The project aims to increase the use of green technology in order to decrease the pollution discharges in the South Baltic area

BAPR

Baltic Phytoremediation

Guidelines

-Phytoremediation technologies and methods for polluted soils treatment

BAPR BALTIC PHYTOREMEDIATION

Interreg South Baltic

EUROPEAN UNION

European Regional Development Fund

Guidelines

Phytoremediation technologies

and methods for polluted soils treatment

BAPR: **Ba**ltic **P**hyto**r**emediation (EU-Interreg project)

Linnaeus University

Department of Biology and Environmental Science

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FOREWORD

This document is a result of project partners' reports of their pilot cases illustrating field applications of phytoremediation.

The guidelines may be useful for teachers and students, construction and real estate services´ companies, environmental consultants and land entrepreneurs. The goal of the guidelines is to provide an overall picture of the work within the BAPR project as a practical tool for implementing various methods of phytoremediation measures, from the present to future.

The guidelines have been produced as one of the main outputs of the BAPR – Baltic Phytoremediation EU project (contract STHB.02.02.00-SE-0155/18). It will be published and made available on the project website https://lnu.se/en/bapr/.

Additional reports/materials related to the project's main outputs are also available on the project website, including:

- **Risks analysis guidance and method/tool for planning and implementation of phytoremediation technologies**
- **Training module** (includes educational elements as well as online tools through the website/link)

This document considers the experiences gained during the project activities. To achieve the goal of creating the BAPR Guidelines, other advisors, consultants, companies and institutions were included in the work and the activities to promote and give advice on the knowledge of phytoremediation technologies and methods for polluted soils treatment in the countries surrounding the South Baltic.

(Lead Partner on behalf of BAPR partnership)

How to use the guidelines

This document has been created to provide a guide for research, development, and regulation on the various phytoremediation processes within the EU-project Baltic Phytoremediation (BAPR). We would like to note that our report is a practical work, which includes activities and suggestions on how to proceed with applications, management, collaboration and work, within the project period of 1 June 2019 to 31 May 2023.

The BAPR guidelines comprise the following chapters:

- **Chapter 1** provides an overview of the general phytoremediation process.
- **Chapter 2** provides applications and challenges, and an historical perspective from within three countries: Lithuania, Poland, and Sweden.
- **Chapter 3** addresses the working plan of the pilot cases in each country. It offers general information on phytoremediation as a green technical solution, and its effects, as well as a full description of each pilot case.
- **Chapter 4** is related to comparing the results from the pilot cases.
- **Chapter 5** includes policy, advisory opinions and a selection of material related to issues of phytoremediation application.
- **Chapter 6** addresses stakeholder networks and collaboration; it includes general forms of management and communication, focusing on stakeholders' involvement: e.g. work plans/workshops, seminars and study tours.
- **Chapter 7** provides a summary of conclusions based on the project's pilot cases in Sweden, Lithuania and Poland, and discusses how organisations can manage the dynamics of implementing the project. The most important challenges are addressed, along with strategies for dealing with these.

Data have been gathered and assessed to develop performance of measures that can be used in future work.

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Introduction

Contamination of soil represents a growing challenge across the world. In Sweden, the government has identified 24,000 contaminated sites that pose a high risk to human health and the environment (Falkenhaug, J. 2017), and in Poland and Lithuania, areas of soil contaminated by heavy metals, fertilisers and other chemical pollutants are probably as abundant. The two most common techniques for cleansing soil are the removal and depositing of topsoil from contaminated areas, and the cleansing of soil using chemical methods, (see Figure 1, Lianwen Liu et al., 2018).

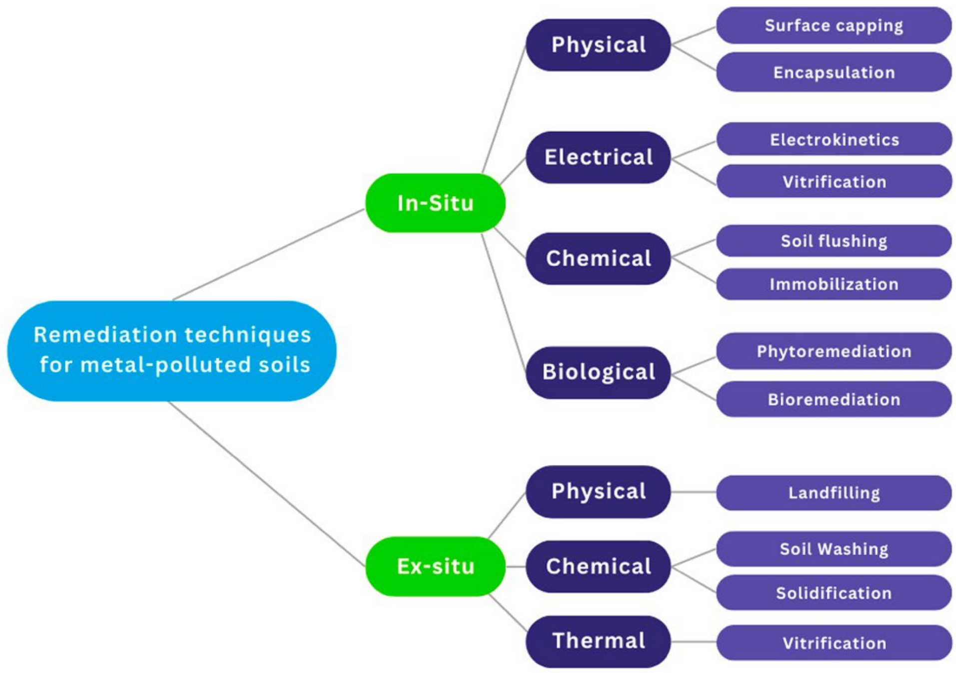

Figure 1. Remediation techniques for heavy metal contaminated soils

Phytoremediation is based on the growing of plants that take up pollutants and store them in their biomass. The plants are then harvested, and the pollutants are easily and inexpensively removed with the plants, which can, for example, be used for the production of biogas. When valuable metals are involved, the metals may even be recovered and re-used. The process can continue for several years, and the area can provide biomass to be used for biogas production or incineration in combined heat and power plants. Phytoremediation also provides a visually attractive area during the remediation process (Lundström, J. et al. 2019).

At the same time, crops/feed crops to some extent can play a role in local energy production, as they can be used as fuel once they have served their purpose in cleaning the soil.

About the project

The aim of the BAPR project, financed by Interreg South Baltic Programme 2014-2020[7] (Subsidy Contract No STHB.02.02.00-SE-0155/18-00, to implement Project BAPR – Baltic Phytoremediation), is to increase the use of green technologies in order to decrease the discharge of pollution in the South Baltic Area.

One of the most important reasons why to apply for funding from the South Baltic Programme is the core belief that cross-border cooperation will benefit the process and the results. By having a cross-border approach, the knowledge exchange can be maximised, the most optimal solution can be chosen, and the opportunity to learn from each other's pilot cases can inspire a new way of thinking.

As one of the main outputs is the BAPR Guidelines, it becomes even more obvious and essential for BAPR to have a cross-border approach. By taking into consideration different preconditions in the participating countries, the platform will have a more solid and broad approach, which will be beneficial when implementing new cases after the project has ended. Having worked with the seed money project through the Energy Authority funding, we have already started to gain valuable experience regarding the different regional challenges, as well as the opportunities.

The main target groups are public landowners and property developers in the region, as well as their municipal subsidiary companies, and regional authorities that can implement similar solutions and promote phytoremediation through BAPR.

There are 11 partners and associated partners from Europe in the BAPR.

- Linnaeus University, Sweden (lead partner)
- NSR AB, Sweden
- Gdańsk University of Technology, Poland
- Klaipėda University, Lithuania
- Gdańsk Municipal Waste Management, Poland
- Lithuanian Research Centre for Agriculture and Forestry, Lithuania
- Water, waste management and district heating company in Hässleholm, Sweden
- The Swedish Embassy in Warsaw, Poland
- Roskilde University, Denmark
- Latvia University of Life Sciences and Technologies, Latvia
- IUC Syd, Sweden

[7] https://southbaltic.eu/-/bapr

Project objectives

The goal of BAPR is to raise cross-border awareness of available green phytoremediation technologies to clean soil from pollutants such as oil, industry related contaminants, heavy metals, nutrients and microplastics through new arenas of cooperation that focus on a circular economy approach.

The guide in **Appendix A** explains how external communications have been used from the moment the Subsidy Contract was signed.

Chapter 1: Fundamental phytoremediation processes

Phytoremediation is a technology based on the use of green plants to remove, relocate, deactivate, or destroy harmful environmental pollutants such as heavy metals, radionuclides, hydrocarbons, and pharmaceuticals. The word "phytoremediation" derives from the Greek "*phyton*", meaning "plant" and the Latin "*remedium*", meaning "to correct" (Cunningham et al., 1996). Phytoremediation is a cost-effective, easy to operate and eco-friendly treatment method. It is a biological-based biotechnology that utilises plants and their collaboration microbes to accumulate, stabilise, or degrade organic and inorganic pollutants in air, water, and soil (Grzegórska et al., 2020).

Air: air pollutants have both natural and anthropogenic sources. Furthermore, commonly referred to as soot, is a component of fine particulate matter (PM) that harms the wellbeing of humans (Gawronski and Gawronska, 2017). The phyllosphere of plant leaves and stems is known as an effective absorber of air pollutants, and adsorbed pollutants in the phyllosphere can be transferred to the soil and rhizosphere via rainfall and leaf fall. Thus, plants are able to effectively metabolise, sequestrate, or excrete air pollutants (Weyens et al., 2015).

Water: plants are allowed to grow in polluted areas, during which time they will absorb or consume heavy metals present in the environment, especially in soil and water. After absorption, certain mechanisms convert the toxic metals into a non-toxic form. Through this process, plants contribute to a toxic free environment. Organic and inorganic contaminants present in the environment are detoxified in different ways. For more than 100 years wetlands have been used for water pollution control. The term "constructed wetland" (CW) is generally used when a wetland has been explicitly built and designed for water pollution and water treatment purposes. The term "treatment wetland" (TW) generally encompasses constructed wetlands but is more expansive, and includes existing natural wetlands that are intentionally used as catchment areas for water pollution.

Soil: for soil purification, phytoremediation techniques seem to be a sustainable alternative to less environmentally friendly traditional methods (Saier et al., 201; Kang, 2014; Vishnoi et al., 2007)**.** Phytoremediation is the use of plants and their associated microorganisms with the aim of removal, degradation, or isolation of toxic substances from the environment. The general term phytoremediation encapsulates several processes, with distinctively different mechanisms of action. The clean-up process may utilise various mechanisms, including phytoextraction, phytovolatilisation, phytostabilisation, phytodegradation, rhizodegradation, and rhizofiltration (Etim, 2012; Wani et al., 2012). The major processes of the phytoremediation mechanisms are shown in Figure 1.1

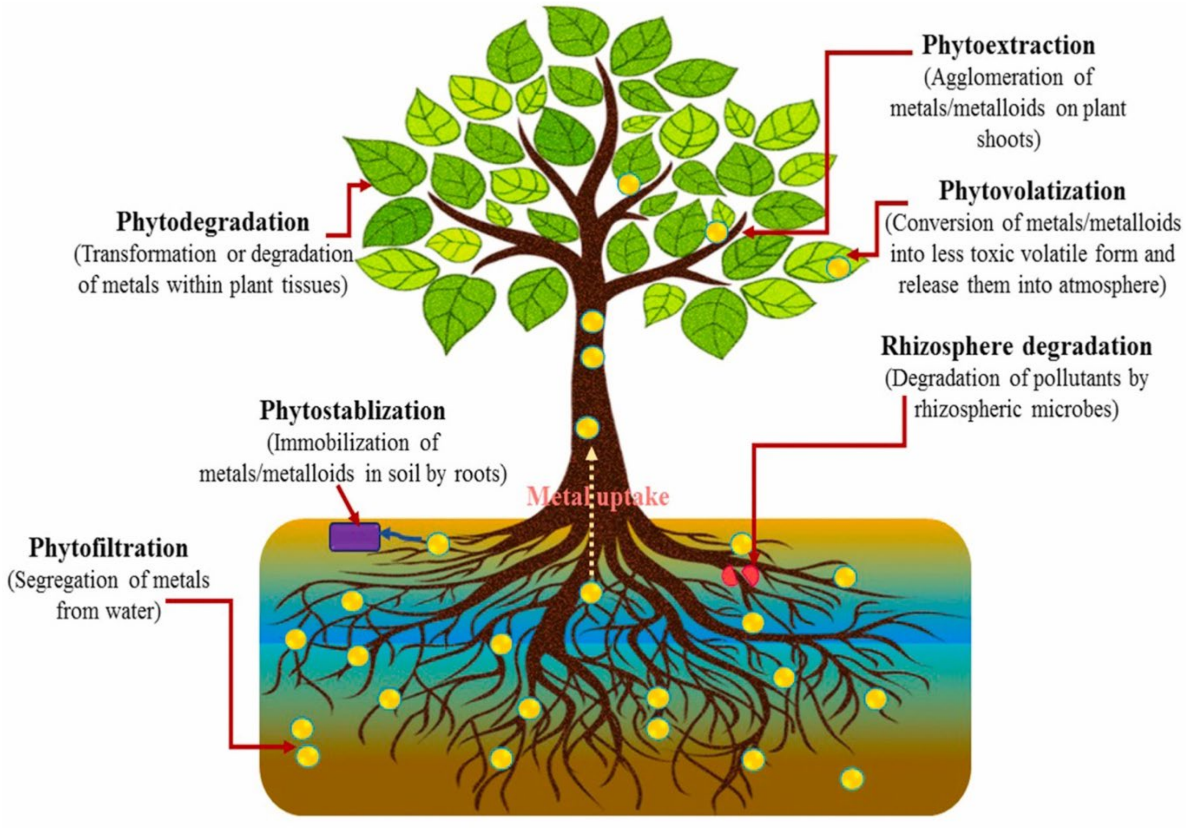

Figure 1.1 The major processes of phytoremediation mechanisms (https://ars.els-cdn.com/content/image/1-s2.0-S0301479721020338-gr6_lrg.jpg)

Different mechanisms involved in the remediation of contaminants is shown in Figure 1.1 and described below:

Phytostabilisation is the first mechanism in phytoremediation in which contaminants in the soil and groundwater are immobilised by using plants through adsorption or accumulation into the roots, or precipitate within the root zone to prevent their movements (Mirck et al., 2005, Kagalkar et al., 2011, Hasan et al., 2013, Schwitzguébel et al., 2006, Rizzi et al., 2004).

Rhizodegradation, also known as phytostimulation, refers to the decomposition of pollutants such as PAHs (polyaromatic hydrocarbons), hydrocarbons, or perchlorates, due to the activity of microorganisms in the rhizosphere. The carbohydrate sources present in the soil enhance soil microflora growth and activity. Sugars, alcohols, and organic acids act as a carbon source for the soil microbes. This type of phytoremediation may be referred to as plant-microorganism cooperation, thus strongly depending on the interactions between these groups of species.

Rhizofiltration is a phytoremediation technique which involves using a plant which can adsorb contaminants occurring in the rhizosphere onto the surface of its roots or absorb them into its roots tissue, and then concentrate and precipitate them (Verma et al., 2006, Tomé et al., 2008).

Phytodegradation (also known as phyto-transformation) is where the degradation of contaminants is carried out by the plant through its metabolic process. This process involves enzymes, such as oxygenases and nitroreductases that are produced by the plants, and which catalyse and accelerate degradation. There are two types of mechanisms involved for the degradation of organic contaminants: plant enzymatic activity and photosynthetic oxidation. Phytodegradation is used in the degradation of petroleum hydrocarbons, pesticides, insecticides, surfactants, or pharmaceuticals in soil and water.

Phytoextraction (or phyto-mining) involves the process of transporting contaminants from the environment to the plants, particularly the shoots of the plant, by uptake or absorption and translocation (Tangahu et al., 2011). The compound secreted by plants for the removal of metals from soil is called phytosiderophores. It has a strong chelating affinity, particularly with Fe^{3+}, and serves as a transporter of metals across the cell membrane (Hider and Kong, 2010) by forming a complex with metals present in the rhizosphere(Dotaniya et al., 2013). The plants were disposed of safely after harvesting once they have grown and absorbed the metal pollutants; contaminants concentration is reduced to acceptable levels by repeating this process several times. Hyper-accumulator plant species are used in many sites for the removal of metal contaminants because they give more effective results than accumulators and excluders.

Phytoaccumulation is the process of storing contaminants in the different parts of the plant tissues, such as leaves, stem and root (Tangahu et al., 2011). The xylem in the tissues transports the heavy metals or contaminants, along with water and nutrients from the soil, across the cell membrane with the help of phytosiderophores. After entering the cytoplasm of the plant cell, the metals can be transported into cell vacuoles in which the toxic contaminants are converted into a non-toxic form through the compartmentation process (Leitenmaier and Kupper, 2013).

Phytovolatisation involves the removal of accumulated contaminants from the leaves of the plants to the atmosphere through the process of transpiration. This mainly concerns volatile organic compounds (Tlustos et al., 2006; Ang et al., 2002; Cunningham et al., 1993) or volatile inorganic contaminants such as Hg, As, or Se (Brennan et al., 1999; Arnold et al., 2007; Edward et al., 2011; Chen et al., 2012). Phytovolatilization can occur either directly through the stem or leaves or indirectly via the root zone.

Chapter 2: Phytoremediation in Lithuania, Poland and Sweden: sustainable development and historical perspective

Phytoremediation has been considered an innovative economic alternative method for remediation of contaminated air, waters, and soils. Plants, dependent on species, have different abilities to gather and break down toxic substances, degrading, for instance, organic pollutants, removing from or stabilising toxic metals in soils. The accumulation of heavy metals in soils and water poses a risk to the environment and human health. The clean-up of soils contaminated by heavy metals is therefore crucial to minimise their impact on ecosystems.

2.1 Lithuania

Nowadays in Lithuania, the potential for the practical application of phytoremediation technologies for the clean-up of various contaminated soils is said to be high. According to data provided by the Lithuanian Geological Survey, the total polluted areas could be 11,500 ha; these areas are polluted by oil products (65% of total polluted area), pesticides (26%) and heavy metals (9%). The map of these polluted areas in Lithuania is shown in Figure 2.1.1.

