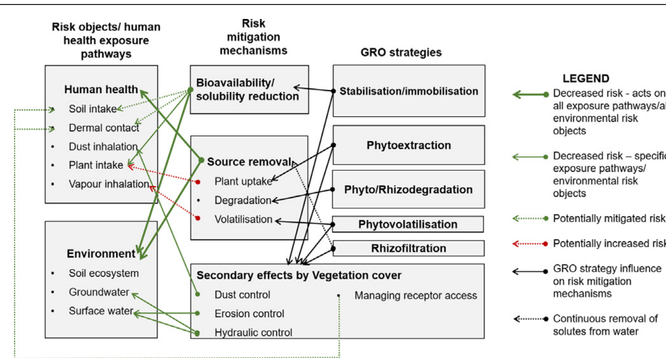
HIGHLIGHTS

- An early-stage risk management and communication framework for GRO is proposed.
- GRO risk reducing mechanisms are supported by scientific literature.
- Relative risk reduction times are estimated from literature review.
- The framework is demonstrated for a case study site to achieve green land uses.
- The framework supports identification of GRO and phytomanagement strategies.

GRAPHICAL ABSTRACT



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ABSTRACT

Gentle Remediation Options (GRO) are remediation measures involving plants, fungi, bacteria, and soil amendments that can be applied to manage risks at contaminated sites. Several studies and decision-support tools promote the wider range of benefits provided by GRO, but there is still skepticism regarding GRO implementation. Key issues that need to be better communicated are the various risk mitigation mechanisms, the required risk reduction for an envisioned land use, and the time perspective associated with the risk mitigation mechanisms. To increase the viability and acceptance of GRO, the phytomanagement approach implies the combination of GRO with beneficial green land use, gradually reducing risks and restoring ecosystem services. To strengthen the decision basis for GRO implementation in practice, this paper proposes a framework for risk management and communication of GRO applications to support phytomanagement strategies at contaminated sites. The mapping of the risk mitigation mechanisms is done by an extensive literature review and the Swedish national soil guideline value model is used to derive the most relevant human health exposure pathways and ecological risks for generic green land use scenarios. Results indicate that most of the expected risk mitigation mechanisms are supported by literature, but that knowledge gaps still exist. The framework is demonstrated to support the identification of GRO options for the case study site given two envisioned land uses: biofuel park and allotment garden. A more easily understandable risk management framework, as proposed here, is expected to act as a communication tool to educate decision-makers, regulatory bodies and other stakeholders for better understanding of risk mitigation mechanisms and preliminary timeframes of various GRO, particularly in the early stages of a brownfield redevelopment project.

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1. Introduction

Soil contamination (used as synonymous to pollution) due to human activity is a widespread phenomenon with serious implications for human health and environmental degradation. In Western Europe alone, there are more than 2.5 million potentially contaminated sites (Panagos et al., 2013; Swartjes, 2011). For human health and ecological risks to occur, the source-pathway-receptor linkages must be unbroken and adverse effects arise at the specific receptor (i.e. humans or living organisms in terrestrial and aquatic ecosystems). Risk reduction measures therefore entail breaking these contaminant linkages either by removing or modifying the source of contamination, interrupting the pathway or managing the receptor to reduce the risk, or the probability of occurrence, of unacceptable harm (Bardos et al., 2020; Cundy et al., 2016; Swartjes, 2011). Conventional soil remediation techniques are those that utilise physical, chemical, biological or a combination of methods to, most often, address the source of contamination ex-situ (entailing soil excavation and subsequent treatment on- or off-site via soil washing, thermal treatment, etc.) or in-situ to degrade, transform, extract or stabilise (in)organic contaminants at the site or utilise barriers like clay liners and permeable reactive barriers to isolate the site from its surroundings (Kuppusamy et al., 2016b, 2016a; Swartjes, 2011). Remediation is not intrinsically sustainable (Bardos et al., 2020; Cundy et al., 2016), and a common issue with many remediation techniques, especially ex-situ measures but also some in-situ techniques, is that they can have negative impacts including serious degradation or even elimination of the soil ecosystem and its essential functions (FAO et al., 2020; Gerhardt et al., 2017; Swartjes, 2011). In Sweden, remediation by soil excavation and landfilling ('dig-and-dump') or ex-situ treatment is the most commonly used method in practice since it is fast and effective for source removal, thereby gaining regulatory approval, but is often the result of oversimplified, generic risk assessments coupled with conservatively applied legislative guidelines (SEPA, 2018; SGI, 2018). There is, however, a recognized need for innovation and development, with fully 78% of practitioners in Sweden indicating a large need, of alternative remediation methods to prevent such 'over-remediation' and overuse of dig-and-dump (SEPA, 2018; SGI, 2018).Excavation is highly energy-intensive, costly and frequently fails to consider the irreversible damage removing soil layers can do to the environment, which calls into question its necessity, particularly if remediation is triggered due to unacceptable ecological risks and may be more damaging than the contaminants themselves (FAO et al., 2020; Swartjes, 2011). As a result, contaminated soil has long been viewed as waste to be disposed of rather than as a valuable resource to be treated and reused (Gerhardt et al., 2017; Mench et al., 2010). "Green" alternatives to conventional soil remediation are Gentle Remediation Options (GRO), which are in-situ remediation measures that utilise plants, fungi, bacteria, and soil amendments to break contaminant linkages while also improving or maintaining soil functions. While they may not be well-suited to highly contaminated sites, 'hotspots' or point source terms such as buried tanks or oil spills, GRO are particularly suitable for contaminated sites that pose low to medium risks to human health and the environment (Andersson-Sköld et al., 2014; Cundy et al., 2016; Enell et al., 2016; GREENLAND, 2014a).

Despite the progress made in successful GRO field application (e.g., Burges et al., 2020; Cundy et al., 2020; GREENLAND, 2014a; Herzig et al., 2014; Mench et al., 2018; Quintela-Sabarís et al., 2017), many regulators are still hesitant towards their application as current policies set remediation targets based on total contaminant removal or destruction, rather than risk reduction to acceptable levels (Swartjes, 2011). The inherent uncertainties and long timeframe potentially required for GRO to achieve such remediation targets pose challenges to their widespread adoption (Cundy et al., 2016). The often-conservative target-based risk assessments may lead to over-designed, invasive, and unnecessary risk management solutions that entail large costs to society (Cundy et al., 2016; GREENLAND, 2014a). Sustainable remediation and 'risk-based land management' (RBLM) have come to the fore in recent years to develop a new paradigm for sustainably managing contaminated land by focusing on efficient risk reduction with minimal adverse effects instead of burdensome complete risk removal (Bardos et al., 2011, 2018, 2020; Swartjes, 2011). Low-input remediation measures like GRO align well with the aims of sustainable remediation and risk-based based land management (SRBLM) (Bardos et al., 2020), which can then be integrated into a more comprehensive 'phytomanagement' approach. Phytomanagement is defined as the long-term combination of GRO with beneficial land use (e.g. profitable crop production but also wider economic and environmental benefits) gradually reducing risks posed by contaminants and restoring ecosystem services (Burges et al., 2018; Cundy et al., 2016; Gerhardt et al., 2017; GREENLAND, 2014a; Robinson et al., 2009). Production of valuable biomass is considered essential for a commercial success of phytomanagement, which can even become a profitable, self-funding land management regime (Andersson-Sköld et al., 2014; Conesa et al., 2012; Cundy et al., 2016; Evangelou et al., 2012; Garbisu et al., 2020; Witters et al., 2012) Additionally, as a nature-based solution, phytomanagement has the potential to be incorporated into urban planning and landscaping as the process of revegetating a contaminated site can result in open green space that can provide numerous benefits, particularly in urban environments (Chowdhury et al., 2020; Kennen and Kirkwood, 2015; Song et al., 2019).

The wider sets of benefits provided by GRO can be captured and communicated by several decision-support tools (DST) for sustainability assessments of remediation alternatives, see e.g. (Beames et al., 2014; Brinkhoff, 2011; Cappuyns, 2016; Huysegoms and Cappuyns, 2017; Norrman et al., 2020; Rosén et al., 2015; Volchko et al., 2014a). Existing tools or methodologies that can support decision-makers on the practical application of GRO are e.g.: the phytoremediation tool for plant selection using fuzzy logic and GIS (Porter et al., 2006); the Rejuvenate DST for RBLM and biomass selection on marginal land (Andersson-Sköld et al., 2014); the Greenland DST for GRO options appraisal (Cundy et al., 2015); the Brownfield Opportunity Matrix to identify benefits gained from soft reuse (Bardos et al., 2016); and a code of good practice on phytoremediation (OVAM, 2019). However, these tools do not answer some of the key issues responsible for the skepticism towards GRO; in particular, communicating the different risk mitigation mechanisms attributable to GRO and time horizons needed for required risk reduction. To our knowledge, there is no study that clearly identifies and compiles the possible risk mitigation mechanisms for GRO and helps to identify suitable GRO given an envisioned land use.

