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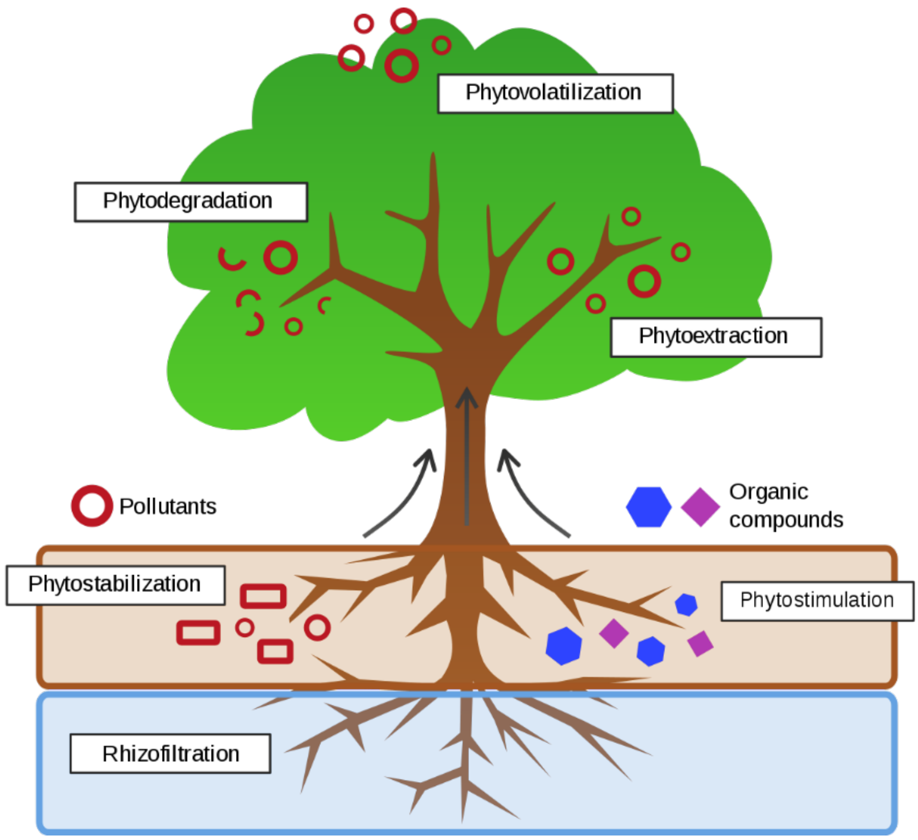

Gentle Remediation Options for Urban Brownfield Sites

Exploring Combinations with Bio-Based Production

Master's thesis in Infrastructure and Environmental Engineering

Paul Drenning

Department of Architecture and Civil Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018, ACEX30-18-88

Master's thesis 2018:88

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Master's Thesis 2018:88
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Typeset in LaTeX
Printed by Chalmers University of Technology
Gothenburg, Sweden 2018

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Abstract

The principal aims of this study were purposed to show that synergistic solutions in brownfield remediation through bio-based production projects can be realistic answers to many of the critical issues facing urban areas today. International recognition of widespread land contamination, natural capital degradation, planetary boundaries, increasing rates of urbanization, and shortages in available land and funds necessitate that low-impact, low-cost remediation techniques become more widely utilized. Implementing gentle remediation options (GRO) at urban brownfield sites can serve to alleviate many of the detrimental consequences from these problems by mitigating the risks posed by the contaminants, remediate the site and regenerate the latent natural capital stocks of soil and land, provide ecosystem services and biodiversity, provide sites for urban agriculture, reinforce holistic soil and land management strategies, and promote a circular bio-based economy through the productive use of the biomass produced on-site.

In this thesis work, a literature review was performed to explore the published field of work covering circular economy, brownfield redevelopment and remediation, GRO, and bio-based production systems for both renewable energy biomass production and food products. Best practices strategies, and knowledge were compiled for conducting a preliminary, feasibility study for two case study sites located in Gothenburg, Sweden. The *Rejuvenate* decision-support tool was applied as a guiding methodology, and the resulting bio-based production proposals were produced by following the four stage, checklist-based procedure as well as assimilating the expertise collected during the research phase. Resulting proposals focus primarily on risk mitigation through short-rotation coppicing (SRC) with willow and/or poplar, incorporating well-established agronomic practices like agroforestry and crop rotations with perennial grasses or other crop species to maximize benefits, and considering the viability of urban agriculture at the sites. The overall value offered by each proposal is demonstrated within the economic, environmental, and social aspects of sustainable development.

Keywords: brownfields, gentle remediation options, bio-based production, urban agriculture, circular economy, natural capital, ecosystem services, land management, phytomanagement, soil management.

Acknowledgements

I would like to thank my wonderful supervisors Jenny Norrman and Marco Adelfio for being patient and supportive throughout the entire writing process. Many thanks for keeping me on track by not letting me get too distracted chasing little details down the rabbit hole and for narrowing my vision to something achievable within the short time period I had. Thank you Lars Rosén for being the world's busiest man yet still managing to find the time to be my examiner. A huge thank you as well to Yvonne Andersson-Sköld for helping me talk through the *Rejuvenate* process and being so supportive. Also, thank you to my opponents Niklas and Bara for providing a critical ocular assessment of the thesis. Finally, a general thank you to all those working on the 4th floor who tolerated my presence at the coffee machine and on the balcony for 5 months.

Last but not least, to Chalmers friends - y'all are alright I guess.

Paul Drenning, Gothenburg, June 2018

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1

Introduction

This chapter provides the contextual background to the thesis, aims and objectives guiding the research, limitations, and the overall structure of the report.

1.1 Background and Key Concepts

Cities all throughout the world are changing. Rising rates of urbanization worldwide are projected to increase the populations of urban areas from the current 3 billion to approximately 6 billion by 2050 (Olofsdotter et al., 2013). At present, resource consumption in urban areas accounts for almost 80% of global emissions of greenhouse gases with disproportionately distributed wealth and environmental impacts affecting poorer areas more severely. While many urban areas are rapidly growing, others are shrinking. The problems faced by rapid growth or reduction differ, but ultimately the wicked problem of managing urban land in a sustainable, equitable manner will have to addressed by all involved in urban development. Rapid industrialization over the past century has introduced the added problem of widespread contamination in and around cities' soil and water systems (Olofsdotter et al., 2013).

In the wake of a surging international, national, and local emphasis on sustainability in all realms of society, many publications, action groups, international coalitions, and worldwide efforts have been designating greater scientific interest and effort into envisioning what a sustainable future could be in a rapidly urbanizing world. By 2020, about 80% of Europeans will live in cities which requires that long-range plans be created to guide the development of the continent's urban development and provide leadership in sustainability planning (Olofsdotter et al., 2013). The report by Rockström et al. (2009) concerning the planetary boundaries and the delicate balance we maintain with the earth has especially added a sense of urgency to recent efforts. Approaching the issues broadly, the European Commission's report, *Roadmap to a Resource Efficient Europe*, (EC, 2011*b*) addresses the challenges and opportunities for Europe as a whole to adapt their collective economies to both stimulate growth and ensure environmental sustainability through paradigm shifting transformations, rethinking the way we develop cities into more circular, holistic drivers of economic growth and innovation. The Vision for a Resource Efficient Europe is stated:

> *By 2050 the EU's economy has grown in a way that respects resource constraints and planetary boundaries, thus contributing to global economic transformation. Our economy is competitive, inclusive and provides a*

> *high standard of living with much lower environmental impacts. All resources are sustainably managed, from raw materials to energy, water, air, land and soil. Climate change milestones have been reached, while biodiversity and the ecosystem services it underpins have been protected, valued and substantially restored.*

Many other European Commission reports corroborate this vision through similar action plans and strategies. This includes the European Biodiversity Strategy to 2020 (EC, 2011*a*), the currently debated EU Strategy for Soil Protection (EC, 2006), the EU Renewables Directive (European Parliament, 2009), and the more recent action plan endorsing a transition to a more Circular Economy (EC, 2015). All of these action plans and strategies overlap and ultimately contribute to working towards a more sustainable future. In addition, many international networks and joint projects have contributed to creating a robust body of literature, research, pilot studies, and decision support tools to aid in the redevelopment of *brownfield* land. This term is used to classify a type of land in an urban area that was previously used for industrial or commercial purposes which is (or is at least perceived to be) contaminated by concentrations of hazardous waste, organic pollutants or metals, and has been wholly abandoned or fallen into a non-productive use state (Bardos et al., 2016; Cundy et al., 2016; Olofsdotter et al., 2013). These brownfield sites are unique in that they provide windows of opportunity to both practice *sustainable remediation* on the contaminated sites (to regenerate for more productive use) and for transitioning into a more *holistic* or *circular land management* strategy (described in more detail in later sections). Furthermore, recent investigations into urban redevelopment has shed light upon the expanded value which brownfields offer. Namely, precious natural capital resources, generation of ecosystem services, and the potential for bio-based production in sync with plant-based remediation all contribute to a circular economy and a more sustainable urban environment. In a recent study, Schröder et al. (2018) state the importance of this task:

> *From an ecological point of view, the rationale for restoration of degraded or marginal land is to recover lost aspects of local biodiversity and ecosystem resilience. From a pragmatic point of view, it is indispensable to recover or repair ecosystems and their capacity to provide a broad array of services and products upon which human economies and human life quality depends.*

In this study, some of the major challenges addressed by the European Commission reports will be discussed to highlight opportunities for sustainable development and circular land and soil management in urban areas through the reuse of abandoned or contaminated land commonly known as *brownfields*.

1.2 Aims and Objectives

The objective of this thesis work is to investigate methods for selecting gentle remediation options (GRO) for both remediating contaminated brownfields and facilitating bio-based production while promoting a circular economy, land use, and soil management strategy. Synergistic solutions focusing on low-cost and low-impact, risk-reducing GRO, supporting biodiversity to provide ecosystem services while simultaneously ensuring soil functionality, and exploring possibilities for bio-based production (e.g. energy crops, urban agriculture) to work in parallel with such remediation options at brownfield sites will be proposed. This thesis work will be targeted towards providing a foundation of useful research into the above mentioned themes for use in future projects performing more robust analyses and practical applications of these techniques. The questions guiding the research are as follows:

1. What different GRO are available and tested? Are there any best practice cases? Under which site conditions are different GRO suitable?
2. What type of bio-based production systems can be applied in an urban setting? Are there any case studies or best practices? Are there regulatory obstacles to such systems?
3. How can GRO and urban bio-based production be combined? How does this contribute to a circular economy?
4. What are the inputs (e.g. nutrients, soil amendments) and outcomes of such systems (e.g. remediation of soil and water, crops, ecosystem services, metal recovery, etc.) and how does it related to a circular, bio-based economy?
5. What are the benefits offered by the various decision-support tools created to guide brownfield remediation and restoration? How are they applied?

Following the research phase, the subsequent aim is to apply the concepts and knowledge gained to propose viable, preliminary bio-based production systems for two case study sites located in Gothenburg, Sweden.

1.3 Limitations

Due to time limitations of performing the Master's thesis work over only 6 months, many issues connected with the main objective and brownfields in general will be neglected in order to focus more specifically on gentle remediation techniques, bio-based production, ecosystem services in an urban context, soil management and the combination of these in a circular economy. An additional limitation is the lack of site-specific soil sampling at either contaminated brownfield site for use in this case study application. Also, pilot testing of the methods covered in the report is impossible due to the time-scale involved. The practical application will need to be performed later in future, related projects.

1.4 Structure of the Report

Following chapter 1's general introduction to the thesis work, chapter 2 provides an in-depth explanation of the methodology followed in performing the study in two parts: thematic literature analysis and case study application of the *Rejuvenate* decision-support tool. Chapters 3-6 discuss the major research themes identified as important in answering the first three research questions, including: 3) Bio-based circular economy, 4) Brownfield redevelopment, 5) Gentle remediation options, and 6) Bio-based production. Chapter 7 presents the important findings from the research in the form of two tables listing best practices in both risk-based and bio-based production approaches to urban brownfield remediation projects.

Chapter 8 presents the two case study sites considered in this study, and then the stepwise application of the *Rejuvenate* DST to determine appropriate bio-based production systems at either site. Chapter 9 summarizes the most important issues, drivers, inhibitors, and DST procedures discussed throughout the thesis as well as other relevant factors for future investigations, answering the final two research questions. Finally, chapter 10 gives a short conclusion.

2

Methodology

This chapter presents the methodology followed in the study via separation into two major parts. The first being a comprehensive thematic analysis of brownfield remediation literature and extraction of best practices, followed by the secondary procedure to apply a decision-support tool for the case study sites.

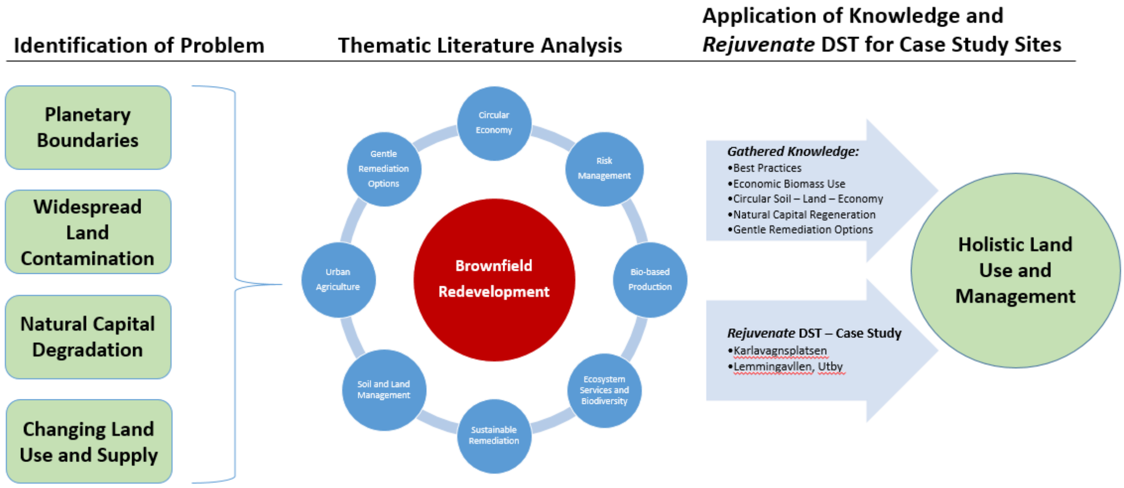

Figure 2.1: Methodology Flow Chart, own work.

2.1 Literature Review

The first phase of this thesis work was to conduct a thorough literature review of the vast sea of research pertaining to the guiding research questions 1-3. As depicted in Figure 2.1, the observed methodology began with identifying the combination of factors contributing to the major problem of widespread contamination which was briefly introduced in the previous chapter. Following identification, qualitative research to identify major themes within the published body of work in this field was performed by loosely following a type of thematic analysis[1] research technique. Initially applied during problem framing, a thematic analysis research approach was useful to move from a broad reading of the data toward discovering patterns and central concepts which could be compiled into coherent strategies and best practices. Four major themes, with corresponding sub-themes, were created for organizing the

[1]http://designresearchtechniques.com/casestudies/thematic-analysis/

important findings from literature. Beginning with broader, macro-level issues and concerns like circular bio-based economies and brownfield redevelopment to understand the big picture, gentle remediation options and bio-based production systems were then explored in greater detail to eventually compile relevant projects and knowledge into best practices tables for both a risk-based and bio-based production approach in implementing GRO on contaminated sites.

2.2 Decision-Support Tool Application

The *Rejuvenate* decision-support tool (Andersson-Sköld et al., 2014, 2013) was developed with the aim of supporting site-specific decision making for evaluating the potential of brownfield sites to produce biomass for bio-fuel production or other bioenergy uses. A practical complement exists in utilizing plants for phytoremediation to rehabilitate brownfield sites and for biomass production on marginal land for economic gain. *Rejuvenate* seeks to support such crop-based systems on marginal land, and aligns closely with the aims and objectives of this study thus making it a valuable tool to apply. The DST has four broad, interlinked stages that can be used to refine choices for biomass production on marginal land, shown in Figure 2.2. The framework forms an iterative funnelling process with the four stages as described below:

- **Stage 1.** Crop suitability: the output from this stage identifies a short list of biomass crops that are able to grow under the local conditions and have a market outlet, preferably within the local region.
- **Stage 2.** Site suitability: the output from this stage identifies a shortened list of crops that could be grown on-site and specifies the management interventions needed to achieve this.
- **Stage 3.** Value management: the output from this stage identifies project options that are financially viable and sustainable.
- **Stage 4.** Project risk: the output from this stage is a realistic appraisal of project risks and a mitigation strategy for these risks.

The aim of incorporating the *Rejuvenate* DST was for use as an analytical framework (i.e. guiding methodology) in evaluating the potential at both case study sites in Gothenburg for bio-based production, answering research questions 4 and 5. Coincidentally, *Rejuvenate* was applied in Sweden and performed in more detail than at other project sites which allowed real-world considerations to be included in this analysis. It also provided better geographic context in using the DST, and allowed the methodology to be followed fairly closely (Andersson-Sköld et al., 2014). Figure 2.3 depicts the stage-gate flowchart used for the overall procedure. See Appendix 3 for checklists used in each individual stage.

The full iterative procedure was not possible to apply in its entirety for each stage, so assumptions based upon knowledge gained during literature review, best prac-

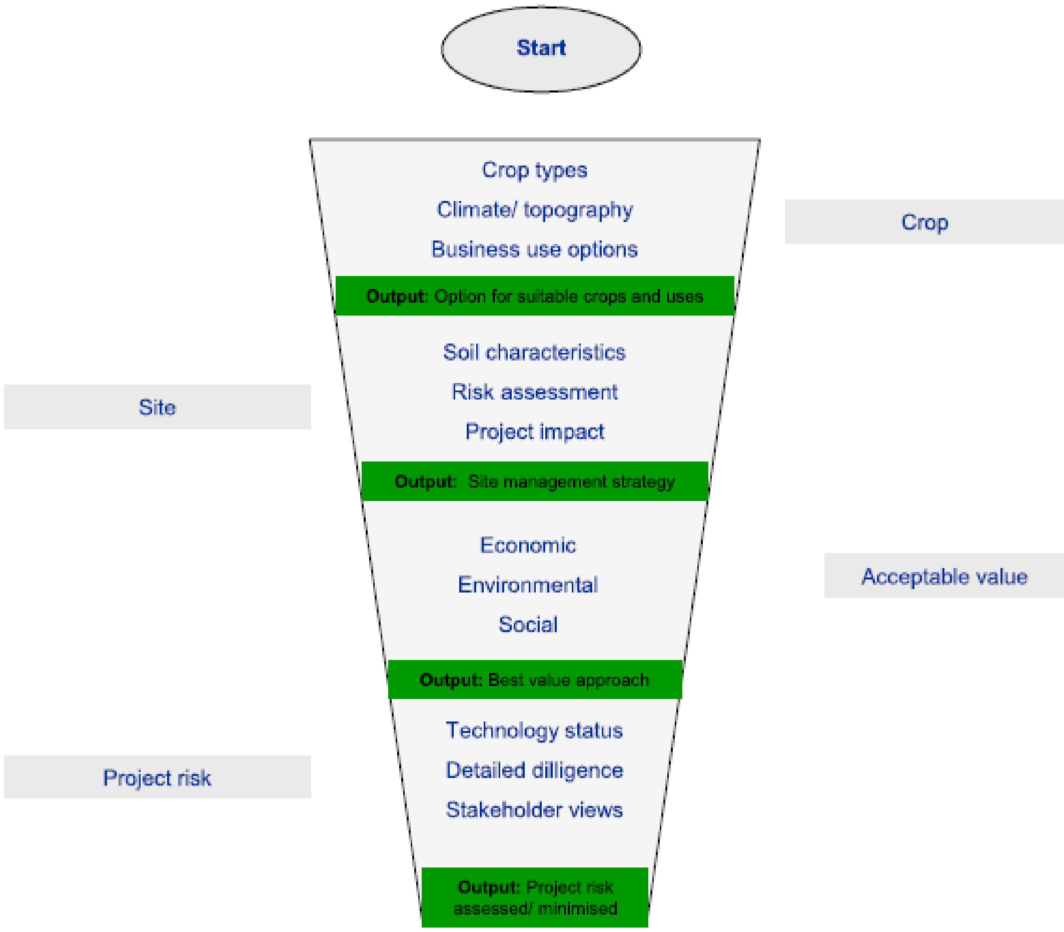

Figure 2.2: Stages of the *Rejuvenate* DST and funneling process, from Andersson-Sköld et al. (2013). Reprinted with permission from author.

tices performed successfully, and personal judgments in consult with expert opinion had to be made. For transparency, assumptions made throughout application are explicitly stated. Certain aspects of the DST were neglected altogether due to lack of information, or falling outside the scope of this study. For example, financial feasibility is only briefly addressed in this study and no detailed CBA calculations were performed. Also, Stage 4 is focused upon practical project implementation and planning like stakeholder involvement, due diligence, and detailed planting trials which are only briefly addressed as points of discussion.

Application of *Rejuvenate* in this study is best viewed as a predominantly qualitative review performed *early in the project planning process* to determine crop suitability and feasibility, important site and risk management considerations, and the potential overall value offered by the proposed bio-based production system. Applying the DST according to Andersson-Sköld et al. (2014), an iterative procedure for crop selection was established, and when performed early it can quickly identify the most viable management options in a project. Specific outcomes and influential factors followed per stage are listed below:

- **Stage 1:** Filter the broad range of plant/crop species gathered from literature into a narrow list which can meet the specific site's needs in terms of: risk mitigation of contaminants, growing potential under local climate conditions, objectives for each site, and usage of produced biomass.
- **Stage 2:** Evaluate each site (qualitatively) to determine: quality of the soil, interventions or soil amendments required, site-specific risk mitigation, agronomic practices to ensure effective plant growth, and other site considerations necessary (e.g. biomass conversion facilities). Feasible bio-production options will be proposed resulting from this stage.
- **Stage 3:** Demonstrate the overall value of proposed bio-based production projects at the site through: evaluation of ecosystem services provided, wider project services and benefits through brownfield redevelopment, economic potential from biomass produced, and sustainability appraisal.
- **Stage 4:** General discussion of wider project considerations, including: involving stakeholders, indicators of project success and verification, and the possibility of urban agriculture at the site.

Furthermore, a guiding question was considered during application of the *Rejuvenate* DST: *How does Rejuvenate work for all forms of bio-based production aside from purely bioenergy?* This was deemed to be an important question so as to evaluate the DST in terms of potential for other forms of bio-based production aside from purely bioenergy (e.g. other bio-products and food crops) in contributing to a circular economy. A brief reflection on using *Rejuevenate* is included in the final discussion section.

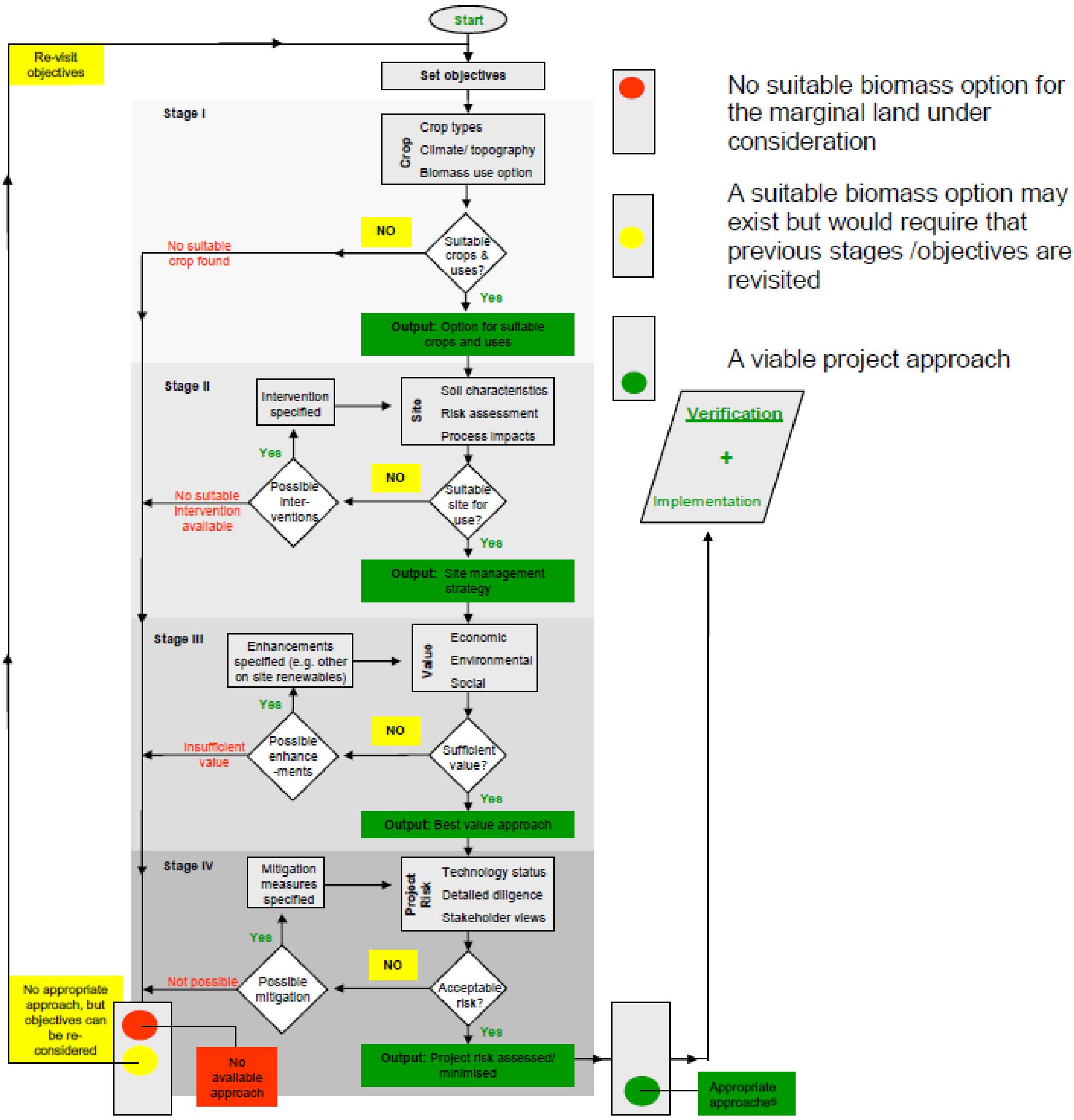

Figure 2.3: Overall *Rejuvenate* decision-support flowchart, from Andersson-Sköld et al. (2013). Reprinted with permission from author.

3

Bio-Based Circular Economy

The following sections introduce theory behind bio-based circular economies, the importance of natural capital, soil management, ecosystem services, and how transitioning towards circular land and soil management can promote circular economy principles.

3.1 Circular Economy

A *circular economy* is composed of two material cycles:[1] a technical cycle and a biological cycle. The technical cycle refers to the use of mineral resources (e.g. metals, plastics) as production inputs, and designing products and their parts in such as way as to allow reuse or recovery of the input materials. In the biological cycle, resources have a biological origin which allows the products or components to be safely restored into the natural system at the end of useful life. This system is meant to be both ecologically and economically restorative, and the concentrated application of circular economy practices is an important tool to achieving the SDGs and the EU's 'closing the loop' strategy (Breure et al., 2018; EC, 2015; Ellen MacArthur Foundation, 2015). Breure et al. (2018) explain the importance of transitioning towards a circular economy through the lens of three distinct perspectives:

- *Planetary Boundaries*: First conceived by Rockström et al. (2009), the global, ecological boundaries erected to stave off worldwide devastation represent the carrying capacity of the earth for 9 distinct categories. Soil is directly related to at least the boundaries of bio-geochemical cycles, environmental pollution, biodiversity, and changes in land use.
- *Integration within the social system*: Considering the future provisioning of resources within a circular economy to society, extraction of mineral resources exerts a degrading pressure on the natural environment which inhibits sustainability. These activities will have significant impacts on the landscape, biodiversity, soil quality, water bodies, and air. Incidentally, a shift towards more bio-resources used in the biological cycle will compete with the agricultural production of food. Soil and land will become precious commodities which further increases the necessity of circular economy principles..
- *Land Management*: Land itself is a finite and shrinking resource. Changes in land use and widespread degradation has put tremendous stress on this natural

[1] `https://www.ellenmacarthurfoundation.org/circular-economy/overview/concept`

resource which affect the role land and its soil systems play in bio-geochemical cycling and the host of other ESS it provides. If the EU hopes to curb land consumption and achieve the goal of net-zero land take by 2050 then circular economic principles are vital.

Given these three key drivers, soil and land must also be included in the circular systems approach to the economy and development through recycling and regeneration. *Holistic* or *Circular flow land use management* are terms used to describe this methodology which entails reducing the consumption of *greenfields* (i.e. undeveloped, natural land) and utilizing the full potential of all pre-existing sites, especially urban brownfields (Preuß and Ferber, 2005). Furthermore, the demands placed by provisioning of food supplies (or biomass in general) to cities is also typically included in a circular economy (EC, 2015; Ellen MacArthur Foundation, 2015). Conventional, large-scale agricultural techniques are one the world's leading causes of greenhouse gas (GHG) emissions and contribute to a plethora of other negative impacts, but there is great potential to mitigate these damages with a shift to food production within cities via *urban agriculture* (UA). Research from Goldstein et al. (2016) show that UA has proven benefits with GHG reductions, reduced urban heat island effect, and storm water mitigation alongside other ESS compared with conventional agricultural practices. Tripathi et al. (2016b) state that coupling (phyto-) bioremediation with carbon sequestration via growing plants at contaminated or polluted land can help to mitigate the many problems caused by rapid industrialization, urbanization, and intensive agricultural activities. Deriving valuable products from renewable and waste biomass produced in bioremediation directly supports the future bioeconomy. Potential bio-products include: bio-fuels, bio-surfactants, bio-composites, industrially important solvents, bio-plastics, and pharmacological products to name a few. Figure 3.1 provides a visual depiction of the range of possibilities for biomass products (including an innovative combined heat and power plant in Stockholm which would benefit from increased biomass stock). Urban food production, bio-energy production systems, and other bio-products produced in sync with brownfield remediation will be a focus point throughout this study to explore the potential in contributing to a bio-based circular economy.