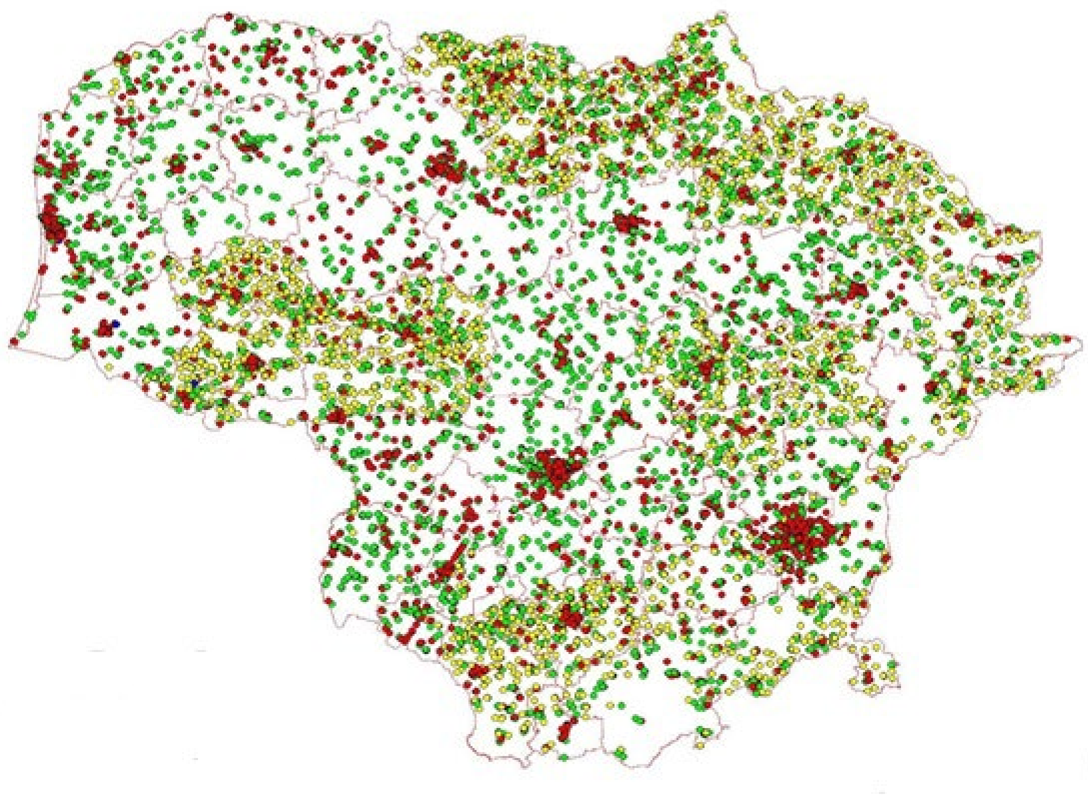

Figure 2.1.1. The map of soil polluted areas in Lithuania, listed as potential areas for soil remediation (data from Lithuanian Geological Survey).

So far, a few phytoremediation projects have been implemented in Lithuania, with aim to restore highly polluted areas. In 2018, the LLI-325 Innovative brownfield regeneration for sustainable development of cross-border regions (BrownReg) project began in three municipalities. The project saw the innovative approach of phytoremediation used for the first time to clean and revitalise soils in brownfield areas in Latvia-Lithuania. These included the following territories:

- a former linen factory in Kraslavas Street 1, Ludza, Latvia (total area: 8.9776 ha)
- a former heating plant in the Kazitiškis subdistrict, Ignalina district, Lithuania (total area: 385 m^2)
- a former oil products station in Naivių village, Skapiškis subdistrict, Kupiškis district, Lithuania (total area: 313 m^2).

A variety of plants were proposed for use during the project, with the species chosen according to the pollution type. The scheme of the phytoremediation site at Ignalina municipality, along with the chart of the method used, is depicted in Figure 2.1.2.

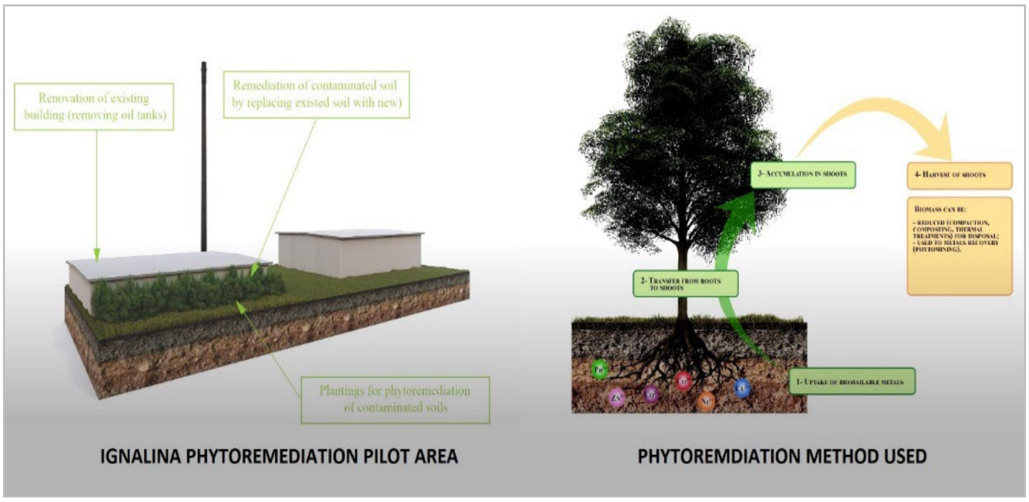

Figure 2.1.2. Phytoremediation pilot site at Ignalina municipality along with phytoremediation method used (BrownReg, 2022).

The three phytoremediation project pilot sites located in Lithuania were all remediated successfully (BrownReg, 2022).

An earlier phytoremediation pilot project, implemented in Lithuania in 2011-2013, and funded by the European Union Structural Funds (2007-2013) Operational Program for Cohesion, should be noted. The phytoremediation project has been organised as part of the national project “Treatment of sites with historical contamination”, The pilot phytoremediation sites were chosen in Panevežys municipality. where old sludge filtration sites were remediated. They had been polluted in 1960-1979 by heavy metals drainage from a television tubes production factory, as well as glass, metal, precision mechanics, sugar factories, brewery, thermal boiler houses etc. The area of 62.3 hectares has been chosen for phytoremediation project (see Figure 2.1.3).

Figure 2.1.3. Phytoremediation pilot site at Panevežys municipality (Gregorauskienė, 2021)

After the phytoremediation process in the pilot areas, the concentrations of heavy metals reduced in the soil, although they were still found to exceed the limits proscribed in national legislation, which sets allowable limits of pollutants in agriculture soils, and defines the necessity for self-remediation of these sites. Initially, the phytoremediation plants chosen were *Alnus Glutinosa*; however, final results revealed that reduction of soil contaminants was slow and irregular due to land drainage, soil lithology, and meteorological conditions, and the extremely polluted areas exposed unfavourable conditions for planting the broad-leaved trees (Gregorauskienė, 2021).

Alongside EU-funded pilot phytoremediation projects implemented in Lithuania, private companies have made their first steps towards the application of phytoremediation technologies for soil treatment. The well-known state-owned enterprise, Soil Remediation Technologies, has implemented soil remediation projects since 2013 (SRT, 2016).

Figure 2.1.4. A: oil contaminated site used by Soil Remediation Technologies; B: root system of the siderates used for the Alfalfa phytoremediation experiment (Meištininkas, 2021).

The company developed phytoremediation technology for remediation of soils polluted by oil products, and in 2012 was awarded "the Product of the Year golden medal award" by the Lithuanian Confederation of Industrialists (Alkas, 2012).

The private science-production biotechnology company, Biovala, founded in 2014, provides phytoremediation and biodegradation technologies for the remediation of soils polluted with chlorinated hydrocarbons, oil products, pesticides, heavy metals, etc. (Biovala, 2022). The private science company, Biocentras, provides bio-treatment technologies for the oil polluted soil along with an ex-situ soil phytoremediation service (Biocentras, 2022). A few private companies based in Lithuania, e.g. Biodegra and Venteco Lt, provide the treatment of hazardous wastes as well as ex-situ soil phytoremediation services (Biodegra, 2012; Venteco, 2022).

2.2 Poland

Phytoremediation is regarded as a sustainable method of environment cleaning, including soil, water, and air. In Poland, several phytoremediation-based wastewater treatment plants were installed in early 1990s. Additionally, several applications of phytoremediation to treat polluted post-mining lands were noted at that time. A brief overview of applications of phytoremediation in Poland is given below, focusing on the polluted air, water, and soil treatment application.

Air cleansing using phytoremediation

In 2018, a reduction in emissions to air of metals such as arsenic, chromium, zinc, nickel, lead, and mercury was noted. The dominant heavy metal is cadmium, and its source is industrial processes (52%), including metal production, as well as combustion processes (40%), including mainly combustion in the energy production and transformation sector. Mercury emissions mainly come from the combustion of fuels in the energy industry, i.e. for the production and transformation of energy in power plants, utility combined heat and power plants, and heating plants. The main source of lead is industrial processes, in particular metal production and fuel combustion processes. The emission of the element arsenic comes mainly from fuel combustion processes in the energy production and transformation sector, as well as industrial processes.

Chromium emissions come mainly come from the power generation sector, including fuel combustion. Copper comes mainly from transport, including road transport (abrasion of tyres and brakes) and industrial processes, including the production of solvents, metal production and combustion in the so-called small units. The main source of nickel was energy production, including fuel combustion in the energy production and transformation sector. The last heavy metal is zinc, the main source of which is combustion of fuels and industrial processes, including metal production and the use of solvents and other products. Due to the large number of heavy metals and their emissions, appropriate measures must be implemented to reduce their quantities in the air. During evolution, plants have developed defence mechanisms that allow them to survive in the harshest conditions. These mechanisms include the production of water vapour and oxygen, as well as the sequestration of soil, water and air pollutants in leaves, roots, and stems. After poisons and the dust have penetrated the surface layer of the leaf, they are immobilised and rendered harmless.

Wetlands for stormwater/wastewater leachate treatment

Poland is a country with constantly diminishing water resources. Statistics report that there is about 1,500 m^3 water/year per each inhabitant, and in times of drought this amount drops to 1,000 m^3/year. On a European scale, there is nearly 4,500 m^3/year per capita. Such a large difference is caused by the uneven distribution of water resources and the large spatial and temporal dynamics of supplementing these losses with rainfall. Central Poland, especially Mazowsze, Kujawy, Łódzkie and Świętokrzyskie voivodeships, as well as Wielkopolska, are regions with poor water abundance compared to southern Poland. Additionally, severe storms are more common in these areas, especially in spring and autumn. The poor quality of surface waters means that these are used in industry. Therefore, the stocks are replenished with groundwater. However, more than half of the average water runoff from Poland to the Baltic Sea comes from underground resources, which causes a decrease in their levels and numerous other unfavourable phenomena: disappearance of small water reservoirs, degradation and disappearance of wetlands, and low levels of rivers and other watercourses.

The wetland cleaning approach referred to as ‘constructed wetland’ comes from Western Europe and North America. The very word ‘wetland’ was problematic, as it has other meanings. In general, wetland treatment is based on a biological process that involves heterotrophic microorganisms, as well as aquatic plants and hydrophytes (hydrophilic plants), that exist in specially designed soil filters or ponds. The entire process is based on intensive oxidation and reduction processes supported by sorption, assimilation, and sedimentation. Therefore, the most commonly used plants are common reed (*Phragmites australis*) and wicker (*Salix viminalis*). Reed is used because of its well-developed root and rhizome system and because of its high resistance to low and high temperatures. Wicker is used since it is a water-loving plant and shows a rapid increase in biomass, which is associated with an intensive uptake of biogenic compounds. In addition to the two above-mentioned plants, the following are also regularly used: broadleaf cattail (*Typha latifolia*), rush (*Juncus* sp.), Lake bullrush (*Schoenoplectus lacustris*) and porcupine (*Sparganium ramosum*). The advantages of wetlands systems include easy and simple operation, low costs compared to conventional treatment methods, and resistance to uneven sewage inflow. In addition, these plants stabilise the surface of the deposits, at the same time protecting it against wind erosion; they also act as a habitat for birds, and the dead plants provide shelter and act as a thermal insulator. Systems of this type allow the removal of nitrogen and phosphorus compounds, as well as heavy metals. However, larger terrain and difficulties with plant adaptation and duration (up to three years development time required for rhizosphere) are disadvantages of this system. Wetland systems are used in the form of:

- wetlands treatment plants, which allow the removal of pollutants in water and sewage
- systems for drainage and partial neutralisation of sewage sludge
- plant buffer zones for the removal of diffuse contamination.

In Poland, wastewater is considered to be rainwater, snowmelt, drainage water, street washing sewage and infiltration water. The most problematic pollutant is suspended solids. In Poland, distribution sewage systems prevail and most of the rainwater networks discharge sewage directly to the receiver, without any treatment. This poses a particular threat to the watercourses that run through the cities. In Poland, wastewater treatment is carried out using retention tanks, retention-sedimentation tanks, sedimentation tanks, sand traps and multi-stream sedimentation tanks, as well as oil-derivative separators integrated with the sedimentation tanks. Devices of this type allow for the removal of petroleum derivatives and flammable suspensions. These treatment facilities comprise sand filters, vegetation filters and the floodplain, which consist of five buffer zones.

Examples of wetlands systems for the treatment of rainwater in Poland include:

a) The Municipal Zoological Garden in Gdańsk Oliwa, Potok Rynaszewki – in 1992, a complex of hydrotechnical and wetland facilities was built. The Rynaszewki Stream is the largest tributary of the Jelitkowski Stream, its receiver being the Bay of Gdańsk. The high nitrogen concentration and microbial contamination reduce the purity class of this stream. In this case, basket willow (*Salix viminalis*) was introduced in Oliwa.

b) Potok Swelina, Sopot – in 1994, a sedimentation and retention reservoir (500 m^3) and a vegetation sand filter (870 m^3) were constructed. The sand filter is planted with common reed and filled with gravel. The facility was built to manage the presence of phosphates and other biogenic compounds, as well as microbiological contamination, e.g. faeces flowing in with rainwater.

c) Bielkowo, the watercourse feeding Lake Goszyńskie – this facility supplies the Goszyńskie Lake, which is a drinking water intake for Gdańsk. This design consists of a wet and a dry element. –The wet part is constantly being filled with water. Some of it is a system of filtration dykes that contain internal drainage in the form of wetlands. The dry part is periodically filled with water and is intended for storage of flood waters. A wet and dry part is used to ensure retention of aged waters and partial retention of rainwater that flows in from the surrounding areas.

Soil remediation using plants

Soil is a three-phase system, composed of soil water, soil pores and solid particles, of which the solid-state accounts for about 45% of the total volume. It consists of an organic part, mineral particles, and organo-mineral particles. Each of these play a very important role in, among others, adsorption processes, oxidation, reduction, exchange, catalysis, and precipitation of pollutants.

The European Directive on Integrated Pollution Prevention and Control, identifies six categories which are potential sources of pollution: energy, mineral, chemical and chemical installations, metal production and processing, waste management, and other activities, i.e. paper and cardboard production, production of fibres and textiles, poultry and pig farming, tanning of hides and skins, slaughterhouses, installations using organic solvents, and the production of carbon and graphite.

Soil has the ability to immobilise incorporated chemicals, including heavy metal ions. This is mainly due to its sorption properties (physicochemical properties, pH, water content, temperature and properties of a given metal ion). The industrial applications of phytoremediation to treat metal-loaded soils are found in the mining territories of southern Poland. Additionally, science research on phytoremediation for soil treatment has constantly been developed since 1990s, including at the universities in Łódź, Kraków, Białystok and Gdańsk.

Despite successes of phytoremediation confirmed by laboratory-scale greenhouse experiments, there is a gap in field research, where the phytoremediation process depends on real conditions and may be affected by numerous factors. Thus, there is a need to investigate phytoremediation at the field level. Furthermore, an essential aspect of phytoremediation is the economic and ecological valorisation of contaminated biomass of plants after harvesting. There is still a need for further experiments to develop a productive and profitable method for plant biomass processing, when "bio-ore" generation with metal recovery is considered. An approach of combining phytoremediation aiming at biomass generation and its utilisation as an energy source should be more thoroughly investigated. This two-track approach for interconnection of phytoremediation processes with renewable bioenergy production from contaminated crops might bring tangible benefits, especially related to the simultaneous clean up-process of large areas and thus significant amount of alternative energy production from waste, also considering reduction of CO_2 production in comparison to using fossil fuel. This will allow phytoremediation to be called a "zero waste" sustainable environmental technology for soil remediation. Moreover, an interesting approach for research may be related to investigations on mutual symbiotic interactions between various plant or microbial activity in terms of enhancing plant growth, and thus phytoremediation efficiency. Another key aspect is development in the field of plant engineering, which provides plant unique features. Furthermore, a focus might be on investigations of factors affecting plant growth and plant selection for obtaining valuable products that could be extracted (not only e.g., metals, but even biologically active compounds).

2.3 Sweden

Soil remediation using plants

Considerable resources are spent annually to clean up polluted areas of water, soil, and air in Sweden and globally (Pérez and Eugenio, 2018; SGU, 2021). Most traditional solutions are very expensive and don't include the circular economy concept. In total, Sweden has about 80,000 polluted areas, of which 1,000 pose high risk to the environment and should be remediated, and another 7,000 are of high risk for environment and health (SGU, 2020). Soil remediation can be made on-site (in-situ) or off-site (ex-situ), for instance on a landfill (Lianwen Liu et al., 2018). Phytoremediation includes combined physical, biological, and chemical processes that should be optimised.

At industrial areas, the selection of remediation technique must be made carefully to be cost effective; eliminate toxicity and not add new pollutants; reduce or eliminate contaminants; reduce the time required as much as possible; be proceeded by physico-chemical, hydrological, and geological characterisation; and consider social, health and environmental aspects. For some time, lupines were used to remediate water and soil on road banks and road ditches. However, these and similar plants can be extremely invasive and should be avoided. Phytotechnologies can address organic compounds such as petroleum hydrocarbons, gas condensates, crude oil, chlorinated compounds, pesticides and explosive compounds, and inorganics – including high salinity, heavy metals, metalloids, radioactive materials and others (ITRC, 2009). Onsite phytoremediation can be an alternative to transportation of polluted masses to a place for treatment or to landfill. At a car wrecking site in the city Nybro, an overfill protection for an oil tank was broken and the soil around the tank was polluted (Marchand, C., Doctoral thesis, 2017). This was an ideal place where onsite phytoremediation could be practiced, and no oil polluted soil needed to be transported through the city, thus avoiding the risk of exposure to humans. A phytoremediation bed was constructed where the oil polluted soil was spread out and oilseed rape was selected for the treatment. However, the test area was invaded by a huge number of insects' larvae that within two days ate all the plants.

Oil polluted soils are commonly found in car wrecking sites. Usually, the most contaminated areas are transported to landfill, where a test area for oil polluted soil can be established. In one of the investigations carried out at Linnaeus University, to accelerate the soil clean-up process during treatment tests, a farmer was contacted, and already well-developed plants (raps) were transplanted to the eco-piles (Marchand, C., 2017). In the first trial, several thousand individual plants were planted on the test area, but all of them disappeared overnight because deer invaded the area. A fence was then installed, and nine eco-piles were established in separate boxes for tests. Lucerne (*Medicago sativa)*, raps (*Brassica napus ssp. Napus*), and willow (*Salix*) were tested. The investigation began with phytoremediation of soil contaminated with petroleum hydrocarbons (PHC) and trace elements (toxic metals), which ended up on site in Nybro (Marchand, C., 2017). During the investigation, PHC reduction in the soil of up to 80% and metals reduction of up to 20% was achieved after 17 months of treatment with the plants. Results showed *M. sativa* and *H. annus* are suitable for phytoremediation of PHC and phytoextraction of toxic metals. It was also shown that 10% of compost added to the soil as a source of microorganisms is a good way to promote PHC degradation (Marchand, 2017). Additionally, it was found that the maintenance and management of a phytoremediation project is crucial to achieving project objectives, including fungus contamination management, protection from insects and wild animals; a fence should be located around the remediation area to avoid similar problems. The factors which influence the efficiency of the phytoremediation include oxygen, nutrients, toxicity, microorganism, biodegradability, pH, hydraulic retention time, temperature, etc. All of these factors could impact plant growth, the microorganisms' activities, and rhizosphere processes, which lead to the efficiency of the phytoremediation function in contaminated soil or water. A novel solution to enhance phytoremediation was protested.