The overall aim of this study was to develop a framework that can be used in the early stages of a brownfield redevelopment project to support remediation contractors, decision-makers, regulatory bodies and other stakeholders related to contaminated sites in identifying and communicating: 1) relevant GRO strategies, including phytomanagement strategies that can manage human health and ecological risks and achieve an envisioned land use, and 2) the preliminary timeframe for achieving a required risk reduction. Specific objectives were to: i) identify and find support for relevant risk mitigation mechanisms for GRO strategies; ii) identify timeframes for risk mitigation mechanisms for groups of contaminants; iii) analyse critical risks (human health exposure pathways and environmental risk objects) for different generic land uses and contaminants; iv) illustrate the risk management framework in a generic diagram, and v) demonstrate its use by application in a case study.

2. Theory

2.1. Risk assessment and risk management at contaminated sites

The biggest challenge for retrofitting brownfields (i.e. derelict, contaminated or potentially contaminated sites requiring intervention to bring them back into use) is managing risks associated with probable soil contamination due to previous, ongoing or even adjacent uses to render it suitable for envisioned future land uses (Debolini et al., 2015; Luo et al., 2012; Yousaf et al., 2017). The risks associated with brownfields are determined by the probability of exposure to contaminants that may cause adverse effects to living organisms, human or non-human (SEPA, 2016; Swartjes, 2011). The source-pathway-receptor concept (also referred to as 'contaminant linkages') is fundamental in human and ecological risk assessment where effects on a specific receptor (i.e. humans or living organisms in the soil ecosystem, groundwater and surface water) is a function of changes at the source of contamination, along the pathways and/or at the receptor itself (Swartjes, 2011). Humans might be exposed to contamination through various pathways, of which the most prominent are ingestion of contaminated soil, consumption of plants grown on contaminated soil, inhalation of vapours or dust, and dermal contact with contaminated media (Scullion, 2006; SEPA, 2016; Swartjes, 2011). As a starting point, tier 1 risk assessments use generic soil guideline values (SGV, i.e. contaminant concentration targets or soil quality standards) that are typically compared to measured total contaminant concentrations in the soil to provide an initial, but oversimplified, estimation of the risks based on generic conservative assumptions. In Sweden and many other countries, SGV are calculated contaminant concentration targets at which human health and ecological risks are acceptable given standardized conditions (SEPA, 2009, 2016; Swartjes, 2011; Swartjes et al., 2012). Higher tier risk assessments use detailed site-specific information to provide a more in-depth, realistic estimation of the risks at a contaminated site (Swartjes, 2011).

The core concept of RBLM is on the reduction of risks to human health and the environment to the degree necessary to ensure a safe, beneficial reuse of site (i.e. fitness for use) while protecting the environment over the long-term (Bardos et al., 2018, 2020; Swartjes, 2011). This requires a clear recognition of the actual risks posed by the contaminants, for which generic risk assessments are insufficient, and necessitates a more complex, site-specific risk assessment wherein a critical factor is the bioavailability of contaminants, i.e. the readily available fraction of a contaminant that can cross cell membranes to enter the organism (Naidu et al., 2015). An RBLM approach can encounter challenges to enmesh with existing environmental objectives and gain acceptance from regulatory agencies due to the emphasis on full decontamination and source removal (Swartjes, 2011). One possibility is to reformulate the remediation objectives in terms of 'risk reduction and management' instead of 'full source removal and decontamination'. Rehabilitation/revitalization of brownfields to improve their functionality to provide ecosystem services and other benefits can also be more effectively achieved by, for example, integrating goals that are aimed towards ecological restoration (i.e. the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed, according to the Society for Ecological Restoration) using clear, measurable endpoints and a realistic restoration target (e.g. revised ecosystem with accepted functional values) (Farag et al., 2016; Gann et al., 2019; US EPA, 2009; Wagner et al., 2016). In many cases, however, the success of ecological restoration can be overestimated (Lilian et al., 2021).

2.2. Gentle Remediation Options – GRO

GRO are 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., 2016, 2013). The most common of these is phytoremediation with or without chemical additives or soil amendments; however, fungi- and microbial-based methods are also considered GRO (Cundy et al., 2016, 2013; GREENLAND, 2014a). In terms of risk management, GRO are primarily applied on contaminated soils to reduce contaminant transfer to local receptors by progressively removing the bioavailable pool of inorganic contaminants (*phytoextraction*), removing or degrading organic contaminants (*phyto- and rhizodegradation*), removing organic compounds by transpiring them into the atmosphere (*phytovolatilisation*), filtering contaminants from surface water and waste water (*rhizofiltration*) or groundwater (*phytohydraulics*), and stabilising or immobilising contaminants in the soil matrix (*phytostabilisation*, in-situ *immobilisation*) often in combination with vegetation cover using excluder plants (*phytoexclusion*) (Cundy et al., 2016, 2013; GREENLAND, 2014a; OVAM, 2019). A table of complete definitions for each GRO with references to studies showing proof-of-concept is available in the Supplementary Material (Table S1).

In practice, the GRO techniques can be separated into 'standard' and 'enhanced' phytoremediation. Standard refers to using the inherent functions of plants and their naturally occurring microbes that enable the various mechanisms. To improve the effectiveness of the techniques, phytoremediation can be enhanced (or 'aided' or 'microorganism-assisted') through enriching the microbes in the rhizosphere or within the plant itself by bioaugmentation (i.e. introducing species to the site) or biostimulation (i.e. enhancing the already existing microbes by the use of soil amendments) (OVAM, 2019). GRO are well-suited to mitigate the risks posed by low to medium concentrations of both inorganic and organic contaminants though the timeframe for remediation can differ significantly between the contaminants and the mechanisms involved (Fig. 1). An important note is that the 'relative remediation time' as used in Fig. 1 represents only the estimated time it would take for full source removal (e.g. via extraction or degradation) and can vary depending on if total or bioavailable concentrations are used as a benchmark.

A key feature of GRO is that they can improve ecological soil functions and in turn provide ecosystem services that are vital for human well-being, e.g. biomass production, flood mitigation, decrease in urban heat islands, amenity and recreation, habitat for animals and microorganisms, and carbon sequestration (Burges et al., 2018; Cundy et al., 2016; Garbisu et al., 2020). In both the short- and long term, GRO positively influence microbial communities (Bourgeois et al., 2015; Burges et al., 2020; Epelde et al., 2009a, 2008; Touceda-González et al., 2017b) and can have an ameliorating effect on soil, benefiting other soil biota like earthworms and nematodes (GREENLAND, 2014a; Hedde et al., 2013; Kumpiene et al., 2014; Mench et al., 2010). These and other soil biota possess intrinsic value by their uninhibited existence and also form the diverse, biological infrastructure essential for the delivery of ecosystem services that provide benefits to humans (Bünemann et al., 2018; Burges et al., 2018, 2016; Epelde et al., 2014b; Garbisu et al., 2020; Gómez-Sagasti et al., 2012; Wall et al., 2015, 2012).

2.3. Green land uses – soft redevelopment of brownfields

As a result of the beneficial effects GRO technologies have on soil, they are most applicable when contaminated or potentially contaminated sites are repurposed for 'soft' or 'green' uses, i.e. green land uses (Cundy et al., 2016; Erdem and Nassauer, 2013; Evangelou et al., 2012, 2015; Fässler et al., 2010; HOMBRE, 2014; Huang et al., 2011; Tripathi et al., 2016). 'Green land uses' or 'greenspaces' are public or private vegetated spaces in urban and rural areas (Juaneé Cilliers, 2015) and are essential in providing a multitude of ecological functions as well as improving the physical and mental well-being of human visitors (Bowler et al., 2010; Kaplan et al., 1983; Oke et al., 1989; Ståhle, 2010; Ulrich, 1981). Though greenspaces are more commonplace in rural areas, planned open spaces with designated facilities and amenities such as parks are more common in urban areas (Wen et al., 2013). Greenspaces in urban areas are also more diverse and frequently studied, especially their association with the citizen wellbeing (Liebelt et al., 2018; Mathey et al., 2018, 2015; Pueffel et al., 2018; Wen et al., 2013). There is a large variation of greenspaces that are found in today's cities that have been developing with time and integrated within the urban fabric. Based on the inventory of a pan European study Green Surge (Haase et al., 2015), Chowdhury et al. (2020) suggest 15 greenspaces that have the potential to be realised on brownfields. Some of these land uses – e.g. biofuel park, recreational park and