3.2 Natural Capital

According to the European Commission, a major problem associated with our current resource consumption patterns is that our common pool of *natural capital*, defined as the world's stock of natural assets including geology, soil, air, water, and all living things[2], are treated as infinite, 'free' commodities whose value is not sufficiently accounted for in modern economic markets (EC, 2011*b*). This has inevitably led to detrimental depletion, pollution, and a wide range of associated threats to our long-term sustainability and resilience to environmental shocks. An important subset of natural capital are *ecosystem services* (ESS), defined here as the goods and

[2] `https://naturalcapitalforum.com`

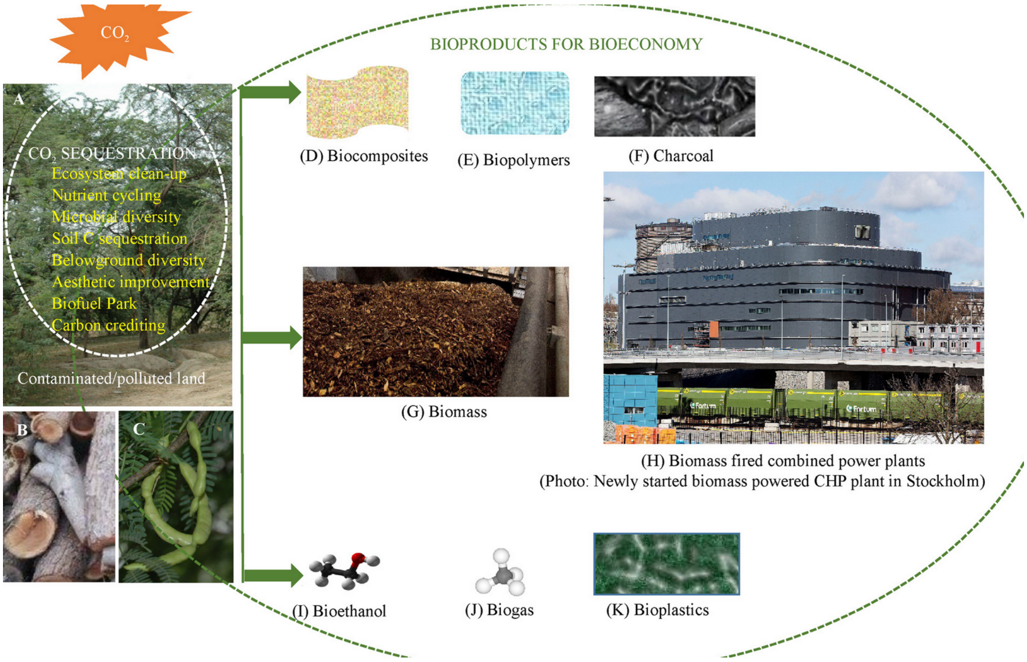

Figure 3.1: Potential Bio-products for a Bioeconomy, from Tripathi et al. (2016b). Reprinted with permission from Elsevier and Lancet.

services that humans derive from natural and human-modified systems on which societal welfare and economic development directly depend (MEA, 2005; TEEB, 2011). According to EC (2011*b*), ESS have been degraded by approximately 60% (in total) worldwide over the last 50 years. In addition, *biodiversity*, the variety of life on earth essential to the health and functioning of ecosystems and their ability to provide ESS to humans (MEA, 2005; TEEB, 2011), has similarly been lost worldwide from neglect, over-exploitation, land-use changes, pollution, etc. Urgent action is mandated in EC (2011*a*) to curb the rapid rates of species loss in Europe by placing greater importance on sustainable practice in agriculture and forestry, nature conservation, economics, and infrastructure enabling ESS. Investment in natural capital, ESS and biodiversity is widely considered to be of tremendous importance, and is reflected in the milestones (e.g. reversing the destructive trends, mitigating damages, and achieving net-zero land take) set by the commission to be met by 2020 (EC, 2011*b*).

More specifically, ecosystem services, as developed by MEA (2005), are broken down into four categories: Provisioning, Regulating, Cultural, and Supporting Services. Provisioning are the most direct services which are the tangible products obtained from ecosystems like food, fibre, and energy. Regulating services are those benefits obtained from ecosystems naturally regulating the environment through processes like air and water filtration, carbon sequestration, etc. Cultural services are non-material benefits humans gain from ecosystems such as spiritual enrichment, cognitive development, recreation, and natural aesthetics. Supporting services are those necessary for the production of all other ESS, underlying all others like nutrient cycling and soil formation (MEA, 2005; Olofsdotter et al., 2013). The full range of urban ESS was explored in great detail by the *Cities and Biodiversity Outlook* consortium which created the first global assessment of the linkages between urbanization, biodiversity, and ESS (Gómez-Baggethun et al., 2013), and in the *TEEB Manual for Cities* (TEEB, 2011). Olofsdotter et al. (2013) believe that: *"Urbanization is both a challenge and an opportunity to managing ecosystem services globally, regionally, and locally."* In order to do so, a shift from predominantly grey infrastructure, traditional built 'hard' infrastructural systems, to blue-green infrastructure must be emphasized. In their report, Olofsdotter et al. (2013) define blue-green infrastructure as: Interconnected networks of land and water that support species, maintain ecological processes, sustain air and water resources, and contribute to the health and quality of life for communities and people. The term 'soft use' is often used to refer to this type of land use that supports ecological systems, as opposed to hard uses, such as paving or sealing over soil systems. Future urban development implementing blue-green infrastructure and ESS shows great potential to mitigate climate change, bolster urban resilience, and increase human well-being; however, land competition is fierce in most of the world's fastest growing cities. The most readily developable land typically goes to the economic activity with the greatest return, not those with predominantly environmental uses and low economic profitability.

3.3 Soil Management

Soil is generally defined as the top layer of the earth's crust, formed by mineral particles, organic matter, water, air, and living organisms. It is the interface between earth, air, and water and hosts most of the biosphere. Furthermore, since soil formation is such a slow process, soil is essentially a nonrenewable resource, and as such, one that is rarely given the attention and priority it deserves (EC, 2006). Soil degradation is a serious problem throughout the world which is exacerbated by human activities like poor agricultural and forestry practices, industrial activities, urban sprawl and pollution, and construction. Degradation, contamination, and rampant *soil sealing* (covering with impermeable surfaces like concrete and asphalt) prohibit soil from performing its essential services (i.e. ESS) which enable human life to exist. Among these services are: providing biodiversity habitats above and below ground, cleaning water for replenishing aquifers, regulating micro-climates in compact urban environments, nutrient cycling, carbon sequestration, and many more (Blümlein et al., 2012; EC, 2006). Of particular emphasis is the effects of soil sealing and how to *limit, mitigate,* and *compensate* for it as urban areas expand. Limitation (and mitigation to a lesser extent), as defined by Blümlein et al. (2012); EC (2006), is most relevant to this study as it entails a two-pronged approach of reducing land take in urban areas and reusing the previously sealed or contaminated land (i.e. brownfields). The comprehensive overview of the strategy is covered in painstaking detail in the EU-27 final report (Prokop et al., 2011).

To achieve any of the ambitious goals set through the action plans and strategies, sustainable soil management must take a higher precedence in urban planning and development as it directly contributes to meeting the goals and milestones set by all previously mentioned European Commission plans (EC, 2006, 2011*a*,*b*, 2015).

In 2006, the *Thematic Strategy on Soil Protection* (EC, 2006) was proposed to bring attention to the seriousness of the situation and prescribe a methodology for lessening the impacts of urban development. Keesstra et al. (2016) take this even further to state that soil science and management is essential to the realization of the United Nations Sustainable Development Goals[3] due to 7 specific functions that soil provides, the 12 associated ESS, and how these correspond to the 17 SDGs (see Appendix 1 for the well-detailed graphical abstract of their paper). The sustainable use of the natural capital in the soil system will enhance the resilience of a city while providing opportunities for urban farming, green space and recreation, and greater well-being for urban citizens (Breure et al., 2018; Norrman et al., 2016, 2015).

3.4 Circular Land and Soil Management

The ideal combination of circular economy principles, natural capital preservation, ecosystem services provision, and sustainable soil management would culminate into a circular or holistic land use management strategy. As previously mentioned, urban brownfield sites play a key role in maximizing the latent potential of land and soil resources and using space effectively in and around cities (Breure et al., 2018; Preuß and Ferber, 2005). According to Preuß and Ferber (2005), systematic rehabilitation of contaminated or otherwise derelict brownfield sites requires the integration of their potential into the urban land use cycle. Obstacles related to planning, cooperation, information, management, financing, etc. will have to be overcome with integrated, turnkey solutions to do so effectively. Municipalities pursuing strict financial gain have historically overlooked brownfield sites which show low economic promise; however, it is precisely these sites which should be exploited for their wide range of other environmental and social benefits. Circular (flow) land use management should reduce the length of time which this land lies vacant or unused, and promote solutions to regenerate land and soil (Preuß and Ferber, 2005).

As stated by Breure et al. (2018):

> *The circular economy provides a framework for the management of natural capital, including land and soil, mineral resources, fossil fuels, water and biodiversity as an asset and provides incentives for efficient use and management.*

[3] `http://www.un.org/sustainabledevelopment/sustainable-development-goals/`

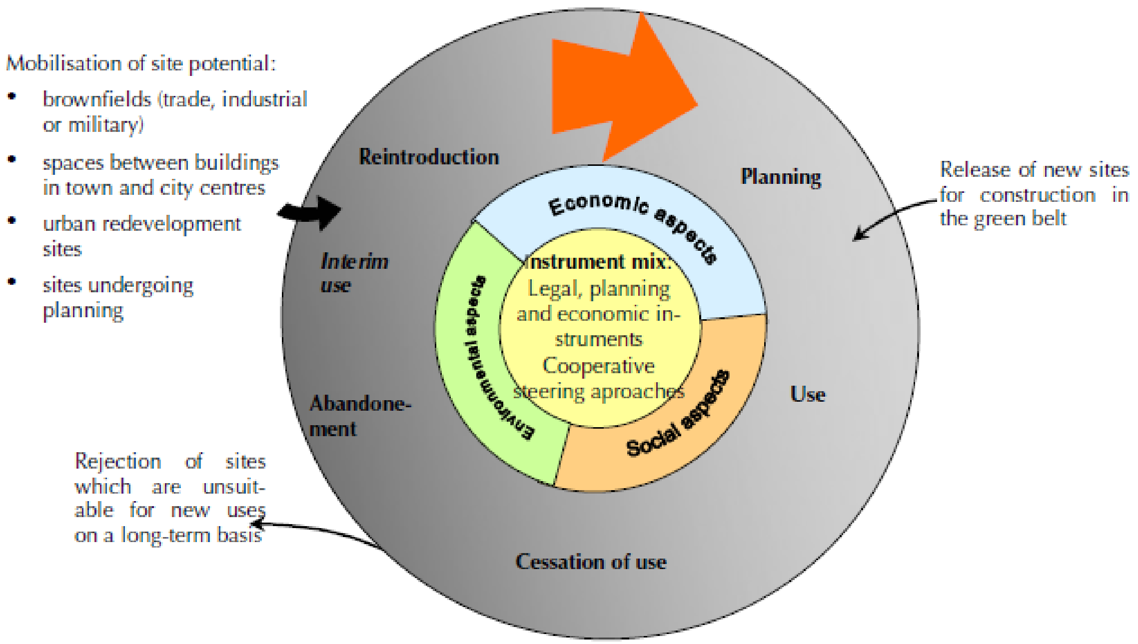

Figure 3.2: Circular land use model of phases and potential for reuse, from Preuß and Ferber (2005). Reprinted with permission from author.

4

Brownfield Redevelopment

This chapter describes in more detail brownfield redevelopment land use issues, soft reuse approaches to remediation, and frameworks used to determine the overall value, sustainability and risk mitigation efficacy of remediation efforts.

4.1 Urban Land Use

A milestone in the *Roadmap to a Resource Efficient Europe* (EC, 2011*b*) states:

> *By 2020, EU policies take into account their direct and indirect impact on land use in the EU and globally, and the rate of land take is on track with an aim to achieve no net land take by 2050; soil erosion is reduced and the soil organic matter increased, with remedial work on contaminated sites well underway.*

In light of the updated view of land as both natural capital and a resource, reusing brownfield land has grown tremendously in importance (EC, 2011*b*). Cundy et al. (2016) state that there are an estimated 1 million potential brownfield sites across the European Union (possibly even up to 2.5 million throughout the whole of Europe according to Cappuyns (2016)), so there are a vast number of test sites and opportunities for applying the new generation of sustainable best practices. 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. This problem is of particular concern for large land areas or smaller, marginal sites where contamination inhibits immediate development, but economic return post-remediation does not justify the costs (Cundy et al., 2016). The European CABERNET project (Concerted Action on Brownfield and Economic Regeneration Network) categorized brownfield sites based on market value ranges as 'A', 'B', or 'C', as shown in Figure 4.1, where:

- A Sites are economically viable and the development projects are driven by private funding for later economic returns. These tend to be for building projects (i.e. hard reuse)
- B Sites are on the borderline of profitability, and tend to be funded through public-private partnerships or co-operation.
- C Sites are not in a condition where restoration could be profitable. Thus, their restoration relies mainly on public sector or municipality driven projects often dependent upon public funding or tax incentives to stimulate projects.

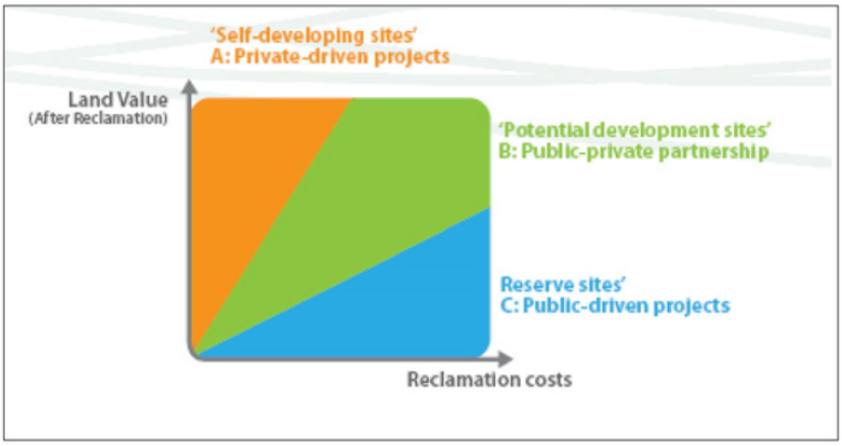

Figure 4.1: Three categories of Brownfields, from Bardos et al. (2016). Reprinted with permission from Elsevier and Lancet.

Based on this analysis, albeit simplified, one could first ascertain that type A sites would be intrinsically valuable enough to warrant remediation in a conventional, rapid sense for immediate reuse. Secondly, type B and C sites have limited profit motive, high risks, and other liability burdens. On these sites where hard reuses (involving some form of building or grey infrastructure) are not feasible, soft reuses (limited building or construction) provide ideal opportunities for long-term, low-input, and low-impact remediation and restoration into a more productive state (Bardos et al., 2016). Olofsdotter et al. (2013) succinctly summarize the issue of land competition and the difficulty of providing land for ESS, stating: *Two of the most intensive competitions for land concern all citizens in their role as users of different types of land: the conflict between agricultural use on the one side and "urban" functions on the other, and the conflict between societal interests and the reproductive needs of nature, upon which all societies depend.* Figure 4.2 shows the many potential overarching benefits from brownfield redevelopment which could provide renewed value to degraded land.

4.2 Soft Reuse

One of the major international efforts to create a comprehensive methodology to approach *brownfield regeneration* is the HOMBRE (Holistic Management of Brownfield Regeneration) project[1] funded by the European Commission within the Seventh Framework Programme. Where, regeneration is defined as "*a set of activities that reverse economic, social and physical decline in areas where market forces will not do this without support from government*" (Atkinson et al., 2014). HOMBRE's overarching aim was to demonstrate that *soft reuse* of brownfield sites managed in a sustainable, holistic way can generate substantial value for both public and private investors. In general, the authors believed that the value generated was costed too narrowly where the full range of benefits and opportunities for improving overall

[1] http://www.zerobrownfields.eu

Environmental	• Reduced use of Greenfield sites • Air quality improvements (from reduced transportation needs to more distant Greenfield locations) • Reduced energy consumption and greenhouse gas production (from reduced transportation needs to more distant Greenfield locations) • Water quality benefits • Environmental benefits (for example reduced negative ecosystem impacts)
Economic	• Site value • Neighbouring property values • Employment and investment benefits • Leverage of additional investment • Leverage of additional employment • Improvement in local property values • Improvement of local taxation revenues • Avoidance of Greenfield infrastructure requirements/-agglomeration benefits (*e.g.* greater urban density)
Social	• Reduced threat to public health • Reduced traffic (from reduced transportation needs to more distant Greenfield locations) • Amenity benefits such as improved appearance • Health benefits

Figure 4.2: Overarching benefits from brownfield remediation, from Bardos et al. (2016). Reprinted with permission from Elsevier.

value were missed in favor of purely *hard reuse*. The defining characteristic of *soft reuse* is that the soil remains biologically active in an 'unsealed' state able to be used as a growing medium for agriculture, animal habitat, forestry, or some other valuable bio-based production. In contrast, *hard* development describes some form of building or infrastructure where the ground is paved (over) and sealed, rendering soil microbial life inert. At the core of HOMBRE's approach is the use of integrated processes (treatment chains) to deliver optimized benefits (services) for targeted beneficiaries or stakeholders through the core concept of *circular land management*. Synergies between environmental, economic, and social services could enhance the overall, multi-dimensional value of a brownfield restoration project to more accurately reflect modern societal wants and needs (Bardos et al., 2016; Menger et al., 2013).

Cundy et al. (2013) state that there are many drivers for soft end uses of contaminated land. The site in question may simply not have a feasible alternative use for reasons of size, location, geotechnical or topographical reasons, or levels of economic activity, as a result of global shifts in land (hard or soft) use and industrial change for example. Urban renewal plans may be an important reason for developing amenity land, particularly in areas of urban deprivation, dereliction or historic contamination. Recent emphasis placed on biomass production aim to fully utilize brownfield as opportunities for generating renewed economic activity. For example, the 2009 EU Renewables Directive (European Parliament, 2009) points out an enhanced sustainability value for biomass from marginal land, and using GROs can be highly compatible with biomass end use (Bardos et al., 2016; Cundy et al., 2016; Menger et al., 2013). This creates an important and expanding niche for GROs, as an important part of the value proposition for the management of degraded land in the future might be an income from biomass-based GRO (Cundy et al., 2013).

In providing support for an improved valuation scheme for soft reuses, the HOMBRE project created an operative framework for optimizing value at brownfield sites, shown in Figure 4.3. Circular land management is a central theme to HOMBRE's approach and is structured around the three key principles of avoiding new brownfields, recycling existing brownfields, and compensating for the effects of land consumption (Bardos et al., 2016; Menger et al., 2013). To better support soft reuse as an effective brownfield regeneration tactic, the framework is oriented around demonstrating the full value of such soft uses (i.e. plant-based techniques), their applicability per specific project, and the range benefits offered which are not typically accounted for in traditional economic valuation.

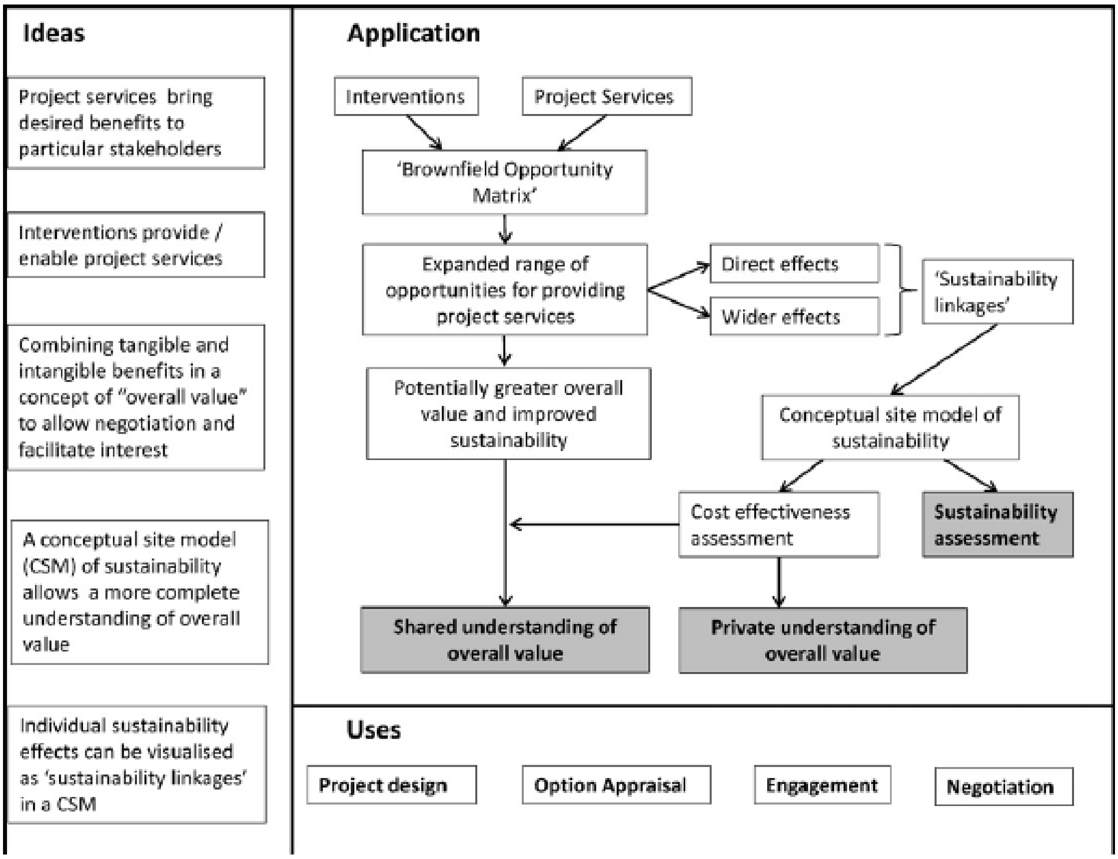

Figure 4.3: Framework for optimizing value from the soft reuse of brownfield sites (Bardos et al., 2016). Reprinted with permission from Elsevier and Lancet.

4.2.1 Interventions and Project Services

Synergistic solutions are the essence of HOMBRE's approach for brownfield value generation. These 'win-win' proposals aim to design an *intervention* at a brownfield site (e.g. remediation treatment, soil improvement) to achieve a particular set of beneficial outcomes for the various stakeholders involved. Therefore, The sustainability of a restoration project is the combination of the benefits as provided by the project and the wider effects of the intervention itself, see Appendix 2 for lists of example interventions and services. It follows then that the value of a project, so far as it stimulates stakeholders to invest capital and effort to gain the resulting benefits, is tempered by the acceptance of these wider effects. Addressing sustainability in this context as a form of transaction has been a point of focus in the HOMBRE project to improve the overall value of a planned brownfield regeneration project. The term *project services* was coined through the HOMBRE project as a functional descriptor to better understand the linkages between a restoration project's benefits and their value to individual stakeholders (i.e the benefits gained by a specific beneficiary as a result of a project). Three components are essential for a deliverable project service: 1) an intervention of some kind at a brownfield site, 2) one or more planned benefits as outcomes of the intervention, and 3) one or more beneficiaries to reap the benefits. Project services as a concept are useful both to lucidly describe the outcomes of restoration projects addressing the main concerns of stakeholders and to demonstrate the value of investments for such projects (Bardos et al., 2016; Menger et al., 2013).

4.2.2 Ecosystem Services

An important classification in the HOMBRE framework is the designation of ESS as a subset of the overarching umbrella-term of project services. The protection or enhancement of ecosystem services is itself a service which could (and should) be designed into a regeneration project (Menger et al., 2013). In general, project services and ecosystem services are not fully aligned in the HOMBRE framework for three main reasons: 1) Not all benefits achievable from brownfield restoration fall directly within ESS but rather as human activity, 2) Some services are consequential economic benefits like the recovery of land values for the site and surrounding areas which have a major bearing on the economic viability of a brownfield project, and 3) ESS describes a 'steady-state' of provision, but benefits from brownfield restoration accrue both from the process and outcome of restoration (i.e. temporal differences) (Bardos et al., 2016). In HOMBRE, the term *green infrastructure* is used as a broader, more inclusive descriptor for soft regeneration of brownfield land to provide direct environmental benefits, ecosystem services, and other amenities. According to Menger et al. (2013), green infrastructure performs the following four roles:

- Protecting ecosystem state, building ecological networks and improving biodiversity
- Improving ecosystem functioning and promoting ecosystem services

- Promoting societal well-being and health
- Supporting the development of a green economy, and sustainable land and water management

In terms of practical site application, green infrastructure and open spaces in urban and peri-urban contexts could take the form of public parks, riparian zones for flood and sensitive environment protection, sports fields, biodiversity reserves and natural parks, urban forests, and gardening allotments (Menger et al., 2013). All of these soft site uses offer a whole host of services, many of which are considered ESS.

Furthermore, many approaches for valuation and inclusion of ESS in an urban context have been explored recently, including: Development for Integration of Ecosystem Service Assessment into the Water Framework Directive and Floods Directive Implementation (COWI et al., 2014), a semi-quantitative ESS-mapping DST (Ivarsson, 2015), framework for assessing urban greenery's effects and valuing its ESS (VEKST) (Andersson-Sköld et al., 2018), and other geographic specific valuation schemes in general (Mell et al., 2013; Schäffler and Swilling, 2013; Vandermeulen et al., 2011). The most applicable use of these ESS valuation schemes in the context of this study is through supporting the added value claims to justify a brownfield regeneration project in an urban area. This is best stated by Ivarsson (2015) in saying that the ESS-mapping procedure "*indicates that a semi-quantitative approach to map the changes in provision of ecosystem services that will follow from different redevelopment alternatives will potentially add important decision support regarding the economic and social desirability of available options. The principal strength of the method is its ability to map and quantify changes in well-being that in many cases are neglected in applications of cost-benefit analysis to redevelopment projects, despite the relevance of those changes in such analysis.*"

Also, a strong emphasis on the provisioning of ESS, green infrastructure, urban agriculture, etc. aligns with modern urban ecology and planning practices seeking to 're-green' cities. A few such theories are ecological intensification, continuous productive urban landscapes (CPULs; Viljoen et al. (2012)), ecological land-use complementation to promote biodiversity in urban areas via 'mosaic' patterning (Colding, 2007), integration of non-urban areas (e.g. agriculture, green infrastructure) into urban areas (La Greca et al., 2011), eco-dynamic design, restoration agriculture, and the 'internalization' of ESS in conventional urban planning practice (Cortinovis and Geneletti, 2018). Without necessarily directly addressing these specific large-scale theories, brownfield remediation projects focusing on regeneration of derelict land support such practices in achieving a more environmentally friendly urban life.

4.2.3 Expanded Valuation Method

Sustainable remediation and regeneration of brownfields via soft end-uses is a viable proposal to both satisfy the demands of urban land and environmental pressures; however, traditional development economics and CBA do not sufficiently reflect the non-monetary benefits to society by not developing arable greenfield land (Bardos et al., 2016; Bartke and Schwarze, 2015). Benefits of brownfield redevelopment will have to be proven and supported on a case-by-case basis within each particular regional context and urban setting while improving value determination methodologies. Bardos et al. (2016) state that the *overall value* of restoration underpins the rationale for any public or private investment in brownfield restoration. They believe that in some cases this measured value is too narrowly costed, and opportunities for improving an overall proposition of value are being missed. Synergies between improvements in environmental, economic and social services could enhance the overall value of brownfield restoration and so help create expanded opportunities for brownfield re-use.

The direct financial case for soft reuse regeneration can be hard to demonstrate clearly, although there is often a high societal demand. HOMBRE identifies four important drivers for soft reuses (Menger et al., 2013):

- In many European countries, densely urbanized areas still need the development of open spaces. For this, brownfield sites are a key potential, because of their availability and relatively cheap purchase price.
- A renaissance of new forms of urban gardening, community gardens, and urban farming increases the demand and feasibility of adapting brownfields for green uses.
- Soft reuses are an option for renewable energy generation (non-food biomass production)
- Soft reuses are a means to create green infrastructures that offer several benefits for communities (e.g. mitigation of heat island effects and improved urban comfort if well-designed). Green infrastructure with trees can help to improve air quality in urban areas by filtering and retaining air particles and contaminants generated by traffic and industry. Green infrastructure can also help creating habitat for migrating birds and other species in urban and peri-urban areas.

The concept of overall value is frequently used in HOMBRE to describe the expanded value of a brownfield regeneration project, because CBA can be unreliable as wider benefits (and impacts) are difficult to monetise in a way that is always acceptable to all stakeholders in a restoration project (Bardos et al., 2016). The overall value of a project can be broken down into three components: the direct financial balance of costs and benefits, economically tangible costs and benefits (i.e. which stakeholders agree are monetisable) and economically intangible costs and benefits (i.e. which stakeholders cannot agree as monetisable) (Bardos et al., 2016; Menger et al., 2013).

More accurately portraying the true value of a brownfield remediation project will require using a combination of CBA, for direct financial and economically tangible costs and benefits, with an alternative aggregation index (i.e. comprehensive sustainability assessment), for intangibles not based on monetary values. This combination may be a viable means of providing a representative expression of the overall value of a restoration project.