Closed landfills

Many polluted areas and old dumps, as well as old landfills, are covered by soil, sometimes according to EU recommendations. For many years the ESEG (Environmental Science and Engineering Group) at Linnaeus University has worked with landfill mining, which means excavation and recovery of materials from an old dump/landfill with the possibility of remediating hazardous materials and contaminated soil. The term "bank account cells" has been created to define cells in landfills where materials of the same type that currently cannot be recovered in an economically beneficial way are stored for recovering and recycling in future. Such "bank account cells" were found in the Kingdom of Crystal in the Kalmar region. At one site are cells with glass containing mainly copper, while another has glass containing mainly cadmium and lead. Glass, bricks, and chemical substances from the glass industries has been dumped at the Kingdom of Crystal since the late 18th century. More the 50 old glass dumps exist in the region and Swedish EPA has decided two dumps shall be excavated each year, and the material transported to a sanitary landfill where the glass waste is sometimes mixed with other toxic waste. This type of handling of the dumped glass material must be avoided, and transportation of the masses from the contaminated site to the landfill might be a human health hazard for people living along the transportation route. One PhD project (Mutafela, 2021) has focused on the recovery of metals and remediation of excavated contaminated soils in the Kingdom of Crystal and h a phytoremediation park has been established at the old Orrefors glasswork(see Figure 2.3.1).

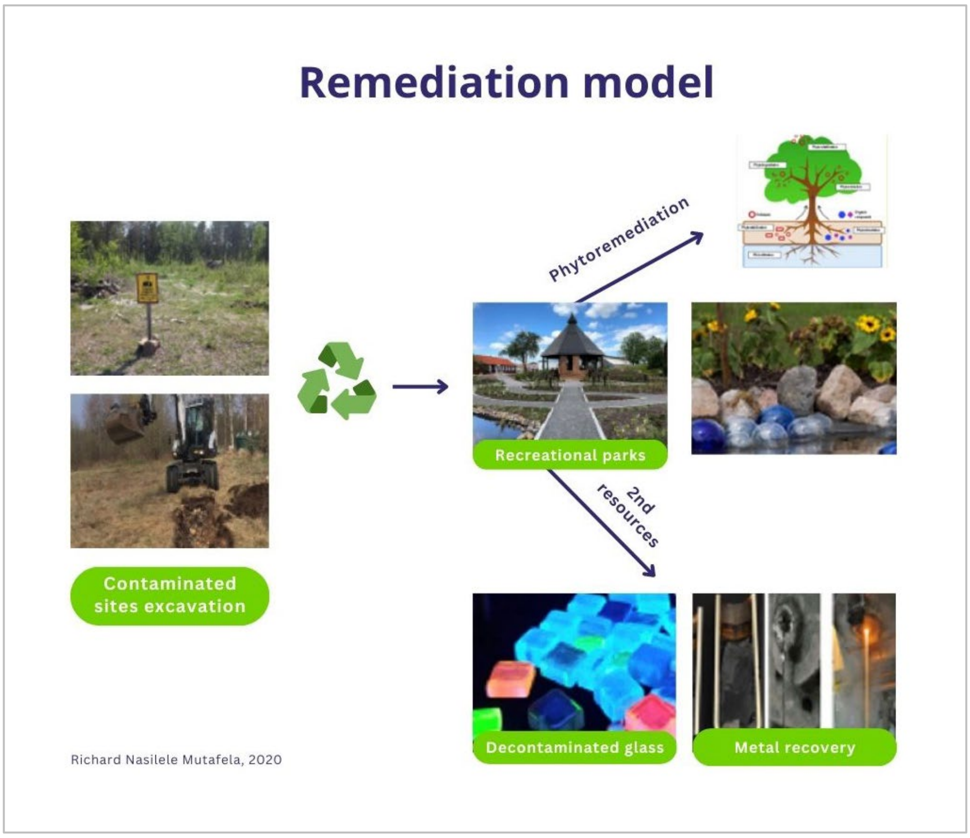

Figure 2.3.1. Glass dump remediation model (R. Mutafela, 2020).

Soil amendment using dredged sediments for plant growth

Fertilisers have been used in agriculture for some centuries, and the Baltic Sea is filled with nutrients from the runoff from agricultural areas, creating algae growth. Some of these nutrients are found in the sediments at Malmfjärden bay in Kalmar. The production of soil amendments using dredged sediments combined with beach wrack found on nearby beaches has been investigated, with a focus on the circular economy (Ferrans, 2021; Schmieder, 2021). Bottom sediments are removed from the bay using a robot-like technology in an environmentally friendly way to minimise turbidity. The robot, "Mudster", comprises one unit above surface and another under the water moving slowly over the bottom and sucking the sediment and a sediment mixture (mostly water), which is pumped to land for future treatment. The process is designed to have a minimum effect on the environment, plants and animals. Different mixtures of bottom sediment, beach wrack and biochar were prepared as soil amendment. The soils were tested for various beneficial uses in agricultural cropping. The dredged sediment was also tested to be used for landfill coverage and for road embankments. The stabilisation of bottom sediments or the solidification of wet sediments were made with help from polymers and geotubes. On northern Öland, stakeholders helped to make a local biocoal reactor, bringing a mixture of bottom sediment from Malmfjärden, biochar and beach wrack from the shore for soil amendment. Beach wrack can be used for biocoal production, but pine tree woodchips are also used. Farmers on northern Öland cut the forest to transform it into agricultural land. The lignin rich soil from such land usually takes many years to break down, but this can occur faster if mixed with beach wrack and cow manure. Besides using the soil amendment for agriculture, it can also be used in horticulture at plant nurseries. The farmers are planning to produce reed beets for juice production and sale.

Pilot tests carried out in a greenhouse using different plant species have included analyses of the germination rate, and toxicity assessment as a result of pollutants. The mixture of bottom sediment and beach wrack give a better germination rate than direct planting in the finely structured dredged sediments. Measurements of plant growth is made by determination of dry biomass weight (DW) of shoot and root after oven drying for 48h at 80ºC. Determination of survival capacity (SC in %) and the uptake of pollutants in different anatomic parts of the plant is also investigated. Different plants have different capacities to store pollutants in their various parts during different growing conditions. Some plant species have about 10% of pollutant in the root system, 45% in the stem, 35% in the leaves, and 10% in the seeds (Haller and Jonsson, 2020; Haller, 2017).

Plastic, microplastic and nanoplastic particles

Recently, the uptake of plastic particles and pharmaceuticals by edible plants have been discussed. Plastics seen on Swedish farmland can end up in soil via wastewater sludge and digest from food waste biogas production. On farmland, for instance, plastics are mechanically defragmented by the tractor and other agricultural equipment as well as by UV degradation, and in the soil, plastics are further defragmented to microplastic or nanoplastics. The transportation of small plastic particulates by edible plants and weeds, by water and agricultural activities is not well known, and further transportation to groundwater or to surface water via ditches and rivers to the sea can result in further uptake in the food chain. During the 1980s and 1990s, there was considerable discussion about the establishment by farmers of protections zones and buffer strips near ditches, so nutrients and pollutants spreading to the water could be better controlled. Today, these buffer strips could be further developed by implementing obligatory phytoremediation technology as part of the agricultural landscape.

Over many decades, wastewater sludge has been used as fertiliser in agriculture, but the environmental and health effects associated with this practice have not been studied sufficiently. Water for irrigation is becoming increasingly scarce in many parts of Sweden, such as in the Kalmar-Öland region.

Current project in Sweden

In the sub-surface horizontal flow wetlands at Filborna landfill in Helsingborg, an extra purification step was constructed in 2021, primarily to further reduce the nutrient content and the metal content in the water that has passed the purification system, i.e. "a polishing step". The construction comprises a rubber seal, filled with sand, in which *Phragmites australis* was planted. The aim of the installation is to increase the biological degradation of nitrogen and phosphorous, and to have a filter function. The newly planted (May 2021) *Phragmites australis* in the sand substrate is shown in Figure 2.3.2.

Figure 2.3.2. Newly planted *Phragmites australis* (May 2021) in the sand substrate (photo by NSR)

There are plans to lay surfaces for transpiration of leachate, “irrigation areas” using plants (such as *Salix* and *Miscanthus Giganteus*) at the landfill site in Höganäs.

Phytoremediation of perfluoroalkyl and polyfluoroalkyl substances (PFAS)
In the EU-project Reviving Baltic Resilience (RBR), the uptake of PFAS in plants, soil substrate and substrate with biochar has been studied.

Chapter 3: Pilot cases

3.1 Sweden: NSR, Helsingborg

Site description

The pilot case and activities were located at NSR AB landfill, Filborna, in Helsingborg, located in south Sweden. During the completion of the western part of the Filborna landfill (2004-5), a mix of sludge from wastewater plants and compost from composted organic household waste was used in the topsoil layer. During the following control of the runoff water from the topsoil layer, high levels of nutrients, mainly nitrogen and phosphorus, were detected.

This runoff was originally planned to be directed to the nearby clean water recipient, but the high nutrient content made this impossible. The runoff issues are shown in Figure 3.1.1. Instead, the runoff water is treated at the local leachate water treatment plant. This results in lost capacity in the leachate treatment and the cost associated with this treatment.

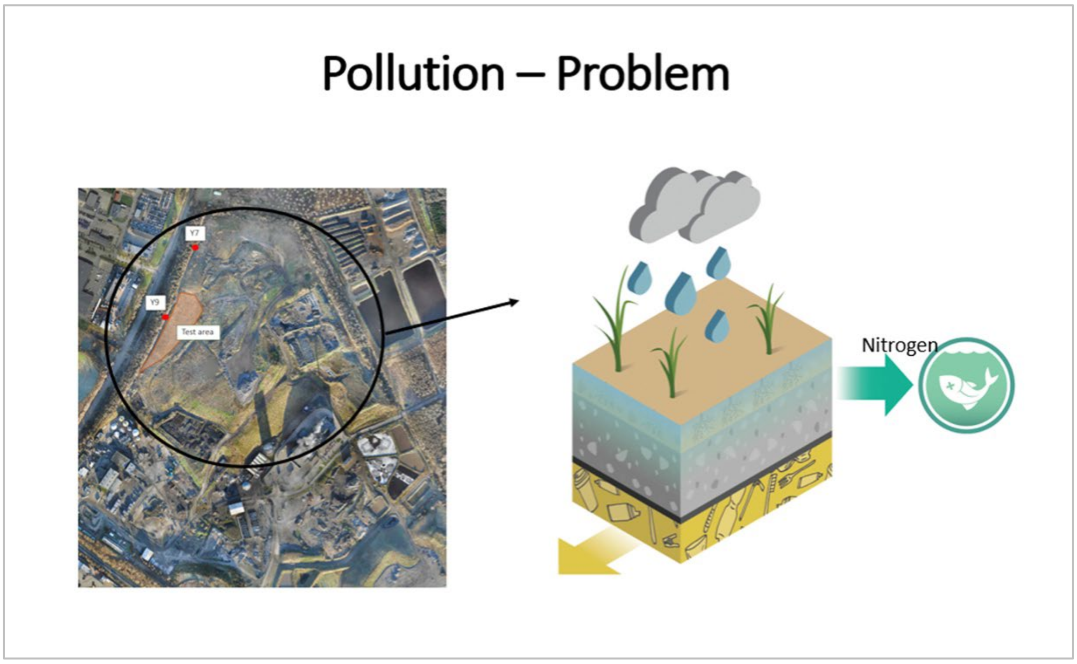

Figure 3.1.1 A schematic picture to illustrate the problem

Design, goal, and approach

The hypothesis in NSR's pilot case was that by phytoremediation, the nutrient levels in the landfill's topsoil would be reduced, leading to reduced pollution of leachate water from topsoil so that it can be released directly to the recipient, and that a way to utilise the harvested biomass would be identified.

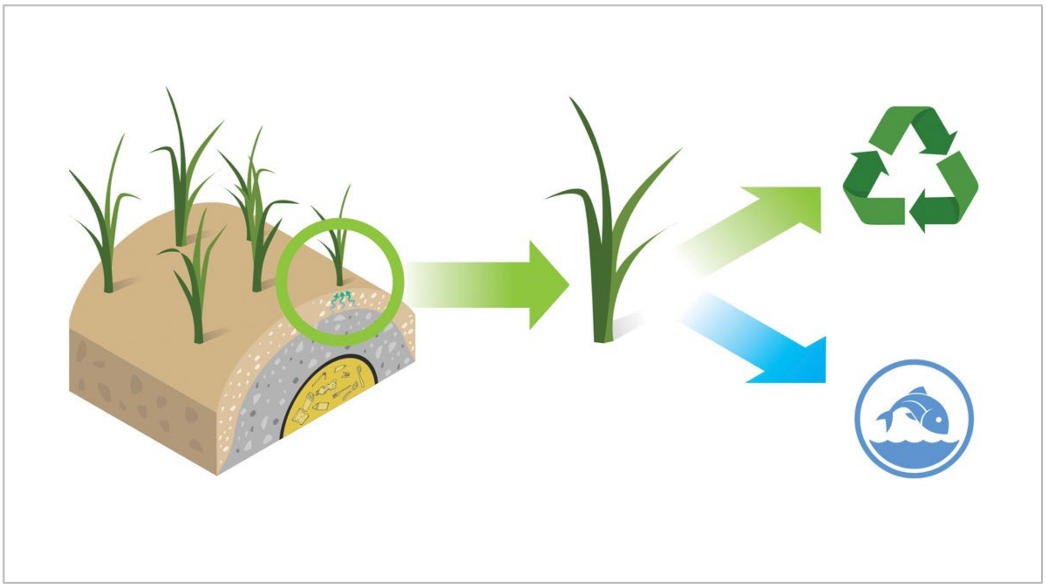

Figure 3.1.2. A schematic picture to illustrate design of the pilot case

The pilot case (see Figure 3.1.2) included a field trial on a larger scale at the landfill as well as in culture beds (see Figure 3.1.3). The purpose of the field trial on the existing landfill was to highlight the practical aspects of using plants for nutrient uptake. The purpose of the cultivation beds was to study the chemical and physical conditions, primarily regarding nutrients, but also metals, in soil and soil water under more controlled conditions.

Figure 3.1.3. A cultivation bed and a field trial

Cultivation beds

NSR constructed six cultivation beds in duplicate (a total of 12 boxes), of 4 m^2 (2 x 2 x 1.2 m). The beds were filled with material from the protection and plant layers of the current landfill; the following plants were chosen (see Table 3.1.1):

Table 3.1.1. Chosen plants for NSR's cultivation beds.

Chosen plants	Motives for selection
Miscanthus x Giganteus	Ordinary European landfill plant. Particularly good for the production of biochar. Harvestable and used as an energy crop
Oil radish and honey herb	Oil radish is one of the best plants for absorbing nutrients. Both plants are nicely flowering. Good for the pollinators.
Reed canary grass	Harvestable and used as an energy crop
Chicory	Produces a lot of biomasses, perennial, flowering
Rye grass	As a reference to biochar + ryegrass
Biochar and rye grass	In other experiments, biochar has shown to absorb nutrients. Rye grass is a common plant used for final cover

Field trial

At the landfill, five surfaces (one of which is a reference area using existing plants, mainly nettles) have been prepared at the top of the final layer of the landfill (approx. 20 x 30 m). Within these areas, the practical aspects of selected plants are evaluated for phytoremediation of plant nutrients. Primarily, we will study:

- Tillage; preparation of the topsoil for establishment
- Establishment, sowing and planting
- Maintenance, ex weed control and irrigation
- Harvesting
- Utilisation of the harvested biomass

Table 3.1.2. *Chosen plants for NSR's field trial*

Chosen plants	Motives for selection
Nettles harvested	Cheapest option. Existing vegetation, well established together with thistles
Biochar and ryegrass	In other experiments, biochar has shown to absorb nutrients. Rye grass is a common plant used for final cover
Reed canary grass, timotej	Harvestable and used as an energy crop
MiscantusxGigantus	NSR has plans to use it on another landfill; can be used as an energy crop
Low growing grass with flowering plants	Many other ecosystems benefits. Can be used on surfaces with greater inclines

Monitoring

Lysimeters were installed in the culture beds to measure primarily plant nutrient and occasionally metal content in the water (see Figures 3.1.4 and 3.1.5 below.

Figure 3.1.4. Cultivation beds with lysimeters

Figure 3.1.5. Lysimeter with soil water from a cultivation bed

Economics

The initial estimation of NSR's pilot case costs resulted in 89,000 EUR for equipment and an additional 19,500 EUR for staff and miscellaneous internal costs (installation, maintenance etc.). In addition to this, we calculated total sampling costs of 9,000 EUR.

Results and discussions

The most obvious conclusion from the experiences, experiments and literature studies is that overly nutritious plant layers at landfills should be avoided, and that the maintenance of the plant layer is of crucial importance for removing and reducing high nutrient levels in the topsoil.

1. The results from the pilot case indicate that phytoremediation is a feasible method for reducing plant nutrients on a final covered landfill, both from a theoretical and practical perspective.
2. It is possible to identify and establish plants suitable for landfills with nutrient-rich plant layers.
3. Park and agricultural machinery both work, but it can be challenging to find machine sizes that are optimal for landfills.
4. If plants are to be regularly harvested and maintained on a landfill after (or during) finalisation, this should be considered as early as possible in the planning or construction process, and provisions such as turning areas for agricultural machinery should be made.
5. Before establishing a specific plant, a plan for the usage of the harvested material should be in place. Specifics like the size of the harvested material limit its use for, e.g. composting, biogas, or biochar production.
6. Achieving an even spread and integration of biochar (with fine particle size) in the plant layer works with existing methods, such as disk fertiliser spreaders and ploughs.
7. The results indicate a minimal risk of jeopardising the impermeable layer of the plants' root systems discussed.

See **Appendix B** for more detailed results.

3.2 Poland, Gdansk Municipal Waste Management Company and Gdańsk University of Technology

Site description

Research on the treatment of post-industrial land using giant miscanthus (*Miscanthus sinensis 'giganteus'*) was carried out in an area of the rendering plant in Gdańsk – Szadółki, located in northern Poland (54° 19' 12.107" N, 18° 32' 23.62" E). Specific location of the pilot case installation is shown in Figure 3.2.1.