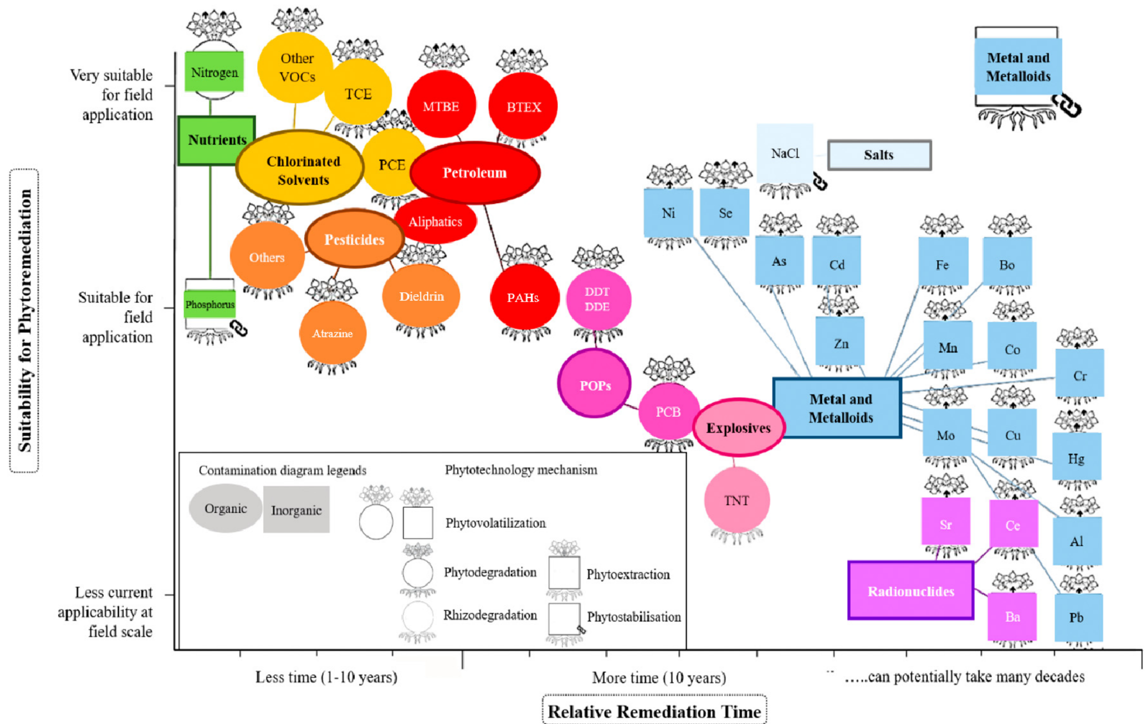

Fig. 1. Relative remediation time for source removal (relevant only for extraction, degradation and volatilisation) of groups of contaminants and applicability of the phytotechnology mechanisms. Colours correspond to contaminant grouping. After (OVAM, 2019) and (Kennen and Kirkwood, 2015).

allotment garden – can potentially be combined with GRO. As previously defined in Chowdhury et al. (2020), biofuel park is land with limited access for people but is instead dedicated to agroforestry for biofuel production like short rotation coppice with willows or poplars; recreational park is larger green area intended for recreational use by residents which can include trees, grassy areas, water bodies, and ornamental beds, and allotment gardens are small garden parcels cultivated on site by different people for non-commercial food production and recreation.

3. Methodology

3.1. The working process

The steps taken to develop and demonstrate the risk management framework for GRO are summarised below:

1) Development of a conceptualisation of linkages between GRO, risk mitigation mechanisms and their impact on ecological and human health risks. An extensive literature review was undertaken to identify studies that can support the hypothesised risk mitigation mechanisms. The conceptualisation is illustrated in a conceptual diagram and forms the basis for the generic framework. Mapping of the expected timeframes for effective risk reduction of different GRO and contaminant groups was based on existing literature. The time perspectives for different GRO and groups of contaminants are added to the figure and together with the results from Step 1, this forms the generic risk management framework.
2) For demonstration purposes, the following selections were made:
   i. Based on Chowdhury et al. (2020), three green land uses were selected – Biofuel Park, Recreational Park and Allotment Gardens – which theoretically represent a “low”, “medium” and “high” risk scenario, respectively. Each land use represents different risk scenarios. Depending on contaminants that are present, different receptors and human health exposure pathways will dominate the risk situation.
   ii. Thirteen specific contaminants that are commonly found at urban brownfields are selected as representatives for the contaminant groups mentioned in Fig. 1: 1) metal(loid)s – lead, cadmium, arsenic, copper and zinc; 2) petroleum products – PAH's (groups of light, medium and heavy density compounds) and benzene; 3) persistent organic pollutants – PCB's, dioxins and ΣDDT (including DDE and DDD); and 4) chlorinated solvents – TCE. The selection is based on that they should represent most of the different groups of contaminants (Kennen and Kirkwood, 2015; OVAM, 2019; Swartjes, 2011) and a report for the European commission on soil contamination and its impacts on human health which documents some of the top contaminants of concern in soils (Science Communication Unit, University of the West of England, 2013).
   iii. In order to calculate land use specific SGV for the selected green land uses and contaminants, the Swedish national soil guideline value model (SEPA, 2009) is used. Relevant adjustments to the generic scenarios implemented in the model are made and based on this, the most important receptors and human health exposure pathways can be identified for each contaminant and each green land use.
3) Finally, a case study is used to demonstrate the risk management framework application. The generic conceptualisation of linkages between GRO, risk mitigation mechanisms and their impact on ecological and human health risks is applied to the Polstjärnegatan case study envisioning two alternative land uses – Biofuel park and Allotment garden – and based on the contaminants and contaminant levels detected at the site.

3.2. The Swedish guideline value model

The Swedish soil guideline value model (available for downloading at the Swedish EPA website (SEPA, 2016)) is based on the source-pathway-receptor linkage concept, and takes four main receptors into account: human health (acute and chronic effects), the soil ecosystem, nearby surface water ecosystems and groundwater (SEPA, 2016, 2009). Generic SGV are determined to protect all receptors for two classes of land use: land with sensitive uses (KM) (e.g. residence, greenspaces, agriculture, kindergarten, etc.) and land with less-sensitive uses (MKM) (e.g. office, industry, roads, etc.) (SEPA, 2009). The guideline value model has become a standard tool that is accepted by regulatory authorities in Sweden and is similar to other models used for generic quantitative risk assessments (e.g. CLEA in the UK (Jeffries, 2009) and SADA in the USA (Stewart et al., 2009)). The model can also be used for deriving site-specific SGV in risk assessments for contaminated sites by adjusting the generic parameters accordingly (a longer description of the model is available as text in the Supplementary Material and in Table S2). The exposure parameters used in the SEPA guideline value model to derive generic SGVs for less-sensitive (MKM) and sensitive land uses (KM) are shown alongside the adjusted parameters used for each exposure scenario in Table 1. For the three green land uses (Biofuel Park, Recreational Park and Allotment Gardens), the human exposure parameters in the SEPA model were adjusted to reflect exposure scenarios more accurately, but still tend to be overly conservative. However, most parameters and assumptions used in the model (e.g. an unrealistically high value of contaminant bioavailability of 100%, hydraulic conductivity, the assumed mix of edible plants and their bioconcentration factors, and several others) were not adjusted and match the standard values for the sensitive land use scenarios, which corresponds with the designation used for green land uses.

4. Results

4.1. The generic framework for risk management and communication

Fig. 2 presents the generic risk management framework for GRO and shows the connections between risk mitigation mechanisms, risk objects, and GRO strategies. In summary, three main risk mitigation mechanisms can be attributed to GRO: 1) bioavailability and solubility reduction, 2) source removal – plant uptake, degradation, volatilisation, and 3) secondary effects by vegetation cover for plant-based GRO.

The GRO mechanisms that can contribute to mitigating risk are presented in detail in Table 2. No studies were found to support bioavailability/solubility reduction mitigating dermal contact, which is therefore regarded as a 'potentially mitigated risk' in the framework and specified with dotted green arrows in Fig. 2, however this exposure pathway (and soil intake) can be mitigated by having dense vegetation cover or other barriers to prevent contact with soil.

As shown in Fig. 2, the 'relative risk reduction time' for each GRO strategy has been estimated, based on (Kennen and Kirkwood, 2015; OVAM, 2019),and added to the generic framework (the colours and time categories correspond with Fig. 1). Time is separated into three broad ranges: 1) *less time* (1–10 years), 2) *more time* (10+ years), and 3) *can potentially take decades*. In Fig. 1, the 'relative remediation time' is estimated based on the estimated time of full source removal (e.g. via extraction or degradation) and does not provide estimation for other risk reduction strategies as stabilisation and managing receptor access. To address this limitation, the relative time perspectives in Fig. 2 is expanded to also include complementary risk reduction strategies (i.e. stabilisation/immobilisation, rhizofiltration and vegetation cover). The relative risk reduction time for these strategies has been estimated to be mostly similar, because the time required for the onset of risk mitigation is dependent on the time it would take for vegetation to establish or for amendments to alter soil properties. Based on literature review, vegetation establishment can be separated into three time ranges depending on plant species (shown in Fig. 2 and discussed here as different shades of colour):

1) Quick (lightest shade) – soil amendments and fast-growing species like grasses, herbaceous species and annuals crops can provide risk mitigation within 6-8 weeks;
2) Medium – shrubs take longer to establish and can provide wider, more lasting risk mitigation within 1-2 years;
3) Slower (darkest shade) – trees provide the most extensive risk mitigation with roots able to reach down to deeper soil layers but even fast-growing tree species like willow and poplar can take from 2 to 4 years to establish.