Sustainability linkages were created to depict the connectivity of the overall value between interventions and generated services per project which are based upon conceptual site models (Menger et al., 2013), see Figure 5.2 for an example. Bardos et al. (2016) states that the importance of a conceptual site model of sustainability for overall value is intended to be twofold: Firstly, its use during design stages of the project assists the identification of opportunities for extending project services. Secondly, it can be used to assist the estimation of overall value. Its individual linkages can be explicitly assigned to the different components of overall value providing a structure for the monetization of direct financial and economically tangible wider effects, and identifying wider effects that stakeholders cannot agree as monetizable. To identify the range of value and services possible with each intervention early in the project planning stage, the Brownfield Opportunity Matrix (BOM) was created. Identifying synergies in practice is a particularly helpful advantage of the BOM, and is utilized in this study to substantiate claims of value in applying *Rejuvenate*.

4.3 Risk Management

According to Smith and Nadebaum (2016) sustainability principles and risk management practices are not mutually exclusive, but rather consistent, related, and overlapping components in brownfield remediation projects. In their experience, the key question is to determine which of these components take precedence and priority in each individual project. It was critical to determine at the onset of each project what was the 'end point' for remediation so as to establish a practical goal for each site-specific project and determine the acceptability of risk to each stakeholder (Smith and Nadebaum, 2016). In practice, this may mean allowing residual contamination in some level of soil with long-term site management to meet other project goals (e.g. bio-based production), and avoid wasted effort appraising unacceptable options (e.g. conventional dig/dump treatment). This, according to Ridsdale and Noble (2016), is where the tricky issue of trade-offs arises. In an effort to maximize the net positive gains per project, transparency and justification in the decision-making process is essential and constitutes and additional component of SR for consideration alongside sustainability and risk management.

Bardos et al. (2016) write that HOMBRE's focus on providing a wide range of project services in association with brownfield restoration can both improve value for projects that would go ahead anyway and enhance value sufficiently to allow projects to regenerate brownfields which would otherwise remain stalled and effectively out of the land use cycle (supporting circular land flow). The most favourable combination is a synergy (i.e. fulfilling multiple positive functions/services with a single or series of interventions or processes), but trade-offs are also likely to be important. A situation to be avoided is where seeking two project services would effectively result in a net loss, and likely be better suited to more conventional remediation techniques or further investigation.

Figure 4.4 depicts the source-pathway-receptor model of understanding the risks involved in contaminated site management, referred to as the a *pollutant* or *con-*

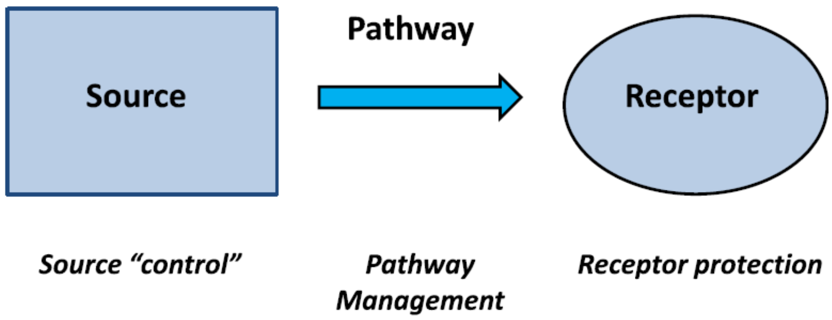

Figure 4.4: Contaminant linkage and risk management options, from Cundy et al. (2013). Reprinted with permission from author.[2]

taminant linkage. Based on this model, risk management can be achieved in three principally different ways: 1) control the source (e.g. extracting the contamination from the subsurface area), 2) manage the pathway(s) (e.g. preventing migration of contamination), and 3) protect the receptors (e.g. planning or institutional controls to avoid sensitive land uses) (Cundy et al., 2013; GREENLAND, 2014*a*). Table 4.1 lists the most likely ways for humans to be exposed to contaminants in soil via these linkages. Conventional remediation approaches to contaminated risk management focused almost exclusively on the containment, cover, and/or transportation of the source of contamination to a landfill. Over the past few decades; however, there has been a growing movement towards treatment-based remediation strategies using *in-situ* and *ex-situ* treatment techniques. More recently, gentle remediation options (GRO) (i.e. plant, fungal or microbiologically-based methods), have emerged as risk management strategies/techniques that result in no gross reduction (even a net gain) in soil functionality and perform the required risk mitigation (Cundy et al., 2013, 2016).

Table 4.1: Transport and pathways causing human exposure to soil contaminants

Transport and Exposure Pathways		
Source	*Pathway*	*Receptor*
Soil	-	Direct intake (ingestion)
Soil	-	Dermal contact
Soil	(Outdoor) dust	Inhalation of dust
Soil	Uptake in vegetables	Intake of vegetables
Soil	Vapor - indoor air	Inhalation of vapor
Soil	Groundwater	Intake of drinking water

[2]From the GREENLAND project (FP7-KBBE-266124) DST publicly available at `http://www.greenland-project.eu/`. The property rights of the content belong to the GREENLAND consortium.

4.3.1 Soil Quality Indicators

In order to sufficiently mitigate the risks of contamination and ensure fertile soil (e.g. to enable biodiversity and biological production), measurements are necessary to evaluate the quality of the soil and the levels of contamination. Typical soil quality standards are derived from a species sensitivity distribution (SSD) model based upon a dose-effect relationship for various soil species in eco-toxicity tests (Volchko et al., 2014). The aim is to reduce soil contamination to a predictable no-effect concentrations (PNEC) to soil organisms through measureable (pseudo)total concentrations of compounds (e.g. metals) in soil. A soil PNEC calculator developed by ARCHE (2014) is an example of this type of soil measurement method which utilizes existing bioavailability models for various metals (e.g. Co, Cu, Mo, etc.), site specific PNECs for direct toxicity to soil organisms based on soil characteristics, and the exposure concentration (predicted/measured environmental concentration, PEC) to calculate the risk characterization ratio (RCR) and potentially affected fraction (PAF) of terrestrial organisms at the given metal concentration in the soil. In many studies, the Triad methodology (Semenzin et al., 2009) was adopted to combine contaminant concentrations (environmental chemistry), eco-toxicity, and effects on biodiversity in relation to soil's ecological functions and especially primary production to evaluate soil quality.

Simply accounting for contaminant reduction and PNEC is not sufficient for this study, because these tests do not account for soil functions relevant for future green areas (i.e. biologically productive use, nutrient cycling, etc.) of remediation sites (Volchko et al., 2014). The supplementary method referenced in this paper is referred to as the SF (Soil Function) Box tool. Benefits of the SF Box tool are that it evaluates the effects of remediation activities on ecological functions through a set of soil quality indicators (SQI), listed below:

Table 4.2: Soil Quality Indicators - minimum data set, summarized from Volchko et al. (2014)

Soil Quality Indicators		
Physical	*Biological*	*Chemical*
Soil texture (ST)	Organic matter content (OM)	pH
Content of coarse material (CM)	Potentially mineralizable nitrogen (NH4-N)	Available phosphorous (P)
Available water capacity (AW)		

Intended as a decision-support tool, the SF Box tool results are best viewed as a complement to ecological risk assessment (Volchko et al., 2014). Volchko et al. (2014) state that there is a lack of studies aimed at exploring a soil's capacity to carry out its ecological functions post-remediation, but conclude that soil functioning is just as important as risk mitigation to ensure that favorable conditions enable soil biota to operate. Regarding soil quality, they conclude: *"If the soil has potentially fa-*

vorable conditions for providing ecological soil functions (e.g., a limited content of coarse fragments and sufficient amounts of water and nutrients for soil organisms) alternative remediation strategies can be considered (e.g., the risks posed by contaminants in the soil can be reduced using biological treatment [GROs]). *However, other important factors should also be considered (e.g., bioavailability and mobility of pollutants in the soil, time aspects, and public acceptance)."*

4.4 Sustainability Framework

In order to define the goals, objectives, and criteria of remediation efforts, a sustainability framework should be explicitly stated to address the sustainability principles reflected in the methodology or practice chosen for use in a project. Cundy et al. (2013) state: "*Remediation is not automatically sustainable. Remediation work can have its own environmental consequences (e.g. the use of energy and other resources, impacts on water and air); its own economic consequences (e.g. on the viability of businesses or projects); and its own social consequences (e.g. safety risks to site workers or impacts of road traffic). Current international debate in "sustainable" remediation is centering on how sustainability benefits can be assessed and maximized and how these negative consequences can be avoided or limited. In broad terms, concepts of sustainable remediation are based on the achievement of net benefits overall across a range of environmental, economic and social concerns that are judged to be representative of sustainability.*" In this context, it is the established sustainable remediation (SR) frameworks which comprehensively consider future land uses, inter-generational equity, and integration of biophysical, social, and economic factors to any significant degree (Ridsdale and Noble, 2016). Two definitions of sustainable remediation, shown below, from professionals in the field explain the general principles behind SR work:

- SuRF-UK: SR is *"the practice of demonstrating, in terms of environmental, economic and social indicators, that the benefit of undertaking remediation is greater than its impact and that the optimum remediation solution is selected through the use of a balanced decision-making process"* (CL:AIRE, 2018)
- Bardos et al. (2016): SR is *"the management, the rehabilitation and return to beneficial use of the brownfield land resource base in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations in environmentally non-degrading, economically viable, institutionally robust and socially acceptable ways."*

The Sustainable Remediation Forum (SuRF) is an international consortium working in multiple countries that has developed one of the most robust SR frameworks to date (Beames et al., 2014; Ridsdale and Noble, 2016) (a detailed evaluation performed by Ridsdale and Noble (2016) is summarized in Appendix 4). SuRF UK, in particular, is frequently cited in literature and thus will be the primary SR framework referred to in this report by following their sustainability indicators. The overarching SR criteria as defined by SuRF UK (Bardos et al., 2010) is shown below in Table 4.3.

Table 4.3: SuRF UK - Sustainability Criteria

Environmental	Social	Economic
Emissions to air	Human health and safety	Direct economic costs and benefits
Soil and ground conditions	Ethics and equity	Indirect economic costs and benefits
Groundwater and surface water	Neighborhoods and locality	Employment and employment capital
Ecology	Communities and community involvement	Induced economic costs and benefits
Natural resources and waste	Uncertainty and evidence	Project lifespan and flexibility

Considering that unsustainable land use and further brownfield generation perpetuates natural capital degradation, soil sealing, pollution, etc., the underlying aim of brownfield redevelopment is to offer a convincing, sustainable alternative to orthodox urban development practices. These negative impacts are attributable to conventional land use practice, characterized by exploiting easily developable greenfield land and sealing the soil in order to generate short-term economic gain from so-called hard uses, which compromise local people's well-being and the ability of future generations to utilize limited soil resources (Bartke and Schwarze, 2015). In general, SR frameworks have tremendous potential to support sustainable land-use decisions through the re-development and revitalization of brownfield land instead of biologically active greenfield land that provide essential ecosystem services.

There is a great deal more which could be said concerning sustainability assessment tools and remediation alternative selection[3] as well as operative SR frameworks[4], but for the purposes of this study it suffices to say that the indicators used in SuRF-UK are suitable analytical guides in (qualitatively) discussing SR options in the early feasibility stage.

[3]See Norrman et al. (2015) Appendix C.

[4]See Beames et al. (2014); Cappuyns (2016); Ridsdale and Noble (2016); Smith and Nadebaum (2016) for more information.

5

Gentle Remediation Options

This chapter analyses the essential theory and state-of-the-art of gentle remediation options in more detail. Soil contamination issues, the techniques considered as GRO, phytomanagement, and constraints to GRO use are discussed.

As defined by the Greenland consortium, Gentle remediation options (GRO) are: "*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*" (GREENLAND, 2014*a*). GRO is the general term covering many technologies based upon the use of plant (phyto-), fungi (myco-), and/or bacteria-based methods (with or without the use of chemical additives or soil amendments) for reducing exposure of local receptors to contaminants by *in-situ* stabilization (using biological and/or chemical processes) or extraction (removal of the contaminant source from the soil medium) (Cundy et al., 2016; GREENLAND, 2014*a*). The types of GROs identified by the Greenland network are listed below in table 5.1.

If well-designed, GROs can provide rapid risk management via pathway control, through containment and stabilization, coupled with a longer term removal or immobilization of the contaminant source term. This combined solution can be durable and long-lasting as long as land use and land management practice does not undergo substantive change causing shifts in pH, plant cover etc. affecting the soil functionality (Cundy et al., 2013, 2016; GREENLAND, 2014*a*). Long-term plans require that some form of institutional or planning control may be necessary in order to be truly effective. Support for this type of long-term strategy is substantiated by virtue of the additional economic (e.g. biomass generation), socio-cultural (e.g. leisure, recreation), and environmental (e.g. carbon sequestration, water filtration) co-benefits offered by GROs coinciding with ecosystem services to form robust, systemic approaches to remediation far beyond conventional remediation techniques (Cundy et al., 2016; GREENLAND, 2014*a*).

5.1 Soil Contamination

A report produced for the European Commission's Science for Environmental Policy (Science Communication Unit (UWE), 2013) was tasked with outlining soil pollution's effects on human health and the surrounding environment. They state that most frequent contaminants found in European soils are heavy metals and mineral oils (approximately 3 million sites). Capturing the full extent of costs and damages that these contaminants inflict upon our health is difficult and studies attempting

Table 5.1: List of definitions for GROs used to remediate soils contaminated by either trace elements or mixed contamination, summarized from GREENLAND (2014*a*)

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 such as rhizosphere and endophytic bacteria) to uptake, store and degrade pollutants.
Rhizodegradation	The use of plant roots and rhizosphere microorganisms to degrade organic pollutants.
Rhizofiltration	The removal of pollutants from aqueous sources by plant roots and associated microorganisms.
Phytostabilization	Reduction in the bioavailability of pollutants by immobilization in root systems and/or living or dead biomass in the rhizosphere soil - creating an environment which enables the growth of vegetation.
Phytovolatilization	Use of plants to remove pollutants from the growth matrix, transform them and disperse them (or their degradation products) into the atmosphere.
In-situ immobilization/ phytoexclusion	Reduction in the bioavailability of pollutants by immobilizing or binding them to the soil matrix through the incorporation into the soil of organic or inorganic compounds, singly or in combination, to prevent the excessive uptake of essential elements and non-essential contaminants into the food chain.

to do so are not yet widely attempted. Generally speaking, health problems from cancers (arsenic, asbestos, dioxins, petroleum hydrocarbons), neurological damage and lower IQs (lead, arsenic), kidney disease (lead, mercury, cadmium), and skeletal and bone diseases (lead, fluoride, cadmium) are serious issues which in many cases have yet to be addressed in terms of soil contamination and human exposure. Human activities like mining, smelting, industry, agriculture, and burning fossil fuels directly introduce these toxic heavy metals into soils. Waste disposal of many materials (e.g. paints, electronic waste, sewage) exacerbate the problem. Some of these metals are actually required in small quantities by organisms (e.g. Fe, Mn), but are detrimental to them in large quantities often found in contaminated sites (Jaishankar et al., 2014; Science Communication Unit (UWE), 2013). A well-detailed table covering the World Health Organization's ten substances of greatest concern to human health, in the context of soils, is shown in Figure 5.1.

Chemical of concern, Sources/uses	In soil?	Used by humans as a nutrient?	Toxic to humans how?	Health effects
Air Pollution	**No**			
Arsenic Pesticides; gold, lead, copper, nickel, iron and steel mining and/or processing; coal burning; wood preservatives. Pharmaceutical and glass industries, sheep dip, leather preservatives, pigments, poison bait, agrochemicals, antifouling paint electronics industry.	**Yes**	**No**	Main exposure through consumption of groundwater containing naturally high levels of inorganic arsenic, food prepared with this water, or food crops irrigated with water high in arsenic.	Intake of inorganic arsenic over a long period can lead to chronic arsenic poisoning (arsenicosis). Gastrointestinal tract, skin, heart, liver and neurological damage. Diabetes. Bone marrow and blood diseases. Cardiovascular disease. Carcinogenic. Organic arsenic compounds are less harmful to health, and are rapidly eliminated by the body. Increased risk of miscarriage, stillbirth and pre-term birth.
Asbestos Mining and milling of raw asbestos (historical) for construction and product manufacture. Historical: releases into the air and soil around refineries, power plants, factories handling asbestos, shipyards, steel mills, vermiculite mines, and building demolitions. Current: repair, renovation, removal, or maintenance of asbestos. Gardening.	**Yes**	**No**	Exposure occurs when asbestos-containing material is crumbling or disturbed, releasing microscopic asbestos fibres into the air and dust. The main route of entry is inhalation, but it can also be ingested or lodge in the skin.	Some inhaled asbestos fibres reach the lungs, where they become lodged in lung tissue and may remain for many years. This causes: • parenchymal asbestosis • asbestos-related pleural abnormalities • lung carcinoma • pleural mesothelioma Health effects may not emerge for decades, but lung cancer and pleural mesothelioma have high mortality rates. Historical, occupational exposure from manufacturing and construction work is a common cause.
Benzene	**No** Benzene is not persistent in surface water or soil, either volatilising back to air or being degraded by bacteria (unless present in very high quantities).	**No**		
Cadmium Zinc smelting, mine tailings, burning coal or garbage containing cadmium, rechargeable batteries (nickel-cadmium batteries account for over four-fifths of cadmium consumption), pigments, TVs, solar cells, steel, phosphate fertiliser, metal plating, water pipes, sewage sludge.	**Yes** Cadmium in soil may enter plant crops (depending on soil characteristics, pH etc).	**No**	Cadmium in soil or water used for irrigation can lead to accumulation in plants that enter the human food chain. Cadmium may also accumulate in animals at levels that do not affect the animal's health, but can affect humans consuming animal products.	Liver and kidney damage, low bone density. These symptoms are known as itai-itai disease. First identified when cadmium from mining in the Toyoma Prefecture of Japan led to high levels of cadmium in rice, which accumulated in local people. Diets poor in iron and zinc vastly increase the negative health effects of cadmium. Carcinogenic (by inhalation).
Dioxin Including Polychlorinated dibenzodioxins (PCDD) and Polychlorinated dibenzofurans (PCDF). Waste incineration, reprocessing metal industry, paper and pulp industry, contaminated herbicides (a major source). Stored PCB-based industrial waste oils (often with large amounts of PCDFs).	**Yes** These chemicals are most commonly found in soils, sediments and food, with low levels in air and water.	**No**	Human exposure to dioxin and dioxin-like substances occurs mainly through consumption of contaminated food. More than 90% of human exposure is through food, mainly meat and dairy products, fish and shellfish.	Dioxins are highly toxic and can cause reproductive and developmental problems, damage the immune system, interfere with hormones and also cause cancer.
Fluoride	**Yes** – but is generally immobile.	**Yes** A micronutrient. Appropriate levels strengthen teeth.	Usually associated with high levels of fluoride in drinking water.	Skeletal fluorosis: fluoride accumulates progressively in the bone over many years. Early symptoms include stiffness and pain in the joints. Crippling skeletal fluorosis is associated with osteosclerosis, calcification of tendons and ligaments, and bone deformities.
Lead Batteries, solder, ammunition, pigments, paint, ceramic glaze, hair colour, fishing equipment, leaded gasoline (vehicle exhausts), mining, plumbing, coal burning, water pipes.	**Yes**	**No**	Leaded fuel and mining activities are common causes for elevated lead levels in topsoil.	• Neurological damage • Lowers IQ and attention • Hand-eye co-ordination impaired • Encephalopathy • Bone deterioration • Hypertension • Kidney disease
Mercury Electrical switches, fluorescent light bulbs, lamps, batteries, thermometers, dental fillings, mining (particularly artisanal/small scale gold mining), pesticides, medical waste, burning coal and fuel oil, chlor-alkali industry.	**Yes**	**No**	Main exposure route for the population at large is via eating contaminated seafood. For children is direct ingestion of soil.	• Central nervous system (CNS) and gastric system damage • Affects brain development, resulting in a lower IQ • Affects co-ordination, eyesight and sense of touch • Liver, heart and kidney damage. • Teratogenic
Hazardous pesticides Herbicides derived from trinitrotoluene may have the impurity dioxin, which is highly toxic. Synthetic insecticides, such as DDT (now banned) can still be found in the environment worldwide.	**Yes**	**No**	Organic pesticides accumulate in the food chain.	Organic chemicals, including pesticides, have been linked to a wide range of health problems, but we tend to be exposed to a cocktail of these chemicals at low levels. Conclusive proof of cause and effect in humans is challenging.

Figure 5.1: Top 10 substances of major public health concern in relation to soils and human health impacts according to the World Health Organization, from Science Communication Unit (UWE) (2013). Open access.

A topic of particular concern, which has been receiving increasing attention recently, is the cumulative effects on citizens' health due to long-term, low-level exposure to a wide range of soil contaminants. Due to the vast number of variables involved, it is extremely difficult to determine the effects from each specific contaminant in the real world. Directly ingesting or touching these compounds produce relatively predictable negative effects, but otherwise there are simply too many issues involved affecting human health. Absolute certainty of cause and effect in the more common cases of life-long exposure to the cocktail of chemicals and other damaging elements in the soil may never be achievable. A site-by-site approach to minimize the risks of exposing humans to whichever harmful substances exist at each individual soil system is likely to best way to achieve peace of mind, and is a problem well-suited to low cost gentle remediation options (Science Communication Unit (UWE), 2013).

5.2 Risk Management Strategies

In terms of technical applicability, GROs are primarily applied on contaminated soils to remove the labile (bioavailable) pool of inorganic contaminants (phytoextraction), remove or degrade organic contaminants (phyto/rhizo-degradation), protect water resources (rhizofiltration), or stabilize or immobilize contaminants in the subsurface (phytostabilisation, in-situ immobilisation/phytoexclusion) (GREENLAND, 2014*a*). As the treated soil remains unsealed throughout the remediation process, GROs are highly applicable, cost-effective treatment alternatives for managing risks in-situ instead of just containing or transferring contamination elsewhere (Cundy et al., 2013, 2016). However, application as practical site solutions is still limited. Barriers to wider adoption arise from both the nature of GROs (e.g. time horizons) and market perceptions of uncertainties over whether these methods can achieve effective risk management in the long term (Cundy et al., 2013). The source-pathway-receptor risk model (shown previously in Figure 4.4) is best used to address contaminant exposure to humans.

Cundy et al. (2013) state that the constraints on acceptability of GROs seem inevitable when remediation success is judged solely using generic soil concentration targets. A target-led approach can be attractive to some because of its simplicity, its inherent conservatism may lead to over-designed risk management solutions, which are costly and may not be sustainable in the long term. A site-specific approach, that properly considers source and pathway interventions in a more comprehensive risk management strategy, allows a more targeted and likely more sustainable risk management solution. This also creates a better rationale for the implementation of plant and microorganism-based GROs. GROs may then facilitate land regeneration in circumstances where the case for intervention is economically questionable due to their lower cost. In addition, the 'greening' of contaminated or marginal land has many co-benefits like educational value, carbon sequestration, public green space, circular resource use (composting, biomass production), boosting surrounding land value, and providing ecosystem services which all support soft-end use of brownfield land and add value (Cundy et al., 2013, 2016; GREENLAND, 2014*a*). This risk management strategy is best exemplified in Figure 5.2, shown below:

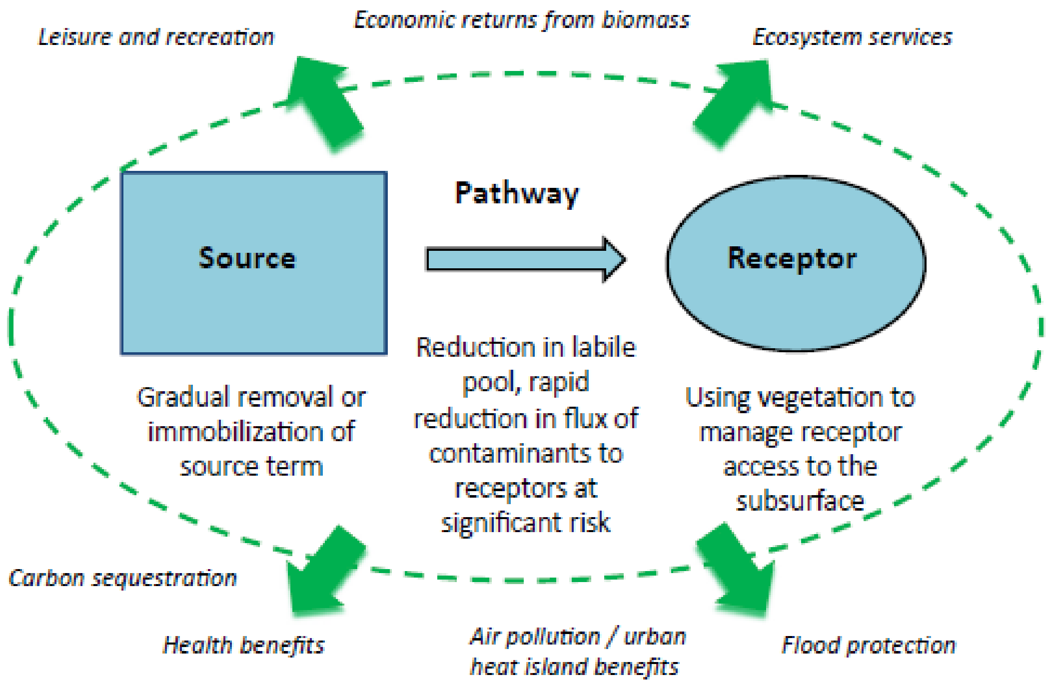

Figure 5.2: Risk management strategy using GROs customized along contaminant linkages. Out-facing arrows link to illustrative wider environmental, economic and societal benefits which may be realized from GRO application, from Cundy et al. (2016). Reprinted with permission from author.[1]

Examples of circumstances which do not favour existing treatment-based remediation solutions, though may be highly amenable to this broader risk management approach, are shown the list below. Typically these constraints describe sites for which a "soft" end use is envisaged (Cundy et al., 2013; GREENLAND, 2014*a*).

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

[1]From the GREENLAND project (FP7-KBBE-266124) DST publicly available at `http://www.greenland-project.eu/`. The property rights of the content belong to the GREENLAND consortium.

5.3 Phytoremediation

A growing number of studies testing the efficacy of GROs have shown the tremendous potential to provide rapid risk management via pathway control coupled with a longer term removal or immobilization of contaminants (Cundy et al., 2016; Gerhardt et al., 2017; Kidd et al., 2015). Chapter 8 in this study provides a collected list of case studies utilizing GROs which have seen success in mitigating or altogether eliminating the risks posed by contamination. In general, phytoremediation is useful for remediation of soil (and groundwater) which has been contaminated by heavy metals, radionuclides, organic contaminants (e.g. chlorinated solvents, non-aromatic petroleum hydrocarbons), nitrotoluene ammunition wastes, and excess nutrients (Juwarkar et al., 2010). Furthermore, numerous case studies have placed primary emphasis on biomass production for use in bioenergy, or other income generative purposes, while also benefiting from the risk mitigation aspects of utilizing specific plants on marginal or contaminated land. These types of phytoremediation practices are presented in a separate table in Chapter 8.

The GREENLAND (Gentle Remediation of trace element contaminated land) consortium's GRO projects and studies are an invaluable resource for the widespread adoption of GROs following a risk-based approach. In these projects tested at large scale throughout Europe, remediation is focused on controlling the sources of contamination and managing mobility of trace metals in soils to prevent exposure pathways affecting humans. To quickly determine if GROs are applicable for a contaminated site remediation project, two quick reference guides were created, shown below in Figures 5.3 and 5.4.

Specific remediation mechanisms depend largely upon the individual plant's physiology. For organic, carbon-based contaminants, degradation (i.e. the hydrocarbons are converted to microbial biomass, bioenergy, carbon dioxide and water) can occur either in the rhizosphere soil zone (rhizodegradation) or *in planta* (phytodegradation) (Gerhardt et al., 2017). Rhizodegradation is more likely to occur due to the size and hydrophobic nature of most organic pollutants which prevents them passing through the cell walls of plants, but uptake is possible in some cases in which degradation occurs within the plant biomass for eventual phytovolatilization (i.e. releasing to the air via evaporation). In general, the key to effective degradation is the presence of biologically active microorganisms (e.g. endophytes) and plant enzymes. Specific types of plants can facilitate the growth of these necessary components by creating a hospitable environment, but often the growth can be impaired by the contaminants themselves or poor soil quality. Growing interest in this form of soil and water treatment has led to more research performed concerning improving the efficacy of these processes, discussed in the next section. For more detailed descriptions of the mechanisms in phytoremediation of organic pollutants, the reader is referred to recently performed studies (Feng et al., 2017; ITRC, 2009; Juwarkar et al., 2010; Vangronsveld et al., 2009).

For inorganic contaminants like metals, uptake is specific to the element and plant species. In phytoextraction, the metals are accumulated in the roots and shoots of

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

Figure 5.3: Are GROs applicable to a site?, from GREENLAND (2014*a*). Reprinted with permission from author.[1]

the phytoremediation plants. Plants best suited to phytoextraction are those which can tolerate high concentrations of contaminants, the ability to (hyper)accumulate at large percentages of total biomass, rapid growth rate, high biomass production, and an extensive root system which is thoroughly discussed in many studies (Chibuike and Obiora, 2014; Gerhardt et al., 2017; ITRC, 2009; Juwarkar et al., 2010; Sarwar et al., 2017). Phytoextracted contaminants generally need to be harvested and disposed of off-site to lower contaminant levels in soils for failure to remove contaminated biomass (e.g. leaves) can result in contaminants being leached back into the soil from plant litter degrading (Gerhardt et al., 2017). Contaminated biomass can be disposed of in a number of ways, and a significant body of research is dedicated to this analysis (Delplanque et al., 2013; GREENLAND, 2014*b*; Nzihou and Stanmore, 2013; Šyc et al., 2012; Witters et al., 2012a). Generally speaking, metal(loid) contaminated biomass can be disposed of in various ways: incineration, gasification, slow pyrolysis followed by steam activation, flash pyrolysis, hydrolysis, and liquefaction (Gerhardt et al., 2017). If the contaminants are not volatilized, they remain in the ash or liquid resulting from the process, and they must be processed further or treated as hazardous waste.