The soil on the pilot case territory was classified as clay loam (CL). The SK-8 soil improver (compost) is a product of the rendering plant in Gdańsk. The fertiliser is made in the process of composting biodegradable waste that is accessible to the disposal facility. A soil improver SK-8 can be used to improve the physical and chemical properties of all types of soil, including the cultivation of ornamental plants and lawns, as a component of the cultivation of potted plants or balconies and terrace plants, as well as in the rehabilitation of degraded areas. It is especially recommended for soils with a low humus content (Grzegórska et al., 2023).

In this pilot case, *Miscanthus sinensis* ‘Giganteus’ plants from the Nursery of Ornamental Plants Paweł Pesta (Lubichowska St. 9, 83-200 Starogard Gdanski, Poland) have been used (according to the European Union Plant Passport, the RUOP registration code: PL 22/13/77, company traceability code: PW 6/01/2020/12736, country of origin: Poland).

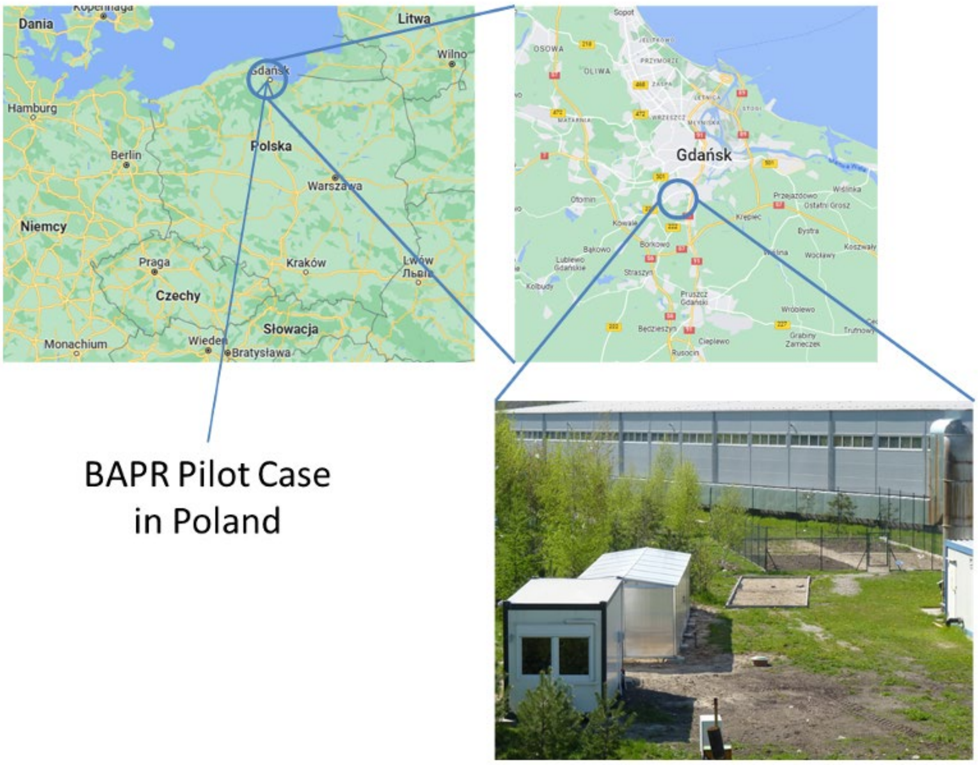

Figure 3.2.1. Location of BAPR pilot case in Poland

Design, goal, and approach

The Gdańsk pilot case is realised in both open-field and in model greenhouse conditions. The main aim of the investigations is related to the utilisation of a soil improver, produced by the Gdańsk rendering plant, to enhance the phytoremediation process of post-industrial soil using giant miscanthus, for environment cleaning and for utilisation of crops for energy production. In 2020, a one-factor open field experiment was established in a randomised block design with three repetitions. The plot area was 51.75 m^2 (11.5 x 4.5 m) with a 0.5 m spacing between plots. The experimental design included four elements: 1 – control (without fertilisation); 2 – a plot with 200 tons of soil improver; 3 – a plot with 400 tons of soil improver; and 4 – a plot with 100 tons of anthropogenic modified, i.e. highly contaminated, soil from the territory of the rendering plant (table 3.2.1). The soil improver and the heavily polluted soil fraction were applied to the soil surface once in spring 2020, then mixed with it for two weeks before planting Miscanthus seedlings. Initially, Miscanthus seedlings were sprinkled with water, as the substrate dried to a depth of 10 cm. In this field experiment, no mineral fertilisation (NPK) was applied, assuming that the compost was used as a source of nutrients for the Miscanthus. An overview of the pilot case installation is given in Figure 3.2.2.

Table 3.2.1. *Combinations and additions used in the field experiment*

Object No.	Symbol	Combination	Dose (Mg/ha^{-1})
1	Ct	Control	0
2	200 t	Single dose of soil improver	200
3	400 t	Double dose of soil improver	400
4	100 t	Addition of contaminated soil	100

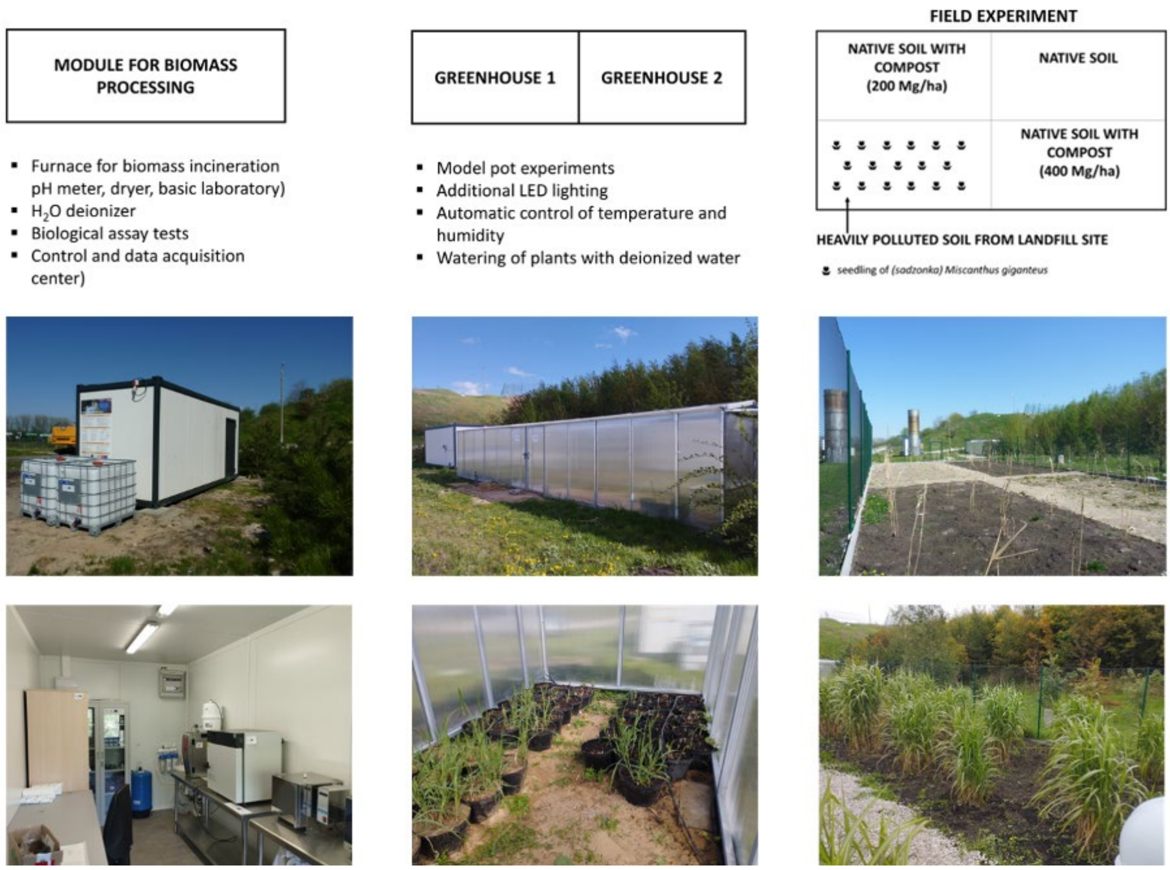

Figure 3.2.2. Overview of Polish pilot case elements

Monitoring

The determination of basic physicochemical properties of the field experiment soils were performed on the top layer of soil (0-25 cm), on the soil improver (SK-8) and on the highly contaminated soil from the rendering plant territory. The following methods were applied: dry mass using the drying method, soil pH – pH in H_2O and 1 mol/dm^{-3} KCl (soil: solution = 1:2.5) were determined potentiometrically, electrical conductivity (EC) with a conductometer, organic carbon using the Tiurin method, and total nitrogen using the Kjeldahl method. The content of available forms of phosphorus and potassium in the soil was determined by the Egner-Riehm method according to the PN-R-04023: 1996 and PN-R-04022: 1996 standards, respectively, and the available magnesium content according to the PN-R-04020: 1994 standard. The content of metal elements (Al, Fe, Zn, Cd, Cr, Co, Cu, Pb, Mn, and Ni) in soil samples was determined using a microwave plasma-atomic emission spectrometer 4210 MP-AES (Agilent Technologies Inc., Santa Clara, CA, USA).

The ecotoxicity of the soil was assessed using two types of biotest Phytotoxkit and Ostracodtoxkit. The Phytotoxkit was carried out for the three plants *Sinapi's alba*, *Lepidium sativum*, and *Sorghum saccharatum*. The measured parameters were inhibition of seed germination and inhibition of root length after their three-day incubation with soil samples. The Ostracodtoxkit biotest measured mortality and inhibition of growth of *Heterocypris incongruens* after a six-day exposure of the crustacean to samples. Both biotests were performed according to the procedure developed by the producer. The results obtained were expressed as a test reaction percentage effect (PE). The toxicity of the samples was assessed according to the following criteria: class I (PE ≤ 20% no significant toxic effect) – no acute hazard; class II (20% < PE ≤ 50% significant toxic effect, low toxic sample) – low acute hazard; class III (50% < PE < 100% significant toxic effect, toxic sample) – acute hazard; class IV (PE = 100% single test) – high acute hazard; and class V (PE = 100% all tests) – very high acute hazard.

The following parameters were determined:

a) Dry matter yield (Y)
b) Content of Al, Fe, Zn, Cr, Co, Cu, Pb, Mn, and Ni in the yield
c) Uptake of elements (U) was calculated as the product of the dry matter yield (Y) and the content of the component (X), according to the formula: U = Y * X
d) The balance of elements was calculated from the difference between the number of elements introduced with the dose of SK-8 compost and highly contaminated soil (100 t), and the number of components taken with the crop yield
e) Phytorecovery of elements was presented as the percentage of uptake of these components in relation to the amount added to the soil with additives.

Economics

The Gdańsk pilot case is composed of four main elements (see Figure 3.2.2 and Table 3.2.2). Installation was purchased via a public tender procedure based on the specification prepared in co-operation between the Gdańsk rendering plant and Gdańsk University of Technology. Installation of the pilot case was completed in spring 2021.

Table 3.2.2. Specification of pilot case elements

No.	Name of element	Components	Estimated cost (in EUR) (recalculated from PLN according to assumptions and real spending in 2020/2021)
1.	Cultivation plot	Removal of topsoil fraction, loosening, fertilisation, plundering, construction of a fence	65,00
2.	Greenhouses	Materials and construction of greenhouses, electrical installation, LED lighting, watering system, temperature, and humidity control system	19,500
3.	Module for biomass pre-treatment	Preparation of land as well as water and electricity supply; insulated mobile building equipped with a heating system, air conditioning and water installation. Contains basic laboratory equipment, e.g. pH meter, laboratory and industrial balances, water purification system, laboratory furnaces and drier, glassware, working desks with one laptop, as well as consumable materials for physicochemical determinations of soil and plant samples, e.g. bioessays or consumable materials for metals determination; installation and start-up of a module	35,000
4.	Documentation and cultivation materials	Documentation, including post-completion documentation, seeds, and seedlings, as well as fertilisers	11,000

Results and discussions

The main conclusions from the Gdansk pilot case investigations area are as follows:

a) The field experiment was performed on post-industrial soil, characterised by high salinity, with the content of heavy metals below permissible limits established for post-industrial soils.

b) The highest plant yield of *Miscanthus x giganteus* was obtained with the soil mixed with 400 Mg DM/ha^{-1} of compost.

c) The highest concentration of Zn, Cr, Cu, and Mn was observed for *Miscanthus x giganteus* cultivated on the post-industrial soil; meanwhile the primary source of Al, Fe, Pb, Co, and Ni was a compost (SK-8). In the case of the cadmium accumulation in the *Miscanthus x giganteus* biomass, the highest content was measured for plants cultivated on the anthropogenic modified soil (100 t).

d) The highest uptake of Zn, Cr, and Cu by *Miscanthus x giganteus* was observed for post-industrial soil (Ct). Incorporation of compost (SK-8) into post-industrial soil led to an increase in the uptake of Al, Fe, Co, Pb, Mn, Ni, and Cd in comparison to control soil. Addition of the highly contaminated soil (100 t) favourably affects the uptake of Al, Fe, Co, Pb, Mn, Ni, and Cd by *Miscanthus x giganteus* in comparison to control.

e) With the dose of compost equal to 400 Mg DM/ha^{-1}, the number of chemical elements introduced to the soil environment was the highest. Furthermore, in this element, the largest balance difference was noticed.

f) Phytorecovery of the elements did not exceed 1% of the amount introduced to the soil. This fact resulted from a short cultivation period and large doses of compost or highly contaminated soil (100t). The greatest phytorecovery was obtained for Cu (0.755%); next in order were Zn, Ni, Mn, Cr, Co, Fe, Cd, Pb, with the lowest being Al (0.019%). These results refer to a one-year study.

g) After two years of vegetation, *Miscanthus x giganteus* showed a good ability to accumulate contaminants, which indicates that this species can be successfully used for the biological management of post-industrial soil, especially in landfills and settling tanks with different levels (i.e. wide range) of pollution.

h) Energetic valorisation of biomass showed the highest potential of energy biomass production from the fields containing 400 Mg/ha of a soil improver.

i) Experiments carried out in the greenhouses for which diluted landfill leachate was added (Miscanthus; dilution with water up to 40% by volume of the leachate) showed good results for production of energetic biomass and the biomass yield was the highest for the lowest dose of the leachate, e.g. 10% by volume.

j) The biotests performed demonstrated no or low toxicity of the soils before starting the experiments.

3.3 Lithuania: Lithuanian Research Centre for Agriculture and Forestry and Klaipeda University

Site description

The pilot case and its related activities are located in Vėžaičiai, Klaipeda District Municipality in Western Lithuania's eastern fringe of the coastal lowland (55°43'N,21°27'E) (see Figure 3.3.1).

Figure 3.3.1. Location of pilot case in Western Lithuania

PP6, the Lithuanian Research Centre for Agriculture and Forestry, was responsible for the design and running of the phytoremediation field experiment to evaluate the ability of different plants to extract and accumulate heavy metals from contaminated soil contaminated in their roots and translocate them to parts above ground by fertilising them with sewage sludge under natural climatic conditions.

The **climate** in the Western Lithuania region is moderately warm and humid. Mean annual precipitation rate ~1100 mm and average air temperature +7.2°C. The maximum amount of rain falls in late autumn and early winter; it accelerates nutrients and heavy metals leaching from the upper soil layers, and results in soil acidification processes and increased water pollution.

The **soil** of the experimental site is *Bathygleyic Dystric Glossic Retisol* (texture – moraine loam (clay 13-15%)). According to the content of clay particles, the soil profile is differentiated into alluvial and illuvial horizons. The soil is very acid (pH_{KCl} 3.9-4.2) across the entire profile to the depth of 160 cm, and the amount of the toxic mobile aluminium is extremely high (>100 mg kg^{-1}), in both topsoil and subsoil.

Goal, objectives, design, and approach

The goal of this pilot case was to evaluate the potential of various plant species to accumulate heavy metals in their biomass by applying sewage sludge as organic fertiliser obtained from water treatment plants.

The main objectives were:

- to assess the accumulation potential of heavy metals of different plant species by fertilising them with sewage sludge (field experiment)

- to assess the changes of heavy metals concentration in a plant-soil-water system over time (field and pot experiments)
- to determine the effect of leguminous plants (red clover) inoculated with bacterial *Rhizobium* preparation in combination with liming ($CaCO_3$) to increase the accumulation potential of heavy metals of traditional grass meadow fescue (*Festuca pratensis*) (field experiment)
- to evaluate the effect of sewage sludge, including chelates (chemical – EDTA and natural origin biochar), to enhance the phytoremediation potential of plants (buckwheat and mustard) under artificial conditions (keeping controlled temperature and lighting regimes in a laboratory) and under natural climate conditions (pot experiments)

To solve these problems, the pilot case was composed of three research elements, including a field experiment and two pot experiments (see Figure 3.3.2). One of the pot experiments was conducted under controlled lighting, temperature, and humidity conditions, and the other under natural climate conditions; only in case of drought was the optimal soil moisture maintained by watering. The pots were filled with the same type of soil as in the field experiment.

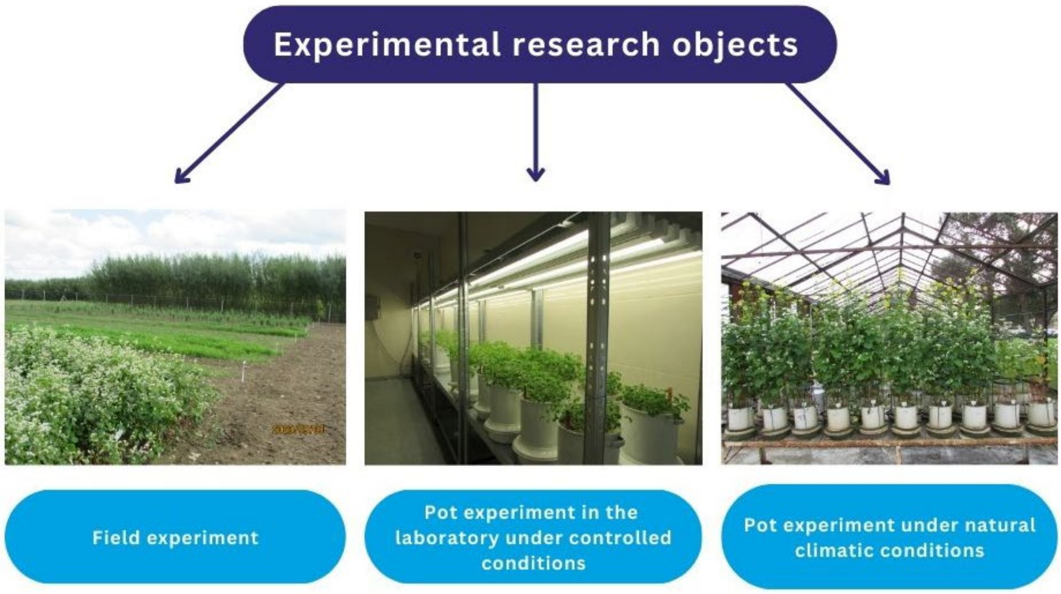

Figure 3.3.2. Research objects of the pilot case

In all experiments, sewage sludge from the water treatment plant of the industrial city of Klaipėda was used. Two plants (common osier (*Salix viminalis L.*) and cup plant (*Silphium perfoliatum L.*) were fertilised in a field experiment (in 2013) with sewage sludge from the Šilutė water treatment plant, i.e. a city without highly-developed industry. Sewage sludge taken from these facilities differed in chemical composition. Granulated sewage sludge taken from the joint-stock company, Šilutės vandenys, had the following chemical characteristic: pH 5.57; total nitrogen 32.8 g kg^{-1}; total phosphorus 4.99 g kg^{-1}; organic matter 65.03%. The heavy metal concentrations were: lead (Pb) 14.48 mg kg^{-1}; cadmium (Cd) 0.45 mg kg^{-1}; chromium (Cr) 11.53 mg kg^{-1}; copper (Cu) 47.7 mg kg^{-1}; nickel (Ni) 8.24 mg kg^{-1}; zinc (Zn) 286 mg kg^{-1}; mercury (Hg) 0.97 mg kg^{-1}. The applied sewage sludge meets the first category for heavy metal contamination, according to nature protection requirements. Meanwhile, the sewage sludge taken from the joint stock company, Klaipėdos vandenys, contained significantly higher concentrations of nutrients and of heavy metals compared to the sewage sludge taken from the water treatment plant of the non-industrial city of Šilutė.