For the quickest risk mitigation, soil amendments (e.g. biochar) used separately or in combination with fast-growing grasses can provide relatively 'instant' effect. For example, biochar has been demonstrated to reduce the bioavailability of PCB and DDT, thus having an ameliorating effect on earthworms, within 50 days (Denyes et al., 2016, 2013). Also, rhizomatous grasses have been recommended to quickly provide soil cover and limit the dispersal of soil particles whilst shrubs and trees establish (Mench et al., 2010; OVAM, 2019). Other fast-growing crop species such as tobacco, sunflower, mustard, willows and poplars can also provide rapid risk mitigation and typically produce high quantities of biomass, which is advantageous for phytoextraction (Herzig et al., 2014; Mench et al., 2010, 2018; OVAM, 2019; Thijs et al., 2018). For stabilisation purposes, it has been estimated that phytostabilisation of metal(loid)s using perennial tree species like willow and poplar can generally take 2-4 years but can vary between contaminant and plant species (Robinson et al., 2006). Rhizofiltration risk mitigation is also dependent upon vegetation establishment though it varies in application (e.g. as constructed wetlands, wastewater irrigation or runoff filters), and has been demonstrated to reduce contaminant concentrations in water outflow within 1-2 years as part of an 'integrated phytomanagement system' (ANL, 2008; Cundy et al., 2020), provide ongoing treatment using willow

Table 1
Selected parameters used in the Swedish guideline value model that were adjusted to create exposure scenarios for each green land use. MKM = less sensitive land use; KM = sensitive land use.

Exposure Scenarios – Green Land Uses							
Human health exposure pathways	Exposure parameters	MKM	KM	Biofuel park	Recreation park	Allotment gardens - 1[a]	Allotment gardens – 2[a]
Intake of soil	Exposure time - child (day/yr)	60	365	60	200	365	365
	Exposure time - adult (day/yr)	200	365	200	200	365	365
Dermal contact	Exposure time - child (day/yr)	60	120	60	120	120	120
	Exposure time - adult (day/yr)	90	120	90	120	120	120
Inhalation of dust	Exposure time - child (day/yr)	60	365	60	200	365	365
	Exposure time - adult (day/yr)	200	365	200	200	365	365
	Proportion of time indoors	1	1	0	0	0	1
Inhalation of vapour	Exposure time - child (day/yr)	60	365	60	200	365	365
	Exposure time - adult (day/yr)	200	365	200	200	365	365
	Proportion of time indoors	1	1	0	0	0	1
Intake of plants	Consumption - child (kg/day)	0	0.25	0	0	0.25	0.25
	Consumption - adult (kg/day)	0	0.4	0	0	0.4	0.4
	Proportion of food grown on site	0	0.1	0	0	0.1	0.1

[a] Allotment Garden scenarios with (1) and without (2) time spent indoors.

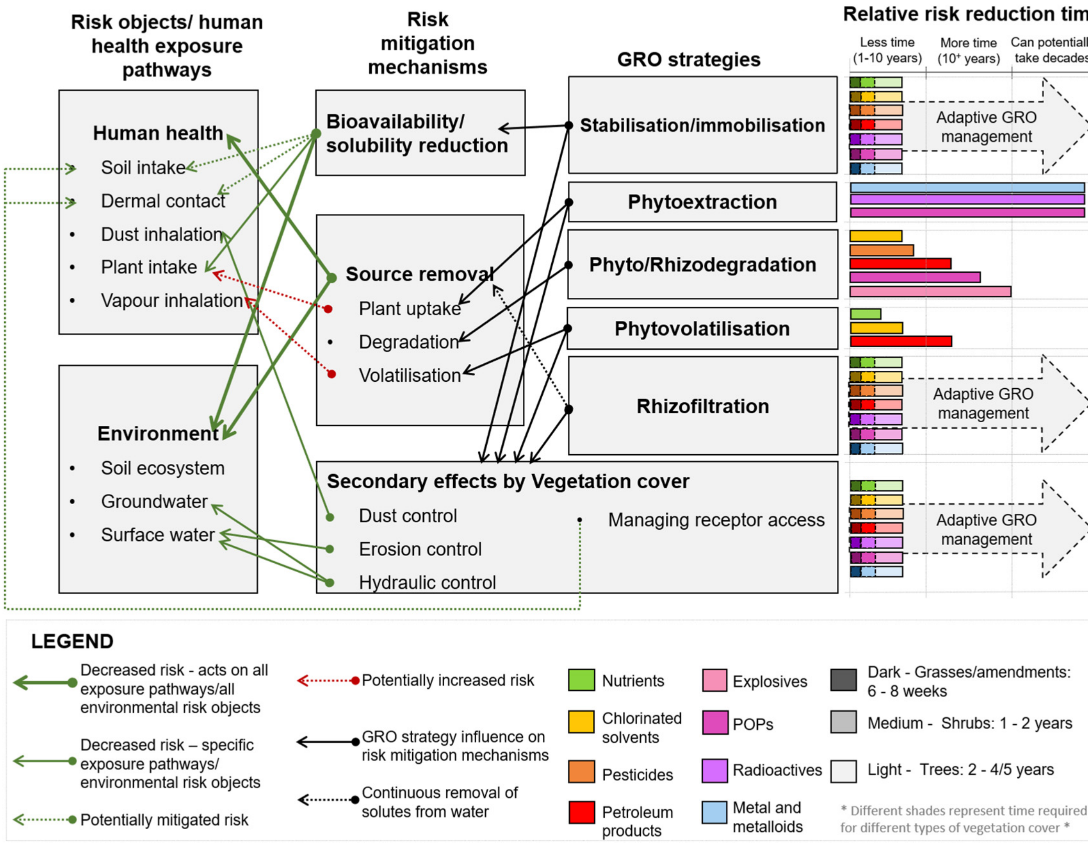

Fig. 2. The generic risk management and communication framework for GRO with columns for Risk objects, Risk mitigation mechanisms, GRO strategies and a bar chart depicting relative risk reduction time for each GRO strategy. Relative risk reduction times are based on those shown in Fig. 1. Relative times for stabilisation/immobilisation, rhizofiltration and vegetation cover are based on literature. Adaptive GRO management is needed for all GRO strategies during their implementation, and includes long-term monitoring, watering, etc. for upkeep and to ensure the risk reduction is maintained over time.

short-rotation coppice (Dimitriou and Aronsson, 2005) and provide effective, continuous wastewater treatment (Kennen and Kirkwood, 2015; Marchand et al., 2010; Pivetz, 2001).

Adaptive GRO management is needed for all GRO strategies during their implementation, and includes long-term monitoring, watering, etc. for upkeep and to ensure the risk reduction is maintained over time. For source removal GRO strategies, adaptive management is only required during their operation until the source is removed. However, for GRO strategies that reduce risks by e.g. stabilisation/immobilisation, vegetation cover and rhizofiltration, it is important to continuously maintain and monitor the GRO while the risk mitigation mechanism is in effect.

4.2. Soil guideline values for selected green land uses and contaminants, and associated risks

Using the Swedish guideline value model (Section 3.2) as a starting point, the SGV and dominating risk and exposure pathways for each of three modelled green land uses (biofuel park, recreational park and allotment garden) were calculated and identified, respectively. See tables showing these results in the Supplementary Material. These SGVs are generic for a specific green land use, and not adopted to a specific site. As expected, in the SEPA model the dominating risk pathways for the representative contaminants change according to the varying exposure parameters and risk levels per green land use.

- In the Biofuel Park scenario, the risks posed to human health by the various contaminants are considered secondary to the risks posed to biological receptors for all but arsenic. This is due to the much lower exposure times (corresponding to the less sensitive land use parameters) used in the model than those typically employed for sensitive land use. This is a reasonable adjustment since the time on site for adults and children given this land use is likely to be much less than the 365 (or 120) days/year used in the generic scenario for sensitive land use. Furthermore, certain risk pathways (e.g. intake of plants and intake of groundwater) are not relevant for this type of land use.
- In the Recreational Park scenario, the predominant risk is still to ecological receptors for most contaminants (except for arsenic, PCB's and dioxins), but the health-based SGV is lower compared to the Biofuel Park scenario, which indicates that the risk posed to humans is higher. Also, intake of soil is shown to be a highly relevant risk pathway according to the SEPA model and would be a critical factor to account for in any proposed Recreational Park site design.
- For the Allotment Garden scenarios, with (1) and without (2) time spent indoors (i.e. residence on-site), the risk to human health is significantly greater and constitute the dominating risk for most contaminants. Human health risks are especially relevant for contaminants that are, according to assumptions of the SEPA model, 1) considered to have a high bioavailability, corresponding to greater uptake in plants, thus posing a risk through intake of plants when food is grown on site (Cd, As, Cu, Zn, PAH-H, PCB's); and 2) readily volatilised, thus posing a risk to indoor inhabitants by vapour inhalation (PAH-L, PAH-M, benzene, TCE).