Phytostabilization is the second-most common phytoremediative technique for inorganic pollutants. Decreasing mobility and bioavailability of soil metal(loid)s or other contaminants is achieved via forming precipitates in the rhizosphere, adsorp-

[1]From the GREENLAND project (FP7-KBBE-266124) DST publicly available at `http://www.greenland-project.eu/`. The property rights of the content belong to the GREENLAND consortium.

GRO / Contaminant	Phytoextraction (stripping of bioavailable metal(loid))	Phytostabilisation (including aided phytostabilisation)	In situ immobilisation / phytoexclusion
Arsenic	✓✓*	✓**	✓**
Cadmium	✓✓	✓✓	✓✓
Chromium	-	✓	✓✓
Copper	✓✓	✓	✓✓
Lead	✓	✓	✓✓
Nickel	✓✓	✓✓	✓✓
Zinc	✓✓	✓	✓

Figure 5.4: Which metal(loid) contaminants can GRO treat? Where, the number of check marks represents the degree of confidence based on data from the GREENLAND network. **For Arsenic**: hindrances in extraction in presence of Cu, and adsorption through stabilization can reverse due to aging and/or building of organic litter, from GREENLAND (2014*a*). Reprinted with permission from author.[1]

tion and sequestration within root tissue, or adsorption onto root cell walls which reduces risk for exposure or migration of contamination (Chibuike and Obiora, 2014; Gerhardt et al., 2017; ITRC, 2009; Sarwar et al., 2017; Vangronsveld et al., 2009). Stabilization rather than uptake of contaminants poses a tremendous advantage for the future usage of the produced biomass as it reduces the concern over contaminant concentrations in the biomass affecting conversion processes or other uses (Andersson-Sköld et al., 2014). Furthermore, by virtue of their own physiology, plants perform stabilization mechanisms effectively, but *aided* phytostabilization (i.e. adding soil amendments or microorganisms) has seen improved results leading to a new "modified concept" of phytoremediation to overcome many limitations which has seen more use recently (Sarwar et al., 2017).

5.3.1 Enhancements: Amendments and Bioremediation

Plant growth can be severely impacted by poor quality soil and high levels of soil contaminants (Chibuike and Obiora, 2014; Gerhardt et al., 2017). Specific plants species can overcome these difficulties somewhat, but often the soil conditions must be improved in order for plants to properly grow and perform their remedial functions. Two distinct approaches are widely used to supplement phytoremediation efforts. The first is to utilize soil amendments to improve soil quality enabling plant growth in a sub-optimal environment. Second, microorganisms are used in conjunction with plants, often referred to as *bioremediation*, to bolster contaminant degradation and plant growth (Gerhardt et al., 2017; Juwarkar et al., 2010). Many detailed studies have been focused on enhancing phytoremediation by one or both of these strategies, and are being validated for field use (Chibuike and Obiora, 2014;

Feng et al., 2017; Sarwar et al., 2017; US EPA, 2007).

Properties	COMPOST[1]	ANIMAL MANURE[2]	DIGESTATE (anaerobic digestion)[3]	BIOCHAR[4]
Increase in content of organic matter	increases soil organic matter, humic substances	increases soil organic matter, depends on animal diet	depends on feedstock - humic acids (mainly solid fraction)	affects the stability of existing organic matter
Modification of C:N ratio			low C/N ratio due to digestion	increase
Improvement of water holding capacity	Increases		improves	increases due to surface structure
Supply of nutrients (N, P, etc.) nutrient balance	enhances nutrient supply	leaching of N and P – content differs with animal species	depends on feedstock - mineral N, P (mainly liquid fraction), possible leaching	reduces leaching of nutrients / slow release fertilizer - provides P and K
Modify pH	lowers pH		high pH	increase in soil pH of acidic soils
Modification of cation exchange capacity	Increases			increase in soils with low CEC
Improvement of texture and aggregation state	amelioration of structure and porosity	reduces density	reduces density, increase in aggregate stability	increase in porosity, stability of aggregates
Sequestration of pollutants/contaminants	through humic substances		not reported	can sequester pollutants, but also increase mobility
Addition of pollutants/contaminants	might contain persistent pollutants	micronutrients supplied to animals	might contain persistent pollutants, metals	can contain pollutants, in this case it is not usable
Decrease in salinity	Improvement		can increase salinity with repeated applications	can sequester salts and modify CEC
Soil conservation (e.g. minimise erosion)	remediates degraded soils		still to be investigated	still to be investigated
Increase in microbial biomass	increase	Increase	considerable increase	increase
Increase in microbial diversity	increase or decrease	Increase	significant changes	significant differences
Stimulation of specific microorganisms	no indication	antibiotic resistance	dominance of slowly growing microorganisms	arbuscular and ectomycorrhiza
Increase in enzymatic activities	increase in soil microbial activity	Increase	nitrogen mineralization, other enzymes	reports on increase in enzymatic activities
Increase in diversity of fauna	Limited observations, differing effects		limited observation, increase	Limited observations, differing effects
Effects on plants growth	positive	very positive	positive	mostly positive
Increase of yield	Positive	Positive	fertilizer capacity	reports on increase of crop yield
Increase of product quality	not significant			not assessed
Improve in defense against pathogens	Positive effects			Limited observations, positive effects
Origin, raw materials	biomass from different sources		biomass from different sources	biomass from different sources
Production requirements	requires large amounts of energy, long time			depends on biomass feedstock - importance of temperature
Standardisation of product	Quality assessment differs in the countries	not possible	not possible	just starting
Cost (including transport)	moderate		depends on feedstock	depends on feedstock - high
Positive carbon emission	emissions during composting	emissions of CH_4 and N_2O, NH_3	during digestion GHG emissions, NH_3 emission	could stimulate CO_2 emissions by microbes
Negative carbon emission	carbon sequestration in humic substances		decrease of emissions from manure	removal during growth of biomass, C - sequestration
Legislation, norms on applicability	Differences among countries		can be amendment or fertilizer	limited
Social acceptability	well established	well established	Low	not yet tested
Additional benefits (e.g. energy production)	scalable to farm		production of biogas	reduction of N_2O emissions
Ecosystem services of relevance				

Figure 5.5: Relevant properties of main categories of organic amendments, from Schröder et al. (2018). Green and orange colour indicates positive and negative effects respectively; yellow colour indicates presence of both positive and negative effects; grey colour indicates lack of knowledge. Creative Commons License: BY-NC-ND.

Biostimulation is the commonly used term for the process involving the addition of nutrients in the form of manure or other organic amendments which serve as carbon source for microorganisms present in the soil, and can be a gentle remediation option in its own right (Chibuike and Obiora, 2014; Juwarkar et al., 2010). Biostimulation is most appropriate when the site is purposed for use in crop production because it is a non-disruptive method of soil remediation which can reduce (or eliminate altogether) the need for mineral fertilizers through the use of organic amendments (Chibuike and Obiora, 2014; Schröder et al., 2018). The added nutrients increase the growth and activities of microorganisms involved in the remediation process thus increasing the efficiency of phytoremediation mechanisms while at the same time improving soil fertility and overall quality for long periods of time. Many different types of organic amendments have been applied for nutrient boosting, stabilization, and microbial function purposes each with their own advantages and disadvantages, shown above in Figure 5.5.

Biochar is one organic amendment of particular interest as it has been proven to possess stabilization capability, stimulates bacteria and fungi, improves soil quality and soil pH, and protects plants from competition and predators. Biochar is the solid product derived from waste biomass (e.g. plant material, manure, sludge) pyrolysis which could play an important role in a circular nutrient cycle through reuse in field application to sequester carbon and stabilize contaminants. An important caveat is that the benefits vary widely depending upon biochar quality and method of production which is still in the early phases of research (Chibuike and Obiora, 2014; Sarwar et al., 2017; Schröder et al., 2018).

Other forms of organic matter amendments like compost/mulch, sludge from wastewater treatment plants or anaerobic digestors, lime, phosphogypsum (useful in Pb stabilization), other biosolids, and ashes from combustion in CHP or metallurgical factors should not be ignored as valuable alternatives as they all have seen success in many applications as stabilizing and soil improvement agents (Gerhardt et al., 2017; ITRC, 2009; Sarwar et al., 2017; Vangronsveld et al., 2009).

Microbial-assisted phytoremediation is a more recently developed and maturing field which shows great potential for a faster and more efficient treatment of a contaminated site. Mycorrhizal fungi has been used in studies involving heavy metals to boost plant extractive capability, stabilization via metal immobilization, increasing soil stability, and increasing disease resistance in plants depending on the circumstance (Chibuike and Obiora, 2014). Plant growth-promoting rhizobacteria (PGPR) can stimulate plant growth in a variety of ways which contribute to overall reduction in plant stress associated with surrounding contamination, and could be employed to great effect in many phytoremediation scenarios (Chibuike and Obiora, 2014; Gerhardt et al., 2017; Juwarkar et al., 2010; Sarwar et al., 2017; Vangronsveld et al., 2009).

A recent study performed by Feng et al. (2017) highlights the importance of plant-endophyte relationships in phytoremediation. Endophytes are a highly varied group of microorganisms that exist inside the tissue of all plants for some duration of their life cycle. The production of phytohormones, plant growth-promoting bioactive substances performing various functions, is one of the most well-studied of these mechanisms which the authors believe can be exploited to enhance the degradation of organic pollutants both inside and around the plants. For example, the endophyte species *Bacillus* sp SBER3 paired with poplar trees has been shown to increase degradation of PAHs and BTEX by boosting plant resistance in their presence, and the endophyte *Pseudomonas putida* PD1 promoted root and shoot growth in both willow species and grasses while protecting against the phytotoxicity of phenanthrene. The authors suggest biostimulation (as shown previously), *bioaugmentation* (i.e. deliberate inoculation of plants with specific competent strains or microorganisms to improve phytoremediation capability), and *genetic modification* via deliberate, targeted genetic engineering are three primary strategies with which to best make use of the wide range of potential benefits offered by endophytes. Further research into this promising field is necessary in order to be successful beyond controlled environment lab testing.

5.3.2 Phytomanagement

Gerhardt et al. (2017) state: "*The perfect scenario for remediating all sites is the rapid and complete removal of all contaminants from soil in an inexpensive and environmentally responsible manner. As this is rarely feasible,the pros and cons of various remedial strategies usually need to be considered. Their potential for efficiently reaching biological receptors (particularly humans) and toxicity of the contaminants are the most critical factors.* In their view, a new paradigm is required which shifts the view of soil as a 'disposable waste' into a valuable (non-renewable) resource. *Phytomanagement* is a positive a new movement expanding phytoremediation as a broader, long-term management strategy (Cundy et al., 2016; Gerhardt et al., 2017; Schröder et al., 2018).

The difference between phytomanagement and phytoremediation could be summarized by the underlying emphasis of phytomanagement as a long-term combination of profitable site use with GROs leading to the reduction of contaminant linkages and the restoration of the ecosystem and other site services (Cundy et al., 2016; GREENLAND, 2014*a*). There has been a shift towards phytomanagement approaches rather than stand-alone phytoremediation strategies shown by an increase in phytomanagement publications over the last decade (Gerhardt et al., 2017). Phytomanagement strategies adopt a more holistic, broader design and management approach by placing the realization of wider benefits (e.g. economic) at the core of the site design alongside risk mitigation. GROs using a mix of economically valuable plants (generally non-food plants) branch off of the typical phytoextraction-only approach based on plant monocultures. In contrast, this approach involves the concerted efforts of many stakeholders to create a diverse plant-based ecosystem which is capable of providing benefits like biomass generation for economic gain, amenity and leisure, ESS, boosting land value, land restoration, etc. that can easily be incorporated into urban design as a semi-permanent land use or short-term, interim 'holding strategy' until other land uses are desired (Cundy et al., 2016; Gerhardt et al., 2017).

5.3.3 Selection of Plant Species

The importance of selecting the right plant species for use at any specific site cannot be overstated. Phytotoxicity and a whole host of other environmental stresses (e.g. climate, water, pH, etc.) can severely limit remediation potential, establishment, and growth of the plants on-site. Therefore, careful selection is critical for successful phytoremediation (GREENLAND, 2014*b*; Kidd et al., 2015; Schröder et al., 2018). Success rates can be boosted through effective agronomic practices like crop rotations, inter-cropping, soil supplements, etc., but the plant species itself is by far the most important determinant for project success (GREENLAND, 2014*b*). ITRC (2009) developed a screening process to determine the eligibility of individual plant species for each particular project context, and was a useful resource to understand the complexities of plant selection. The compiled information gathered in the plant selection process for this study is presented in Appendix 5.

For example, plants for phytoextraction must be able to accumulate high concentrations of TEs in their harvested parts (e.g., shoots, stems) and have a reasonably high biomass production. Hyper-accumulator species (e.g. *Thlaspi caerulescens*) meet these demands and are those species which are able to accumulate extreme concentrations of metal(loid)s (e.g. Cd, Ni, Zn, etc.) in their above-ground biomass and at the same time possess some economic added value as renewable biomass or even bio-ores to reclaim certain metals from the biomass (GREENLAND, 2014*b*; Kidd et al., 2015). Tang et al. (2012) performed a study where a hyper-accumulator species (*T. caerulescens*) was co-cropped with a non-accumulator (*Thlaspi arvense*). The results showed increased growth of the non-accumulator and reduced Zn uptake, while the hyper-accumulator had an increased Zn uptake. Co-cropping, inter-cropping, and other agronomic practices may alter conditions in shared rhizosphere and thereby affect the availability of selected metals to neighboring plants. Therefore, it is possible that planting some low-metal crops in association with hyper-accumulators or other appropriate plants may allow agricultural production on heavy metal-contaminated soils (GREENLAND, 2014*b*; Kidd et al., 2015; Singh et al., 2011; Tang et al., 2012; Zegada-Lizarazu and Monti, 2011).

The field of study behind plant species selection and agronomic science is massive with a huge variety of ways to design a phytoremediation procedure. However, a primary consideration which should be foremost in the plant selection procedure is a focus on using native species. Introducing invasive species will add another problem with potentially troublesome consequences. Cultivating native species eliminates many ecological risks and are likely to be well-adapted to the climate, soil conditions, and other environmental stresses (Gerhardt et al., 2017; Nikolić and Stevović, 2015). Nikolić and Stevović (2015) focused their study on the wide range of uses for the diverse plant family Asteraceae (e.g. sunflower, safflower) as a vegetative cover for contaminated land. Due to the resilience of individual species, native range of growth, possibility for modelling plant systems for genetic engineering and experimentation, and affordability to establish on derelict land where no alternative treatment is feasible there exists a wealth of opportunities to fully utilize these plants. This proposal could even be extended to many other cover crop type species, like the alpine pennygrass (*Thlaspi caerulescens*) which is native to Scandinavia. García-González et al. (2018) tested the efficacy of winter cover crops and found that, compared to the fallow, cover crops promoted greater carbon sequestration, nitrogen retention, soil structural stability, and water retention capacity. The soil restoration potentional of cover crop species is immense and ought not be neglected in creating a cropping plan. Species like honey clover (*Melilotus alba*), pea shrubs or trees (*Caragana* species), the Asteraceae family, the Brassicaceae family, or long-term stabilizing trees (e.g. Alder tree - *Alnus glutinosa*) should also be considered in rotations if deemed appropriate in the site context.

5.4 Barriers to GROs

Cundy et al. (2016) state that despite the wide range of benefits offered by GROs there still exist barriers to their practical application throughout Europe. Perceived (or actual) shortcomings in their technical performance or with stakeholder perceptions are major limitations which could inhibit their practical adaptation. In general, the application of GROs as practical remediation solutions is still in its infancy despite the success of other 'green technologies' like constructed wetlands, reed beds, and other sustainable urban drainage systems. Barriers to adoption typically arise from doubt as to the efficacy of risk management with GROs in the long term. Similarly, the time taken before prescribed 'total' concentration-based risk management targets are reached is a major limitation for GROs, particularly phytoextraction. Acceptance of phytostabilization and *in-situ* immobilization are also limited due to the lack of source removal and the perception that the stabilization is reversible over time (GREENLAND, 2014*a*,*b*).

Furthermore, the majority of remediation work in Europe has been carried out as a result of regulatory demand for critical risks and/or to stimulate the re-use or development of brownfield land. Most brownfield reuse development is strongly driven by economic factors, and these projects are often constrained by pressure for rapid treatment on relatively limited site areas. Both of these factors have tended to exclude consideration of GROs which are perceived as slow and more suited to large area problems (Cundy et al., 2016; GREENLAND, 2014*a*).

Long-term monitoring, evaluation, and a lack of knowledge and experience were perceived as the major disadvantages for application of GROs at many sites. The absence of these factors resulted in failure to meet expectations when phyto-technologies were first applied in the 1990s, causing a loss in confidence in GROs (Bleicher, 2016; Cundy et al., 2016; Doick et al., 2009). The Greenland project was created to alleviate the perceptions of inadequacy in remediation potential of GROs, so their reputation is still slowly recovering. Gerhardt et al. (2017) provide a comprehensive list of the many possible reasons for the continuing slow uptake of phyto-technologies despite proven effectiveness in the field. They conclude with a series of 14 recommendations to gain greater acceptance for phytoremediation by industry and government.

Finally, Montpetit and Lachapelle (2017) identified a troublesome 'mental' block in their study which they dubbed the *Status quo bias*. They show in their study that remediation professionals demonstrate a strong bias towards using conventional methods even if GROs or other alternatives are shown to be more suitable. They focus on the influence of experience and familiarity with the conventional technologies overriding the clear evidence favoring GROs. This coincides with the socio-cultural theory of 'non-knowledge' discussed in the study performed by Bleicher (2016). She states that phytoremediation challenges the established wisdom of the more one-dimensional remediation technologies, and to become a fully-fledged remediation alternative phytoremediation requires an expanded body of knowledge and expertise to generate a better *practical understanding*. The full range of possibility with phyto-technologies could incorporate expertise from many different disciplines to provide a hybridization of practices into new *practice-arrangement bundles* wherein multiple purposes can be served (e.g. remediation via biomass production).

6

Bio-Based Production

This chapter covers the collected knowledge on bio-based production for both energy crops and urban agriculture. The different forms and practices these production systems can take, how they work in practice, and other associated information is discussed.

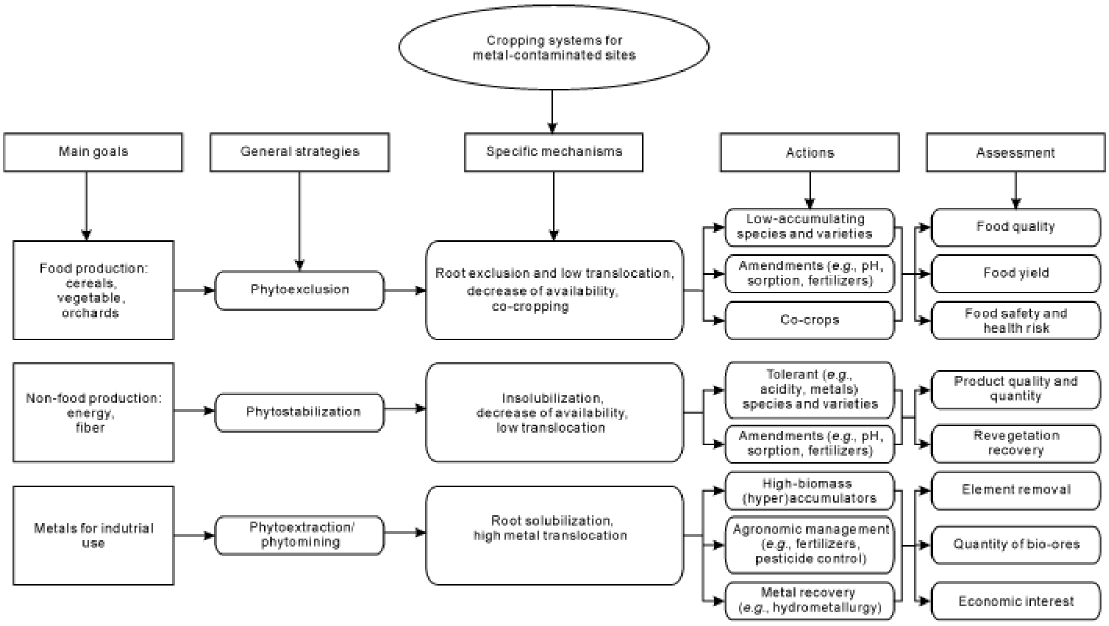

Figure 6.1: Summary of designing cropping systems for metal-contaminated sites, from Tang et al. (2012). Reprinted with permission from Elsevier and Lancet.

There are many studies and projects performed recently which have explored the synergy of combining the phytoremediation of contaminants at brownfield sites and the economic potential of biomass production (Enell et al., 2016; Gerhardt et al., 2017; Lord, 2015; Schröder et al., 2018; Soldatos, 2015). Literature suggests that the utilization of biomass for energy production could even become a profit making operation, and is of great interest to policy makers aiming to transition to a bio-based, circular economy (Witters et al., 2012a). The critical issue of growing energy crops on prime, food-producing land (i.e. the 'land-fuel-water nexus') can even be avoided altogether by producing biomass on marginal, brownfield land instead (Breure et al., 2018; Lord, 2015; Mehmood et al., 2017). This can even lead to a "self-funding land management regime," according to Andersson-Sköld et al. (2014).

Furthermore, Andersson-Sköld et al. (2014) state that there are a wide range of co-benefits related to biomass cultivation on degraded land aside from economic value and risk management, including improving soil conditions, carbon sequestration, and increased biodiversity. Regulations governing restoration of marginal lands using organic waste materials vary from country to country, but two considerations tend to be most important: the quality of the biomass produced and the effective management of risks to human health and the wider environment (Andersson-Sköld et al., 2013). Figure 6.1 provides a summary of the various approaches used in designing cropping systems for contaminated land.

A notable exception to the discussion presented in this chapter is the exploration of producing biomass for use in bio-products aside from use purely as bioenergy (fuels and/or heat) or as food products, as shown previously in Figure 3.1. Much of the research into the utility of bio-based production on contaminated sites does not place much emphasis on this form of biomass use. So, this field remains largely explored and is a key area for further research. More information can be found in the following articles by Tripathi et al. (2016a,b).

6.1 Renewable energy biomass production

Zegada-Lizarazu and Monti (2011) state that biofuels for transport rely mainly on annual energy crops (e.g. rapeseed, sugar beet, and cereals) while electricity and heating on perennial herbaceous and woody plants (e.g. miscanthus grass, switchgrass, canary reed grass, willow, and poplar) as well as waste biomass. The 4F Crops European Commission project[1] was created to expand upon and identify the most influential bioenergy crops used in Europe to contribute to a bio-based economy (EC, 2010). The project resulted in a list of 15 select, non-food crops that were categorized in five groups; oil crops for biodiesel production, sugar and starch crops for bioethanol, fibre crops, lignocellulosic crops, and short rotation forestry crops:

- Crops for biodiesel: rapeseed, sunflower, and Ethiopian mustard
- Crops for fiber: hemp and flax
- Lignocellulosic crops: giant reed, miscanthus, switchgrass, reed canary grass and cardoon
- Crops for bioethanol: sweet sorghum and sugar beets
- Short rotation forestry: willow, poplar, and eucalyptus

An important note is that these crops listed for the rotation are not the only crop species deemed suitable for the local growing conditions. In fact, many willow and poplar tree species are widely grown in Sweden and have seen success in phytoremediation projects. In addition, miscanthus, switchgrass, and reed canary grass can produce large yields of useful biomass. Following extensive feasibility review, seven

[1] https://cordis.europa.eu/result/rcn/90439_en.html

possible cropping systems were recommended as a result of the 4F Crops project for the Nemoral climactic region in which Gothenburg is located: 1/2) willow (perennial), 3) Pea (legume) - Cereal (barley) - Rapeseed, 4) Hemp - Rapeseed - Pea (legume), 5) Rapeseed - Cereal (barley) - Pea (legume) - Rapeseed, 6) Rapeseed - Flax - Sunflower, and 7) Red clover- Rapeseed - Flax (EC, 2010). These recommendations were useful to inform about the range of possibilities at large-scale biomass production; however, suitability for small-scale brownfield plots in urban areas must meet different objectives and needs which may not align directly with the proposals in the 4F Crops project. Figure 6.2 provides an illustration of what a diverse biomass production could be with customized plant species and agronomic practices on a limited site area for use as a biofuel park:

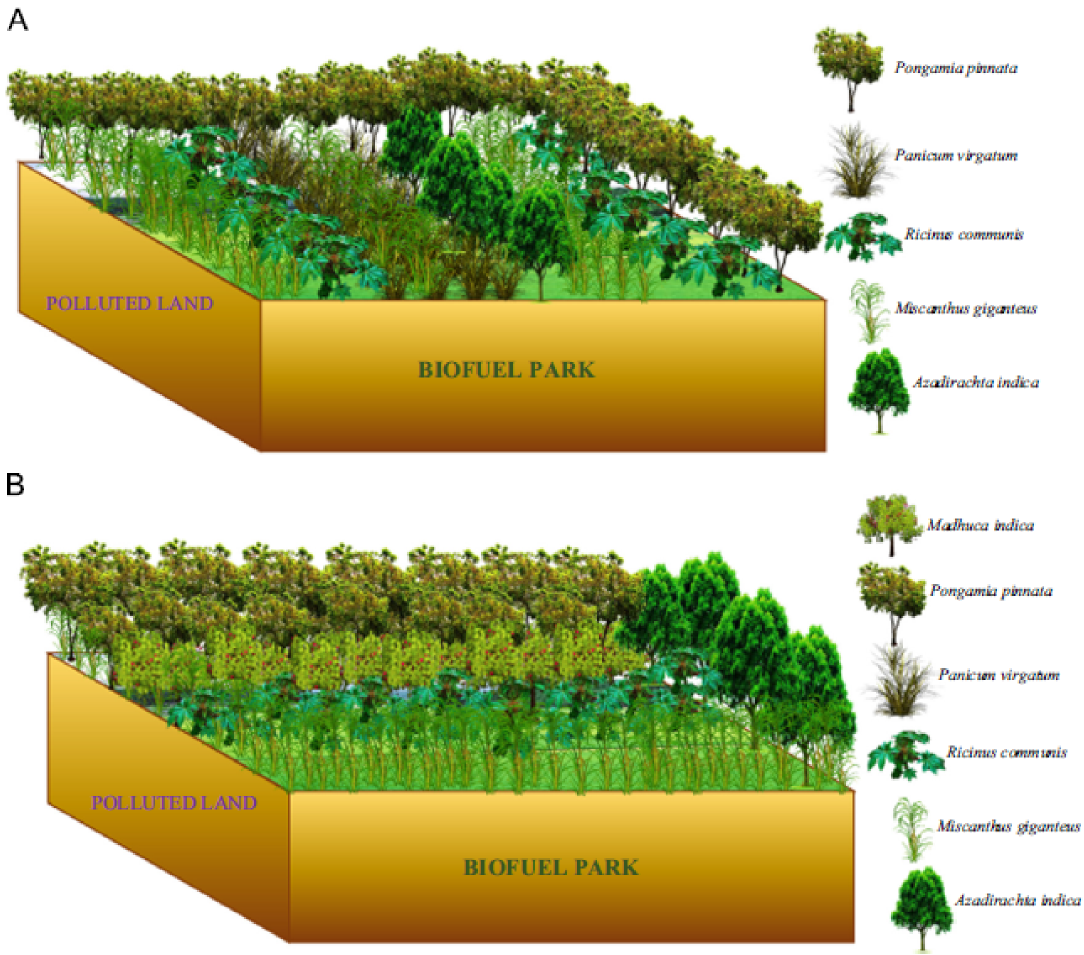

Figure 6.2: Two intensive biomass production models based on multiple crops utilizing agroforestry and inter-cropping techniques, from Tripathi et al. (2016b). Reprinted with permission from Elsevier and Lancet.

These rotations are supported by research on agronomic practices and science conducted by Kidd et al. (2015); Mehmood et al. (2017); Schröder et al. (2018); Tang et al. (2012); Zegada-Lizarazu and Monti (2011) and others. Generally speaking, crop rotation has been long recognized as a system that can reduce soil erosion, improve soil structure, enhance permeability, increase the soil microbial activity, enhance soil water storage capacity, and increase soil organic matter. Rotation systems can even reduce the use of external inputs through internal nutrient recycling, maintenance of the long-term productivity of the land, avoidance of accumulation of pests associated with monocultures, and consequently increase crop yields. It is important that the selected crops can perform some or all of the following functions: contribute to build up soil fertility, conservation and cycling, improve soil physical characteristics (e.g. aggregate stability), and minimize problems related with weeds, diseases and others pests. Best said by Mehmood et al. (2017), "*Trees are the silent benefactors of the human kind, they have uncountable crucial roles to play in ecosystems and provide products and services to both urban and rural population.*" Agroforestry, based upon the integration of tree species into agriculture alongside traditional crops to maximize benefits of both species, is another agronomic practice which should be considered in any bio-based production system. Figure 6.3 shows a short rotation coppice willow plantation with a mixed variety of smaller species.

Figure 6.3: Short Rotation Coppice (SRC) willow planting with mixed smaller species. Reprinted image by Katy Walters, Creative Commons License: BY-SA 2.0.