Field experiment

The field experiment was installed in the spring of 2020, when the perennial grasses were weeded out with a disc scraper and cultivator, and the soil was prepared for sowing and planting in the middle of July. These energy and food plants species were selected for cultivation in the field experiment because they best tolerate the current climatic and acidic soil conditions, produce a lot of biomasses, and have different phytoremediation potential. The selected plants were fertilised with 45 t/ha^{-1} granular sewage sludge several times (see Figure 3.3.3).

- Perennial herbaceous plants introduced: *Artemisia dubia* and *Miscanthus x giganteus*
- Perennial grasses of local origin: tall fescue *(Festuca arundinacea L.);* reed canary grass (*Phalaris arundinacea* L.); meadow fescue (*Festuca pratensis* L.); meadow fescue – red clover mixture (*Festuca pratensis* + *Trifolium repens* L.)
- Annual plants for food purposes: sunflower (*Helianthus annus* L.); maize (*Zea mays* L.) and buckwheat (*Fagopyron repens* L.)
- Perennial woody plants of local origin: common osier (*Salix viminalis* L.)
- Perennial herbaceous large-stem plants introduced: cup plant (*Silphium perfoliatum* L.)

Figure 3.3.3 The most important stages of setting up the field experiment in a perennial grassland: soil preparation and spreading of sewage sludge (dark plots – first three photos on the left), and a general view with plants (on the right)

Perennial plants used for energy purposes – common osier and cup plant – were fertilised in 2013 with two different rates (45 and 90 t/ha^{-1}) of granular sewage sludge taken from the joint-stock company Silutes vandenys. These plants were fertilised once. Meanwhile, the other plants were fertilised in 2020 with the lower dose (45 t/ha^{-1}) of sewage sludge by spreading it in sections (two or three times), to avoid the toxic effect of on plant physiological processes in the first stages of growth. The biomass yield for all plant species was estimated in the following two years (2021 and in 2022).

All investigated plants were grown in the selected treatments (66 m^2): not fertilised with sewage sludge (control), and fertilised with sewage sludge at two rates (45 t/ha^{-1} and/or 90 t/ha^{-1}). In these treatments, three fixed sites were systematically selected where plants were analysed and soil and lysimeter water samples taken.

Pot experiment in the laboratory under controlled conditions

The pot experiment was conducted under controlled lighting, temperature and humidity conditions (see Figure 3.3.4.) and two plants were grown in vegetative pots (with a 7.0 kg soil capacity): buckwheat (*Fagopyrum repens* L.) and mustard (*Brassica juncea* L.), which were fertilised with sewage sludge at the two rates: 45 t/ha^{-1} and 90 t/ha^{-1}.

Figure 3.3.4. Pot experiment in laboratory

These plants were selected as they are characterised by their high phytoremediation potential and tolerate acidic soil reaction. Plants were grown in the unfertilised soil (control) and in soil fertilised with two rates of the granulated sewage sludge (see Figure 3.3.5). To increase their ability to take up more heavy metals from the soil and accumulate it in their biomass, plants were watered twice with a chelate EDTA solution (29.224 g EDTA per litre of water). Plants (20 units in pots) were watered twice with the prepared EDTA solution (0.1 mol/l). The experiment was conducted in three replicates and repeated three times.

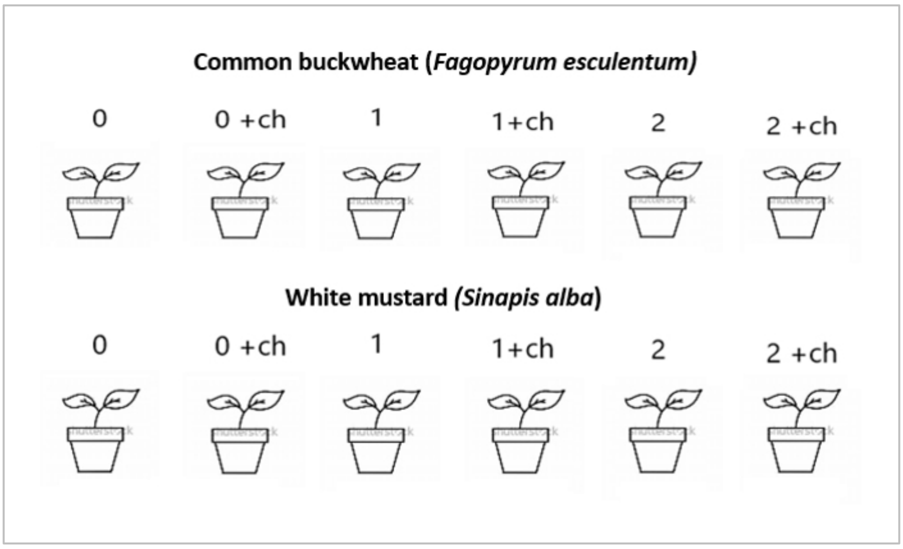

Figure 3.3.5. Scheme of the pot experiment, where 0 – unfertilised (control); 1 – fertilised with 45 t/ha of sewage sludge (126 g of sewage sludge/pot); 2 – fertilised with 90 t/ha of sewage sludge (252 g of sewage sludge/pot); Ch –EDTA added as chelate (0.1 mol/l)

Pot experiment under natural climatic conditions

The pot experiment in natural climatic conditions was set up in 2021 to evaluate the effect of the organic amendment (chelate) – biochar – produced by applying two temperature regimes from different plant waste products on the accumulation of heavy metals in plant biomass, by fertilising them with 45 t/ha^{-1} sewage sludge obtained from the industrial water treatment plant at Klaipėda city. The experiment was carried out with two plants: buckwheat (*Fagopyron repens* L.) and mustard (*Brassica juncea* L.) according to the scheme below (see Figure 3.3.6):

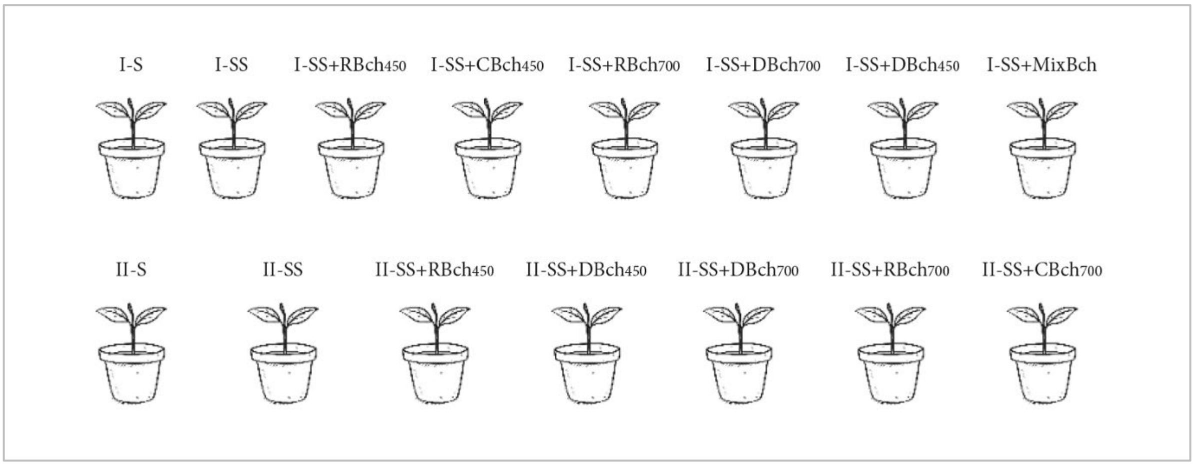

Figure 3.3.6. Pot experiment scheme where: I – buckwheat plant; II – white mustard plant; S – soil; SS – sewage sludge; $RBch_{450}$ – rapeseed biochar at 450°C; $CBch_{450}$ – corn stalk biochar at 450°C; $DBch_{450}$ – digestate biochar at 450°C; $RBch_{700}$ – rapeseed biochar at 700°C;

CBch700 – corn stalk biochar at 700 °C; DBch700 – digestate biochar at 700°C; MixBch – mixed biochar

Figure 3.3.6a. Pot experiment

Pots (capacity 7 kg) were filled with naturally acidic soil (6,672 g) by adding and mixing 118 g of sewage sludge, which corresponds to the rate of 45 t/ha^{-1}, and 3% of biochar (210 g). Optimum soil moisture was maintained by watering plants during the growing season. During the flowering stage, an analysis of the plant biomass yield and its chemical composition was performed in both pot experiments, as well as an analysis of heavy metals concentration in the soil and lysimeter water.

Monitoring

During the 2020-2022 study period, plants, soil and lysimeter water were analysed in all three experiments.

Plants. In the field experiment, biometric analysis of all studied perennial plants was performed at the end of the growing season. In the pot experiments, these analyses was conducted at the flowering stage of buckwheat and mustard, i.e. the height of the plants and the dry matter yield of the aboveground biomass were determined. In the annual food crops, such as buckwheat, sunflower and corn, the dry matter yield of the underground part of the plants was also determined. The concentration of heavy metals (Cu, Zn, Cd, Ni, Pb, Cr) was determined in these parts of the plant, allowing the evaluation of the plants' ability to translocate heavy metals from the roots to the separate aboveground biomass sections. In the investigated perennial plants, the concentration of heavy metals was determined only in the aboveground part at the end of vegetation.

The soil. In a 2020 field experiment, the concentration of heavy metals, amounts of the main nutrient elements (N, P and K) available to plants, pH and organic carbon were evaluated in the topsoil (0-20 cm soil layer) before the spreading of sewage sludge. The same chemical indicators in the soil were also evaluated after the 2022 harvest, i.e. two years after the sewage sludge (45 t/ha^{-1}) application. In the pot experiments, the concentration of heavy metals and other chemical parameters in the soil was determined before the start of the study and after harvesting the plants.

Lysimeter water. In 2021 and 2022, the concentration of heavy metals in lysimeter water was determined from all treatments in the field experiment during the autumn period, when the precipitation is higher (see Figure 3.3.7). In both pot experiments, the percolation water samples for the analysis were taken after harvesting of plant biomass at full flowering stage.

Figure 3.3.7. Lysimeter water sampling in the field experiment.

Chemical analysis methods: soil pH was measured in 1 M KCl (according to the standard ISO 10390:2005), soil total nitrogen was determined using the Kjeldahl method, and soil mobile potassium content according to the AL method. Organic carbon content was determined by photometric procedure at the wavelength of 590 nm using the UV-VIS spectrophotometer, using the glucose as a standard after wet combustion, according to Nikitin. Humic substances were determined using the Ponomariova and Plotnikova version of the classical Tyurin method.

For the analysis of heavy metals, soil samples were homogeneously mixed and passed through a 1 mm sieve for concentration measurement. After the acidic digestion of the prepared samples, the total amounts of the examined heavy metals (Cr, Ni, Pb, Cu, and Zn) were determined. The homogeneously mixed sample (~0.3 g) was digested with 10 mL of concentrated (≥65%) nitric acid and 2 mL of concentrated (≥37%) hydrochloric acid. The samples were submerged in an acid solution for 30 min at room temperature before digestion. For performing microwave-assisted extraction (MAE), the CEM MARS 6® was used with the required necessary conditions: microwave power of 800 W, temperature of 180°C, pressure of 800 psi, ramp duration of 20 min, and hold duration of 20 min. After the MAE, the sample was cooled and diluted. All prepared samples were measured three times, considering that each digestion cycle contained a blank sample. Heavy metals were evaluated and validated using an inductively coupled plasma mass spectrometer (ICP-MS) in standard mode, using an external multi-element calibration curve in the range of 10-500 µg L^{-1}. The same analysis was evaluated for the determination of total heavy metal concentrations in the plants'' aboveground biomass and in lysimetric water.

The heavy metals (Cd, Cr, Cu, Ni, Pb, Zn) concentrations of five different fractions in soil samples after plant vegetation were measured according to the method described by Wang et al. (2018).

Evaluation of potential ecological risk: Improvement of soil quality requires assessing contamination levels and potential risks, as well as identifying potential sources of contamination. To determine the potential risks to the environment that heavy metal pollution could pose, metal contaminant factors (C_f), and potential ecological risk index (R_I) of heavy metals in soils contaminated by sewage sludge were calculated.

The contamination factor *(Cf)* is determined by dividing heavy metal content in the soil by the reference value: $C_f = C_i/B$, where C_i is the heavy metal content in certain treatment and the B reference value of heavy metal content determined in the control (unpolluted) treatment. Low contamination is denoted by a Cf 1; moderate pollution is denoted by $1 < Cf < 3$; considerable contamination is denoted by $3 < Cf < 6$, and very high pollution is denoted by a $Cf > 6$. Based on the toxicity of heavy metals, this index evaluates the environmental risk posed by heavy metal contamination:

$$R_I = \sum_{1}^{n} E^i$$

$$E^i = T_R^i \times C_f$$

where R_I is the summation of all risk factors posed by heavy metals contamination in soil, E^i is each possible ecological risk factor, and C_f is the contamination factor. T_R is the toxic response criterion, which indicates toxicity of heavy metals and so defines metal pollution risk. The standardised toxic response factors for heavy metals are Zn-1, Pb-5, Cr-2, Cu-30, and Ni-5.

Economics

Economical calculations of the pilot case installation and necessary materials are as follows:

1. Information stand layout and printing: 96.80 EUR
2. Fencing of the area for phytoremediation field experiments and plant collection: 11,193.79 EUR
3. Adaption of premises for initial sample preparation and storage: 12,069.52 EUR
4. Installation of a system for measuring and monitoring the leaching of heavy metals from the soil: 12,075.00 EUR

5. Installation of soil moisture collection, measurement, and monitoring system: 10,000.00 EUR
6. Room preparation for plant growth: 11,511.00 EUR
7. Installation of a plant growing system: 7,090.00 EUR
8. Installation of microclimate system: 6,490.00 EUR

Results and discussion

From the data obtained from the pilot case experiments (one field and two pot experiments carried out under controlled and natural conditions) in 2020-2022, it was determined that plants grown for energy and food can tolerate these conditions and growing in soil fertilised with sewage sludge (SS), and produce a large amount of biomass in which considerable concentrations of heavy metals could be accumulated. So as an organic compound, **sewage sludge (SS) might be a suitable fertiliser for many non-food plant species for higher biomass yielding under West Lithuania's pedoclimatic conditions. (Appendix C,** Annex 3.3.5.1)

The accumulation of heavy metals in plant biomass depended on the plant species and the chemical composition of the sewage sludge and the amount applied. The use of SS (at 45 and 90 t/ha^{-1} rates) significantly increased dry matter (DM) yield of *Salix viminalis* (perennial plant grown for energy purposes) by 54 and 63% (at first growing rotation) and by 18 and 41% (at second growing rotation). The highest accumulation of heavy metals in *Salix viminalis* biomass was determined in the first growing rotation, when plant growth was the most intense. Later, the process slows down. On average per seven growing years, the annual energy plant *Silphium perfoliatum* DM yield varied from 6.70 t/ha^{-1} (without any fertilisation) up to 10.01 t/ha^{-1} (45 t/ha^{-1} SS application). On calculating the amount of metal ions in the total biomass DM yield ($g\ kg^{-1}$), it was found that fertilisation rate of 90 t/ha^{-1} SS significantly increased the uptake of six metal ions in both *Silphium perfoliatum* and *Salix viminalis*. **(Appendix C,** Annex 3.3.5.2)

Traditional perennial grasses fertilised with SS are also potential plants for remediation of heavy metal-contaminated soils. First of all, fertilisation with a product of organic origin sewage sludge (45 t/ha^{-1}), which contains a considerable amount of nutrients and organic matter, promotes the growth of the biomass of these plants. Perennial grasses (tall fescue and reed canary grass) reacted to sewage sludge application at the first and second harvesting years, so in this respect, tall fescue DM yield increased by 248 and 341%, respectively, and reed canary grass by 247 and 412%. **(Appendix C,** Annex 3.3.5.3) Also, the highest (18.7 t/ha^{-1}) *Artemisia dubia* DM yield in the case of first time cutting was obtained when sewage sludge was applied. Tall fescue, which produced high biomass yields, also showed the highest capacity to accumulate all six heavy metals, and especially Zn, Ni, Cr and Cu, in comparison with other studied grasses. In terms of biomass productivity, meadow fescue in general is a less yielding grass species; however, growing this grass together with clover inoculated with *Rhizobium* bacteria can increase the yield of the biomass and increase the phytoremediation potential.

***Miscantus giganteus* and *Artemisia dubia*, the large-stemmed energy introduced grasses grown in the study, adapted well to the region's existing conditions and, fertilised with**

sewage sludge, produced a large amount of biomass and accumulated a considerable amount of heavy metals. *Artemisia dubia* (irrespective of the cutting time) showed a higher capacity to accumulate heavy metals in its biomass compared with *Miscantus x giganteus*. Primarily Zn, Ni, Cr and Cu were accumulated in *Artemisia dubia* biomass after fertilisation with sewage sludge, when the biomass yield was harvested in October **(Appendix C,** Annex 3.3.5.4).

Traditional annual food plants (maize, sunflower and buckwheat) fertilised with sewage sludge, depending on meteorological conditions, can accumulate high concentrations of heavy metals in their biomass, which forces us to be careful when fertilising these plants with the aforementioned organic fertiliser. Sunflower as a species is capable of accumulating high amounts of heavy metals, in the following order: Zn>Ni>Cu>Cr>Pg>Cd. In comparison with sunflower or maize, buckwheat is a low yielding crop; its ability to remove heavy metals from contaminated soils is much lower **(Appendix C,** Annex 3.3.5.5).