4.3. Application of the framework

4.3.1. Case study site Polstjärnegatan

The case study site is part of a concept plan of a large-scale housing and commercial development area “Karlastaden” in Gothenburg (South-West Sweden) and has confirmed contamination issues. The

Table 2
Description of risk mitigation mechanisms and support in literature. Risk mitigation mechanisms are separated into categories corresponding to the black arrows shown in Fig. 2. Red bold text indicates that the risk mitigation mechanisms potentially create an increased risk along a certain pathway. Italic text indicates that no evidence was found in literature.

Risk object	Exposure pathway	Descriptions of risk mitigation mechanisms and scientific evidence as support
Risk mitigation mechanism: bioavailability and solubility reduction		
Human health	Soil intake	Description: Potentially reducing bioavailability of contaminants by e.g. using amendments to alter soil properties affecting bioavailability leading to stronger binding to soil particles and affecting chemical speciation, or binding strongly to or being stored within plant roots (Foucault et al., 2013; Friesl-Hanl et al., 2017; GREENLAND, 2014a; Mench et al., 2010; OVAM, 2019). Soil amendments, single or combined, have been shown to reduce the solubility and bioavailability of various metal(loid)s (Pb, Cr, As, and Cd) using e.g. iron grit, beringite, phosphates, lime, metal oxides, red mud, organic amendments, etc. (Friesl-Hanl et al., 2017; Jardine et al., 2007; Kumpiene et al., 2019, 2008; Mench et al., 2006; Paltseva et al., 2020; Sanderson et al., 2015). The oral bioaccessibility of metals in the gastric and intestinal phase has been reduced, with varying success, via phytostabilisation with giant miscanthus or elephant grass (Miscanthus x giganteus) for Cd, Pb, and Zn as evidenced by in-vitro tests using the unified bioaccessibility method (UBM) (Pelfrêne et al., 2015) and via soil amendments like lime and magnesium oxide for Pb according to physiologically based extraction tests (PBET) (Sanderson et al., 2015). However, the effectiveness of GRO reducing the oral bioaccessibility of metal(loid)s like As, Cu, Cd, Pb and Zn has been questioned in other studies (Gray et al., 2006; Mench et al., 2010, 2006; Paltseva et al., 2020).
	Dermal contact	Description: In theory, reducing solubility of contaminants would cause them to bind more strongly to soil particles or plant roots, which in turn could mitigate the risk of absorption through skin due to exposure to contaminants in aqueous phase and transfer from soil particles that cling to skin (Friesl-Hanl et al., 2017; GREENLAND, 2014a; Mench et al., 2010; OVAM, 2019). *No studies were found to support this mechanism.*
	Plant intake	Description: Reduces uptake into plants by lowering the concentration of soluble, phytoavailable (i.e. bioavailable fraction) contaminants through the use of amendments and/or non-accumulator plant species (Friesl-Hanl et al., 2017; GREENLAND, 2014a; Mench et al., 2010; OVAM, 2019). Non- or low-accumulating willow species/clones (intended for bioenergy production) have been used to prevent uptake of metals into plant biomass thus reducing the risks to humans through transfer into the food chain by e.g. grazing animals (Ciadamidaro et al., 2019; Enell et al., 2016; GREENLAND, 2014a; Mench et al., 2010; Vangronsveld et al., 2009). Demonstrated the use of crop variants that exclude (i.e. 'phytoexclusion') uptake of contaminants thus avoiding entering into the food chain (GREENLAND, 2014b, 2014a; Kidd et al., 2015; Tang et al., 2012). Amendments can be used to prevent uptake of contaminants in crop species, e.g. uptake of PCBs in pumpkin reduced by biochar (Denyes et al., 2016, 2013; Henry et al., 2013; Vangronsveld et al., 2009).
Environment	Description: Risks to the environment could also be mitigated by this mechanism through reducing the readily available concentration of contaminants in soil pore water thus limiting mobility (e.g. leaching to groundwater) and exposure to ecological receptors in soils and local surface waters (GREENLAND, 2014a; Mench et al., 2010; Quintela-Sabarís et al., 2017; Touceda-González et al., 2017b). Demonstrated that using phytostabilising willow clones could reduce ecological risks and improve soil quality by preventing further spreading of contaminants in soil porewater (i.e. reducing bioavailable fraction) (Andersson-Sköld et al., 2014, 2013; Enell et al., 2016). Reduction in toxic pressure to soil environment due to reduction in bioavailability of contaminants using plants and/or amendments; demonstrable improvement in soil quality measured by microbial indicators including restoration of soil enzyme activities, improved respiration curves, increased microbial biomass and PLFA, shifts in microbial community structure (Burges et al., 2017, 2016; Epelde et al., 2014b, 2008; Gómez-Sagasti et al., 2012; GREENLAND, 2014a, 2014b; Kidd et al., 2015; Kumpiene et al., 2009; Quintela-Sabarís et al., 2017; Touceda-González et al., 2017b). Biochar in combination with zucchini to reduce and/or extract bioavailable PCBs or DDT/DDE from soil and storage in plant tissue led to reduced accumulation in earthworms (Denyes et al., 2016, 2013).	
Risk mitigation mechanism: Source removal – plant uptake, degradation, volatilisation		
Human health and Environment		Removal or degradation of the bioavailable pool of inorganic and organic contaminants greatly mitigates (or altogether eliminates) the risks posed to humans and the environment (Cundy et al., 2016; GREENLAND, 2014a, 2014b).
Human health	**Plant uptake**	Description: Potentially introducing risks to humans or biological receptors (e.g. grazing animals) by increasing contaminant concentrations in plants or creating an 'attractive nuisance' where contaminants are more readily available than if the site were capped (Cundy et al., 2016; GREENLAND, 2014b, 2014a; Wagner et al., 2016). Change of land use from food crops to bioenergy crops, e.g. SRC, reduces risks (GREENLAND, 2014b, 2014a). Pre-cultivating or co-cropping metal-accumulating species with non-accumulating or metal-excluding (i.e. phytoexclusion) food crop cultivars can further reduce plant uptake in concurrent and subsequent crops (GREENLAND, 2014b; Greger and Landberg, 2015; Kidd et al., 2015; Tang et al., 2012).
	Volatilisation	Description: Could exacerbate the risks posed by vapour inhalation at a site if this is a dominant risk pathway, dependent upon the contaminant's volatility (GREENLAND, 2014a; Mench et al., 2010; OVAM, 2019; Vangronsveld et al., 2009). Due consideration must be paid to these risks although they can be avoided if the GRO strategy is well-designed. In some cases, vegetation may even be useful to mitigate exposure to volatile contaminants (e.g. PCBs) in air as they can adhere to the waxy cuticle and plant leaves and bark and via 'phyto-forensics' as biosensor to detect VOCs in groundwater and shallow soils potentially leading to vapour intrusion in buildings (Henry et al., 2013). Possible to bioaugment the bacteria in-situ with endophytic strains capable of degradation, e.g. poplar trees growing on a TCE-contaminated site inoculated with the TCE-degrading bacteria which reduced TCE evapotranspiration by 90% under field conditions (OVAM, 2019; Weyens et al., 2009b, 2009a).
Risk mitigation mechanism: Secondary effects by vegetation cover		
Human health	Managing receptor access, dust control	Description: Preventing soil intake and dermal contact by using vegetation (e.g. densely planted grasses) with or without amendments (e.g. compost or mulch) to manage receptor access to the subsurface thereby mitigating exposure by providing a barrier between soil and humans (Cundy et al., 2016; Gil-Loaiza et al., 2018; GREENLAND, 2014a; Henry et al., 2013; Mendez and Maier, 2008) Soil intake, dermal contact and dust inhalation: Many field trials show stabilisation of contaminants with effectively 100% vegetation cover (with or without amendments, e.g. mulch) thereby reducing soil – human contaminant linkages via direct soil exposure and dust inhalation (Bert et al., 2012; Cundy et al., 2016; GREENLAND, 2014b, 2014a; Kidd et al., 2015).
	Dust control	Description: Vegetation cover provides dust control by stabilising soil thereby reducing the fine dust particles mobilized by wind erosion, and agronomic practices like no-tillage cultivation can further limit dust (Cundy et al., 2016; Gil-Loaiza et al., 2018; GREENLAND, 2014a; Henry et al., 2013; Kidd et al., 2015; Mendez and Maier, 2008). Measurements of horizontal dust flux following phytoremediation reveals that vegetated plots with 16% and 32% canopy cover reduced average dust deposition by 74-84% in comparison to the control treatment and was effective at reducing the concentration of fine particulates posing the greatest health risks, including PM1, PM2.5, and PM4 (Gil-Loaiza et al., 2018).