In a study from Schröder et al. (2018), changes in large-scale agricultural practices in northern Europe were investigated showing shifts into an intensive, cereal-based cropping pattern from the more balanced, cereal-legume-tuber crop rotation that had formerly been applied. Only recently, following a renewed focus on ecology and sustainability, was it discovered that abandoning crop rotation resulted in soil fertility decline and increased soil erosion. Cultivation of legumes via crop rotation; however, reverts land degradation, increases soil fertility and enhances nitrogen availability. Another beneficial aspect is the regulation of weeds and disease suppression, a major inhibitor to successful crop establishment. In perhaps the most extensive study on applying agronomic practices to improve performance of GRO and establishment on contaminated land, Kidd et al. (2015) identified the shortcomings of applying monocultures for phytoremediation and propose alternative cropping patterns and practices. Considering that GRO processes are generally expected to be of a long duration, remediation based on a single species cultivated in monoculture is unlikely to be effective and simultaneously can lessen soil nutrients and fertility ultimately leading to lower biomass yields. They show in their study that alternative cropping patterns can significantly influence the phytoremediation process and the extraction or immobilization of contaminants, as well as soil protection and quality. Rotating trace element-accumulating species with agronomic crops supports the remediation process by yielding economically useful biomass and aiding the growth of remediation-focused species. In practice, certain annual crops can be fitted into crop rotations where they serve to control weeds, diseases and pests. The incorporation of annual cover crops can also bring additional benefits such as contributing to the maintenance of soil organic material in upper soil layers and an improved soil aggregation, or a promotion in biological soil tillage through root development, or weed and pest control. Legume cover crops can fix nitrogen (N2), thereby improving soil N status for subsequent crops planted in the following growth season (Kidd et al., 2015). Kidd et al. (2015) is highly recommended for more information concerning such agronomic practices.

For the purposes of this study it was valuable to investigate the phytoremediation capabilities of these various energy crops to determine both what effects (if any) the contaminants would have on the crops as well as the ability of the crops to extract or stabilize in the soil matrix. Enell et al. (2016) state in their study on willow SRC that crops intended for bioenergy production, grown on brownfields, should be low-accumulators and preferably act as stabilizers to immobilize the contaminants and prevent migration. In general, there is a lack of field studies where both the ecological risks and the potential benefits with this kind of land rehabilitation have been evaluated, and there exists a huge potential to exploit synergies in practice. Some cultivars within specific species from major staple crops such as wheat, barley, rice, potato or maize differ widely in their ability to accumulate metal(loid)s. Selection of pollutant-excluding cultivars for cultivation on contaminated and/or remediated land contributes towards reducing the entrance of harmful trace elements into the human food chain. Cadmium is one of the elements of major concern regarding uptake into the food chain due to its severe toxicity. The stable crops previously mentioned have been tested for certain species to determine low-Cd cultivars (i.e. exclusion types) which all show great potential for continuing food and forage production on contaminated land (Kidd et al., 2015). Referred to as Cadmium-safe Crop Cultivars (CSCC) by Ashrafzadeh and Leung (2016), they state that not enough work has been done to identify and fully utilize the huge potential of CSCCs in producing these kinds of essential staple crops in more widespread application.

One such study focusing on the intersection between remediation on biomass use was performed by Lord (2015). In his study (BioReGen[2]), three perennial rhizomatous grasses (PRGs) commonly used for energy crop production (miscanthus, switchgrass, and canary reed grass) were compared to typical woody energy crops (willow SRC). Overall, perennial grasses offer better productivity, net calorific values and ecological benefits than annual crops, with lower environmental impacts, lower carbon debt and greater greenhouse gas reductions, especially when grown on degraded or abandoned agricultural land. Environmental benefits of the continuous annual cropping regime of PRGs included reduced tillage, soil degradation and carbon loss, higher radiation capture and root density, better soil stabilization, improved run-off quality and wildlife habitat. Results from the study showed the reed canary grass outperformed all other crops in yield at all of the case study sites. The combination of rapid establishment, low initial cost and annual harvesting means that temporary cropping of non-agricultural land with reed canary grass is a technically viable proposition. In terms of economic viability, feasibility is dependent on consideration of the associated natural capital and ecosystem service gains, synergies or trade-offs resulting from its use as part of the 'energyscape.' Lord (2015) identifies the significant potential that reed canary grass offers as biomass supply in developing or well-established renewable energy markets as second generation bioethanol production, pyrolysis for biofuels, combustion for heat and power, carbon sequestration, and as a feedstock for anaerobic digestion (in northern Europe and marginal land especially). Perhaps the most important result from the study was that average concentrations of all trace elements in energy crops from the BioReGen trials were lower than the acceptable limits for commercial or residential use of the resultant biomass pellets with the exception of Cd and Zn in SRC or miscanthus. The highest measured values were also likely unsuitable for industrial use and ash resulting from combustion must be properly managed, so careful measurements are required.

6.1.1 Sustainability and biomass valorization

According to Lord (2015), the discussion of the economic, social and environmental impacts of biofuel and bioenergy production and use has centred on three aspects: 1) the net carbon reduction benefit of using bioenergy when the whole life-cycle energy balance including fossil fuel use and greenhouse gas emissions of production and transport are considered; 2) the additional demand from direct utilization of food crops for liquid biofuels manufacture, or the potential for purpose-grown "energy crops" to compete indirectly with food production on agricultural land, together impacting on global food supplies or price, water and land availability - the so-called 'land-fuel-water' nexus; 3) negative impacts on the environment through land use change or deforestation from biofuels production, or indirect land use changes from displaced agriculture. Using locally available, non-agricultural land for energy crop production could potentially circumvent many of the major concerns. Many studies for field-scale demonstrations of biomass production on brownfields, contaminated land or landfills have mainly involved growing woody biomass as short rotation

[2] http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=2833

coppice or forestry and rarely field-tested oil seed crops or perennial grasses. So, there exists a wide range of opportunity which as yet to be fully explored (Lord, 2015).

One of the main issues for phytomanagement on marginal land is the valorization of phytoremediation biomass to offset the costs of remediation, and the importance of effective stakeholder involvement to ensure minimization of site risk and maximization of benefits (Gerhardt et al., 2017). In other words, the value of such projects is highly dependant upon classification of biomass as a waste or an economically useful resource. Such projects could reliably generate income, become a net cost if classified as a waste, and/or provide long-term phytostabilization and carbon sequestration contributing to overall benefits and low-cost remediation (Andersson-Sköld et al., 2014). The economic opportunities with these types of projects are numerous. Licht and Isebrands (2005) performed a study which discusses plants used to phytoremediate brownfield sites (e.g. post-industrial areas, landfills) in terms of 'vegetative caps' or *in-situ* phytoremediation plantings directly targeting sources of contamination. They focused on the application of poplar and willow trees, and proposed that the woody biomass produced could provide massive economic opportunities for not only bio-energy use, but also pulp and paper products, composite wood products, feed products, and a host of other intangible economic benefits generally classified as ESS.

In one of the most recent studies concerning biomass valorization, Schröder et al. (2018) propose that an attractive option is to valorize the plant biomass to face energy and global change problems (e.g. by supercritical gasification, liquefaction and pyrolysis as potential routes). The first process results in the formation of syngas to produce heat or electricity, while the other processes lead to biofuel, biochar or valuable chemicals. However, the feasibility of such options is still in its infancy as they are relatively new technologies in this field of application. If the digestate is tested and contains too high trace element concentration for commercial fertilizers, pyrolysis may be an alternative. During pyrolysis mineral elements are concentrated in the solid fraction (sand and char). This may open possibilities for trace element recovery from this fraction, or when metal recovery seems not feasible, they are at least concentrated in only a very small mass fraction (needing to be disposed) compared to the initial biomass amount.

Two life cycle analyses have been conducted to determine whether phytoremediation is sustainable without favorable biomass valorization (Vigil et al., 2015; Witters et al., 2012a). The results showed that if the produced crop was not utilized beneficially then the sustainability of phytoremediation is questionable, but if converted into energy or fuel at a bioheating plant like shown in Figure 6.4 than there are many advantages of phytoremediation over conventional remediation techniques in the tested situations. Both studies evaluated different conversion routes for the biomass, and found the best results when used in to produce synthetic natural gas in anaerobic digestors or directly combusted in combined heat and power plants (depending on the biomass). Witters et al. (2012a) produced two interesting findings which have a profound impact on the viability of bio-based production on marginal land: 1) elevated concentrations of metals in biomass likely have no significant im-

Figure 6.4: Bioheating plant in Skellefteå, Sweden utilizing biomass for combined heat and power. Reprinted image by Mattias Hedström on Wikimedia, Creative Commons License: BY-SA 2.5.

pact on biomass conversion process but could affect secondary product (e.g. ash, digestate) handling, and 2) net energy potential from biomass conversion combined with carbon dioxide abatement (if economically valued) and long-term remediation provides a convincing case economically and otherwise to support the projects.

6.1.2 Constraints for energy crops

The main constraints in the utility of energy crops grown on contaminated land is the real or perceived effect that the contaminants would have on the biomass itself and its ability to be used in bioenergy, biofuels or other bio-products. This might occur directly by contaminant uptake (e.g. phytoextraction), or indirectly, by cross-contamination from adhering soil dust during growth or forage harvesting. This would detract from the economic viability and environmental validity of the approach, unless an adequately productive energy crop can be identified with an acceptably low level of contamination to allow both its safe cultivation on these challenging sites and subsequent suitable use (Lord, 2015). Studies have shown that metal concentrations found in biomass are not expected to have a negative effect on the conversion process or technical efficiency of the installation (van Slycken et al., 2013; Witters et al., 2012a), but there are not many regulations and standards for established contaminant thresholds as of yet. Also, the presence of local conversion chains for the produced biomass is instrumental to success (Cundy et al., 2016).

Additionally, Menger et al. (2013) highlight the problem of altering or damaging the pre-existing, unique ecosystems or habitats which brownfield sites can develop through redevelopment of a site as green infrastructure.

Another difficulty concerns ash management resulting from biomass conversion to energy (Delplanque et al., 2013; Witters et al., 2012a). Following combustion of metal enriched wood or other biomass, Cd and other metals may be dissipated to the environment through ash recycling in field application. This would contradict the phytoextraction goal of removing harmful pollutants from soils. Depending on the conversion process used (e.g. combustion, pyrolysis, gasification), volatilization temperatures of metals and equipment used for filtration, a significant fraction of a metal-free ash may be obtained, either the bottom ash, the cyclone ash or the filter ash. Ash management may have to consider just the small volume of metal rich ash, with the remainder of low metal ash recycled as raw material for agricultural and forestry with respect to regulation. In the study performed by Delplanque et al. (2013), French regulations, which compared the contaminated wood with commercial wood, classified the produced biomass not as a potential fuel but as a waste. Co-combustion of the biomass with another fuel source (e.g. fossil based) would likely be more acceptable to regulators. Ideally, bottom ash resulting from combustion would be used as a basic mineral amendment to boost soil quality, but this would depend on the classification of the ash as a valid soil amendment fertilizer.

To summarize, Tripathi et al. (2016a) listed several problem areas for which suitable strategies must be framed: 1) enhancing the growth and yield of selected bio energy crops under varying agroclimatic conditions, 2) limiting the transfer of pollutants into the end products, 3) ensuring the safety of stakeholder involved in such activities, 4) identifying the potential markets of such phytoproducts, 5) proper certification of phyto-products, and 6) ensuring the overall safety and sustainability of such coupled systems (i.e .phytoremediation and bioenergy production).

6.2 Urban Agriculture

One of the many innovative ways in which soils may contribute to solving societal tasks in urban environments, is their application in urban gardens. Soils, often neglected, deserve a place in urban green space management as they may help to address societal challenges such as urbanization, climate change, aging populations, and restoring ESS to urban areas. Urban agriculture is currently riding a wave of surging interest as shown in Figure 6.5, and is part of a global trend towards developing more parks and green areas in cities, consuming organic, locally grown products, and establishing a closer relationship with one's own living environment. All of which are supported through many recent studies and informational publications (Breure et al., 2018; Edmondson et al., 2014; Goldstein et al., 2016; Schram-Bijkerk et al., 2018; Schröder et al., 2018; URBES, 2014; US EPA, 2011*a*,*b*; Van Bemmel et al., 2017).

According to Schröder et al. (2018), "*the main challenge* [in agriculture] *is no longer simply to maximize productivity of a single crop, but to optimize farming across*

Figure 6.5: Urban Agriculture at a derelict site in Chicago. Reprinted image by Linda on Wikimedia, Creative Commons License: BY-SA 2.0.

a far more complex landscape of production, environmental, and social outcomes. When agriculture thrives under the auspices of land-owners educated in sustainable land use, the potential of marginal lands will be unlocked and strengthened, and local stakeholders will defend their region from further degradation to establish economically sound management systems."

The scale of the task as described above necessitates a shift in values to prioritize the small-scale, biodiverse bio-based production systems like those based on the principles of permaculture, as discussed by Van Bemmel et al. (2017). Schram-Bijkerk et al. (2018) created a conceptual framework via a set of indicators useful in valuation of urban gardening and for identification of the connections between various themes and concepts that are inherent in green space and gardens, shown in Figure 6.6. Ecosystem health and human health were shown to be strongly connected which in turn highlights major opportunities for synergies in practice. One overarching indicator that summarizes several effects on determinants of health is the 'perceived (self-reported) health' of gardeners or visitors. This indicator has been assessed frequently in studies evaluating the health effects of green infrastructure and urban gardening, and the authors report that overwhelmingly positive effects were shown in support of these dedicated green spaces.

Similarly to the green infrastructures discussed earlier in this study, urban garden-

Figure 6.6: Indicators of physical (orange boxes) and experience-based (green boxes) benefits of urban gardening, from Schram-Bijkerk et al. (2018). Reprinted with permission from Elsevier and Lancet.

ing also stimulates the delivery of ESS thereby contributing to the development of resilient cities and healthy citizens (Breure et al., 2018; Goldstein et al., 2016; Schram-Bijkerk et al., 2018). On the neighborhood level, healthy soils in green areas may buffer traffic noise and reduce the exposure to air pollution. At a city-scale, urban gardening contributes to the quality of the physical environment (e.g. through climate regulation and the enhancement to environmental quality), and to experienced living environment. At the social aspect level, gardening has been shown to raise the aspirations of local people and provide them with the skills to bring about positive changes to both their own lives (i.e. health promoting behavior) and in their neighborhood (Breure et al., 2018; Schram-Bijkerk et al., 2018). A soil-based approach in addressing societal challenges curtails the indiscriminate use of resources associated with conventional, high-tech solutions by endorsing the more efficient use of resources. Indeed, Edmondson et al. (2014) prove definitely that small-scale urban food production can occur without the penalty of soil degradation seen in conventional agriculture, and can even maintain the high soil quality seen in urban green spaces. They believe that considering the involvement of over 800 million people in urban agriculture globally, and its important contribution to food security, better protect soil functions, local, national and international urban planning and policy making should promote more urban individual growing in preference to further intensification of conventional agriculture to meet increasing food demand.

Notwithstanding the many apparent benefits with urban agriculture, the key question remains: *Is it safe to cultivate food crops in soil with a high likelihood of contamination?* Unfortunately, this question is not readily answerable due to the large difference in safety conditions per brownfield site context. However, many recent papers have been dedicated to providing solutions to the problem and suggesting a series of best practices for universal application (Brown et al., 2016; Henry et al., 2015; Hettiarachchi et al., 2016; Singh et al., 2011; US EPA, 2011*a*,*b*). Generally speaking, contamination could be a problem growing all food crops and root vegetables in particular due to increased exposure and accumulation. Prevailing research shows; however, that there is in fact minimal risk of exposure from eating plants grown in contaminated soils provided that the harvested food crops are thoroughly washed before eating to remove potential surface level exposure. Overwhelmingly, the most probable risk of exposure to humans is during the act of gardening itself through soil ingestion (mainly a concern for children playing in the garden), breathing contaminated dust, or direct exposure to the skin. Many of these problems can be mitigated or removed altogether by applying layers of organic matter (or other suitable material) as both a physical barrier and stabilizing/fertilizing soil amendment. Raised gardening beds filled with clean soil could also be a viable solution to entirely avoid interaction with the contaminated soil. Also, a healthy degree of personal safety equipment like gloves, garden shoes, and diligent washing can eliminate much of the exposure risk (US EPA, 2011*a*,*b*).

Many studies focus on Pb in soils due to its ubiquitous presence in urban environments and acute human health effects. Many studies report that Pb exposure from the soils can be mitigated through regular application of compost to reduce bioavailability and limit exposure pathways in general. Phosphorous-based organic amendments in particular (e.g. phospho-gypsum) could induce Pb phosphate which has especially little uptake by vegetation leading to better stabilization (Brown et al., 2016; Henry et al., 2015; Hettiarachchi et al., 2016; Singh et al., 2011). Perhaps counter-intuitively, Brown et al. (2016) state that it is highly unlikely that urban agriculture will increase blood-Pb levels in children in urban areas due to the fact that the agricultural practices themselves will improve the soils in urban areas, thus resulting in reduced bioavailability of soil Pb and exposure via inhalation or contact. They reason that since plant uptake of Pb (and As and PAHs) is also typically quite low then the benefits of urban agriculture far outweigh the potential risks and obstacles.

Further investigations and validation are certainly necessary before creating a garden in contaminated brownfield soil. For safe production of edible food crops such as cereals and vegetables, further research is also needed to select low-accumulating species/cultivars by means of agronomic and genetic breeding. Chemical and organic amendments (e.g., alkaline agents, adsorption agents, and fertilizers) should be optimized according to their efficiency of metal immobilization and the economic feasibility. In the cases where food production is desired, the designed cropping system possibly needs to be evaluated mainly by food production quality rather than soil remediation (Henry et al., 2015; Tang et al., 2012)

7

Best Practices

This chapter presents the collected best practices in using GRO for both a risk-based remediation and bio-based production focused approach.

7.1 Best Practices - Risk-based Approach

Practical testing of GRO at both the experimental, controlled lab level and field-scale, pilot study has been steadily growing within the past few years. Proven successes of using GRO in risk mitigation at contaminated sites is extremely valuable for increasing acceptance and for building a body of knowledge which practitioners (and students alike) can exemplify in future implementation. Figures 7.1 and 7.2 show the compiled table of GRO projects which were frequently referred to in this study to gain knowledge of best practices in risk-based application. Other papers (Gerhardt et al., 2017; Kidd et al., 2015; Vangronsveld et al., 2009) also have collected information on successful GRO projects which are highly recommended for further information. As seen in the tables, the Greenland network[1] is the main driver for most remediation focused GRO applications, and is an invaluable resource.

7.2 Best Practices - Bio-based Production

The second collected best practices, shown in Figure 7.3, were those which focused on maximizing production of biomass, investigating ways to find advantageous uses for the varying types of produced biomass, and also determining the effects in the bio-based production system on both the contaminated site in terms of remediation and contaminant levels in the biomass itself. Much of this research was highly significant as it pertains directly to the aims and objectives in this study. The SNOWMAN network[2], created to bolster the knowledge of sustainable soils, was a key supporter for most of the projects and is a useful resource for further information.

[1] http://www.greenland-project.eu/
[2] http://snowmannetwork.com/

Network	Location	Site Type	Contaminants	GRO Strategy	Plant Species	Fate of Biomass	Comments	Source
Greenland Network	Austria	Agricultural soil	Cd, Pb, Zn (As, Cu)	*In-situ* stabilization/ phytoexclusion	Crops (barley, maize)	Tested to see if still permitted for consumption (Cd-excluding cultivars)	The goal was to limit metal uptake into biomass through in-situ stabilization; field trials did not match efficacy of pot trials	Friesl et al. 2006, 2009
	Belgium	Agricultural soil	Cd, Zn, Pb	Phytoextraction	Poplars, willows, maize, rapeseed, tobacco, sunflower, hemp	Explored in use as bio-energy (e.g. Maize: 33,000-46,000 kWhr/ha*yr - CHP) to substitute fossil fuels	Providing alternate income at contaminated agriculture sites; Primary objective was sustainable risk-based land use	Meers et al 2010; Ruttens et al. 2011; Witters et al. 2012; Janssen 2015
	France	Industrial soil in urban area	Cd, Zn, Pb	Phytoextraction	Arabidopsis halleri, willows	Not specifically mentioned	Controlled study of Cd hyperaccumulation	Bert et al. 2012; Huguet et al. 2012
	France	Dredged sediment landfill	Cd, Zn, Pb, As, Cu	Aided phytostabilization	Tufted hair grass, willows	Long-term implacement of vegetation	Contaminated alluvial soils testing in-situ phytoremediation to manage at-risk ecosystems over time	Bert et al. 2009, 2012a/b
	France	Industrial soil	Cu and Cu/PAHs	Phytoextraction; phytostabilization and rhizodegradation	Sunflower, tobacco, sorgum, poplars, willows, grasses, vetiver	Not specifically mentioned	Testing soil amendments affecting biolability and accumulation;	Bes and Mench 2008; Cundy et al. 2013; Hattab et al. 2014, 2016
	Germany	Agricultural soil	Cd, Zn, Pb	Phytoextraction; *in-situ* stabilization/ phytoexclusion	Poplars, willows, crops, grassland	Wood pellets for thermal use and bioenergy (if not classified as waste)	Testing to determine feasibility of SRC growth, biomass product use, risk mitigation, and expanded natural benefits	Dietzsch 2011; Cundy et al. 2013
	Poland	Post-industrial soil	Cd, Zn, Pb	*in-situ* stabilization/ phytoexclusion	Grassland	Not specifically mentioned	Testing established plant species to determine which metals are accumulated or excluded and affect on microbial activity	Siebielec et al. 2006; Wojcik et al. 2014

Figure 7.1: Best Practice - Risk-based approach, part 1

Network	Location	Site Type	Contaminants	GRO Strategy	Plant Species	Fate of Biomass	Comments	Source
Greenland Network	Spain	Tailings	Cd, Zn	Phytoextraction	Noccaea caerulescens	Not specifically mentioned	Testing established plant species to determine which metals are accumulated or excluded and affect on microbial activity	Becerra-Castro et al. 2012; Monterroso et al. 2014
	Spain	Tailings	Cu	Phytostabilization	Poplars, willows	Not specifically mentioned; Some long-term implacement, possibly bioenergy	Extensive discussion of best SRC practices, clones for various applicaiton, and agronomic practices	Kidd et al. 2014, 2015
	Sweden	Commercial sludge-amended	Cd, Zn (Cu, Ni, Cr, Pb)	Phytoextraction	Willows	Wood chips and pellets for energy and thermal use (CHP)	Comparing survivability and biomass production of various willow clones	Heinsoo and Dimitriou 2014; Dimitriou and Rutz 2015
	Switzerland	Agricultural soil on former landfill	Zn (with some Cd, Cr and Cu)	Phytoextraction	Sunflower, tobacco	Not specifically mentioned	Lowered labile Zn pool by 45-70% over 5 years	Herzig et al. 2008, 2009, 2014
	France	Dredged sediment landfill	Cd, Zn	Phytoextraction	Willow (3 Salix clones)	Combustion (analysis of ash) - suitable for bioenergy production if boilers equipped with efficient filters and combined with other 'cleaner' biomass; bottom ash can be recycled as fertilzer/amendment if low conc.	Cd: 2.39mg/kg DW -> 2 mg/kg (19 years/2 yrs if based on extractable Cd)	Delplanque et al. 2012
Independent Research	England	Post-industrial soil	Cd, Zn, As, Pb, Cu , Ni	Phytoextraction	Willow, poplar, birch	>8-10 t/ha*yr (productive threshold) - combustion	Low Pb uptake, 5.6mgCd/kg, 96mg Zn/kg, immobilize other trace metals	French 2006
	Belgium	Agricultural soil	Cd, Zn	Phytoextraction	Willow (8 Salix clones)	Tested and determined fitting for use in renewable energy production via combustion without affecting conversion efficiency - economically feasible	Yields comparable to those on non-contaminated soils (~12 ton DM/ha*yr); high Cd and Zn extraction potential increased if leaves are also removed; best species perform better than alternative energy crops previously studied (maize and rapeseed)	Van Slyken et al. 2012

Figure 7.2: Best Practice - Risk-based approach, part 2

	Location	Site Type	Contaminants	GRO Strategy	Plant Species	Fate of Biomass	Comments	Source
Biomass, Remediation, re-Generation (BioReGen)	England	Post-industrial soil	PAHs, As, B, Cd, Cr, Cu, Pb, Hg, Ni, Zn	Phytoextraction, phytostabilization	Reed canarygrass, miscanthus, willow	renewable energy biomass - 97 GJ/ha (4-7 odt/ha*yr)	500t/ha green-waste compost used; Reed canarygrass outperforms other species	Lord 2015
Independent Research - LCA Comparison	Spain	Industrial soil in urban area	**Pb**	**Phytoextraction**	***Legume (Melilotus alba)***	**anaerobic digestion - SNG and digestate**	**20,860 kg Dm/ha yield; best case scenario**	Vigil 2014
			Pb	Phytoextraction	*Legume (Melilotus alba)*	Landfilled	Phytoremediation drastically loses value if biomass is landfilled	
			Pb	Dig and Dump - excavation	N/A	N/A	Conventional technique scenario - top 30 cm soil landfilled - worst case	
Independent Research - SNOWMAN	Sweden	Post-industrial soil	Heavy metals (e.g. Cu, Pb, Zn)	Phytostabilization	*Salix Klara, Salix Inger*	Yield: 5.4 ton DW/ha*yr over 20 years; Revenue: €70/ton Dw (excluding subsidies); Energy: 4.4kWh/ton DW	Fertilizer application - 0.1 kg/m2; permeable geo-textile applied for weed suppression	Enell et al. 2015
SNOWMAN - LCA	Belgium	Agricultural soil	Cd, Zn, Pb	Phytoextraction	Willow (*Salix spp.*), silage maize (*Zea Mays* L.), rapeseed (*Brassica napus* L.)	anaerobic digestion (maize) - 30,000-42,000 kWh CHP; Cold pressing + esterification (rapeseed); Co-combustion (willow)	700km2 shallowly (0-40cm) contaminated area; CO2 reduction of 21 tons/ha*yr; sustainability validation	Witters et al. 2012; Meers et al. 2010
Rejuvenate	Sweden	Industrial Landfill site (Häggatorp)	Heavy metals	Phytostabilization	Poplar trees, willow (Salix inger) and grasses	Biomass energy generation (combustion); ethanol production; wood chips; other biofuels	Costs and benefits dependant on classification as usable biomass or waste	Andersson-Sköld 2013, 2014
	Sweden	Post-industrial soil (Vista Varv)	Dioxins, heavy metals, PAHs	Phytostabilization, rhizodegradation	*Salix Klara, Salix Inger*	Biomass energy generation (combustion); ethanol production; wood chips and pellets; other biofuels	Pine and Hemp also considered but dismissed due to obstacles; soil improvements necessary for cultivation	Andersson-Sköld 2013, 2014
	Romania	Uranium mining waste site	Heavy metals, radionuclides	In-situ stabilization - enabling natural rehabilitation	N/A	No cultivated biomass solution considered viable	Biomass production deemed unfeasible for radionuclide contaminated sites - best option was to prevent contaminant migration	Andersson-Sköld 2013, 2014
	France (PHYTOPOP project)	Wastewater sludge dumping site	Cd, Zn, Pb, Cu, other trace metals	Phytostabilization	Poplar and willow species, Miscanthus gigantus grass	Biofuel production, wood chips for use in local boilers	Used primarily to evaluate biomass valorisation to validate the DST; valuable agricultural land deemed unfit for food production	Andersson-Sköld 2013, 2014
	France (PHYTOSED Ec1 project)	Dredged sediment landfill site	Cd, Zn, Pb, As, Cu; various organic pollutants	Aided phytostabilization and in-situ stabilization agents - basic slag (TBS)	Willow and poplar species and hairgrasses (possible rotations with grain crops - wheat/barley)	Biomass energy generation (combustion)	Used primarily to evaluate biomass valorisation to validate the DST; major goal to preserve biodiversity in surrounding area	Andersson-Sköld 2013, 2014

Figure 7.3: Best Practice - Bio-based production

8

Case Study Application

This chapter presents the step-wise application of the four stages in the Rejuvenate DST in order to determine the most suitable bio-based production systems for the two case study sites.

The prevailing purpose of this case study application was to conduct a feasibility study and ultimately propose a viable, preliminary bio-based production system for two idle case study sites located in Gothenburg, Sweden. By means of an extensive literature review, certain decision-support tools, best practices and evidence-based expertise were shown to be the most applicable in conducting this study. By following the *Rejuvenate* DST framework and combining the knowledge gained in the research process, the recommendations and discussion aim to demonstrate that a synergistic solution accounting for both profitable biomass production and remediation of contaminated soil could contribute to circular, bio-based economy while also providing wider benefits like ESS.

8.1 Description of Case Study Sites

Two brownfield sites in the city of Gothenburg, Sweden were evaluated for application of the various techniques researched in this study. Proposals for bio-based production combined with risk mitigation of contamination are accommodated to the specifications at each site. Information for the two sites was obtained from site investigations performed by the consulting company Sweco.

8.1.1 Lemmingvallen, Utby

The first site is located in Lemmingvallen near the area of Utby in northeast Gothenburg. At an estimated size of slightly over 1 hectare, the site lies in close proximity to detached housing units and the nearby stream of Säveån, see Figure 8.1. Currently, the site is a vacant green area with grass covering and scattered trees, and is occasionally used as a recreation area and dog walking park Field investigations revealed elevated levels of organic pollutants like PAH, BTEX, and aliphates (carcinogens) as well as various heavy metals (e.g. Zn, Cu, Pb). The soil itself varied between petroleum saturated deposits, clay, sandy earth, and crushed brick up to depths of 3.5 meters. Concentrations of contaminants were measured in high enough concentrations to exceed Naturvårdsverkets risk classification for sensitive land uses (KM) and even less-sensitive land uses (MKM). It was determined by investigations

Figure 8.1: Satellite image of Utby site outlined in red, from Almqvist (2017)

that there exists a risk to human health and the environment (groundwater leakage towards Säveån) for both current and future planned land uses such as housing units, though no immediate development is currently planned (Almqvist, 2017).