The possible contamination level was generally minimal for all experimental treatments, except for the accumulation of Zn, which exhibited significant potential ecological risk in the soil after fertilisation with sewage sludge. Based on the overall risk factors, a moderate ecological risk was identified for all studied treatments due to the presence of Cr, Ni, Pb, Cu, and Zn in soil.

The phytoremediation potential of buckwheat can be increased by using chelates of chemical or organic origin. After evaluating the effect of chelate on heavy metal accumulation in common buckwheat biomass, it was found that EDTA had an effect of increasing accumulation of some heavy metals in its biomass: Ni, Pb, Zn in leaves and stems, and Cr, Ni, Pb, Cu, Zn in roots. The accumulation of heavy metals after adding chelate in buckwheat was higher compared to mustard. Unlike buckwheat, sludge fertilisation and chelation reduced or had no effect on the accumulation of some metals in both stems and roots of white mustard.

Addition of biochar as a soil amendment showed a positive trend in cultivation of buckwheat and mustard. Significant amounts of zinc and copper were found in the aboveground section of the plants. The wider range of heavy metals was found in the roots – Cr, Ni, Pb, Cu, Zn **(Appendix C,** Annex 3.3.5.6).

After biochar application, the predominant heavy metals fraction in the soil was residuals, which indicates that heavy metals are unavailable for plants uptake. Biochar incorporation increased the amount of Cr, Ni, Cu and Zn bonded to organic matter. Heavy metals immobilisation efficiency in the soil after biochar treatment followed the order Ni>Cr>Pb>Cu>Zn and Ni>Pb>Zn>Cr>Cu after buckwheat and white mustard cultivation, respectively.

Among the heavy metals found in the lysimeter water, lead was the highest, especially in miscanthus and reed canary grass growing sites. Zn was mostly found in lysimeter water in reed canary grass growing sites where sewage sludge was applied **(Appendix C,** Annex 3.3.5.7).

Conclusions

From a phytoremediation point of view, annual food plants – sunflower (*Helianthus annus* L.) and maize (*Zea mays* L.), and energy plants – *Artemisia dubia* L. and tall fescue (*Festuca arundinacea* L.) had the highest capacity to accumulate large quantities of heavy metals in biomass from contaminated moraine loam Retisols.

Amounts of heavy metals, which were the highest in sewage sludge, were also the highest in the biomass of the plants themselves. By increasing the application rate of sewage sludge, the amount of heavy metals (Zn, Cr, Ni, Pb, Cu) in the upper soil layer tended to increase gradually.

The use of chelate EDTA can only slightly increase the phytoremediation potential of plants, while the use of chelate (or soil amendment) of organic origin, biochar, showed a greater capability to increase the accumulation of heavy metals in buckwheat and mustard.

As the result of sewage sludge application, heavy metal contents tended to increase in groundwater. The highest concentration in lysimeter waters was determined for lead, which was the least accumulated by the studied plants.

The concentration of copper (Cu) in the lysimeter water decreased up to 10 times compared with treatment without biochar. Biochar helps to immobilise heavy metals in the soil, which reduces their ingress into the lysimeter water.

Chapter 4: Comparison of results from the pilot case studies

There were considerable differences between pilot cases with regard to experimental set-up, methods used, plant choice, selected parameters analysed, and targeted pollutants, reflecting different overall aims and principal approaches by which the pilots were implemented. For instance, the experimental set-ups in the Polish and Lithuanian trials aimed at a scientific evaluation of the potential of different plants species to grow and take up metals depending on soil conditions and nutrient supply with metal containing fertiliser products. The Lithuanian pilot could be described as an investigation into the effects of contaminated sewage sludge on plant development and contaminant uptake, as the soil was originally not particularly contaminated. Correspondingly, the number of studied plant species included edible and ornamental plants as well. The Polish pilot was similar in this regard, as here also fertiliser products introduced to improve soil quality were contributing to the overall soil contamination with heavy metals. Since plant uptake was analysed in both pilots and related to the soil contamination levels, the experiments can be interpreted as phytoremediation studies. The results from the Polish pilot have been scientifically published (Grzegórska et al., 2023), and a publication on the Lithuanian is in preparation. The Swedish pilot, on the other hand, had a clearly practical approach focusing on the implementation of phytoremediation under realistic conditions of an actual landfill. Another major difference in the Swedish pilot was that the targeted types of soil pollution were excess levels of nutrient P and N, instead of heavy metals as in the other two pilots. Metal content in the soil and plant uptake were not determined. In addition to the plots directly situated at the landfill, the Swedish pilot also evaluated plant nutrient uptake of different species in smaller scale cultivation beds filled with landfill soil. In the Polish and Lithuanian pilots, field trials were complemented with small scale studies under more controlled conditions. The Lithuanian pilot included a lab study and a pot study, while the Polish pilot included a greenhouse pot study. In the Lithuanian and Swedish pilots, lysimeters were installed in the lab experiment and the cultivation bed trial, respectively.

Laboratory or greenhouse studies in the Lithuania pilot dealt, for instance, with the evaluation of the effect of biochar of different source materials on metal uptake of plants fertilised with contaminated sewage sludge. Biochar incorporation was, however, also included in the Swedish field trial, as well as the cultivation bed trial.

In both the Swedish and Lithuanian pilots, lysimeters were installed to measure metal or nutrient content in the soil solution. In case of the Lithuania pilot, lysimeters were installed in the field trial and in a greenhouse column study. In case of Sweden, lysimeters were used in the cultivation beds. However, since the analysed parameters did not match (P and N in Sweden and metals in the Lithuania pilot), a comparison is difficult.

Table 4.1. *Initial soil properties in the pilot cases*

	Unit	Poland	Lithuania	Sweden
Dry mass	[%]	+		56.9
Clay		clay loam	15	organic rich
Sand			51	
Silt			34	
pH Kcl	[-]	4.8	4.4	
pH H2O		5.52+	5.41	
Bulk density	[kg dm^{-3}]		1.48	
Exch. Cations	[mmol kg^{-1}]	143		
El. conductivity	[ms cm^{-1}]	4.53		
Org C	[g kg^{-1} dm	8.77	9.55	130
P avail	[mg kg^{-1} dm]	20.28+	62.50	
K avail		79.88	107.00	
Mg avail		37.77		
N tot	[g kg^{-1} dm]	0.39	0.53	6.1 (5.75 end of trial)
P tot		0.34		12 (8.8 end of trial)
K tot		0.94		
Al	[mg kg^{-1} dm]	9950	35.90	
Fe	[g kg^{-1} dm]	12492		
Zn		513.3	21.73	
Cd		4.6	<0.1	
Cr		73	46.71	
Co		10.7		
Cu		496.7	4.72	
Pb		284.7	17.05	
Mn		284.8		
Ni		15.4		
Mg			<0.1	

4.1 Field trials – soil characteristics

The Swedish field trial covered approximately 60 m^2 of landfill area and consisted of five plots and treatments without any replicates. Each cultivation bed measured approximately 4 m^2 with a depth of 120 cm. The Polish field trial was 51 m^2 overall, and consisted of four treatments, each having three replicates, resulting in individual plots of about 4 m^2. This matched the area of the Swedish trial's cultivation beds. There was no information available on the size of the Lithuanian field trial nor on the experimental set-up, e.g. number of replicates. It should be pointed out that these differences in experimental set-up may increase uncertainty when comparing results from the different pilots. Climate data throughout the experiment period was only available from the Polish pilot, which may add to uncertainty regarding comparison. Table 4.1 shows available data regarding properties of the different soils in the studies. Texture in the

Polish soil was determined as clay loam. According to the FAO texture classification (Minasny and McBratney, 2001), the soil in the Lithuanian pilot could be classified as loamy soil. Both soils had an acidic pH. The soils also shared a similarly low organic carbon content of about 8-10 mg kg^{-1}, corresponding to an organic matter content of approximately 2%. The soil in the Swedish pilot was, in comparison, highly organic with about 26% organic material (C org 130 g kg^{-1}). The content of nutrients N, and particularly P, in the Swedish landfill soil can be considered extremely high (see Table 4.1). High leaching losses reported from the landfill soil reflect this. The exact soil contents of P and N in the Lithuanian soil are not known but the fertilised plots in this pilot received about 40 t ha^{-1}) of sewage sludge containing 5,02 and 33.4 g P and N, respectively. As this corresponds to hundreds of tons per hectare, it may be considered unlikely that a deficiency of these nutrients would limit plant growth, at least in the fertilised plots. According to the Swedish classification system, the Polish soil initially showed a deficiency in available P (Jordbruksverket, 2010). With only 20 mg k^{-1} of dried soil of available P, the initial Polish soil would have been assigned P -Al class 1 i.e. clearly deficient in available P (see Table 4.1). However, the fertilised plots in the Polish pilot received either 200 or 400 t per hectare of fertiliser product containing 1.4 and 5.3 g kg^{1} P and N, respectively (see Table 4.2). From this information it can be expected that the fertilised plots were unlikely to be N and P deficient. This was also valid regarding potassium content (see Table 4.2). However, it cannot be excluded that growing conditions in the soils may have been compromised due to unidentified macro or micronutrient deficiencies or for other reasons. The Polish pilot reported, for instance a high soil salinity based on measurements of electric conductivity (see Table 4.1). However, no visible signs of any negative impact on *Miscanthus x giganteus* growth were observed (Grzegórska et al., 2023). Moreover, none of the pilots reported any significant issues with pests or plant diseases. The Swedish pilot did, however, report problems with excess soil moisture, which they proposed as the main reason for the failure of *Miscanthus x giganteus* plug plants to establish in the field trial plots.

Table 4.2. *Selected properties of the fertiliser products used in the Lithuanian and Polish pilot case*

	Unit	Poland Fertiliser product SK8	Lithuania Sewage sludge (SS)
pH	[-]	7,34	5.5
Dry mass	[%]	58.25	
Org C	[%]	221.1	64.97
N tot	[g kg^{-1}]	5.3	33.4
P tot		1,42	5.02
K tot		4.82	
Al	[mg kg^{-1}]	3538	
Fe		1457.7	
Zn		133.8	287
Cd		1.8	0.44
Cr		54.2	11.51
Co		5.2	47.8
Cu		85.2	+
Hg			0.96
Pb		115.3	14.47
Ni		29.2	8.22
Mn		58.4	

4.2 Metal contamination

Initial metal content values related to soil weight were provided both for the Polish and the Lithuanian pilots. In addition, the amount of metals per unit area to which fertiliser product had been added were available or could be calculated from available data. For a surface soil layer of 20 cm depth and assuming a soil density of around 1.4 t m^{-3}, being typical for loamy clay/loam soils, the heavy metal contamination per unit area of soil was approximated for both pilots (Zeri et al., 2018). These calculated contamination levels are presented in Table 4.3 for both soils. Fertiliser application rates for the contamination levels shown in the table were 200 t a^{-1} of fertiliser product for the Polish pilot and 90 kg h^{-1} of sewage sludge in the Lithuanian pilot. These treatments were selected because relative metal uptake by *Miscanthus x giganteus* was generally observed to be highest in the Polish and Lithuanian field trials. *Miscanthus x giganteus*, a perennial grass hybrid between *Miscanthus sinensis* and *Miscanthus sacchariflorus,* was the only plant species studied in all three pilots. The comparison will focus on the phytoremediation performance of this plant, hereafter referred to only as *Miscanthus x giganteus*.

Table 4.3 also shows critical soil concentrations for respective metals according to Swedish EPA (Naturvårdsverket, 2022). In Sweden, two different guideline values are valid depending on the land use purpose. The values under "MKM" ("less sensitive land use") refer e.g. to industrial areas or office buildings. The stricter guideline values for sensitive land use apply to residential areas and agricultural land for food production. The values provided in Table 4.3 have been calculated from weight-related soil concentration, with the same assumptions made regarding density and layer depth as in the case of the soil contamination levels. The latter were generally higher in the Polish soil after being amended with 200 t of fertiliser product SK8. A comparison with Swedish guideline concentrations reveals that the contamination levels in the Lithuanian trial may be considered low. According to the guidelines, the soil would be suitable for crop production in Sweden. The content of Zn, Cd, Cu, and Pb in the Polish soil clearly exceeded guideline values for sensitive use, and in case of Zn and Pb also those for less sensitive land use as well. Here a removal of pollutant would also practically be indicated.

***Table 4.3**. Approximate soil metal content in Polish and Lithuanian pilots after amendment with fertiliser product in comparison with critical soil concentration levels according to the Swedish EPA*

	Calculated Metal content [kg ha^{-1}] [A]		Critical Values Sweden [kg ha^{-1}] [B]	
	Poland (200 t ha^{-1} SK8)	Lithuania (90 t ha^{-1} sludge)	KM (“sensitive land use”)	MKM (“less sensitive land use”)
Zn	1530	75,80	740.0	1480
Cd	13.63	0.314	2,368	35.52
Cr	216.5	138.7	236.8	444.0
Cu	1472	15.88	236.8	592.0
Ni	45.91	26.97	118.4	355.2
Pb	843.3	51.05	148.0	532.8

[A] calculated from weight-related soil content and metal addition with fertiliser product assuming a soil density of 1.4 kg ha^{-1} and layer depth of 0.2 m

[B] Naturvårdsverket (2022)

4.3 Plants used in the field trials

Besides Miscanthus, other plant species included in the Lithuanian field study were annual food crops such as sunflower (*Helianthus annus*), maize (*Zea mays*) and buckwheat (*Fagopyrum esculentum)*; different perennial grass species were also tested. The Swedish pilot used annual and perennial plants such as oil radish (*Raphanus sativus*) and common chicory (*Cichorium intybus*) but also grass species such as English rye grass (*Lolium perenne*). In the field trial in one plot, the native vegetation was left to grow and contained species such nettles (*Urtica dioica)*, several thistle (*Cirsium spec.)* and other weed species.

4.4 *Miscanthus x giganteus*

As mentioned previously, the only species grown in all pilots and hence suitable on which to base a comparison between the pilots, was *Miscanthus x giganteus*. In the Swedish pilot, *Miscanthus x giganteus* rhizomes were planted both in the field trial and the cultivation bed trial. In the field trial, however, plug plants of miscanthus failed to establish and died during the first winter. In the cultivation bed, establishment of rhizomes was successful and plant growth was visually satisfactory. At the end of the trial the plants had developed an extensive fine root system that reached towards a soil depth of 30 cm. However, no further data were available from the Swedish pilot regarding biomass yield or content of nutrients or metals. Soil nutrient content in the cultivation beds was determined at the beginning and end of the trial (see Table 4.1). Tremendous reductions of both N and P soil content of 15% and 27%, respectively, at the end of the trial did, however, indicate that nutrient uptake by *Miscanthus x giganteus* had been substantial even though part of the observed nutrient reduction in the soil may have been due to leaching.

In the Lithuanian pilot, *Miscanthus x giganteus* seedlings were planted in the first year and harvesting took place at the end of the growing season in October. The trial continued for two years. In the Polish pilot, seedlings were planted and required initial irrigation due to the drying out of the soil surface. Data on yield biomass were provided by the pilots from Lithuania and Poland. In both pilots, adding fertiliser product did cause a growth response and higher yields were observed in the fertilised plots; in the Lithuanian pilot, however, only in the second year. Overall dry matter yields per ha were far greater in the Lithuanian pilot, with a maximum dry matter yield of up to 15 t ha^{-1} compared to a maximum of 1.6 t ha^{-1} in the Polish trial. Yields reported for the Lithuanian pilot were within the range of previously reported yields for Central European climatic conditions (10-25 t ha^{-1}) (Stefanoni et al., 2023).

With 2 mg per 100 g of dried soil of available P, the Polish soil was deficient. However even for plots that received generous amounts of N and P via application of fertiliser product, the observed mean yield amounted to only 11% of the yield observed in the Lithuanian trial. While it would require further investigation to identify factors that led to the relatively low Miscanthus growth in the Polish trial, a P or N deficiency is likely not the main reason. An inhibitory effect of the higher contaminant levels in the Polish soil may have played a role. For instance, a comparable soil concentration of zinc as found in the Polish trial has been reported to be potentially phytotoxic (Baderna et al., 2015). A difference in the spatial density in which Miscanthus was initially planted may also have contributed to the observed differences in the yield between the Polish and Lithuanian field trials.

4.5 Metal extraction from soil by *Miscanthus x giganteus*

Table 4.4 shows the uptake of metals per unit area for plots that received 200 t ha^{-1} and 90 t ha^{-1} of fertiliser product in the Polish and Lithuanian pilots, respectively. The greater uptake of metals into *Miscanthus x giganteus* was generally observed in the Lithuanian field trial, which to a great part reflects the greater biomass development of *Miscanthus x giganteus* in this trial. Exceptions were, however, Cd and Pb accumulation in harvested *Miscanthus x giganteus* biomass, which may be explained by the substantially higher soil content of these elements in the Polish soil. A proportionality between plant metal accumulation and soil concentration was also observed by Dean et al. (2023). The accumulation rates shown in Table 4.4 are based on one growing season. Particularly with regard to the actual contamination levels in Polish pilot, the observed rates by which *Miscanthus x giganteus* removed metals from the soil has to be considered very low. Based on these annual removal rates, reducing contaminant levels of most metals in the Polish soil to acceptable levels, e.g. those defined by the Swedish EPA (see Table 4.3) would require an unreasonable amount of time; in case of Zn and Cd, for instance, thousands of years. A low efficiency of contaminant removal is one of the major challenges with phytoremediation (Shen et al., 2022).

The rate of removal of metals per unit area by *Miscanthus x giganteus* observed in the two pilots was low in comparison with removal rates observed for other plant species, both in the Lithuanian pilot and other studies. Vangronsveld et al. (2009) reported in their review, for instance, an annual removal of Cd amounting to a maximum of 340 g ha^{-1} observed for a Salix species and harvest of both twigs and leaves. For non-woody plant crops such as maize, tobacco and sunflower, Cd removal per area unit was ranging between 50 and 100 g ha^{-1} and hence also considerably higher than the reported removal rates by *Miscanthus x giganteus*. Partly, this could be attributed to higher biomass production observed in these studies. In case of Zn, the use of hyperaccumulator species *Thlaspi caerulescens* was estimated to results in a Zn removal of up to 40 kg ha^{-1} per growing season as compared to 106.55 g ha^{-1} of Zn removed by *Miscanthus x giganteus* in the Lithuanian pilot (McGrath et al. 1993).

Available literature (Shen et al., 2022) and the results from the pilots indicate that the removal of metals may be very variable depending on species, local conditions and contaminant. The potential of *Miscanthus x giganteus* is well documented in several studies (Barbosa et al., 2015; Korzeniowska and Stanislawska-Glubiak, 2015; Tripathi et al., 2016). The results from the pilots highlight the importance of ensuring optimal growing conditions to maximise biomass production. Not being a hyperaccumulator of toxic metals, a high biomass development is key for the use of *Miscanthus x giganteus* in phytoremediation and for its subsequent use in energy production. One of the factors promoting the use of Miscanthus instead of potentially more effective hyperaccumulators, is indeed the economic incentive for an energetic exploitation of the *Miscanthus* biomass (Vangronsveld et al., 2009; Shen et al., 2022). The latter represents an important aspect contributing to increasing the economic feasibility of phytoremediation.