(continued on next page)

Table 2 (*continued*)

Risk object	Exposure pathway	Descriptions of risk mitigation mechanisms and scientific evidence as support
		Native vegetation stabilised mine tailing sites in air/semi-arid environments to reduce the dust flux of PM1 and PM2.5 by approximately 60% (Henry et al., 2013; Mendez and Maier, 2008).
	Hydraulic control	Description: Vegetation cover provides hydraulic control by both influencing the flow of groundwater and reducing the flux of contaminants (i.e. spreading or leaching) infiltrating into the groundwater stream via plants acting as 'bio-pumps' absorbing significant volumes of water due to evapotranspiration (Cundy et al., 2016; GREENLAND, 2014a; Kennen and Kirkwood, 2015; OVAM, 2019; Robinson et al., 2009, 2006, 2003) Deep-rooting phreatophyte tree species (e.g. willows, poplars) have been planted at sites contaminated with BTEX, other petroleum products and VOCs to control the groundwater plume and can even enhance degradation (Barac et al., 2009; Cundy et al., 2020; Ferro et al., 2013; OVAM, 2019; Robinson et al., 2007).
Environment	Erosion control	Description: Vegetation cover provides both erosion control (i.e. reduced horizontal migration of contaminants from lateral runoff due to higher soil porosity, root stabilisation and plant evapotranspiration) and hydraulic control by preventing the infiltration and spreading of contaminants via groundwater streams into local water bodies (Cundy et al., 2016; GREENLAND, 2014a, 2014b; Kennen and Kirkwood, 2015; OVAM, 2019; Robinson et al., 2009, 2006, 2003). Shrubs and trees provide an extensive canopy cover and establish a deep, stabilising root network acting as natural barriers and resistance to erosion and leaching (i.e. horizontal and lateral migration of contaminants). Plants with fibrous root systems (e.g. grasses and herbaceous species) can quickly provide a soil cover and limit the dispersion of soil particles by physical processes, whilst shrubs and trees become established. Roots also provide higher soil porosity thereby reducing runoff and horizontal migration (GREENLAND, 2014a, 2014b; Mench et al., 2010; OVAM, 2019). Many studies have shown soil stabilisation and improvement on contaminated mining sites through revegetation, with or without amendments, for ecological restoration and provisioning of ecosystem services (Burges et al., 2018; Epelde et al., 2009c; Gajic et al., 2018; Gerhardt et al., 2017; Gray et al., 2006; GREENLAND, 2014a; Mench et al., 2010; Vangronsveld et al., 2009; Wong, 2003).

planned future use is a park area with new roads constructed along the edges of the site. It was initially used as a railyard for coal products and was later transformed into a golf course. The golf course closed in the early 2000s and the site has been abandoned ever since. According to the environmental investigation conducted at Polstjärnegatan, the site is characterised by several small hotspots resulting from illegal cable burning with high contamination levels, and the rest of the area with lower contamination, primarily in the upper soil layer, 0–0.7 m (Kaltin and Almqvist, 2016). The primary contaminants are metal(loid)s (As, Cu, Pb, and Zn), petroleum products (primarily PAHs with high molecular weight) and PCB) (see Supplementary Material Table S7 for compilation of contaminant concentrations). As the hotspots have concentrations at levels corresponding to hazardous waste, remediation by excavation some other type of faster source removal technology at those spots is likely needed but requires a site-specific risk assessment. For the demonstration of the suggested framework, the rest of the area is considered, where contamination levels are lower. To account for the varying contamination levels and provide an indication of the relative risk, the Risk Quotients (RQ) for each contaminant was calculated by dividing the mean (total) concentration in the soil by either the corresponding health-based SGV or the lowest environmental SGV determined in the land-use specific SEPA model (see Tables S3-S6 in Supplementary Material).

4.3.2. Demonstration at case study site Polstjärnegatan

The generic framework (Fig. 2) was adapted to include the contaminants at Polstjärnegatan and create a site-specific application of the framework for two different land uses 1) Biofuel Park and 2) Allotment Garden (with permanent residence on site), see Fig. 3. The dominating human health exposure pathway, or most sensitive environmental receptor, per contaminant and land use are indicated, linked with the corresponding risk mitigation mechanisms and potential GRO strategies. The calculated risk quotients are shown in the figure where a $RQ > 1$ indicates an elevated risk. In Fig. 3, for the Biofuel Park scenario only Cu indicates a potential risk ($RQ = 1.1$, primary receptor: soil ecosystem). For the Allotment Garden scenario, the same is valid for Cu and in addition, RQs for As and PCB indicate potential human health risks (4.7 and 2.8 for soil intake and plant intake, respectively). The GRO strategies that are identified to be able to mitigate the dominating exposure pathways are highlighted in green boxes in Fig. 3.

For the Biofuel Park, the risks posed to the soil ecosystem is of primary concern, which can be mitigated by 1) reducing the bioavailability and consequent exposure for soil organisms, and 2) removing the source of the contamination by extraction for metals or degradation for organics. A combination of those strategies could lower the risks on the short-term (stabilisation) and achieve source removal in the longer term (extraction, degradation). The application of a 'treatment chain' could be suitable for this site entailing, for example, excavation, or some other technique to manage the source, of the highly contaminated hotspots for treatment off-site followed by use of GRO for 'soil polishing' via phytoextraction of bioavailable metal(loid)s as a risk mitigation strategy; whereby, the slightly elevated contaminant concentrations could be reduced to acceptable levels (Dickinson et al., 2009). Implementing the Biofuel Park option could potentially lead to a phytomanagement strategy that over time can allow for alternative, more sensitive land uses for unrestricted use.

In the Allotment Gardens scenario, As and PCB mean concentrations exceed the SGV for human health, and PAH-H is close to the threshold ($RQ = 0.9$). According to the SEPA model, the exposure pathway of plant intake (As, PCB & PAH—H) is of primary concern, and to a lesser extent soil intake (As). Plant intake can be mitigated by 1) reducing the bioavailability of contaminants using amendments and plants and/or 2) selectively designing the vegetation cover with excluding or non-accumulating species for relevant contaminants. Soil intake can also be managed with vegetation cover consisting of dense grass species and amendments functioning as a barrier to manage receptor access to the soil and prevent humans from inadvertently ingesting the soil. Some studies indicate that GRO can also potentially reduce As oral bioaccessibility using amendments or plants, though this strategy would require a more extensive human health risk assessment and feasibility studies to actually confirm the effectiveness and viability as a legitimate risk reduction measure. An unrestricted Allotment Garden land use may thus not be immediately feasible and the time perspective for using GRO to meet the required risk reduction (e.g. by reducing contaminant levels via phytoextraction) would in practice be long (> 10 years). Phytoextraction cannot easily be combined with Allotment Gardens and is only a viable option if it could be safely designed and implemented to avoid potentially increased risks to human health or grazing wildlife due to possible contaminant uptake in edible crops grown on site (indicated by the red dotted arrow in Fig. 3). An Allotment Garden land use with restrictions regarding crop selection and implementing safe agriculture practices could be a more feasible option in combination with using soil amendments with low- or non-accumulating plants to stabilise/immobilise the contaminants in the soil matrix and reduce bioavailability to prevent uptake into plants. However, it would require control of user's behaviour at the site, which in practice may be difficult.

5. Discussion

5.1. The risk management framework and its application

The risk management framework presented in this study is intended to support remediation contractors, decision-makers, regulatory bodies and other stakeholders involved in contaminated sites. It can be used in the early stages of a brownfield redevelopment project as a tool for 1) communication of risk mitigation mechanisms by GRO and their associated timeframes, and 2) identifying opportunities for GRO implementation at specific sites preceding necessary site-specific risk assessments. A primary aim in developing the generic framework is to demonstrate the range of possible applications of GRO for effective risk management that can be customised along linkages to act on source, pathway and/or receptor. The generic risk management framework for GRO can be used for educating and informing stakeholders in other countries regardless of their national risk assessment frameworks. For site-specific considerations, relevant contaminants and corresponding risks related to an intended future land use can be integrated into the generic framework by applying any risk assessment framework as is here demonstrated with the Swedish soil guideline value model. The framework can function as a complement to existing decision-support tools (DST) for GRO implementation as it targets to educate stakeholders – who are not necessarily trained in GRO and risk assessment – on the connections between risk mitigation mechanisms, risk objects, and GRO strategies. As demonstrated in the case study application, the risk assessment changes significantly depending on the desired end use and the framework strengthens the decision basis by clarifying relevant risk mitigation mechanisms to manage contaminant linkages and corresponding GRO strategies. An important note regarding the demonstration of the framework is that the background parameters and generic assumptions built into the SEPA model for sensitive land uses are inherently conservative. For example, the bioavailability for all soil contaminants is considered to be 100% of the total amount, which is unrealistic for most contaminants and will overexaggerate the risk by e.g. intake of plants or soil. Therefore, evaluation of the contaminant bioavailability at a site should be a standard analysis when considering GRO feasibility, as is usually determined in site-specific risk assessment and by conducting controlled experiments before application. For instance, a test in the SEPA model showed that to reduce the RQ for As to 1 for Allotment Gardens the bioavailability (as measured by plant uptake and oral intake) would have be reduced by >80%. More in-depth knowledge would facilitate refining the parameters and assumptions used in the SEPA model to create more realistic exposure scenarios for the green land uses.