8.1.2 Karlavagnsplatsen

Figure 8.2: Concept image of Karlavagnsplatsen development with investigation area outlined in red, from Kaltin and Almqvist (2016)

The second site is part of Gothenburg's planned development in the Lindholmen area north of Göta Älv. The site is located between Polstjärnegatan and the railway, and is called Karlavagnsplatsen. This area has a history of diverse uses (e.g. sediment deposits, storage yard, wastewater sludge deposits) which has led to a wide mix of contaminants throughout the site. Most notably, cable burning sites are scattered within the area creating hotspots of concentrated pollutants like lead. Large swaths of the outlined area are designated to be park area, stormwater capturing, or other roadway surfaces. However, in the development plan there exists a sizeable 'blank spot' of approximately 2 hectares not planned for use, see Figure 8.2. It is in this specific blank spot where the bio-based production proposal will be focused. Within this area, investigations revealed elevated concentrations of metal(oid)s (Zn, Cu, Pb, As, Ba), organic pollutants (PAH, BTEX, PCB, etc.), traces of pesticides, debris and elements from passing traffic (e.g. brakes), and other trace chemical solutions or pthalates. In general, the site as a whole does not pose acute health risks with the exception of the cable burning sites with elevated lead concentrations. The reports indicate that future development plans for the study area expressed the desire for a more 'natural character' which signals great potential for integrating phytoremediation and bio-based production into future plans (Ardung and Almqvist, 2015; Kaltin and Almqvist, 2016).

8.2 Stage 1: Crop Selection

In order to filter the extensive list of potential plant/crop species compiled from literature review (see Appendix 5), eight criteria for evaluating the individual species were created (based of off based practices and the case-specific requirements) to create a 'binary' system of selection. Where, a '1' was assigned if the species met the criteria and a '0' if it did not. The filters used are listed below:

- **Ability to grow well in local climate**: An essential first filter where those species which seemed unlikely to thrive in Gothenburg's climate conditions were immediately dismissed from further consideration.
- **Phytostabilization capability**: Valuable phytoremediative ability in order to prevent the migration of contaminants at site and not uptake excessively into plant biomass.
- **Phytodegradation of organic pollutants capability**: Both sites had detectable levels of PAHs and other organics which could be phytodegraded directly by certain species.
- **Phytoextraction of metals (Zn, Cu, Pb) capability**: Certain species could directly uptake the metals prevalent at the sites which is valuable to remove the risk directly.
- **Economically useful biomass**: Based upon local capacity to utilize the produced biomass to produce biofuels, pellets/chips for electricity or heat, and other bio-products in general.
- **Well-established procedure**: For greater chances of success those species which have been proven effective at small-scale production on derelict land were favored.
- **Site-specific suitability**: General public acceptance of the plant/crop species in each urban setting was considered as well as ease of implementation without

significant capital cost.

- **Soil restoration potential**: An underlying goal in applying GROs was to improve the soil conditions to restore soil fertility, sequester carbon, and provide ESS in urban settings which varies depending on species.

As a result from applying these eight filters to the crop species, three 'tiers' of potential plant species were created: Tier 3) Those species that failed the initial check of growing capability in the local climate, and were deemed unsuitable for this study. However, these plants perhaps still could be useful for other similar projects elsewhere. Tier 2) Those species which could grow in the local environment but did not fully meet all the criteria specified in the filters. These crops could be useful for other projects in the local area in the future, or possibly as options for crop rotations to diversify production. Tier 1) Those species which fully met 7 or 8 of the criteria and were deemed best suited to this study, and have been proven to work in similar studies. The results of stage 1 are presented below in Figure 8.3; where Tier 1 is shaded in green, Tier 2 is in yellow, and Tier 3 is in red.

Tier	Biomass Crop Type	Common Name	Ability to grow well in climate	Phytostabilization	Phytodegradation of organic pollutants	Phytoextraction (Zn, Cu, Pb)	Economically useful biomass (locally)	Well-established procedure (small-scale)	Site-specific suitability (acceptance)	Soil restoration potential (fertility)	Total
3	Biomass Crop	Soya Bean	0								
	Biomass Crop	Tobacco	0								
	Biomass Crop	Castor Bean	0								
	Fibre Crop	Hemp (perennial)	0								
	Fibre Crop	Kenaf	0								
	Grain	Sugar Beet (annual)	0								
	Grain	Maize or Corn (annual)	0								
	Oil Crop	Indian Mustard, Ethiopian Mustard	0								
	Perennial Grass	Switch grass (perennial)	0								
	Woody Biomass (SRC)	American sweet gum or Satin walnut or Alligator wood	0								
	Woody Blomass (SRC)	Eucalyptus, Flooded gum or Rose Gum (some perennial)	0								
2	Fibre Crop	Flax and Camelina (false flax)	1	0	1	1	1	1	0	1	6
	Grain	Barley	1	1	0	0	1	0	0	1	4
	Grain or Grass	Sweet Sorghum	1	1	0	0	1	0	0	1	4
	Grain	Winter Wheat (annual)	1	1	0	0	1	0	0	1	4
	Oil Crop	Rapeseed	1	0	1	1	1	0	0	1	5
	Perennial Grass	Alpine pennygrass (perennial)	1	0	0	1	0	1	1	1	5
	Perennial Grass	Wheatgrass (perennial)	1	1	0	0	1	0	0	1	4
	Woody Biomass (SRC)	Loblolly Pine	1	1	1	1	1	0	0	1	6
1	Oil Crop	Sunflower (annual)	1	0	1	1	1	1	1	1	7
	Perennial Grass	Giant perennial silvergrass (C4)	1	1	1	1	1	1	1	1	8
	Perennial Grass	Canary Reed grass (perennial)	1	1	1	1	1	1	1	1	8
	Woody Biomass (SRC)	Poplar	1	1	1	1	1	1	1	1	8
	Woody Biomass (SRC)	Willow	1	1	1	1	1	1	1	1	8

Figure 8.3: Crop Selection results from Stage 1

Due to similarity in site conditions, local climate, and general objectives per site, the crop selection for each site was combined into one procedure. Thus, the 5 species which are most fitting (Tier 1) to establishing bio-based production are:

- Short-rotation woody biomass: Willow (*Salix*) and Poplar (*Populus*)
- Perennial Grass: Canary reed grass (*Phalaris arundinacea*) and giant silver-grass (*Miscanthus giganteus*)
- Oil crop: Sunflower (*Helianthus annus L.*)

This crop selection outcome aligns closely with those recommended by Andersson-Sköld et al. (2013) for Swedish climate conditions, and with the most valuable energy crops as per the 4F Crops project in EC (2010). The final point in the the *Rejuvenate* Stage 1 checklist pertains to an initial appraisal of the practical use of the produced biomass. Usage of short-rotation forestry is well-established with possibilities to produce ethanol from stems and roots, production of pellets and wood chips for combustion coversion for heat and power (Andersson-Sköld et al., 2014; EC, 2010). The perennial grasses, classified as ligno-celluosic, could be used to produce second generation bio-fuels or combusted directly to generate power (EC, 2010). Sunflower is classified as an oil crop and depending on the oil content of the seeds can be valuable to produce bio-diesel or other types of bio-fuels (EC, 2010).

Regarding local capacity, it is not easy to predict market values for the biomass but the Gothenburg area has a well-established market with growing interest for producing bio-fuels and utilizing biomass for combined heat and power (CHP) (Enell et al., 2016). Indeed, the energy company ST1 has recently completed a large-scale ethanol production plant which recycles biomass (or biowaste depending on classification) into second generation biofuels.[1] Göteborgs Energi[2] also produces biogas using waste biomass in the local area, and biomass produced on brownfield sites could readily become feedstock. Additionally, government regulation and policy has been pushing for increased biomass use all across Europe, and small-scale biomass use is becoming more feasible. Relevant policies applicable in Sweden are neatly summarized in Appendix 6 of Andersson-Sköld et al. (2013), all of which support the use (indirectly) of the *Rejuvenate* methodology to increase biomass production on brownfield sites and biomass usage in general to promote a bio-based circular economy. Recent research performed by Ericsson and Werner (2016) confirms the long history of biomass use in Sweden. Their study consists of a detailed evaluation of energy policies and incentives, biomass market prices, and well-established infrastructure and procedures which all contribute to a continuing, growing competitive use and need of biomass to supply feedstock for CHP, biofuels, bio-plastics, etc.

An additional factor to consider for improved chances of success is the clonal variety of each plant species. Modern genetic engineering has provided a vast field of research and breeding programs to specifically tailor clones of willow, poplar, or other important biomass crops for increased performance. Individual clonal varieties often are designed to maximize specific features like biomass yield, disease

[1] `http://www.st1biofuels.com/solutions`
[2] `https://www.goteborgenergi.se/`

resistance, water use reduction, etc. as shown in Figure 8.4. Sweden has been one of the world leaders in breeding varieties of SRC tree species, so there are many well-researched clones to choose from in applying for each site (e.g. *Salix Inger* and *Salix Klara*). Dimitriou and Rutz (2015) provides a detailed evaluation of willow and poplar varieties and their characteristics for situations which they are best suited. Further information and consultation in choosing varieties, of both SRC and other Tier 2 annual varieties, is available through the Swedish breeding programme at Svalöf-Weibull AB (SW)[3] and Salixenergi Europa AB[4].

	Clonal Variety	Description	Sources
Willow	*Klara*	*Stabilization*; One of highest yielding in a cold climate	Andersson-Skold et al. 2013; Enell et al. 2015; SalixEnergi AB; SRC Handbook 2015
	Inger	*Stabilization*; Highest yield in mild, warm climate, good performance in dry soil, high dry matter content, susceptible to pests	Andersson-Skold et al. 2013; Enell et al. 2015; Van Slycken et al. 2013; Kidd et al. 2015; SalixEnergi AB; SRC Handbook 2015
	Tordis	*Extraction/Stabilization*; High yield in north-central Europe, free from leaf rust, low bulk density, high calorific value, low dry matter, susceptible to pests	SRC Hanbook 2015; SalixEnergi AB; Kidd et al. 2015
	Tora	*Extraction*; Among highest yields in north-central Europe, low leaf rust and pests, high yield in 2nd rotation, suitable for all environments, less preferred by game	Delplanque et al. 2012; Van Slycken et al. 2013; SRC Handbook 2015; SalixEnergi AB; Kidd et al. 2015
	Zwarte Driebast	*Extraction*, High yields	Van Slycken et al. 2013
	Loden	*Extraction*, High yields	Van Slycken et al. 2013
	Sven	*Extraction*; High yields, low leaf rust, chips with low bulk density but high calorific value, sensitive to late spring frost	Kidd et al. 2015; SRC Hanbook 2015; SalixEnergi AB
	Olof	High yields, robust variety with few shoots, spring flowering varitety favorable for bees, not preferred by game, susceptible to leaf rust	SRC Hanbook 2015; SalixEnergi AB
Poplar	*Max 1, 3, 4*	*Extraction*; High yields, susceptible to pests	SRC Handbook 2015; Kidd et al. 2015
	Matrix	*Extraction/Stabilization*; Medium yields at all soils, high growth rate especially at cooler and humid areas	SRC Handbook 2015; Kidd et al. 2015
	Hybrid 275	*Extraction/Stabilization*; Medium yields at all soils, high growth rate especially at cooler and humid areas, susceptible to pests	SRC Handbook 2015; Kidd et al. 2015
	Muhle Larsen	*Stabilization*; Medium yields at all soils	SRC Handbook 2015; Kidd et al. 2015
	Fritzi Pauley	*Stabilization*; Medium yields at all soils	SRC Handbook 2015; Kidd et al. 2015
	Trichobel	*Stabilization*; Medium yields at all soils, fast growth rate	SRC Handbook 2015; Kidd et al. 2015

Figure 8.4: Clonal varieties of Willow and Poplar species

[3] http://www.swseed.com/
[4] http://salixenergi.se/planting-material/

8.3 Stage 2: Site Suitability

The primary sources of site information for both sites were field investigation reports performed by Sweco (Almqvist, 2017; Ardung and Almqvist, 2015; Kaltin and Almqvist, 2016). As such, the main focus of these reports was an investigation of contamination at the sites and the risks posed to human health and the surrounding environment. The risks vary per site so Stage 2 was performed separately in order to apply the *Rejuvenate* checklists more exactly. However, one important similarity these reports shared was a lack of in-depth investigation into specific soil conditions facilitating growth of vegetation (i.e. SQIs, see Table 4.2). The soil information per site was used to provide a general overview of growing conditions, but further investigations are suggested for each study site.

8.3.1 Lemmingvallen, Utby

The site analysis revealed elevated levels of contaminants variously throughout the site, see Figure 8.5. Contaminants of greatest concern are metals (Zn, Cu, Pb), PAHs, BTEX and various other organic pollutants (Almqvist, 2017). Soil sampling revealed that the highest levels of contamination were concentrated in specific areas of the site; namely, the northwest and southwest corners of the site had measured contaminant levels consistently exceeding the thresholds for the less-sensitive land uses (MKM). In these areas, soil saturated with petroleum-based compounds were detected as well as unsafe levels of Pb, Cu, and Zn which require direct, targeted remediation due to health risks for locals using the area. Aside from these two areas of the site, the remainder was shown to have significantly lower levels of contaminants and could even be safely used by locals. Sampling also showed that the groundwater in the site was not contaminated as of yet, but pollutants could migrate downwards and eventually towards Säveån if left unchecked.

Contamination aside, the site's potential for cultivation of the selected crops is uncertain. However, trees and grass are currently growing freely, without maintenance, on the site which is a positive sign indicating that nutrients and water are present and that contaminant levels are not overly phyto-toxic. Site investigations revealed a wide range of soil material, including sand, clay, coarse filling material, brick, inorganic wastes, and other matter which may or may not inhibit the growth of desired vegetation. Further investigation into the specific soil quality indicators about organic matter in the soil, essential available nitrogen and phosphorous, pH, etc. to evaluate the soil via the SF Box tool (Volchko et al., 2014) and determine growing conditions and the necessity of soil amendments or other improvements is required. Most likely, some form of organic amendment like compost or biochar will be necessary for both boosting plant growth and aided *in-situ* stabilization.

In the context of the Utby site, a crop system based upon the principles of agroforestry, including inter-cropping and rotations, would likely be effective for both remediation and biomass production. In this case, tree species could be grown alongside the perennial grasses, sunflower, or even the Tier 2 crops in some degree

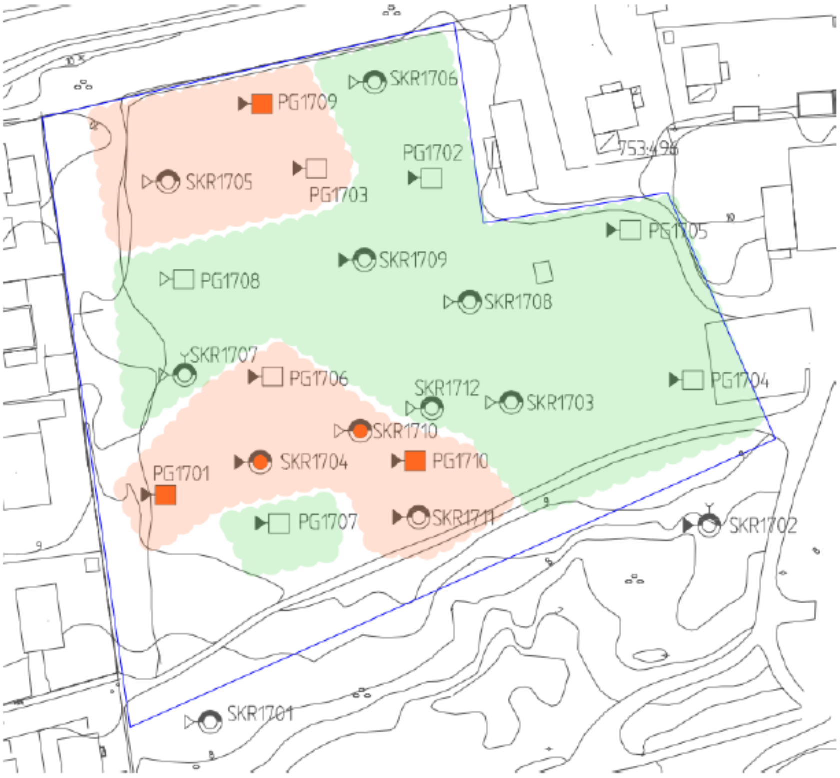

Figure 8.5: Map of sampling sites and contamination at Utby site; red-shaded areas had detectable petroleum saturation and high contaminant levels, and green-shaded areas had contamination levels under the threshold for sensitive-land uses (KM). From Almqvist (2017)

to provide a diversity of plant life and ecosystem conditions thus bolstering surrounding biodiversity and ecosystem resilience. Willow SRC in particular have been proven to increase arthropod species (an extremely valuable insect species providing innumerable ESS) in the surrounding area, and is even improved with increasing tree genetic diversity by growing multiple clones types (Dimitriou and Rutz, 2015; Mehmood et al., 2017; Müller et al., 2018; Rowe et al., 2013).

In terms of specific site cultivation, a potential planting scheme could employ various species based upon contamination levels. The western areas with concentrated contamination require more specifically tailored phytoremediation techniques, and facilitating rhizodegradation via plant-based microbes is of particular importance. *Salix* and *Populus* species have proven to be adept at fostering the growth of microbes and the combination with specific *endophytes* and soil amendments (as detailed in section 6.3.1 in this study) could even enhance the bio-degradation of organic contaminants and boost plant growth; however, many of these techniques have yet to be fully field-tested and should be thoroughly reviewed before implementation. The grasses have also been shown to possess rhizodegradation capability, and are also a valid option. In these same areas, Zn, Cu, and Pb could inhibit plant growth and/or be absorbed into plant biomass (depending on clone/species). Research indicates that elevated metal concentrations should not have a detrimental effect on biomass conversion for energy or fuels, but the metals could be recycled into the environment through decaying biomass unless actively cleaned off the site.

On the eastern side, a focus on soil stabilization and growing a greater variety of crops is possible at low risk. Furthermore, the eastern side could even become small-scale, urban agriculture *in-situ* allotments (at low risk) for locals to cultivate food crops and build recreation facilities. Interactive landscape design and stakeholder consideration would be instrumental to success in this regard and is discussed later.

8.3.2 Karlavagnsplatsen

Site investigations performed at Karlavagnsplatsen revealed similar contamination concerns to the Utby site; namely, organic petroleum-based pollutants (PAHs, BTEX, aliphates, etc.) and heavy metals (Zn, Cu, and Pb). Elevated levels of arsenic and traces of various other contaminants (e.g. pesticides) were also detected spread throughout the site, due to its diverse history of use as a waste deposit and storage area, which pose additional risks to human health and the environment (Ardung and Almqvist, 2015; Kaltin and Almqvist, 2016). By far the greatest concern at the site are the 13 discreet locations identified as 'cable-burning sites.' Initially noted in the 2015 report (Ardung and Almqvist, 2015), 11 of these sites were identified and examined via soil sampling. Later investigation revealed 2 more and testing showed very high levels of metals (Zn, Cu, Pb) in the topsoil layer (0-0.1m) which may pose acute health risks to humans and wildlife using the site. Based off of sampling locations, it is estimated that 5 of these sites are located within the 'blank spot' of the development map. Due to the severity of the contamination risk and toxicity, phytoremediation is not well-suited for these locations and the soil should be excavated for *ex-situ* treatment elsewhere. As recommended by Sweco, an estimated 25-50 m^3 of the highly contaminated topsoil mass (0-0.1 meters depth) at these hotspots would require excavation at a cost of approximately 0.1-0.3 Mkr (Kaltin and Almqvist, 2016). Considering further excavation requirements, Sweco investigated an excavation of the entire soil area up to 0.7 meters depth (10,000 m^3) throughout the park area. It was estimated to cost approximately 8-12.5 Mkr, and 90% of the mass is expected to contain detectable levels of contamination exceeding the sensitive land use designation (KM). An important note with this second volume estimate is that it considers the park area aside from the 'blank spot,' but for simplicity these sizes and accompanying cost estimate are considered comparable.

Excavating the cable-burning hotspot sites is a necessary remediation measure, but phytoremediation is still a valid strategy for large swaths of the site since contamination levels are not too severe. Sweco even recommended further investigations into the practical necessity of large-scale excavations (up to 0.7 meters in depth) for the larger area to determine whether or not the risk reduction from the excavations justifies the high cost (Kaltin and Almqvist, 2016). The report states that most of the site area shows only little risk for negative health effects in the long-term, so more sustainable gentle remediation options are certainly viable.

General soil makeup regarding coarse material and other soil quality indicators for successful plant growth can be approximated from the site investigations, but incompletely. Concerning specific cultivation capability, widespread growth of thick grasses and weeds suggests that newly introduced crop species should be able to grow on the site. Investigations showed that the large majority of the site is composed of various filling materials like humus, sand, gravel, and wastewater treatment sludge from Ryaverket which is likely also a source of trace contamination as well as beneficial nutrients. Many areas in the site also contained more man-made substances like plastics, bricks, and various other wastes. As with the Utby site, further investigations into SQIs is necessary to evaluate the soil conditions on-site according to the SF Box tool methodology (Volchko et al., 2014). Stabilizing and nutrient boosting amendments (e.g. compost, biochar) will likely still be prudent in this case as well.

As previously suggested for the Utby site, a crop system based upon agroforestry and crop rotations will likely be effective for the Karlavagnsplatsen site. Following the targeted excavation of toxic hotspot soil, an SRC crop system with varying willow and poplar clones to stabilize the contaminants in the local soil matrix as well as degrade the organic, petroleum-based pollutants in the soils would provide long-term remediation and biomass stock. Planting the perennial grasses intermittently throughout the site would also provide benefits in terms of biodiversity, local ecosystem resilience, and perhaps most importantly the *Miscanthus* and canary reed grasses have both proven to be efficient phytoextractors of arsenic (and most other trace metals). Arsenic poses a severe threat to human health linked directly as carcinogenic and detrimental to the surrounding environment, so directly targeting the areas with detectable arsenic levels is a critical risk mitigation action.

Due to the central location of this site and its close proximity to surrounding dense residential areas, the site will most likely be desired for use as a open green space for recreation or even to create allotments for community gardening. Aside from the hotspot areas, site investigations showed residual contamination levels rarely exceeding the sensitive land use (KM) contamination levels throughout most of the site. Therefore, it is possible to rotate annual crop species like sunflower or other Tier II plants at the site to meet a wider range of needs and uses for the biomass while restoring the soil fertility and stabilizing contaminants in the soil with minimal risk of uptake into the plant biomass. Further investigation is necessary to determine whether cultivation of food crops in the local soil could be safely performed, or if external clean soil is needed to grow in designated planter boxes. Collaboration with stakeholders will be important in this context especially to determine what kind of bio-based production is suitable at the site, and whether urban agriculture or certain recreation facilities are desired.

8.3.3 Summary of Proposals - Stage 2

As a consequence of the two sites having many similar conditions (e.g. climate, contaminants), the preliminary proposals for bio-based production at either site tend towards the same central features. A primary contributor to this is the list of viable crops resulting from Stage 1's selection procedure thus narrowing the range of possibility to what is considered most achievable. The crop systems and techniques which are considered important for cultivation of the chosen species per site are listed below:

- **Risk Mitigation**: A wide range of contamination was found at either site which must take priority in plant cultivation. Most importantly, some combination of phytostabilization (aided with organic amendments and/or microorganisms), phytoextraction, and phytodegradation will need to be designed for each site in order to be effective.
- **Willow and Poplar SRC**: Short-rotation coppicing (3-4 years) is a well-studied and effective measure for generating useful biomass, phytoextraction of select contaminants, and stabilization of contaminants in the soil matrix while providing useful ESS. An important consideration is that selection of a particular willow or poplar clone species is crucial to success per circumstance and desired outcome as each clone performs different functions.
- **Agroforestry and Crop Rotations**: A mixture of tree species in sync with perennial grasses or other annual species in Tier 2 provides additional benefits per each site well-supported by literature. Rotations of crops at the site is also an important agronomic practice which, if well-planned, will ensure successful plant growth in the long-term and minimize external inputs into the crop system. Also, soil amendments like biochar or compost will likely be necessary to ensure sufficient soil quality and stabilization of contaminants.
- **Urban Agriculture**: Due to proximity to residential areas, both sites could feature small-scale emplacements or allotments for locals to grow their own desired food products. Further investigation is necessary to determine the risks of contaminant uptake into food products by growing *in-situ* or by bringing in clean external soil for growing in planter boxes as an interim use until the soil is considered safe to grow in.

8.4 Stage 3: Value Management

Demonstration of the value in Stage 3 at the case study sites focuses largely on a preliminary sustainability assessment and how the proposals could contribute to sustainable urban development. In previous *Rejuvenate* applications, Stage 3 was primarily focused on choosing the most economically viable bio-based production option at a site. So, economic aspects of the proposals are first discussed with basic calculations concerning cost estimates, profit generating potential, and other financial feasibility considerations. Secondly, the environmental aspect is discussed in terms of tracking the changes of ESS provided by the proposed systems, how they align with sustainable remediation criteria outlined in SURF-UK (see Table 4.3), and other associated considerations. Finally, social aspects to the project are evaluated alongside other wider project services offered via brownfield redevelopment by tying-in the Brownfield Opportunity Matrix and HOMBRE.

8.4.1 Economic Aspect

Andersson-Sköld et al. (2014) state that financial viability depends on the amount of biomass produced (growth), what the product can be used for, and the market value. In general, the revenue depends on financial support/subsidies related to bioenergy offered by the government, and in the worst case, the product may be legally regarded as waste resulting in a net cost. Thus, the success of a bio-based production project at a brownfield site is heavily dependent on the classification of the produced biomass as a resource or a waste. Fortunately, a study performed by Witters et al. (2012a) demonstrated that biomass with elevated levels of metals has no negative effect on biomass conversion efficiency, and that metals are separated into ash which can be managed directly. van Slycken et al. (2013) conclude that high performing SRC clones (i.e. high biomass production) are indeed a viable economic option for farmers while slowly remediating the land. Many studies performed worldwide have confirmed this evaluation, and extend the economic viability to marginal land SRC as well (Edrisi and Abhilash, 2016; Enell et al., 2016; Ghezehei et al., 2015; Licht and Isebrands, 2005; Mehmood et al., 2017; Witters et al., 2012a). Economic benefits from urban agriculture were not considered, but they could be a potential boon for demonstrating future economic value.

Detailed economic calculations at this 'preliminary investigation stage' of a bio-based production project (in the context of this study) are difficult to perform due to lack of detailed information. However, previous applications of *Rejuvenate* projects, related phytoremediation literature, and rough market rates for biomass provide a good initial basis for estimating the costs involved and the potential for income generation. Overall phytoremediation costs in a project performed by Wan et al. (2016) resulted in costs of \$75,375/ha (or \$38/m3) to remediate a large contaminated farmland site. The expected payback period after monetizing all benefits (including ESS) was only 7 years. In general, phytoremediation costs are approximately 50% lower than excavation costs in most cases (Gerhardt et al., 2017). Additionally, Witters et al. (2012b) performed an economic assessment directly determining the sustainability of phytoremediation and carbon abatement benefits of using the crops for renewable energy production. Their results indicated a carbon abatement benefit of approximately 550-5000 SEK/ha when converted into a monetary value. Furthermore, to accurately depict the true economic value of a bio-based production system the ESS and other benefits provided would have to be quantified to reflect their added value. These indirect values directly support the economic case for this type of bio-based production which is typically overlooked. A detailed procedure for doing so is discussed in Schröder et al. (2018), but not performed in this study. However, the brownfield opportunity matrix of HOMBRE (Menger et al., 2013) provides a good overview of the added economic assets attributed to gentle remediation options in general. The major factors they consider which GROs have significant potential to boost if well-designed are job generation, land value recovery over time, surrounding area value uplift, and interim land management and productive use.

The *Sustainable Short Rotation Coppice Handbook* (Dimitriou and Rutz, 2015) provides meticulous detail on best practices in establishing SRC plantations, including cost and profit estimates. For example, an SRC plantation in Sweden cost approximately 370 euros per year in upkeep and establishment, generated 864 euros in income, and resulted in 494 euros per year in overall revenue. A similar, larger scale willow SRC in Sweden resulted in 637 euros per year of revenue including a 550 euro plantation establishment subsidy. No poplar SRC in Sweden were discussed, but the overall revenue from a German plantation was approximately 2,899 euros from 130 hectares. Each of these examples is on a significantly larger scale with much more intensive farming machinery and costly procedures used to establish the SRC. However, they are valuable examples to demonstrate the potential profitability of such an operation, and if a minimal input SRC system is prioritized then the profit margin and numerous co-benefits could be even greater.

Cost calculations for the perennial grasses and sunflower grown for bioenergy on marginal lands were more difficult to find. These types of production systems are not yet studied as extensively, so estimates for production costs, yields, and revenue vary considerably per study. In general, reed canary grass has been shown to produce higher yields at lower cost than miscanthus thus making it more economically viable (Lord, 2015; Soldatos, 2015). However, Soldatos (2015) stresses that cultivating perennial grasses alone will likely not prove to result in financial returns without financial incentives. The report from EC (2010) stresses the importance and economic potential of sunflower, but specific revenue from cultivation on brownfield land is uncertain at this point. Figure 8.6 provides simplified cost estimate calculations (based off of literature review) for the major Tier 1 crop types. As can be seen in the table, the range of estimated profit varies widely for each species. A major factor in this variation is due to the large differences in production costs between different types of cultivation systems, so a focus on low-intensity, minimal input production greatly increases the chances of economic viability.

Crop Species	Projected Mass Yield (ton dw/ha*yr)	Buying Price (SEK/ton dw)	Cost of Production (SEK/ton dw)	Profit Margin (SEK/yr)	Potential Subsidies (SEK/ha)	Source
Willow	6	700-875	650-750	-300 <> +1350	5000	Enell et al. 2015, SLU
Poplar	6	700-875	650-800	-600 <> +1350	-	SRC Handbook
Reed Canary Grass	8	650-800	650-1150	-3000 <> +900	-	Lord 2015, SLU, Soldatos 2015
Miscanthus	8	650-800	650-1200	-3300 <> +900	-	Andersson-Skold et al. 2013, SLU, Soldatos 2015
Sunflower	2.1	-	-	-	-	4F Crops (EC), Smith et al. 2013

Figure 8.6: Simplified economic estimates for yields, buying prices, production costs, and profit.