***Table 4.4** Heavy metal uptake by Miscanthus x giganteus in Polish and Lithuanian field trials*

	Miscanthus uptake [g ha^{-1}]	
	Poland (200 t ha^{-1} SK8)	**Lithuania (90 t ha^{-1} sewage sludge)**
Zn	92.6	106.55
Cd	0.3	0.037
Cr	10.5	63.40
Cu	17.1	55.054
Ni	21.4	29.08
Pb	11.6	0.052

In the Polish pilot, *Miscanthus x giganteus* biomass development stayed clearly below its potential, hence the low overall removal of metals. As mentioned before, from the information available regarding soil properties and other factors relevant for plant growth, it is difficult to identify the reason for the comparably low growth. Besides a possible nutrient deficiency, the high contents of some metals in the soil may have affected growth. A soil concentration of zinc comparable to soil concentration in the Polish trial has, for instance, been reported to be potentially phytotoxic (Baderna et al., 2015).

It is therefore recommended to carefully consider local growing conditions in a phytoremediation project and the specific requirements of the plants of choice to be used in phytoremediation, such as nutrient demand, drought, and temperature tolerance etc. A potential toxicity of the inherent soil contamination should also be included in the initial assessment. It may also be important to obtain information on the bioavailability of the target metals in the soil affecting the potential of phytoremediation to remove those metals. Due to the sheer complexity of chemical, physical and biological factors interacting in affecting plant growth, it is advisable to test potential suitable plants under field conditions but at a smaller scale prior to a full-scale implementation of a phytoremediation project. This may be practically feasible since phytoremediation is a long-term effort, requiring several years at least.

Chapter 5: Laws and regulations

Stakeholder dialogue regarding the project, both in Sweden[8] and in Lithuania, show some scepticism to the application of phytoremediation and other nature-based solutions for the remediation of contaminated land. The predominant remediation technology in the countries involved in the project is digging up the contaminated soil and transporting it to a treatment plant or a landfill.

The stakeholder dialogue touching upon legal aspects, economic incentives, level of knowledge on phytoremediation, as well as attitudes and opinions, were conducted with researchers, land-owners, consultants and public authorities.

The scepticism is rooted in uncertainties concerning the efficiency of phytoremediation, the relatively long time that the method requires, land-owners' fears of facing liability if the remediation does not work out according to plans, and a lack of knowledge or availability of successful examples to be inspired by. These are some of the reasons why the practical implementation of phytoremediation is low in countries involved in BAPR.

With the purpose of addressing the fears on legal liability connected to the application of phytoremediation as a cleaning method, the BAPR project decided to look closer at laws and regulations in relation to phytoremediation. We hope to promote the use of phytoremediation through clarifying the actual legal issues connected to the technology.

Laws and regulations, as well as supervision and control authorities, and even jurisprudence (court decisions), tend to deter stakeholders from applying phytoremediation for environmental protection and restoration. An interview study performed in Sweden found that Sweden's environmental goals, the rules in the Environmental Code, liability legislation (responsibility for pollution) and the supervision authorities issuing permits (e.g. methodology for treatment of polluted areas, supervisory guidelines, etc.) influence the choice of treatment method. What scope does current legislation leave for choosing phytoremediation? Is the interpretation of laws changing as conflicts of interest between a non-toxic environment on the one side, and resource efficiency and climate challenge on the other, become more relevant?

This chapter presents a short description of some of the most important regulations concerning phytoremediation in Europe and in participating countries. The purpose is to introduce these issues, and this should not be seen as a comprehensive description. The chapter is based on a study produced within the frame of BAPR by an environmental law bureau in Sweden, an environmental law bureau in Lithuania, and a meeting with a legal bureau in Poland.

European legislation on soil and land

While air and water protection regulations have existed for a long time in Europe, soil issues are still not comprehensively regulated. The new EU Soil Strategy for 2030, adopted by the Commission in November 2021, is therefore a big step forward. Earlier efforts to develop a comprehensive regulation on soil issues were stopped in 2015 because of the opposition of a

[8] White arkitekter AB and Hässleholm Miljö AB, Fytoremediering intervjustudie, 2021-09-14.

minority of countries in the Council[9] despite reports[10] recognising the lack of coherent and strategic policy framework as a problem for the adequate protection of soils in Europe.

After renewed efforts, the European Commission presented a soil vision for EU in November 2021. The vision states that all EU soil systems should be healthy and thus more resilient by 2050, and that the protection, sustainable use, and restoration of the land must become the norm by then. Healthy land is seen as an important step towards solving all major environmental challenges in the EU, e.g. achieving climate neutrality and becoming resilient to climate change, developing a clean and circular bio economy, protecting human health, reducing the loss of biodiversity and soil degradation.

The soil vision is connected to the Biodiversity Strategy for 2030 and to the Climate Adaptation Strategy. Therefore, it will contribute to several of the goals in the Green Deal as well as other EU goals. Contaminated land is only a part of the strategy. According to the goals for 2030, significant progress must be made in recovering contaminated soil. By 2050 no net land should be taken into use.[11] Soil pollution must be reduced to levels that are no longer considered harmful to human health and natural ecosystems, and that respect the limits of the planet.

The soil strategy presents a hierarchy for use of land. Excavated soils that are not contaminated should be reused. If reuse is not possible due to levels of pollution, such land should primarily be recycled or reused rather than landfilled. To be able to separate contaminated soil from clean soil, a close monitoring throughout the value chain, with traceability and quality control ensured from the excavation site to the final recipient, might be achieved by an "excavated land passport", containing quantity and quality of the excavated soil.

As already stated above, the EU has so far not been able to establish a legal framework that provides soil with the same level of protection as water, air and the marine environment. Europe lacks relevant legislation for protecting soils from contamination with two exceptions: the Industrial Emissions Directive (IED) that regulates emissions from industries, and the Environmental Liability Directive that includes the polluters pay principle, according to which the polluter has to pay for preventing and restoring environmental damage.

The IED regulates, among other things, emissions to air, water and land and aims to ensure that the establishment of an industry does not lead to a deterioration of land and groundwater. If the business has caused significant pollution in soil or groundwater, and measures for restoration are technically feasible, the IED requires operators to restore the industrial area to the condition it was in prior to the start of the operations, according to the status report of the soil conditions. The Environmental Assessment Directive regulates environmental impact assessments in private and public projects that have a significant environmental impact. Environmental assessments must identify, describe, and assess the direct and indirect effects of a project on, among other things, land.

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[9] See EU Soil policy - Environment - European Commission (europa.eu), 2022.
[10] Ecologic Institute, Updated Inventory and Assessment of Soil Protection Policy Instruments in EU Member States, Berlin, February 2017.
[11] Land take is the loss of agricultural, forest and other semi-natural and natural land to urban and other artificial land development. This includes areas sealed by construction and urban infrastructure, as well as urban green areas and sport and leisure facilities.]

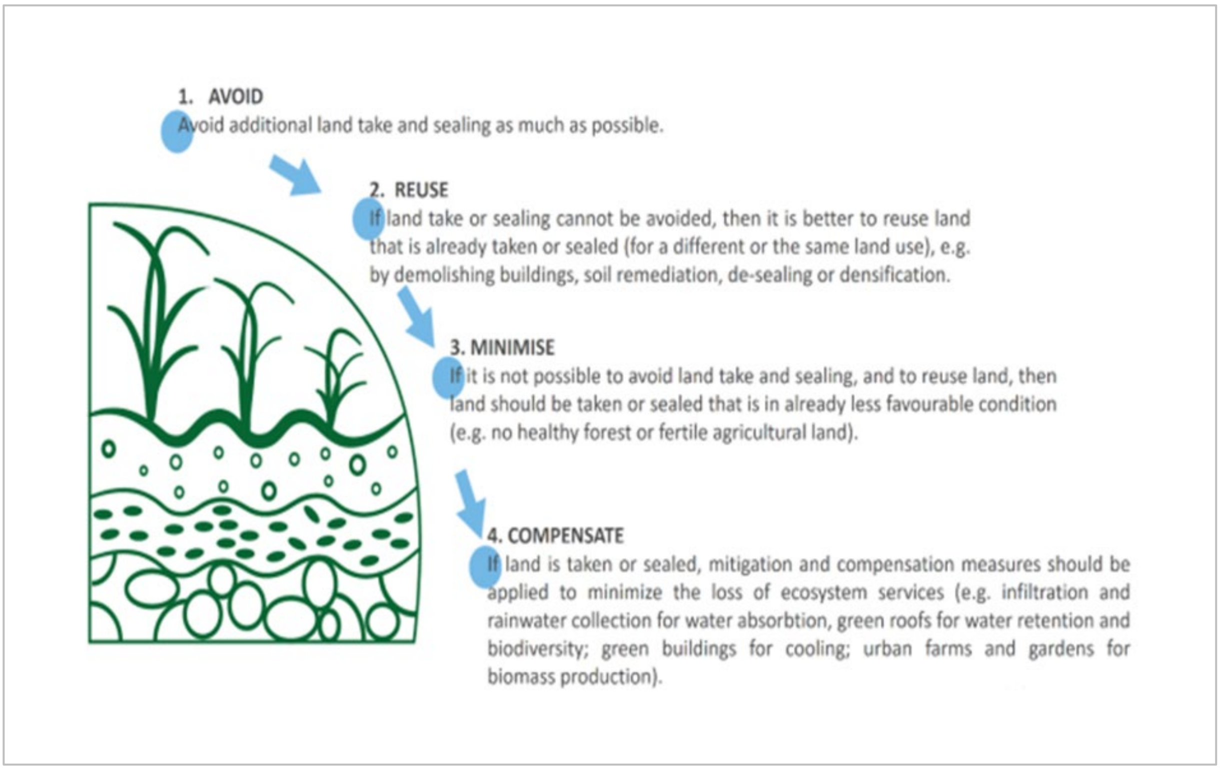

Figure 5.1. Land take hierarchy in the EU Soil Strategy 2030. *The European Commission plans to present a specific legislative proposal on soil health by 2023. The EU will also consider options for proposing legally binding provisions to identify contaminated sites, carry out an inventory and establish a register of those sites as well as recover sites that pose a significant risk to human health and the environment by 2050.*

Sweden[12]

The rules of consideration in Chapter 2 of the Environmental Code consist of several principles such as the precautionary principle, the knowledge requirement for operators, and efficiency in the use of resources. The central provision for contamination is the ‘polluter pays principle’ (Chapter 2, paragraph 8 of the Swedish Environmental Code) that states that persons who pursue or have pursued an activity or taken a measure that causes damage or detriment to the environment shall be responsible for remediation to the extent deemed reasonable pursuant to Chapter 10. When the Code so provides, the person may instead be liable to make compensation for the damage or detriment.

Chapter 10 regulates contamination of land and water areas, groundwater, buildings, and structures that are so polluted that they may cause damage or detriment to human health or the environment. Remediation is needed when a land area is contaminated to such a degree that it entails unacceptable risks to human health, the environment, or natural resources. Remedial actions are intended to reduce such risks to acceptable levels.

[12] This section is based on the legal report from Agnes Advokater that was produced in Sweden in March 2022 during the BAPR project. The tittle of the document is “”Juridisk utredning avseende möjligheten att tillämpa fytoremediering vid efterbehandling”.

According to the Swedish Environmental Protection Agency's guidance document for remedial selection, the process of selecting remedial measures entails the following steps: formulation of remedial goals, investigations and studies, risk assessment, evaluation of remedial alternatives, selection of a remedial alternative, and formulation of quantifiable remedial objectives. During the process, the number of possible remedial alternatives is reduced stepwise using a range of criteria (remedy evaluation criteria and remedy selection criteria).

It is primarily the person who conducts or has conducted an activity or has pursued a measure that has contributed to the pollution (operator) who is responsible for remediation. Remediation refers to investigation, post-treatment, and other measures to remediate pollution damage or serious environmental damage. If several operators are liable, they shall accept joint liability to the extent that the liability is not limited. An operator who shows that their responsibility for the pollution is so insignificant that it does not by itself justify remediation shall, however, only be liable to the extent that corresponds to their share of responsibility. The payment made by the liable persons shall be shared between them as appears reasonable regarding the extent to which each of them was responsible for the pollution and to other relevant circumstances.

The Code applies to environmentally hazardous activities after 30 June 1969, if the effects of the activities were still ongoing at the time of the entry into force of the Environmental Code, and if there is a need to remedy any damage or inconvenience caused by the business.

If there is no operator who can perform or pay for remediation in accordance with the provisions of the Environmental Code, everyone who acquired the property is responsible if the acquirer at the time of the acquisition knew about the pollution or should have discovered it. The same applies to contaminated buildings. The property owners have also joint and strict liability to the extent that the liability is not limited. According to the transitional provisions to the Environmental Code, the rule shall not apply to acquisitions that have taken place before the Environmental Code entered into force on 1 January 1999. A property owner can, even though they are not responsible for remediation, be liable for compensation for the increase in value of the property that the remediation results in.

The jurisprudence (case law) regarding decisions on remedial alternatives is very limited. There are no legal cases concerning phytoremediation in Sweden. This is because most remediation is performed by the state or in conjunction with land exploitation activities, e.g. construction sites.

Despite the absence of legal hinderances to applying phytoremediation as a remedial alternative, there are not that many examples of practical applications. As described above, a combination of uncertainty on the effectiveness of the method for accomplishing remedial goals, both on the operator and supervising authorities, as well as the extended length of time the method requires, might deter stakeholders from using phytoremediation. There are concerns that this might lead to less sustainable remediation techniques, such as excavation and landfilling.

Poland[13]

There are two regimes for contaminated sites in Poland:

- Liability for contamination that happened before 30 April 2007 is dealt with under the Environmental Protection Law that states a strict responsibility for the owner of the land. Legal liability goes with the land; whenever the land is sold, liability follows to the next owner.
- Contamination caused since 30 April 2007 is dealt with under the Act of 13 April 2007 on the Prevention of Damage to the Environment and its Remediation.

However, solutions for these two situations are the same in terms of remediation. In both cases, remediation is needed but the main difference lies in the semantics – in the Environmental Liability Directive the term "environmental damage" is used, and the solution is called "restoration", while in the historical contamination regime it is called "remediation". The goal is basically the same, though.

For contamination of the Baltic Sea, maritime law and laws on international cooperation apply, among others the maritime law directive. For inland waters and rivers, a new set of regulations is being developed on the EU-level.

The landowner must notify the contamination, or suspicion of contamination of land, to both the General Directorate for Environmental Protection (GDOŚ) and to the voivodship (province) Inspectorate of Environmental Protection. An investigation is obligatory following a notification. Every contamination must be cleaned up and remediated.

Whenever contamination is found on a site, a risk-based assessment is performed to identify the risks. The assessment is made taking into consideration the historical use of the land for tracing potential contaminants, as well as the planned used in the future. Depending on the planned use, different pollution limits apply.

As soon as contaminated soil is dug up, waste law and the waste hierarchy apply and therefore removed soil should be reused or recycled in the first place, with landfill being the last option.

Land remediation methods are classified as "ex-situ methods" (excavation and removal) and "other methods", mainly reducing or mitigating pollution in-situ. This second group includes phytoremediation among others.

The permit for phytoremediation is included in the remediation decision issued at the request of the landowner (in cases of historical contamination) or the polluter (in cases of contamination after 13 April 2017). The set of documents to be filed with the regional director for environmental protection includes:

[13] This section was written in consultation with Ewa Rutkowska-Subocz, environmental lawyer at Dentons in Warsaw, Poland, with experience in more than 15 cases of soil remediation proceedings and two cases on phytoremediation regarding landfills.

- the application specifying the party applying for the decision, the land to be remediated, the method of remediation, timeframe, etc.
- the remediation action plan (including the risk assessment, the types of pollution to be removed and the specifics of plants to be used). This plan is subjected to a technical assessment

There are two categories of penalties for contaminating land:

- Administrative fines and the possible revocation of permits
- Clean-up and remediation of the contaminated land

Criminal liability can also result from the contamination of land and can lead to fines, restriction of liberty, and imprisonment.

"Gentle onsite methods" are becoming more popular. There are no legal obstacles but the interpretation of the law and the solutions that are designed for the site depend on the interpretation of the regional control authorities. Certain offices are open to these modern technologies while others are not. As in Sweden, excavation followed by transport to a landfill is considered "the best method". Despite its conventional character, this method is being increasingly questioned.

Phytoremediation cases usually deal with reducing the risk for migration of heavy metals and polycyclic aromatic hydrocarbons (PAH) by using plants that allow reduction of contamination. There are few examples of approval by the authority and some procedures are pending.

Commercial developers with short business cycles tend to prefer to dig and remove. They are planning to sell the land in the short term and don't want to delay the cleaning up, something that happens when phytoremediation is applied. But with stakeholders who think more long term, and are planning to own the site for a longer period, then phytoremediation is an interesting alternative.

Lithuania[14]

Similar principles apply in Lithuania for regulation of contaminated sites. Applicable legislations among other are:

- The Environmental Liability directive
- Waste management regulations
- Environmental accidents legislation
- Sea legislation and maritime protection law

The laws are irrespective of the technology used. The solutions are left to the authorities, who decide on permits on a case-by-case basis. There is a silence about technologies; for example, nothing about phytoremediation.

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[14] This section is written in consultation with Robert Juodka, environmental lawyer at Primus in Lithuania, a Baltic law firm with a broad set of competences, among others in real estate, industrial law, maritime law and environmental law.

The 'polluter pays principle' is entrenched in Lithuanian law, e.g. in the Law on Environment Protection of the Republic of Lithuania (Lith. Lietuvos Respublikos aplinkos apsaugos įstatymas). In Lithuania, the operator, the landowner, and the user of a site are responsible for managing chemical contamination, i.e. responsible for drawing up a management plan, selecting a management method, and implementing the overall management itself (Order of the Minister of Environment of the Republic of Lithuania of 30 April 2008 No D1-230).

Pursuant to applicable legal acts, contaminated soil shall be deemed to be in need of management if, following a detailed eco-geological investigation, it has been established that the concentrations of chemical substances in the soil are higher than the revised limit values, which shall be calculated in accordance with the specific formulae laid down by the order of the Minister of Environment.

Once a detailed eco-geological investigation is performed, a risk evaluation is made and environmental measures to eliminate, reduce or stabilise pollution must be decided. Remediation measures may include excavating and removing polluted soil.

As in Poland, in Lithuania the Ministry of Environment is responsible for the performance of overall environmental governance of the country, inter alia establishment and control of the norms and accounting procedures for emissions into the environment, establishment of the procedure for issuing permits for emissions, development and approval of methodologies for calculating environmental damage, supervising the state of the environment, and the use of natural resources.

The Environmental Protection Department under the Ministry of Environment and its territorial units performs the state control of the environmental protection, inter alia monitors whether natural and legal persons comply with the requirements laid down in the applicable legal legislation on environmental protection in various areas.