There are several DST developed for GRO, which are often focused on the technical application details and practical considerations for designing the remediation strategy for a site, e.g. (Andersson-Sköld et al., 2014; Cundy et al., 2015; ITRC, 2009; Onwubuya et al., 2009; OVAM, 2019). These DST can be viewed as complex by decision-makers and may not be well-suited as a communication tool in the early stages of a site remediation project since they require knowledge and in-data that stakeholders may not have available. Many studies have reported the lack of knowledge amongst stakeholders of GRO generally and of currently available DSTs for brownfield redevelopment and GRO application, so a clear target is to raise awareness and inform stakeholders of available DST and the viability of GRO including the handling of biomass originating from phytomanagement (Berghel et al., 2021; Bert et al., 2017; Cundy et al., 2016, 2015; Gerhardt et al., 2017; GREENLAND, 2014b; Onwubuya et al., 2009). Risk communication is a fraught topic that would benefit from a clear, transparent framework, in line with existing regulations, to use in the early stages of planning for brownfield redevelopment for discussing the wide variety of contaminant linkages that can be managed using GRO (Cundy et al., 2015; GREENLAND, 2014b; Hammond et al., 2021; Onwubuya et al., 2009). A recurring debate in GRO application is regulator acceptance regarding managing risks without necessarily reducing total concentrations (i.e. source removal) and time concerns (Cundy et al., 2016; Gerhardt et al., 2017). The relative time for risk reduction in the generic framework provides transparency with respect to the effectiveness of GRO strategies relative to time which in turn provides a starting point for setting reasonable expectations and communicating with stakeholders. It is indeed a simplified generalization but given that time requirements are typically one of the primary concerns it was deemed useful to compile preliminary time estimates for risk reduction. Time estimates can be more accurately predicted with more site-specific information. Phytoextraction, for example, can be a valid strategy and remove readily bioavailable metal(loid)s (e.g. As, Cd, Co, Mn, Ni, Se, and Zn) from soil within a reasonable timeframe if contaminant concentrations are low. Additionally, gradual removal of the source term will eventually allow for other sensitive, unrestricted land uses as the risks are reduced over time.

It is worth reiterating that a bioavailable fraction is much more relevant from a risk standpoint than a total contaminant concentration, since it is available for uptake into sensitive receptors and mobile to spread or leach into groundwater (Faber and Van Wensem, 2012; Gutiérrez et al., 2015; Kumpiene et al., 2017; Volchko et al., 2020, 2014b). Bioavailable contaminant stripping is a strategy that utilises phytoextraction to gradually remove the bioavailable fraction of the contaminant, which potentially poses the greater risk (i.e. induces the contaminant linkage), but despite recent successes it may not be readily recognisable as a viable remediation strategy by regulatory agencies or decision-makers that rely on conservative assumptions and threshold values based on total soil concentrations (Herzig et al., 2014; Mench et al., 2018; Robinson et al., 2015). GRO could also be used for phytostabilisation or immobilisation to significantly reduce the bioavailability and solubility of contaminants in a relatively short time. The vegetation cover itself controls erosion, dust and groundwater hydraulics to physically reduce the risks and manage the receptors.

For organic contaminants, GRO degradation mechanisms have been shown to be highly effective for many contaminants and could reduce risks directly by source removal over a shorter time. However, in the case of highly volatile organic contaminants (VOCs), eventual volatilisation by plant transpiration that releases VOCs into the atmosphere could potentially increase the exposure risks in some situations (OVAM, 2019). This is a non-trivial possibility and must be accounted for in GRO design and monitored accordingly. Similarly, possible human exposure due to plant intake necessitates caution and more in-depth risk assessment when food crops are considered for cultivation on a contaminated site as in, for example, the studied allotment garden scenario. It is, however, possible to safely cultivate food crops in contaminated soils by either i) selectively cultivating crop varieties or clones that exclude (i.e. do not take up) contaminants from their edible biomass, or ii) pre-cultivating or co-cropping contaminant accumulating (i.e. extractive) species with non-accumulating or excluding food crop varieties to further reduce plant uptake in food crops, or iii) pre-cultivating contaminant accumulating species to strip the bioavailable fraction and reduce contaminant uptake in subsequent crops (GREENLAND, 2014b; Greger and Landberg, 2015; Kidd et al., 2015; Tang et al., 2012). If growing food crops in the contaminated soil is still considered to pose an unacceptable exposure risk, then vertical systems could be used alongside safe agricultural practices and institutional controls (US EPA, 2011). Contaminant uptake into plants (or mesofauna) could also potentially increase the risk of exposure for grazing or predatory wild animals, but this risk can be effectively reduced through careful GRO site design and other engineered solutions to reduce access to contaminated areas in collaboration with stakeholders. GRO could be employed to enable simultaneous land use by tailoring the vegetation to stabilise contaminants in the soil matrix thereby

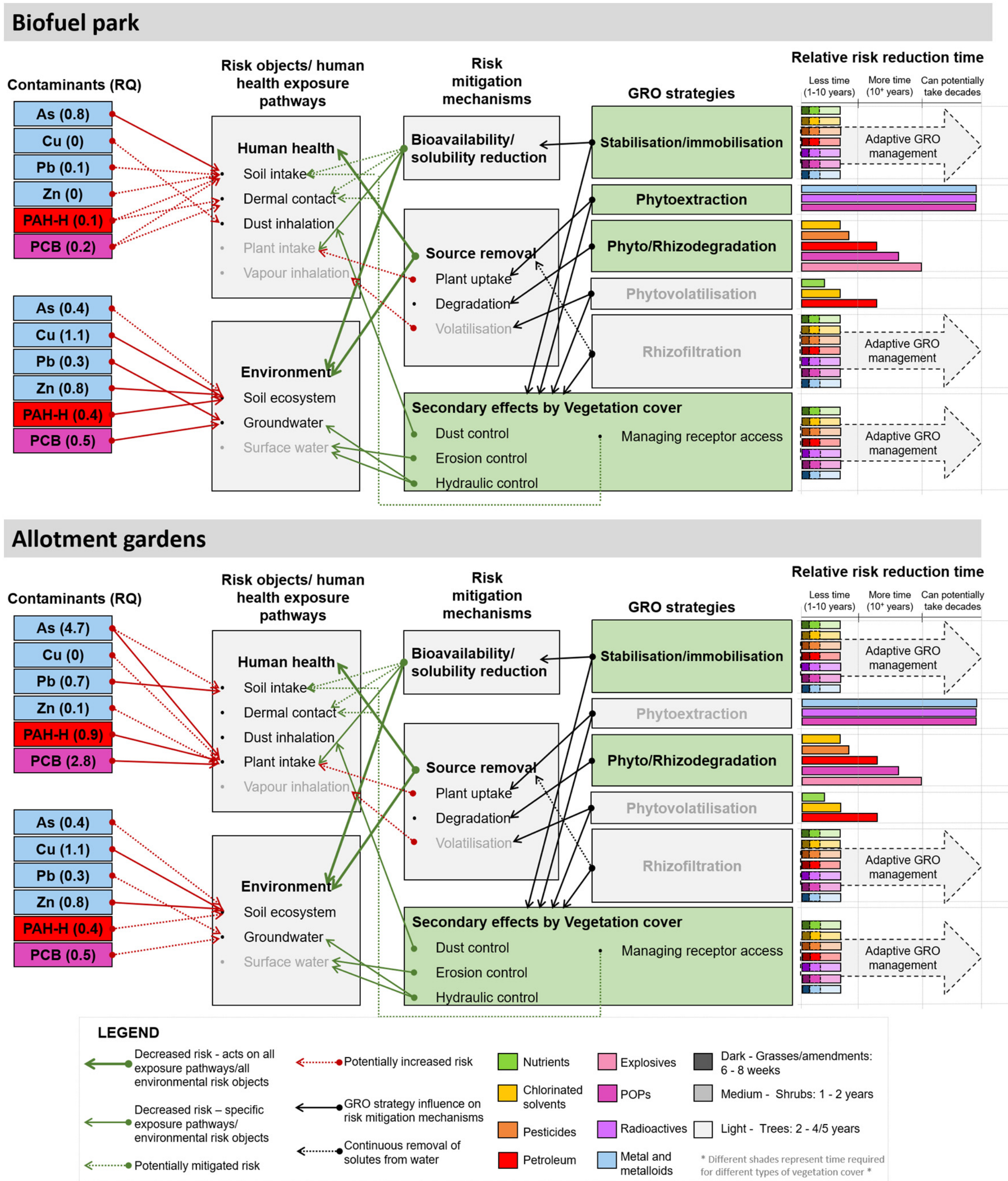

Fig. 3. Site-specific application of the GRO risk management framework for two green land uses: Biofuel park and Allotment gardens. The contaminants detected at the site, Polstjärnegatan, and risk quotients (RQ) are included in the furthest left column and are separated into exposure pathways for human health (above) or for the environment (below). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

preventing spreading by leaching, dust and erosion. Soil amendments could be used to enhance this effect while also providing a barrier between humans and the soil to further limit exposure risk by ingestion, dermal contact or dust inhalation. This strategy could be especially beneficial in urban gardens, for example, where it has been shown that the primary exposure pathways for humans to As and Pb are soil and dust ingestion, rather than vegetable consumption (Paltseva et al., 2020).