8.4.2 Environmental Aspect

A summary provided by Dimitriou and Rutz (2015) describes the sustainability benefits of SRC as follows: *If managed in a sustainable way, SRC can generate significant synergies with other agricultural practices, with ecosystem services and* *nature conservation measures. SRC usually helps to improve water quality, enhances biodiversity [phyto- and zoo-diversity], provides ecosystem services (hunting, beekeeping, water supply, fire protection), mitigates animal diseases between farms, prevents erosion, reduces artificial input materials (fertilizers, pesticides) and mitigates climate change due to carbon storage. These advantages have to be promoted to produce sustainable woodchips from SRC, enhancing the positive impacts of SRC to the environment. Thereby, sustainability aspects must be considered: SRC has most positive impacts on marginal soils and especially as structural elements in the landscape, bordering for instance fields, roads, and electricity lines.* The breadth of environmental benefits offered by SRC are well-researched and proven through extensive project testing. Despite not being as thoroughly explored, the range of benefits gained by incorporating perennial grasses and other crops in rotation are similarly impressive. Studies performed by Lord (2015); Mehmood et al. (2017); Zegada-Lizarazu and Monti (2011) confirm the co-benefits. Moreover, the environmental benefits are instrumental to demonstrate the overall value of the bio-based production systems.

A 'semi-quantitative' approach to tracking the ESS and wider environmental benefits potentially delivered at the site, provided successful establishment, was followed according to the 'ESS Mapping' procedure developed by Ivarsson (2015). This methodology was particularly useful as it is comparison based to weigh remediation alternatives (i.e. in this case comparing between the proposed phytoremediation or leaving the site as is), to show the ESS commonly considered applicable in urban contexts, and it was similarly conducted in the early project stage when little detailed information was available and much of the knowledge was qualitative (i.e. desk study for initial feasibility). Many of the considerations and important findings from the use of the mapping procedure were also useful in this case. Justifications of the positive or neutral effects of the proposed systems at each site were gathered via literature review, comparison with HOMBRE's brownfield opportunity matrix (BOM), and conclusions drawn by Ivarsson (2015) in their study. See Figure 8.7 below for the resulting table.

Concerning remediation in general, Ivarsson (2015) concludes that the creation of green space had a strong impact on the final score of each alternative in the ESS Mapping. Both urban and soil ESS were considerably more influential in designated green spaces, and major changes in land use via soil sealing in adjacent areas was avoided. The most detrimental impact for each alternative in the procedure was the deposition of polluted soils at land off-site (e.g. landfills). This is primarily a concern for Karlavagnsplatsen as the highly Pb-contaminated soil will be dumped at some waste site to likely lessen the environment of that area instead. The excavation is a necessary precaution to mitigate risks at this site, but due diligence is required to ensure that depositing the soil is performed responsibly at landfills capable of handling the contamination.

The aim in applying the ESS Mapping method was to demonstrate the range of possibility that each bio-based production proposal offers in terms of overarching value to the environment via ESS. Ideally, these values would be monetized in order to be applied in sync with a traditional cost-benefit analysis to support the value of

Sources: TEEB, MBA, CBO, Ivarsson, HOMBRE			Case Study Site Propsals - Estimated Effects		
Ecosystem Service		Urban Context	Karlavagnsplatsen	Lemmingvallen (Utby)	Comments
Provisioning	Food	Food products produced via urban gardening	+	+	Depending upon risks
	Fresh water	Securing storage and controlled release of water flows. Vegetative cover influences quantity and quality	++	++	
	Biomass	Provision of non-food products like fibres, oils, etc. used for other bio-products or fuels; increased soil fertility	+++	+++	
Regulation and Maintenance	Air Quality	Improving air quality by removing pollutants	-/++	-/++	Risk of phyto-volatilization
	Climate Regulation	Carbon sequestration and storage, regulating surround local temperatures, lessening urban heat island effect, providing shade, wind protection, etc.	++	++	
	Water Regulation	Percolate water through soil to groundwater, regulate stormwater runoff, evapo-transpiration	++	++	
	Noise Reduction	Mitigate noise pollution via absorption, deviation, reflection, and refraction of sound	+	+	Possibility to lessen noise from road traffic
	Water Purification and Waste Treatment	Decomposition of labile pollutants, extraction of metals, filtering water	-/++	++	Landfilling of Pb-polluted soil off-site moves negative effects elsewhere
	Pollination and Seed Dispersal	Biodiversity habitats which supports pollination, pest regulation, and seed dispersal	++	++	
	Maintaining Nursery Populations and Habitats	Refuge for many species of birds, amphibians, bees, and butterflies	++	++	
	Natural Hazard Regulation	Storm, flood, and heat absorption by vegetation	++	++	
	Erosion Regulation	Stabilizing topsoil to decrease rates of erosion and sediment loading into recepient water	+++	+++	
Cultural	Knowledge Systems	Allotment gardening and green infrastructures sponsoring socio-ecological knowledge sharing and community gathering	+	+	If well-designed
	Aesthetic Values	Urban parks providing visually pleasing areas	+	+	Varies depending upon preferences of local stakeholders
	Cultural Heritage Values	Depending upon archaeological context or spiritual value	0	0	No unique context known for either site
	Recreation and Ecotourism	Urban green areas providing opportunities for recreation, meditation and relaxation	-/+	-/+	Recreation areas can be provided but crop cultivation may take up desired open space

Figure 8.7: ESS mapping applied to the case study sites indicating possible changes resulting from proposed systems; where, +++ = strongly likely, ++ = likely, + = possible, -/+ = possibly negative and/or positive, and 0 = no likely relationship

such an undertaking. This was not done at this stage in the project, but as stated by Ivarsson (2015): *The methodology describes the links in the causal chain between ecosystem features or functions on one end, and effects on human well-being on the other end. These links being e.g. a compilation of suitable biophysical indicators to represent ecosystem services, facilitating the assessment of the relation between those biophysical indicators and related human uses. In doing this, it paves the way for monetized valuations of benefits accruing to different redevelopment alternatives.*

The BOM was also valuable to consider as it expanded the consideration of benefits to the wider project services designation. A comprehensive assessment of each facet of the project (e.g phytoremediation, amendment addition, producing renewable feedstocks, etc.) was considered for each umbrella project services which allowed a holistic analysis of all possible benefits and ramifications. Indeed, the authors were diligent in frequently addressing the potential disadvantages of a poorly designed system, such as introduction of non-native species, disturbance of the local ecosystem, transference of contaminants into the air via volatilization, visual intrusion of trees, and stakeholder considerations (Menger et al., 2013).

8.4.3 Social Aspect

Cultural ESS are most related to social aspects in the ESS Mapping method. It is crucial to the success of the project that these not be neglected during implementation throughout the life cycle of the bio-based production. Preliminary assessment showed that socio-ecological knowledge systems and aesthetic value are possible; however, conscious design and stakeholder involvement will be important to ensure these are realized. Cultural heritage is likely not applicable to either site. Recreation and eco-tourism were difficult to determine as this could either be a positive or negative for the site. This was the case because the provisioning of open space versus crop production, the preference of locals using the site, and success of plant establishment will determine whether the site is used as a recreation area. Any future urban agriculture at the site would also play a large role in providing benefits at the social level.

HOMBRE combines economic and social aspects into 'socio-economic benefits' since they tend to feedback into each other and are strongly interconnected (Menger et al., 2013). The economic assets were discussed previously, but the designation 'amenity' is used to address the benefits more closely tied to the human element. Amenity includes: Open space, leisure, education, improved health and well-being, access (footpaths, cycling), tourism, community centers, views, framing built developments, and grazing. If appropriately designed then the proposals at either case study site could contribute to improving local amenity value, but precautions should be taken for some factors (e.g. grazing, access) at contaminated spots. The authors are quick to point out that biomass crop cultivation approaches may be antagonistic with other forms of land use (e.g. open space for recreation), but propose that a mosaic landscape design approach could allow multiple land uses for a single site. Integrated planning is required to build amenity value for each particular site.

8.5 Stage 4: Project Risks

In practice, the output of stage 4 is a firm project concept where project risk are known, mitigated where necessary, and ready for detailed planning and implementation (Andersson-Sköld et al., 2013). However, in this preliminary feasibility study, stage 4 is considered largely as a focused discussion upon factors deemed important in *Rejuvenate*. The stage 4 checklist focuses on project risks with regard to stakeholder views and consensus, technology status and viability, and detailed diligence in financial matters. To the extent possible via literature review, viability of bio-based production and remediation has been investigated. Financial feasibility was not a primary focus in this study, so further iterations would have to focus on providing more detailed cost and revenue estimates as well as permitting and legislative matters. Perhaps the greatest risk which could undermine the entire project is if the produced biomass is classified as a waste or as biomass. Unfortunately, there are no previous experiences in Sweden to refer to in which legal classification is explicitly stated (Andersson-Sköld et al., 2014). Furthermore, the overall aim of the land use is important to determine whether the wider value (i.e. environmental and social) generated in cultivating crops justifies the project or whether the site must be economically profitable in and of itself. The BOM specifically addresses potential risks in phytoremediation, and states that long-term monitoring may be essential to determine efficacy, the long time duration of these processes may limit functionality, treatment depth is limited to the depth of plant rooting, and that changes made to the pre-existing land use could alter the local site ecology which may not always be acceptable (Menger et al., 2013).

The value of stakeholder engagement early in the planning process was covered extensively by Cundy et al. (2013), and in this case the verification of project performance can be seen as the process by which stakeholders can be assured that the project has met its planned objectives, and will continue to do so in the long-term (Andersson-Sköld et al., 2013; Doick et al., 2009). Indicators of success and methods for verification have engendered a robust field of literature which can be referred to in evaluating the success of this particular project. To separate the body of work, the definitions of success were classified as either 'micro' or 'macro.' Where, micro refers to a specific risk management approach in mitigating contamination, and macro refers to the success of the project as a whole in meeting its pre-determined objectives:

- **Micro**: Risk management approach - direct soil measurements combining contaminant measurements with soil quality measurements. Methods for direct soil testing include those suggested by ARCHE (2014); GREENLAND (2014*b*); Volchko et al. (2014), and Table 8.1 below shows the recommended minimum tests to evaluate soils remediation via GRO.
- **Macro**: Project scale - overall sustainability, meeting project goals, and broader focus in project delivery than purely economic motivations with owner/manager/developer success. Notions of success should include local community (stakeholders) more, and place less emphasis on the traditional funder and developer-centric approach to simply deliver a project on time and within budget (Doick et al., 2009). Recent research explores the shortcomings of typical project delivery plans in meeting the defined objectives, including 'logic models' used to link achieved/desired outcomes to specific aims and project phases (Atkinson et al., 2014; Doick et al., 2009), project stage specific decision-trees (ITRC, 2009), and 'sustainability linkages' which integrate sustainability assessment criteria, overall value, and wider project outcomes with conceptual site models (Bardos et al., 2016).

Tripathi et al. (2015) discuss a robust, expanded definition of success, including both micro and macro, which evaluates the performance of a remediation-based project according to several sustainability indicators or benchmarks: 1) *Clean-up potential* - pollutant level/residual concentration after the phytoremediation process, 2) *Soil quality* - key variables depicting the improvement of the physico-chemical properties of soil 3) *Soil microorganisms* - the enrichment of microbial biomass and their functional diversity in soil, 4)*Biodiversity* - the positive changes in biodiversity

Table 8.1: Recommended minimum test set to evaluate the success of remediation by GROs, summarized from GREENLAND (2014*b*)

Test	Purpose	Reference
1M NH4NO3-extraction	Plant available TE	DIN ISO 19730:2008(E)
Dwarf bean Plantox test	Soil phytotoxicity	Vangronsveld et al. 2009 ISO 15685 protocols
Plant stress enzyme activity	Soil phytotoxicity	Vangronsveld et al. 2009
Nitrification and ammonification potential	Soil toxicity	ISO 14238, ISO 15685
Soil microbial biomass and respiration	Soil microbial stress	ISO 14240-1, ISO 16072
Soil enzymes	Soil toxicity	ISO 23753-1, ISO/TS 22939

component including the sensitive and key indicator species after the remediation process, 5) *Groundwater quality* - positive changes in the improvement of groundwater quality, 6) *Carbon emissions* - the carbon emission/accounting during the each and every step of the remediation process, 7) *Bioeconomy* - stocktaking of potential phyto-products for bio-based economy and entrepreneurial activities and most importantly, 8) *Social aspects* - the social aspects including the social acceptability of the remediation process.

Ultimately, validation and verification requires long-term monitoring and needs to be supported by effective conceptual site and geochemical/biological models (Menger et al., 2013). Dedicated research support claims that large capital expenditures do not guarantee visitor satisfaction, quality or project success, but that mindful design and on-going management and maintenance are even more influential to achieve the full potential of each site. Greenspaces are dynamic places, so success is more than just 'attaining a desired state,' because it has to be embedded within a process of review and re-evaluation as a site matures (Atkinson et al., 2014; Doick et al., 2009). Also, Vieira et al. (2018) show that the form of vegetation in terms of structure, composition, and management are vitally important to optimize the capacity of green spaces to purify air and regulate local climates. Monitoring and evaluation affords many opportunities beyond solely assessment of project delivery, including: 1) supporting the site management cycle, management efficiency and effectiveness, 2) informing funding bodies and other stakeholders, 3) learning valuable lessons, 4) formulating best practices, and 5) providing opportunities for community engagement (Doick et al., 2009).

9

Discussion

This chapter presents a follow-up discussion around the proposed bio-based production systems, important points of consideration in conducting this project, a reflection on applying Rejuvenate, and factors for future consideration.

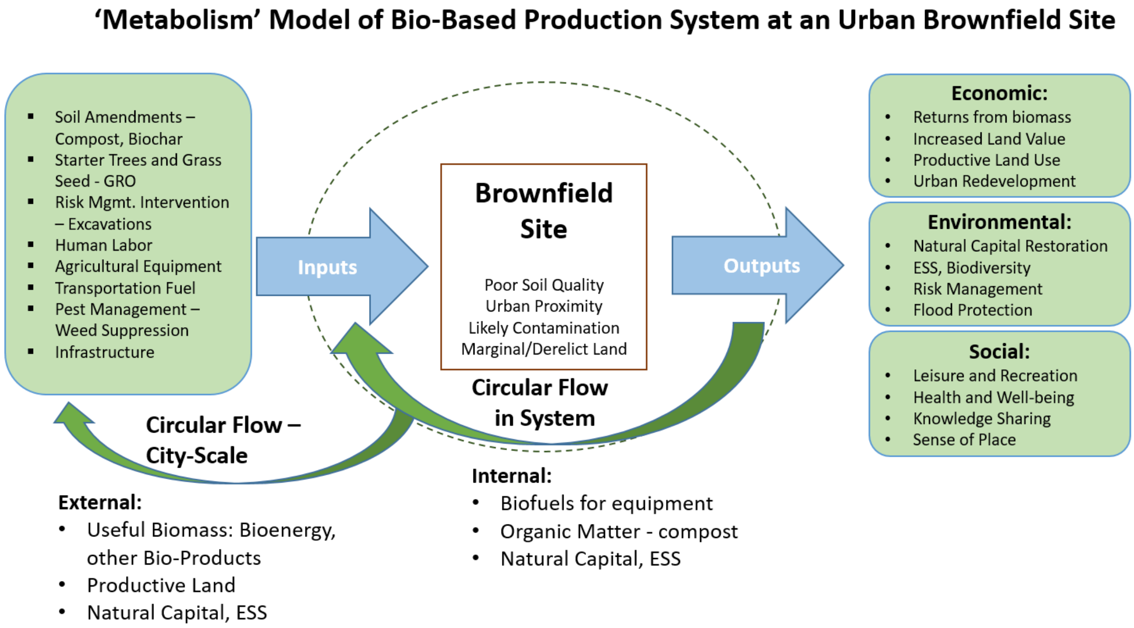

Figure 9.1: Metabolism model of bio-based production system at an urban brownfield site

9.1 Summary: Step-wise Procedure

As depicted in Figure 9.1, a bio-based production system at an urban brownfield site focusing on both risk management and holistic land use can be effectively visualized as a type of systemic, 'metabolism' model. In this case, site metabolism was created to represent a dynamic system with variable inputs and outputs capable of circular flow within and outside of the system boundaries (defined simply as the site land area). This simple model is not all-inclusive, but it is useful to visually understand the many facets in the such a system and how it contributes to promoting a circular economy as well as succintly resolve research question 4. The list below briefly summarizes some of the more important factors in designing and implementing a bio-based production system at a brownfield site:

- **Risk management**: A large focus in this study has been placed on mitigating the risks posed by the contaminants at brownfield sites. GRO were able to be applied for the two case studies, but it is important to keep in mind that at sites of very high contaminant levels it may be prudent to include more intensive remediation techniques (e.g. excavation).
- **Decision-support tools**: The *Rejuvenate* DST was invaluable as an analytical framework, replete with checklists, to guide the user in addressing the major concerns in bio-based production on contaminated sites. Integrating HOMBRE's Brownfield Opporunity Matrix provided supporting evidence and information to build the case supporting the value of such systems.
- **Soil quality**: The SF Box tool was recommended for both sites to use SQIs to evaluate the soil, determine if there is limited soil functionality, and prescribe necessary improvement measures. Due to limited time and access to the sites, soil sampling was not performed. Thus, specific soil quality indicators (SQI) were unknown and required that assumptions were made concerning site-specific growing conditions for plants. In any case, biostimulation of the soil via amendment additions (e.g. compost, biochar, or phosphate/limestone for Pb stabilization) and/or beneficial microbes are advantageous to increase soil fertility and stabilize contaminants.
- **Agronomic practices**: This category encompasses such strategies as agroforestry, intercropping, and crop rotations which all vastly improve the quality of the biomass produced, soil quality, and success of plant establishment. The underlying principles of phytomanagement, permaculture, and restoration agriculture were also influential for the strategies proposed in this study. Projects like Losaeter[1] in Oslo, Norway, representing the culmination of these ideas, are worthy of emulation.
- **Plant selection**: The plant species chosen for cultivation is critical to the success of a bio-based production project. Phytoremediation capability is but one crucial factor in the selection process, and monocultures should be avoided. In this study, potential rotation crops (e.g. cover crops, annual species in Tier 2) have been emphasized for the wider range benefits offered by cultivating them in sync with the well-established woody SRC tree species and perennial grasses, and are worth considering in a long-term cropping plan.
- **Biomass use**: Valorization of the produced biomass is critical to project success. If the biomass is classified as a waste then much of the value is lost. Future use of the biomass ought be determined beforehand to ensure that appropriate biomass type is produced to meet local demand for bioenergy crops or other bio-products. Also, the possibility for urban agriculture in some form (i.e. *in-situ* or in planter boxes) to grow food crops should be considered and evaluated for the risk of growing in contaminated soil.
- **Overall value**: One of the principal aims in this study was to establish the overall value of bio-based production systems on brownfields by showing the economic, environmental, and social benefits within stage 3 of *Rejuvenate* and incorporating ESS Mapping and HOMBRE's BOM.

[1] `http://loseter.no/en`

9.2 Reflection on *Rejuvenate* DST

Following the initial application of the *Rejuvenate* DST, Andersson-Sköld et al. (2014) concluded: "*This initial iteration quickly identifies the most viable management options in a project, reducing future decision making and site evaluation effort and avoids unnecessary in-depth analysis of individual alternatives when fairly simple considerations already determine their effectiveness. Further iterations performed by a larger project team and more detailed investigations will validate the feasibility proposals or whether updates are required.*

In the context of this study, the experience in applying *Rejuvenate* during this thesis work, albeit at a preliminary, largely qualitative level, matches their conclusions. Being able to systematically follow a checklist based procedure was extremely helpful for including the multitude of diverse factors which are important in this type of project. In stage 1, following the checklist provided a solid, working foundation from which to develop the filtering criteria in the plant selection projecess. Since a site management option based upon GRO was decided in the beginning of this project, much of the work in evaluating various remediation or risk management alternatives in stage 2 (e.g. applying a multi-criteria analysis) was bypassed. However, the comprehensive procedure was invaluable to ensure that the most important criteria were considered. One major boon for *Rejuvenate*, which was valuable for this study in particular, was the possibility to incorporate the breadth of knowledge and strategies (e.g. SF Box tool, Greenland, HOMBRE, etc.) gained during the literature review process as support during the four stages. Especially in stage 3: value management, tying-in HOMBRE's BOM was instrumental to building the case for a broad overall value. However, as cost estimates are difficult to procure, especially in the preliminary feasibility stage, there exists a real opportunity for developing a knowledge bank for referencing in acquiring economic data for similar projects. Unfortunately, a detailed plan capable of practical evaluation was not produced in this study so the full application of *Rejuvenate* was not possible. Stage 4, concerning project implementation risks and planning, was beyond the scope of this study, but it would have been interesting to carry the proposals for each case study site a bit further into this more detailed design stage if time permitted.

Finally, the guiding question: How does *Rejuvenate* work for all forms of bio-based production aside from purely bioenergy? For transitioning to a bio-based circular economy, all bio-products (and food crops) ought to be considered during the early project design phase. *Rejuvenate*'s primary focus is bioenergy and is exclusively discussed throughout the decision-support guides and methodology; however, the checklist procedure for the four-stage approach does not exclude the expanded use of biomass for all bio-products. Stage 1: crop suitability is the pivotal stage to determine whether growing biomass for more sophisticated end-use is applicable, and it will be the role of future practitioners to ensure that these crop types are given due consideration. Most likely, it will be the local markets' capacity for processing these types of biomass into useful products that is the deciding factor. For growing food products, the risks vary per site and will have to be justified on a case-by-case basis.

9.3 Influential Factors for Further Consideration

The following list provides several influential factors which are important for the success of bio-based production on brownfields and worthy of further consideration:

- **Landscape design, aesthetics, and interim uses**: The idea of a "holding strategy" (i.e. phytomanagement) has often been mentioned throughout this study and by referenced works (Breure et al., 2018; Cundy et al., 2016; Menger et al., 2013; Todd et al., 2016). Most studies referred to in this study are focused almost exclusively on the engineering perspective, and leave much desired concerning the aesthetic design strategy for implementing projects or as part of a long-term management plan. Todd et al. (2016) provide an interesting study where they designed interim use guidelines for contaminated sites during phytoremediation to improve the amenity value of the land, and improve the overall impression of the project. Also, urban planning and development experts were vital to ensure that these strategies were effective, and ought to be included in bio-based production system design as well. Norrman et al. (2016, 2015) discuss urban development considerations which must be considered for holistic brownfield redevelopment.
- **Stakeholder involvement**: Interacting with interested parties was beyond the scope of this project, but the importance of this for the success cannot be emphasized enough (Cundy et al., 2013).
- **Agronomic practices**: Many agronomic practices were discussed throughout this study, but so far have only scratched the surface of their potential in application. The study from Kidd et al. (2015) is recommended to learn more.
- **Phytomining**: Also known as *Bio-harvesting*, metals can sometimes be recovered from the biomass of hyperaccummulating plant species through various processes. Largely still in the experimental phase, phytomining shows potential for improving the economic value of bio-based production projects; discussed further in Rosenkranz et al. (2017); Sheoran et al. (2009).
- **Force-field analysis**: An idea early in this study was to conduct a force-field analysis (i.e. analyzing the forces for or against change as discussed in Cronshaw and McCulloch (2008)) in terms of the DPSIR framework (drivers, pressures, states, impacts, or responses) (Kristensen, 2004); however, time was not permitting. Supplementary material to Schröder et al. (2018) provides selected indicators and measurements, classified according to DPSIR, which they believe are key to intensifying crop production and is the most robust 'force-field analysis' found during literature review.

10
Conclusion

A highly relevant question, raised by Atkinson et al. (2014), challenges the grandiosity of proposals (such as this) aiming to solve many problems at once, asking: "With projects aspiring to such multiple benefits, the question arises *are project aspirations too grand, or should more be done to enable these aspirations to be realized?*"

The first three principal aims of this study were purposed to show that synergistic solutions in brownfield remediation via GRO through bio-based production projects can in fact be pragmatic answers to many of the critical issues facing urban areas today. Taking into account the international recognition of widespread land contamination, natural capital degradation, planetary boundaries creeping closer, increasing rates of urbanization, and shortages in available land then perhaps delusions of grandeur are more prudent than ever. Implementing gentle remediation options at urban brownfield sites can serve to alleviate many of the detrimental consequences from these problems by mitigating the risks posed by the contaminants, remediate the site and regenerate the latent natural capital stocks of soil and land, provide ecosystem services and biodiversity, reinforce holistic soil and land management, possibly even provide sites for urban agriculture, and all the while promote a circular bio-based economy through the productive use of the biomass produced on-site.

In this study, the leading research in the field was reviewed for best practices and strategies to apply via the *Rejuvenate* decision-support tool methodology on two case study sites in Gothenburg, Sweden to answer the 4th and 5th research questions concerning practical application and analysis. The bio-based production proposals resulting from *Rejuvenate* application sought to incorporate the most well-established research and expertise and demonstrate the overall value that these projects offer within the economic, environmental, and social aspects of sustainable development. Perhaps these suggestions are ambitious, but the evidence backing up such projects supports the claims that more should in fact be done in both the public and private realm to enable these aspirations to be realized.

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A

Appendix 1

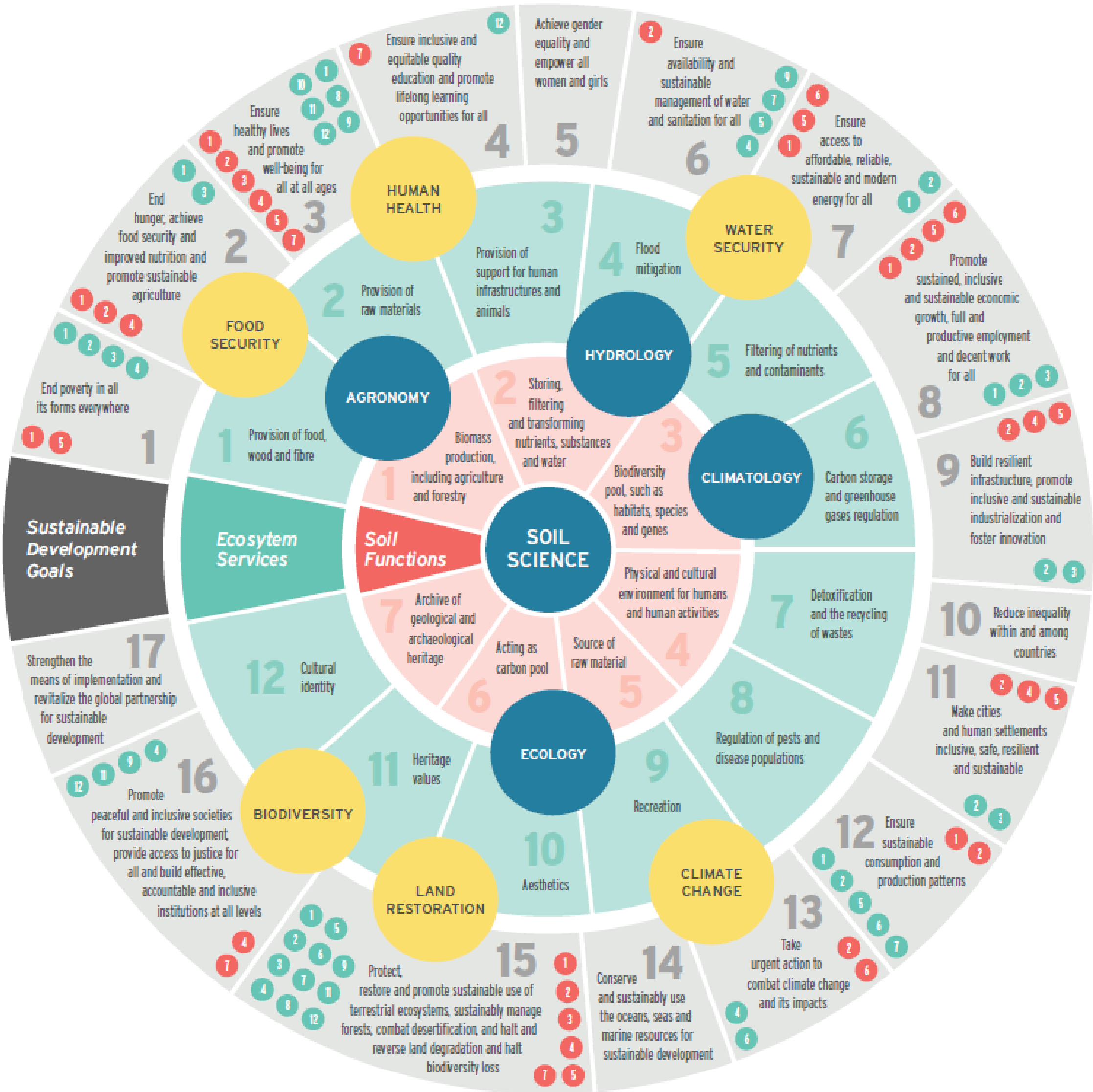

Figure A.1: FORUM paper: The significance of soils and soil science towards realization of the UN sustainable development goals (SDGs), from Keesstra et al. (2016). CC-BY 3.0

B

Appendix 2

Table B.1: Examples of Interventions under the HOMBRE designation, summarized from (Bardos et al., 2016)

Broad Intervention	Variants	Example
Gentle Remediation Options	Phytoremediation	Phytoextraction
	Amendment Addition	In-Situ Stabilization
	Natural Groundwater Attenuation	Monitored Attenuation
Conventional Remediation	*Ex-situ*	Soil Washing
	In-situ	Soil Vapor Extraction
Soil Management	Traditional Methods	Dig and Dump
	Re-naturalisation	Removing Artificial Surfaces
	Amendment addition	Using Organic Compost
Water Management	Contamination Attenuation	Passive Treatment (e.g. Wetlands)
	Drainage Engineering	Flood Management
Green/Blue Infrastructure	Green Infrastructure	Ecological Engineering
Renewables	Producing Renewable Feedstocks	Producing Biomass

Table B.2: Examples of project services via soft reuse under the HOMBRE designation, summarized from (Bardos et al., 2016)

Broad Service	Subcategories	Examples
Risk mitigation of contaminated land and groundwater	Biosphere	Human health protection Ecology protection
	Water resources (hydrosphere)	Surface water treatment Groundwater treatment and protection
Soil improvement	Fertility	Managing nutrients and micronutrients availability Improve soil biological function
	Soil structure	Improve soil resilience Provide vegetative cover Mitigating erosion and landslide
Water resource improvement	Water resource efficiency and quality	Water supply for on-site uses Provision of potable water Improved water quality
	Flood and capacity management	Retention of runoff Surface water storage Flood mitigation
	Rehabilitation of water	Rain/drainage water capacity Leachate treatment and reuse
Provision of green infrastructure	Enhancing ESS	Habitat and biodiversity protection Developing new habitat and increasing biodiversity
	Enhancing local environment	Improving urban soundscapes and air quality Landscaping provisioning Urban climate management
Mitigation of human -induced climate change	Renewable energy generation	Energy of on-site/off-site use Supply to an integrated energy mix
	Renewable material generation	Bio-feedstocks (biofuels and bio-products) Re-use of organic and aggregates
	Greenhouse gas mitigation	Reduced emissions and carbon sequestration
Socio-economic benefits	Amenity	Open space/Leisure/recreation Education Improved well-being
	Economic assets	Job generation Land value recovery Interim land management

C

Appendix 3

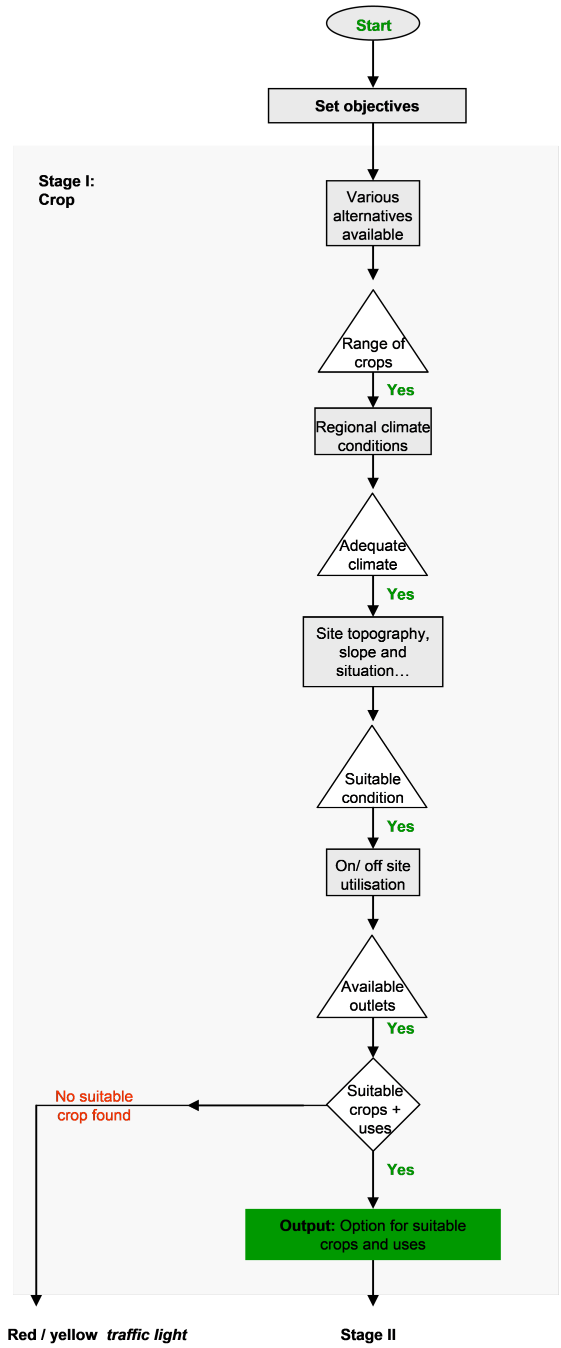

Figure C.1: Rejuvenate DST Stage 1: Crop Selection, from Andersson-Sköld et al. (2013). Reprinted with permission from author.