5.2. Implications for phytomanagement

Considering contaminated soils, it must be acknowledged that the ultimate objective of any remediation process is not only to remove the contaminants from the soils (or instead break contaminant linkages) but also to restore soil functioning and quality (Burges et al., 2018; Epelde et al., 2009b, 2008; Gómez-Sagasti et al., 2012). Phytomanagement has been demonstrated to be an effective strategy for sustainably managing and monitoring risks posed by a wide variety of contaminants (Bardos et al., 2020; Burges et al., 2018; Cundy et al., 2016; Gerhardt et al., 2017; Robinson et al., 2009), improving soil functions and ecosystem services (Burges et al., 2018, 2016; Cundy et al., 2016; Epelde et al., 2014b, 2009a, 2009c; Gómez-Sagasti et al., 2012; Kidd et al., 2015; Mench et al., 2010; Touceda-González et al., 2017a), and generating profits where local conversion chains are present to value biomass (Andersson-Sköld et al., 2014; Conesa et al., 2012; Cundy et al., 2016; Evangelou et al., 2012; GREENLAND, 2014a). While the economic aspect is undoubtedly important for long-term sustainability, the wider environmental benefits generated in phytomanagement, especially at larger sites, are becoming increasingly salient in the modern context of widespread environmental degradation, biodiversity loss, rising sea levels, climate change and other challenges to meet the Sustainable Development Goals (Bardos et al., 2020; Keesstra et al., 2018a, 2016; O'Connor et al., 2019). Also, when viewed in this broader context as a nature-based solution (NBS), phytomanagement may gain wider acceptance as a mainstream land management strategy for broader situational applicability to contribute to sustainable development (Keesstra et al., 2018b; Song et al., 2019).

The GRO mechanisms listed in this study are well-established and their capability for managing contaminant linkages according to the source-pathway-receptor model as part of a risk-based land management (RBLM) scheme has been discussed at length, e.g. (Bardos et al., 2020; Cundy et al., 2016; GREENLAND, 2014a). However, GRO have rarely been broken down according to their specific risk mitigation mechanisms and synthesized in a manner that directly connects to specific exposure pathways for consequent risk reduction, as done here. For example, risk assessment in the Greenland project evaluated the long-term field studies in the program employing GRO according to certain contaminant linkages (e.g. soil to human, soil to animal, etc.) and showed how the respective risks could be reduced by GRO (GREENLAND, 2014a). The suggested generic framework presented in this study can support phytomanagement as a strategy by better communicating how different GRO strategies, and the main risk mitigation mechanisms that have been discussed throughout the literature, can be tailored to reduce risks to both humans and the environment by breaking specific contaminant linkages. The evidence base built into this framework can be used as a foundation from which to bolster the argumentation for phytomanagement and to understand its inherent limitations such as the longer time requirements for some GRO strategies comparative to conventional techniques, which can be addressed by educating stakeholders and giving decision-makers more realistic expectations.

Phytomanagement offers many opportunities for sustainable risk management but faces substantial obstacles to implementation, including regulator reluctance and legal frameworks that predicate contaminant removal based on total concentrations, the need for long-term maintenance and monitoring, inherent uncertainties in effectiveness, challenges imposed by climate change such as changing water supply and other such barriers that limit commercial use (Bardos et al., 2020; Conesa et al., 2012; Cundy et al., 2016; Gerhardt et al., 2017). Long-term monitoring is a key aspect to evaluate the effectiveness of phytomanagement for both ensuring regulators that contaminants are being managed as well as improving soil quality by monitoring important soil parameters linked to key soil functions or ecosystem services (Birgé et al., 2016; Burges et al., 2018; Epelde et al., 2014a; Garbisu et al., 2011; Gómez-Sagasti et al., 2012). Adaptive maintenance and monitoring (i.e. programs evolving iteratively to continuously improve) can be applied for phytomanagement projects in order to reduce uncertainty regarding remediation effectiveness and responses by soil biota to management (Birgé et al., 2016; Chapman, 2012; Epelde et al., 2014a). By including iterative decision points (e.g. every 5 years), it is also possible to re-examine the risk situation at the site after a period of phytomanagement to determine whether the site is fit for a different type of land use that was previously excluded given the prior risk situation. As noted in Chowdhury et al. (2020), alternative green land uses with various degrees of permanency are made possible over time with GRO interventions.

5.3. Limitations and need for future research

A primary limitation in the proposed framework for risk management and communication is the approximation of 'relative risk reduction time' that is inherent to GRO. Estimates for certain source removal mechanisms could be more easily gained from the literature (Kennen and Kirkwood, 2015; OVAM, 2019), however, risk reduction measures that focus on more complex soil chemistry dynamics like bioavailability reduction are more difficult to estimate and vary with site-specific conditions. For this mechanism, as well as vegetation cover, the time estimate was instead based on the approximate time for vegetation establishment or amendment activation to alter the soil environment. Future research to provide models enabling better prediction of the time required for the various GRO mechanisms would allow for greater sophistication in designing phytomanagement strategies to achieve an envisioned land use within a certain timeframe, though this would also require extensive monitoring and long-term field trials. Furthermore, the various risk mitigation mechanisms and how they reduce exposure to risk objects were based on available literature and made to generalise the GRO strategies included in this framework. From the literature review, no supporting evidence could be found on whether a lower bioavailability would reduce the human uptake of contaminants via dermal contact, but it is typically not a dominating exposure pathway for most contaminants. Also, there is no consensus for measuring and including bioavailability in existing risk management frameworks (Kumpiene et al., 2017). In addition, the evidence for the reduction of contaminant oral bioaccessibility in the gastro-intestinal system via GRO is controversial, with conflicting results, and would require further examination to be considered a viable strategy (Gray et al., 2006; Mench et al., 2006; Paltseva et al., 2020; Pelfrêne et al., 2015; Sanderson et al., 2015).

6. Conclusions

The main conclusions from the study are summarised below.

- The expected timeframes identified from literature are very generic and identified for groups of contaminants but could still be of considerable use to decision-makers. Models for more accurate predictions of timeframes under specific conditions would further strengthen the decision basis for GRO implementation. By including iterative decision points (e.g. every 5 years), it would be possible to re-examine the risk situation at a site after a period of phytomanagement to determine whether the site is fit for a different type of land use that was previously excluded given the prior risk situation.
- Improved communication is needed to support risk reducing strategies that emphasise a risk-based perspective instead of focusing exclusively on total amounts of soil contaminants. The generic framework is expected to facilitate better understanding and communication of the risk mitigating mechanisms and required timeframes of various GRO to support remediation contractors, decision-makers, regulatory bodies and other stakeholders related to contaminated sites. Ideally, the SEPA model would be better adjusted to reflect actual, realistic exposure scenarios and not be based on total contaminant concentrations but bioavailable concentrations along contaminant linkages derived from site-specific risk assessment.
- The case study application demonstrated that an envisioned land use, site-specific contaminants and indication of the important contaminant linkages can be integrated into the generic framework to support the identification of relevant GRO strategies and also provide preliminary timeframes for risk reduction. The framework can thus act as an early-stage decision-support tool to educate and engage remediation contractors, decision-makers, regulatory bodies and other stakeholders related to contaminated sites to identify relevant GRO, including potential phytomanagement strategies.
- The extensive literature review shows that there is evidence in literature to support the majority of the risk mitigation mechanisms associated with various GRO. However, no evidence could be found for whether a lower bioavailability would reduce the human uptake of contaminants via dermal contact and the evidence for the reduction of contaminant oral bioaccessibility is controversial and would require further examination to be considered a viable strategy. These exposure pathways can however be mitigated by other GRO mechanisms to remove the contaminants or to manage receptor access and prevent exposure.

CRediT authorship contribution statement

The authors contributed as follows: Conceptualization: P.D., S.C., Y.V., J.N.; Methodology: P.D., S.C., Y.V., J.N.; Investigation: P.D.; Visualization: P.D., S.C., Y.V., J.N.; Writing—original draft preparation: P.D., S.C., Y.V., J.N.; Writing—review and editing: P.D., S.C., Y.V., L.R., Y.A-S., J.N.; Supervision: Y.V., L.R., Y.A-S., J.N.; Project administration: J.N.; Funding acquisition, Y.V., L.R., J.N. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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