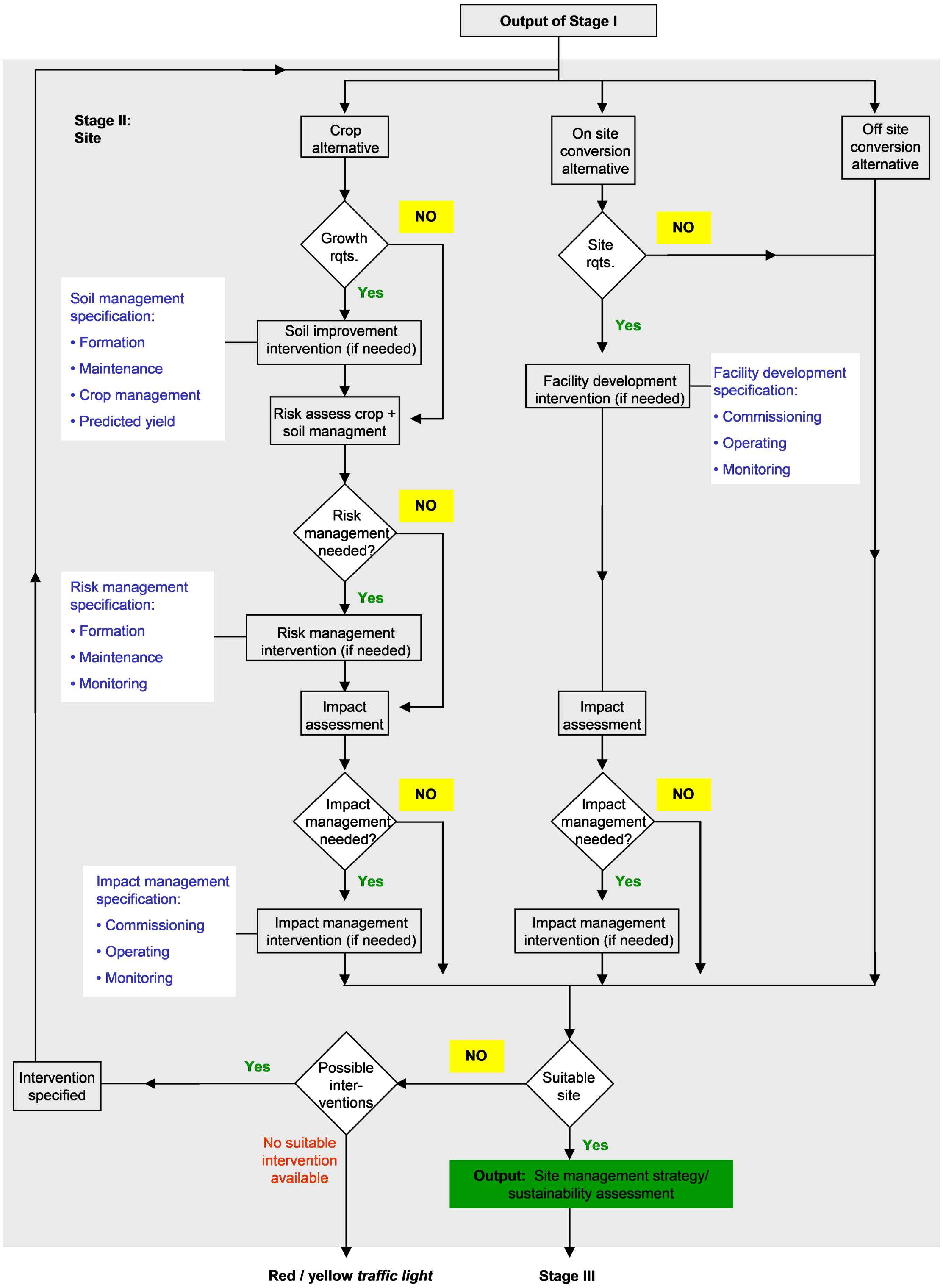

Figure C.2: Rejuvenate DST Stage 2: Site Management, from Andersson-Sköld et al. (2013). Reprinted with permission from author.

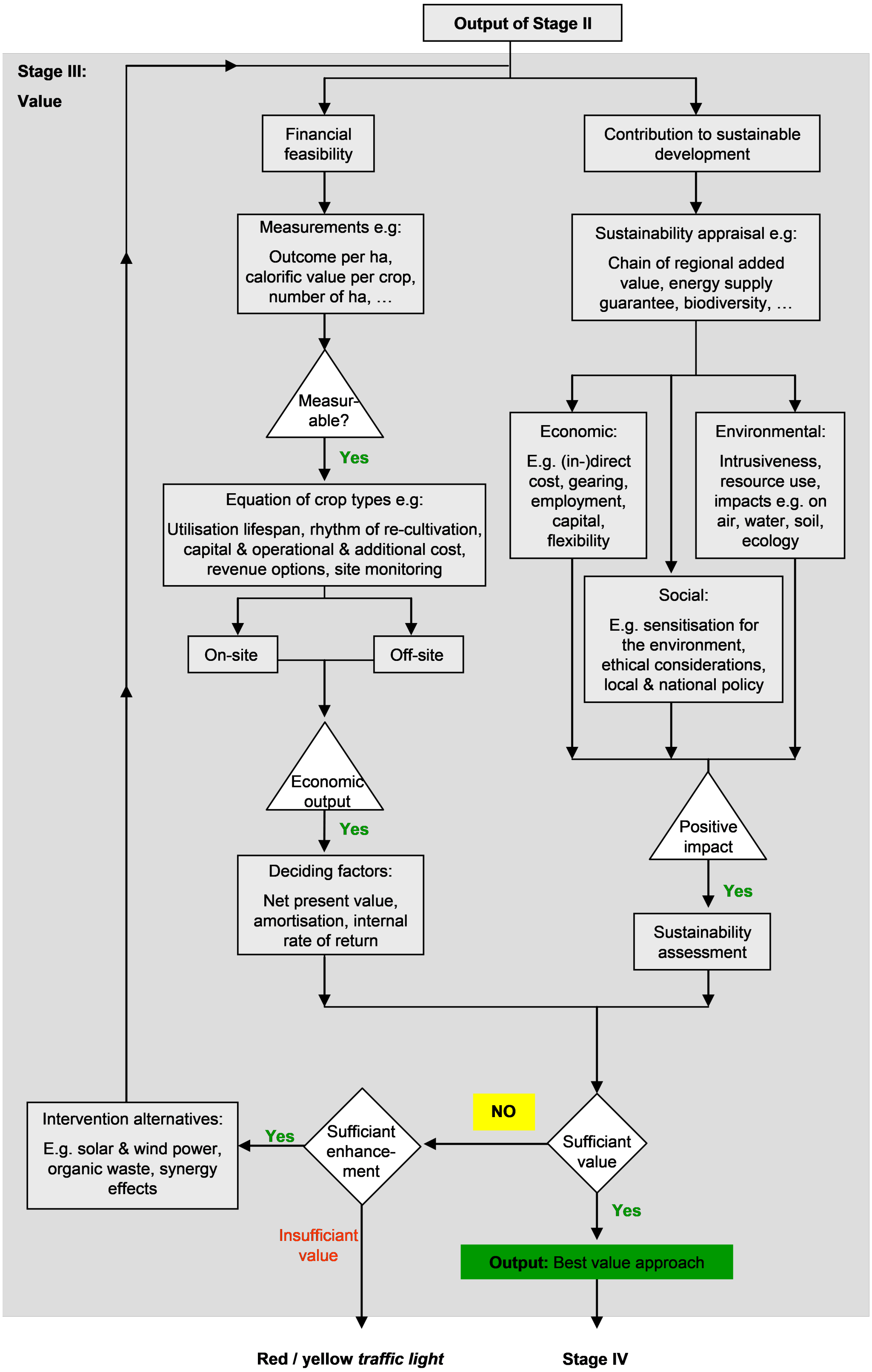

Figure C.3: Rejuvenate DST Stage 3: Value Management, from Andersson-Sköld et al. (2013). Reprinted with permission from author.

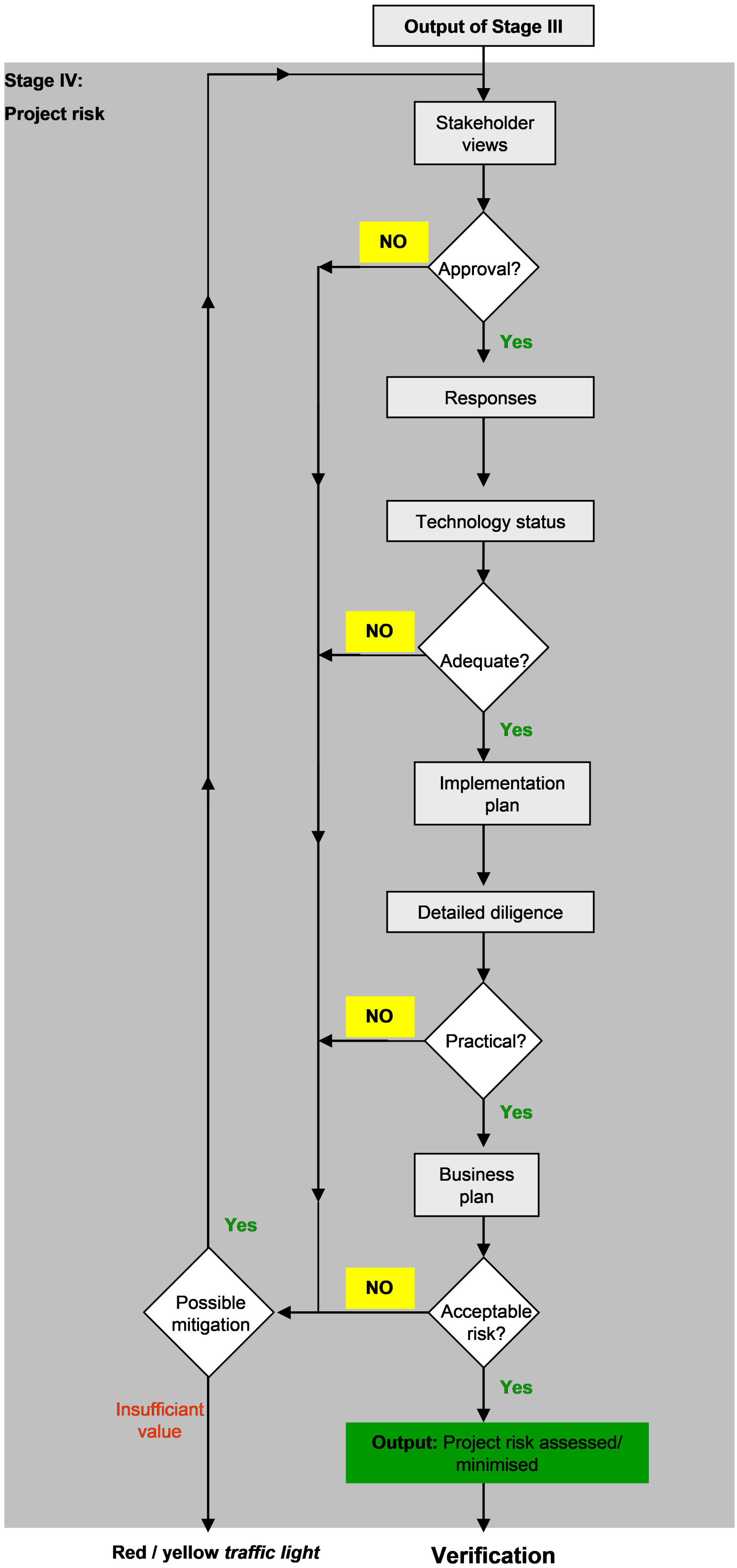

Figure C.4: Rejuvenate DST Stage 4: Project Risk Management, from Andersson-Sköld et al. (2013). Reprinted with permission author.

D

Appendix 4

Sustainability principles for remediation	Review criteria
1. Inclusive of social, economic and biophysical factors	C1. The framework is inclusive of TBL (social, economic, biophysical) factors throughout the remedial process.
2. Facilitates the integration of triple-bottom-line	C2. The framework provides guidance (e.g. criteria, tools) for approaching or assessing the interrelationships between TBL factors.
3. Provides guidance on how to deal with trade-offs	C3. The framework provides a clear approach (e.g. rules, criteria, principles) for identifying and assessing tradeoffs in end use and remedial options assessments.
4. Considers future land use early and throughout the life cycle of the remediation process	C4. Post-remediation land use(s) is addressed early in the remediation design, and considered in the assessment of remedy alternatives.
5. Contributes to the assurance of intra-generational equity	C5. The framework addresses *and* provides direction to assess intra-generational considerations regarding the distribution of impacts and benefits (e.g. distribution of risks due to exposure; distribution of benefits and use from reclaimed site; consideration of cultural values or marginalized groups).
6. Contributes to the assurance of inter-generational equity	C6. The framework addresses *and* provides direction to assess inter-generational considerations regarding the distribution of impacts and benefits (e.g. adopting measures that minimize energy consumption, resource use and waste, and that maximize material reuse).
7. Participatory by design	C7. Participation or engagement of affected communities or land users is integrated throughout the framework's prescribed remedial process.

Figure D.1: Sustainability principles and review criteria for remediation frameworks (Ridsdale and Noble, 2016). Reprinted with permission from Elsevier and Lancet.

Criteria	ASTM Int.	FCSAP	SURF UK	SURF US	US EPA	WGSR	Criteria synopsis
C1	●	○	●	●	○	○	●●● ○○○
C2	●	⊘	●	○	⊘	⊘	●● ○ ⊘⊘⊘
C3	○	○	○	⊘	○	⊘	○○○○ ⊘⊘
C4	●	○	●	●	●	●	●●●●● ○
C5	●	●	●	●	●	●	●●●●●●
C6	●	⊘	●	○	○	○	●● ○○○ ⊘
C7	●	●	●	●	⊘	●	●●●●● ⊘
Framework synopsis	●●●●●● ○	●● ○○○ ⊘⊘	●●●●●● ○	●●●● ○○ ⊘	●● ○○○ ⊘⊘	●●● ○○ ⊘⊘	

[a] ●= criterion fully satisfied; ○= partially satisfied; ⊘= not satisfied

Figure D.2: Syntheses of framework performance based on sustainability review criteria (Ridsdale and Noble, 2016). Reprinted with permission from Elsevier and Lancet.

E

Appendix 5

Biomass Crop Type	Plant Species	Common Name	Soil Type	Soil pH	Remediation Potential	Growing Zone (Tested)	Bio-Energy Potential	Additional Benefits	Reference
Biomass Crop	*Glycine Max (L.)*	Soya Bean	well drained, loamy soil; wide range of soil conditions	5.8-7.0	Phytoextraction of Cd, Cr, Ni, As, Fe, Zn; degradation of PAH, POPs and Atrizine	Worldwide	Bioenergy, Bioethanol, biochar	Land reclamation	Edrisi and Abhilash 2016; Tripathi et al. 2016; Tang et al. 2012
Biomass Crop	*Nicotianna tabacum*	Tobacco	-	-	Phytoextraction of Cd, Cr, Pb, Zn and other trace metals	North America, Europe	Biomass	Successful *in-vitro* cultivars of tobacco targeting specific metals	Kidd et al. 2015; Herzig et al. 2014
Biomass Crop	*Ricinus communis L.*	Castor Bean	Sandy and clayey loamy soil	4.5-8.3	Phytostabilization of Cd; degradation of DDT	Worldwide, south Europe	Biodiesel, multi-purpose oil, solubilizer for toiletry and cosmetics	Soil restoration	Edrisi and Abhilash 2016; Pandey et al. 2016; Tripathi et al. 2016
Fibre Crop	*Cannabis sativa L.*	Hemp (perennial)	Prefers loamy soils; tolerant of high metal concentrations	Around 7	Phytoextraction of Cd, Cr, Cu, Ni, Pb, and Zn; degradation of PAHs and pesticides; phytostabilization	Worldwide	Biofuel production, Bioenergy or use in other bio-products as fibre	Carbon sequestration, soil restoration, large biomass quantity, natural control of pests and weeds	Pandey et al. 2016; Lizarazu 2011; Tang et al. 2012
Fibre Crop	*Hibiscus cannabinus L.*	Kenaf	Tolerant of high metal concentrations	Wide range	Phytoextraction of As, Fe, Cd, and Pb; degradation of lubricant oils; phytostabilization	Worldwide	Biofuel production, Bioenergy or use in other bio-products as fibre	Large biomass quantity, drought resistant, natural weed suppression, soil restoration	Pandey et al. 2016; Lizarazu 2011; Tang et al. 2012; Kidd et al. 2015
Fibre Crop	*Linum usitatissimum L; Camelina sativa*	Flax and Camelina (false flax) - annual	Suitable to a wide range of soil types	Wide range	Phytoextraction of Cd, Ni and other metals; degradation of PAHs and Atrazine	Worldwide	Biofuel production, Bioenergy or use in other bio-products as fibre	Large biomass quantity, biofuel, bioenergy, well-suited for rotations with deep-rooted crops; enhanced interaction with soil mycorrhiza	Pandey et al. 2016; Lizarazu 2011; Tripathi et al. 2016; Andersson-Skold 2013
Grain	*Beta vulgaris*	Sugar Beet (annual)	Medium to high grade agricultural quality soil; emperate climate with mean summer temperature around 21C, uniform soil moisture	max 6.5	Phytostabilization (Cd-exclusion) - needs further investigation	Europe, North America	Biofuel production (bioethanol)	Useful for co-cropping systems to maximize benefits - rotation with winter wheat	Andersson-Skold 2013
Grain	*Hordeum vulgare*	Barley	Medium to high grade agricultural quality soil	max 6.5	Phytostabilization (Cd-exclusion)	Worldwide	Biofuel production (bioethanol)	Useful for co-cropping systems to maximize benefits	Kidd et al. 2015; Tang et al. 2012; Andersson-Skold 2013
Grain	*Zea Mays*	Maize or Corn (annual)	Long, warm growing seasons; medium to high quality agricultural soil	max 6.5	Phytostabilization (Cd-exclusion)	Worldwide	Biofuel production (biodiesel)	Useful for co-cropping systems to maximize benefits (e.g. use as feedstock)	Witters et al. 2012; Vangronsveld et al. 2009; Tang et al. 2012; Kidd et al. 2015; Andersson-Skold 2013
Grain or Grass	*Sorghum bicolor L.*	Sweet Sorghum	Higher abiotic conditions, grows in diverse climates and suitable for dryland conditions	Wide range	Phytoextraction of various metals; phytostabilization	Canada, USA, Australia, Sweden	Biofuel production (bioethanol) or use in other bio-products	Large biomass quantity, well-suited for rotations with deep-rooted crops, can be used as feedstock	Pandey et al. 2016; Lizarazu 2011; Mehmood et al. 2017; Kidd et al. 2015
Grain	*Triticum aestivum*	Winter Wheat (annual)	Medium to high grade agricultural soil	max 6	Phytostabilization (Cd-exclusion)	Worldwide	Biofuel production (bioethanol)	Useful for co-cropping systems to maximize benefits	Kidd et al. 2015; Tang et al. 2012; Andersson-Skold 2013

Figure E.1: Compiled plant species list of potential crops for bio-based production and risk mitigation from literature review, part 1

Biomass Crop Type	Plant Species	Common Name	Soil Type	Soil pH	Remediation Potential	Growing Zone (Tested)	Bio-Energy Potential	Additional Benefits	Reference
Oil Crop	*Brassica juncea (L.) Coss., B. carinata*	Indian Mustard, Ethiopian Mustard	sandy to heavy clay soils, shallow soil, calcareous, inceptisols	7.0-8.0	Phytoextraction of Cd, Zn, Pb, Ni	South Asia	Biofuel production (biodiesel) and Bioenergy	Carbon sequestration, land reclamation	Edrisi and Abhilash 2016; Lizarazu 2011
Oil Crop	*Brassica napus*	Rapeseed	-	Wide range	Phytoextraction of As, Sn, Cd, Cr,, Cu, Ni, Pb, Zn, and Al; degradation of PAHs and PCBs	Worldwide	Biofuel production (biodiesel) and Bioenergy	Soil restoration, large biomass quantity, natural pest control	Lizarazu 2011; Witters et al. 2012
Oil Crop	*Helianthus annuus L.*	Sunflower (annual)	clay, most sandy, inceptisols	6.0-7.5	Phytoextraction of Cd, Cr, Pb, Ni, As, Fe, Zn; degradation of PAH and Atrizine	Worldwide	Bioenergy, bioethanol, charcoal	Bioenergy, land reclamation, drought resistant, efficient use of soil resources; large biomass quantity	Edrisi and Abhilash 2016; Lizarazu 2011; Nikolic and Stevovic 2015; Tripathi et al. 2016
Perennial Grass	*Miscanthus x giganteus (sacchariflorus and sinensis)*	Giant perennial silvergrass (C4)	Low to medium grade agricultural quality soil; prefers well-drained soils but wide range of tolerance	5.5-7.5	Phytoextraction of As, Sn, Cd, Cr,, Cu, Ni, Pb, Zn, and Al; degradation of PAHs and pesticides; phytostabilization	Europe, USA, Japan, China	Bioethanol, biogas, bioenergy	Carbon sequestration, soil restoration, large biomass quantity; non-invasive genetic mutant	Pandey et al. 2016; Mehmood et al. 2017; Tripathi et al. 2016; Andersson-Skold 2013; Kidd et al. 2015
Perennial Grass	*Thlaspi caerulescens*	Alpine pennygrass (perennial)	Highly adaptable to diverse soil conditions	Wide range	Phytoextraction of Cd, Pb, and Zn, Ni (hyperaccumulator)	Northern Europe	Biofuel production and Bioenergy	Useful for co-cropping systems to maximize benefits; soil restoration	Tang et al. 2012
Perennial Grass	*Panicum virgatum L.*	Switch grass (perennial)	Hardy plant adapted to a wide range of soils and climates; easiest to establish on loamy or sandy soils than clay	>5.0	Phytoextraction of Cd, Cr, Ni, As, Fe, Zn; degradation of PAH, POPs and Atrizine; phytostabilization	USA, Central America, Canada, Italy	Biofuel production (biodiesel) and Bioenergy	Bioenergy, land reclamation, large biomass quanitity; drought and flood tolerant	Edrisi and Abhilash 2016; Pandey et al. 2016; Mehmood et al. 2017; Tripathi et al. 2016; Andersson-Skold 2013; Kidd et al. 2015
Perennial Grass	*Phalaris arundinacea*	Canary Reed grass (perennial)	Temperate regions, suitable to wet-soils, colder climates, and flood plains	4.9-8.2	Phytoextraction of As, Sn, Cd, Cr,, Cu, Ni, Pb, Zn, and Al; degradation of PAHs and pesticides	Northern Europe, USA, Canada, Russia	Biofuel production and Bioenergy	Carbon sequestration, soil restoration, large biomass quantity; drought tolerant	Pandey et al. 2016; Lord 2015; Mehmood et al. 2017; Andersson-Skold 2013
Perennial Grass	*Thynopyrum poniticum/ intermidium*	Wheatgrass (perennial)	Wet, alkaline soil, temperate conditions	-	Reduce soil salinity; Cd-excluding cultivars	Eurasian	Biofuel production	Large biomass quantity	Mehmood et al. 2017; Kidd et al. 2015
Woody Biomass (SRC)	*Liquidambar styraciflua L.*	American sweet gum or Satin walnut or Alligator wood	loamy, sandy, clay, well-drained soil	6.1-7.5	Phytoextraction of various metals, degradation of POPs	Worldwide	Bioenergy, paper and pulp	Soil restoration	Edrisi and Abhilash 2016; Tripathi et al. 2016
Woody Biomass (SRC)	*Eucalyptus grandis (W.Hill), E. camaldulensis (Dehnh), E. globulus (Labill)*	Eucalyptus, Flooded gum or Rose Gum (some perennial)	Temperate, tropical, and subtropical, Poor soils	6.0-8.0	Excessive phosphate/nutrients removal, Phytoextraction of As	Worldwide	Biomass, biogas, plywood, biochar	Essential oils, various bio-products, fast growing	Edrisi and Abhilash 2016; Pandey et al. 2016; Tripathi et al. 2016
Woody Biomass (SRC)	*Pinus taeda L.; Pinus silvestris L.*	Loblolly Pine	Predominantly ultisols, sandy soil	6.1-6.5	Phosphate removal, phytoextraction of various metals, degradation of POPs	Worldwide	Biomass, biogas, plywood, biochar	Biomass and bioenergy production	Edrisi and Abhilash 2016; Tripathi et al. 2016
Woody Biomass (SRC)	*Populus, Hybrid aspen (P.tremula x P.tremuloides) - many other species*	Poplar	loamy soils, inceptisols, well-drained soils with adequate moisture; can establish on derelict land	5.5-7.5	Degradation of TNT and POPs, phytoextractor of various metals; phytostabilization	Worldwide	Biomass, biogas, plywood, biochar	Carbon sequestration, large biomass quantity, pulp and paper, composite wood products, fast growing	Edrisi and Abhilash 2016; Pandey et al. 2016; Licht and Isebrands 2005; Mehmood et al. 2017; Tripathi et al. 2016; Andersson-Skold et al. 2013
Woody Biomass (SRC)	*Salix spp., S. klara, S. inger, tora - many other species*	Willow	Moist soils in cold, temperate regions; can establish on a wide range of soil conditions including derelict land	5.5-7	Phytoextraction of Cr, Mn, Fe, Ni, Cu, Zn, Pb, Rb, Sr, Ti, Co; degradation of chlorinated solvents and POPs; phytostabilization	Canada, USA, Australia, Sweden	Biomass, biogas, plywood, biochar	Carbon sequestration, soil restoration, large biomass quantity, fast growing; extensive testing of clones	Pandey et al. 2016; Delplanque et al. 2012; Licht and Isebrands 2005; Mehmood et al. 2017; Tripathi et al. 2016; Andersson-Skold et al. 2013; Enell et al. 2015

Figure E.2: Compiled plant species list of potential crops for bio-based production and risk mitigation from literature review, part 2