The national government decides which contaminated sites are required to be cleaned. Protected natural areas are, of course, prioritised and after that industrial sites or waste management plants. The Lithuanian Geological Survey under the Ministry of Environment is responsible for research, development of technology, and knowledge building.

5.1 BAPR Lithuanian pilot case results' contribution to the legal aspects of the phytoremediation technology application

While working on BAPR pilot projects, the question regarding the applicability of the phytoremediation technologies has been raised. Furthermore, the discussion organised by the BAPR project partner PP4 (Klaipeda University) with Lithuanian Geological Survey and Environmental Ministry representatives showed that Environmental Authority and Institutions responsible for the healthy soil are not too convinced about the efficiency of phytoremediation methods. During a remote discussion, PP4 recognised that the most important argument, which could prove the technology application's success, is the evidence that immobilised heavy metals are, in their chemical form, inaccessible for further vegetation, and heavy metals concentration in plants or even in agricultural products will not exceed the maximum available concentration. The project can demonstrate results that support the idea that heavy metals in the soil are not chemically active, and the environmental authority can revise the existing rules/norms and recommendations regarding phytoremediation technology application for the contaminated soil.

Moreover, the additional conversation regarding popularity and suitability of the technology from the local authority, such as the city municipality, revealed that local landscape architectures and environmental protection specialists are not familiar with phytoremediation as the one of the best technologies for soils contaminated by heavy metals and petrol application.

Therefore, the decision to analyse heavy metals' chemical forms in the soil has been made. One of the well-known agents of heavy metals immobilisation, biochar, has been prepared and used in the pots experiment. The aim of the research was to study the influence of biochar raw materials on its properties to immobilise heavy metals in a soil, as well as the influence of the cultivation of certain crops (buckwheat and white mustard) on the efficiency of HM immobilisation and the potential ecological risk for the environment. In addition, the distribution of heavy metals' fractions after the introduction of biochar obtained from three types of biomasses into acidic soil (pH<5) was analysed. The most important task was to determine qualitative and quantitative distribution of the five possible chemical forms of the immobilised metals in the soil. Stabilisation of heavy metals in a soil using biochar can be described by several mechanisms: electrostatic attraction; ion exchange of heavy metals with Ca^{2+}, Mg^{2+} and other cations associated with biochar, interaction with various functional groups, surface complex compounds and inner-sphere complexes with the free hydroxyl radical of mineral oxides; precipitation and indirect interactions between biochar and heavy metals in soils.

The PP4, together with project partner PP6 (Lithuanian Research Centre for Agriculture and Forestry), has analysed the obtained data of the heavy metals' chemical forms in the soil of the experimental pots. PP4 and PP6 prepared the article (*Heavy metal immobilisation by biochar amendments in polluted soil: efficiency and potential ecological risk)* to scientifically validate the correctness of the investigation of the heavy metals' chemical fractions in the experimental soil.

Based on experiments carried out, we can assume that a significant part of the metal's chemical fraction belongs to the residual form, which provides the information that immobilised metals are not able to participate in the chemical reactions, and are passive in the soil. The question of how long such a form can be in the soil in a non-active state is not yet clear, and further studies are required. The process should be controlled and monitored because once the metals are transferred from a non-bioavailable to a bioavailable form, they could be leached to the groundwater, taken up by plants or other living organisms, causing irreparable damage to the environment.

Therefore, PP4 and PP6 are planning to inform the Lithuanian Environmental Ministry of obtained results by providing the authorised representatives with the article's conclusions. Together with its conclusions, the proposal is to revise the existing requirements for the phytoremediation application in cases where analysis has shown that, after certain treatment or amendments of the soil, there is no chemical activity of the heavy metals in the soil for a particular period of time.

Trends and hopes

As interviews performed within BAPR show, there is a need to increase knowledge on phytoremediation, specially moving from laboratory trials to field trials, to draw conclusions on the application in real environments, under real climate and local conditions. As Dr Danutė Karčauskienė put it: “we need more workshops, with more people, with more stakeholders, with more conclusions and more recommendations so policy makers can develop the law in a way that favours phytoremediation”.

Interest in more sustainable restoration methods is growing in the three countries, because of increased environmental concerns as well as increasing pressure on land resources in Europe. In Sweden, the government approved new guidelines for evaluation of contaminated sites, partially as an effort to open up to more sustainable restoration methods.

The legal proposal that the European Commission is expected to present in 2023, because of the adoption of the EU soil strategy, should lead to more circular uses of soils and prioritise reuse over new exploitation of natural areas, in line with the waste hierarchy. Depending on how a future land planning hierarchy is implemented, it could also lead to contaminated areas being re-used to a greater extent, as claiming new land should be avoided as much as possible.

Chapter 6: Cross-border cooperation and network within the project

Introduction to the stakeholders' network

There are many definitions of the term stakeholder. Common to all these definitions is a person or group of persons, organisations, institutions who are interested to be involved in the activities, and who want to take an active role.

The aim of each activity is to promote outputs on a field and to contribute to an increased understanding of the themes.

Local and international stakeholders should be interested in a specific subject and willing to adopt a triple helix concept approach to collaboration between the business sector, companies, authorities, municipalities, and academy.

Within the BAPR, project stakeholders have been divided in following categories:

1. Direct stakeholders – this group of stakeholders has been actively involved from an early stage of the process in order to provide the skills, knowledge, materials and equipment, e.g. suppliers, harvesters, landowners, public agencies.
2. Indirect stakeholders – could have an interest to participate in the cross-border seminars and follow the project results, but are not directly engaged in the pilot cases.
3. External stakeholders – a group of people with extra expertise and a different level of power, e.g. consultants, local citizens, interest organisations, media and government.

The stakeholder register form template is shown in Table 6.1 for an insightful analysis defining our audience and nurturing potential stakeholders. The identification of stakeholders consists of various entities, grouped by interests, e.g. for pilot case, training modules and education, and future potential users.

Table 6.1. *The stakeholders register form template.*

Organization name	Organization typ	Stakeholder engagemen	Stakeholder analysis	Country	Contact
The name of organization stakeholder belongs to	Company, municipality, university, authority	Informed (pdf, website, instagram)	Key players, keep informed, monitor		Email address/ web/ instagram

Strategic collaboration

Meetings, workshops, conferences, training courses and study tours play a significant role in networking with experts from different countries, areas and sectors with knowledge and experience.

During the project workshops, meetings and seminars have provided a chance to learn from each other, exchange knowledge and discuss phytoremediation technologies and methods for cleaning polluted soil, with a focus on the recovery of heavy metals.

The selection of speakers for the training module was as diverse as possible to bring valuable contributions to our workshops. We wanted to achieve diversity in terms of gender and status, inviting experts and promising research group leaders.

Outsourcing experts from research and industry from different countries have been invited to exchange knowledge and professional experiences in relation to available techniques and environmental aspects in port areas related to effects in the Baltic Sea region. Taking account of this collaboration helped to build a close international network for the future development of new highly-skilled research activities and incentives.

When the pandemic meant that all project meetings had to be virtual, for many of us the digital meeting platform was unfamiliar. The situation changed all plans in each country. Remote work must function differently; simply jumping into a virtual meeting room won't provide the same benefits as an in-person huddle when it comes to the pilot case discussions or talking to potential stakeholders over the "screen".

The coronavirus threat made it difficult to meet potential stakeholders and present projects for increased potential units. There were difficulties related to no physical contact, and onsite study visits to implement the pilot cases and stimulate stakeholders to plan for them was problematic. The partners also had different working site conditions and traditions.

The importance of good cooperation among the project partnership became obvious. Using mixed methods to communicate with stakeholders, such as emails, website, letters and reports, was a positive way of keeping stakeholders closer and establishing a friendly working environment.

Chapter 7: Final thoughts and conclusions

This report has shown the development of the countries' green biotechnologies in order to preserve a sustainable environment and cleaner soil. The effect of biochar and nutrients on both plant biomass and height was most promising in the *Miscanthus x giganteus* (in the Lithuanian and Polish cases). During the project, it was observed that, regarding the efficiency of phytoremediation, a two-three year period is too short to clean soil sufficiently.

The effects of meteorological conditions on a large scale pilot area are most noticeable in plants. Irrigation during a dry period must be taken into account with regard to the initial high-risk growing stages.

The handling and distribution of plant protection products should be carried out in accordance with each country's laws and regulations. Relevant skills and experience is required for the assignment to be successful, and staff should at least be in a position to comprehend the technology in relation to phytoremediation.

The report has introduced a modern and useful tool for online learning – the training module. The e-learning platform has been developed and is available at Gdansk University of Technology (Gdańsk Tech). It enables users to learn about the basics, understand the potential of phytoremediation to clean soil and see the real-life applications of this technology. The module is based on the project's experiences and results, as well as containing educational elements to further increase knowledge capacity. The Gdańsk Tech staff will continue to update the module with more material related to green technology.

One of the project outputs was to identify the risks in the pilot cases related to technical, economic, and social factors. The excel file is considered as a risks analysis tool based on the results obtained with each pilot case. These relate to pre-mitigation risks as well as those that follow. The risks were greatest at the beginning of the project when many factors could not be foreseen, such as a global economic crisis or diseases. It is important to keep the risks on track and update the risk management plan in order to fulfil the project requirements.

The BAPR partnership was extremely pleased to keep the project on track during the difficult COVID-19 situation, especially when the partners could not meet each other in real life or predict how things would develop. It was a virtual learning process for the whole partnership.

Moreover, the partners hope to be involved with and contribute to improvement proposals regarding methods, processes, etc., and would welcome the opportunity to contribute actively as project members in various evaluations.

Phytoremediation in comparison with other techniques

A major challenge limiting the application of phytoremediation, particularly for the remediation of highly contaminated sites, is the time factor. Hyperaccumulating plants with a high potential for metal extraction tend to have slow growth rates, while high biomass producing plants are often less effective in metal uptake. In consequence, the time demanded for a phytoremediation project often has to be calculated in decades, if not centuries (Shen et al., 2023; Guidi Nissim et al., 2023). In many cases, it may not be acceptable to withdraw contaminated land from a potential use site, due to the extensive timespans involved. However, the potential use of the plant biomass in a phytoremediation project can give an additional economic incentive for the use of this technique, together with its comparatively low cost in implementation and maintenance.

Current research is focusing on improving the efficiency of phytoremediation, for instance by crossbreeding or genetic engineering, but also through the development of chemical or microbial additives to aid in metal uptake by plants or to increase the plant availability of soil metals. For instance, promising results were obtained with arbuscular mycorrhizal fungi (Cabral et al., 2015). The ongoing effort to improve the removal efficiency of phytoremediation is not least motivated by the fact that this technique does have a number of advantages in comparison with other available chemical or physical techniques. The latter tend to be energy and labour intensive, and as such are often economically unfeasible. Similar problems also affect the applicability of many chemical techniques, such as chemical leaching or chemical stabilisation. In the latter case, it may be challenging to ensure long-term effectiveness of applied techniques or the resistance to weather extremes (Saravan et al., 2022).

As laid out in Chapter 1, phytoremediation is not limited to phytoaccumulation of heavy metals but includes numerous other processes, e.g. phytostabilisation or rhizofiltration, that reduce bioavailability of contaminants and aid in the microbial decomposition of organic contaminants. This versatility may be advantageous, for instance, in soil contaminated with multiple pollutants. One plant species may be used for soil remediation simultaneously targeting different pollutants, with different remediation processes occurring. While focus in the Lithuanian and Polish pilots was on evaluating the ability of *Miscanthus* to accumulate toxic heavy metals, the Swedish pilot demonstrated in addition the effective removal of nutrients from soil with this plant species. Moreover, the rhizosphere of *Miscanthus* has been shown to improve soil conditions for the establishment of soil microbial communities that degrade polycyclic aromatic hydrocarbons and other organic pollutants (Didier et al., 2012).

One important advantage of phytoremediation is the multitude of additional ecosystems functions this technique may provide besides the mere removal or stabilisation of pollutants. These ecosystem functions need to be included in the evaluation of the suitability of phytoremediation. Besides the before mentioned use of plant biomass in energy production, those may for instance be an improvement of overall soil quality at the polluted site, while thermal or chemical techniques often cause a serious disturbance of the soil. In an urban area the vegetation cover in a phytoremediation project may contribute to counter urban heat island effects and air pollution. Phytoremediation sites may also help in urban flood control and noise attenuation. Important is also the positive effect on urban biodiversity that phytoremediation project cans have, by providing habitat and nutrition for different species (Guidi Nissim et al., 2023).

Potential use in the future

In future, the wastewaters must be sorted and treated to a certain level and sent back for different uses, some of which should be in agriculture. Mankind needs clean air to breath, clean water to drink and healthy food to eat, and phytoremediation might be an important technology to help meet those demands. In the case of frequent use of treated wastewater for irrigation and for fertilisation in agriculture, or soil amendment used in different types of horticulture, it might be necessary to introduce new forms of crop rotation in agriculture and introduce new plants in phytoremediation.

The Cd in wheat has increased more than three times since the beginning of the 20th century, therefore immobilisation of metals in soil is of high importance, and biochar has started to be used to improve long-term carbon sequency, affect soil production and pH. Metals can be free/bioavailable or bound, and can be made more bioavailable for better effect by phytoremediation. The toxicity factor is not equal for all metals, and Cd and Zn are more toxic than others. Plants can also be used for phyto-mining, whereby the harvestable part of the plant is of interest for instant amounts of Cd mg/kg in plant biomass; even more interesting is the cleaning of the area in question. Perennial plants are considered better than annual plants for treatment of the soil.

Phytoremediation also increases biodiversity and might contribute to re-develop earlier well-developed cultures that have either disappeared or been heavily reduced.

Organic household waste are collected in green plastic bags for further biogas production and digest used biofertilisation of farmland. In recent years, pieces of those green bags have been found in fields in south of Sweden. Normally it takes 10-20 years for a plastic bag to break down in nature. Little research has been done on how much of the smallest plastic particles – micro and nano plastics – are stored or broken down in soil, crops, and plants. This is a huge open question and there is yet no simple answer. Scientists are able to see more new forthcoming pollutants.

For future development in phytoremediation, specific new cultivation techniques are of interest and new methods for taking care of the harvested polluted plant materials as an alternative to burning them. Economical extraction methods for metal recovery must be developed; new applications for phytoremediation are welcomed.

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Appendices

Appendix A: Project communication elements

Appendix B: Pilot cases descriptions

Appendix C: LAMMC, Lithuanian pilot case – additional tables and characteristics

Appendix A:

Project communication elements

[DATE]
LINNAEUS UNIVERSITY
[Company address]

Contents

1 LOGO AND INDENTIFICATION

From the moment of signing the Subsidy Contract, each project partner is obliged to inform the general public about the project and that is co-financed by the European Union within the South Baltic Programme.

Documents and materials drawn up for the project purposes should be labelled.

Full information is on www.southbaltic.eu/communication

1. BAPR identity

2. A key colour card for logo

C 73 M 4 Y 100 K 0	C 76 M 17 Y 100 K 15	C 100 M 70 Y 5 K 21	C 85 M 50 Y 0 K 0	C 100 M 0 Y 0 K 0
R 76 G 162 B 70	R 62 G 127 B 60	R 7 G 64 B 113	R 53 G 109 B 168	R 0 G 162 B 227

3. The Programme logo, the European Union symbol and ERDF

The Programme logo and EU emblem are available on the Programme website: https://southbaltic.eu/programme-logo-and-eu-emblem

4. The BAPR (project) logo together with the Programme logo: logo versions should have a white background.

In case of space limitations, use the Programme and the EU logos only.

Logos are available in png, eps and pdf formats in the BOX (BAPR folder/logotype & emblem).

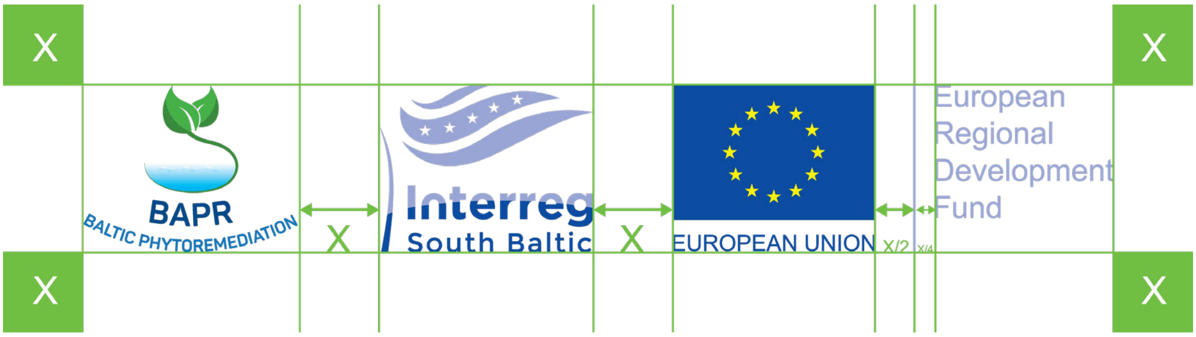
2 BASIC RULES

The project logo should always be next to the Programme logo, on its left hand side and on the same line with it. The project logo and the Programme logo are treated as a "set of logos" – in these cases they are separated from the partner logo by a line.

See the Programme www.southbaltic.eu/communication, page 9 below.

The project partners' logos may be placed next to the Programme logo, on its right hand side as shown below.

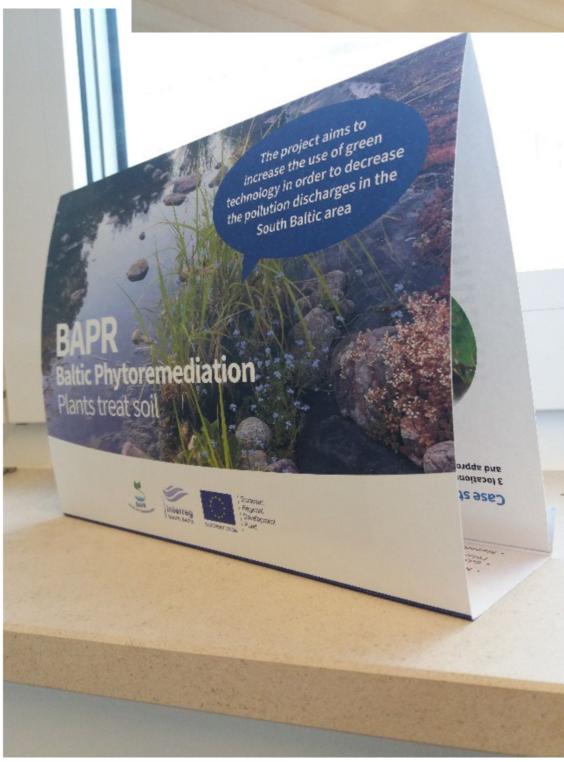
Refer to the Programme guidelines www.southbaltic.eu/communication to ensure the logo is created with the recommended sizes. Clear space refers to a distance of “X”, as a unit of measurement surrounding each side of the compound logo. “X” equals the distance between the Programme logo and the EU emblem.



Logo formatting, as shown below, is not allowed!

No other logos or objects can be positioned between the project and Interreg logos.

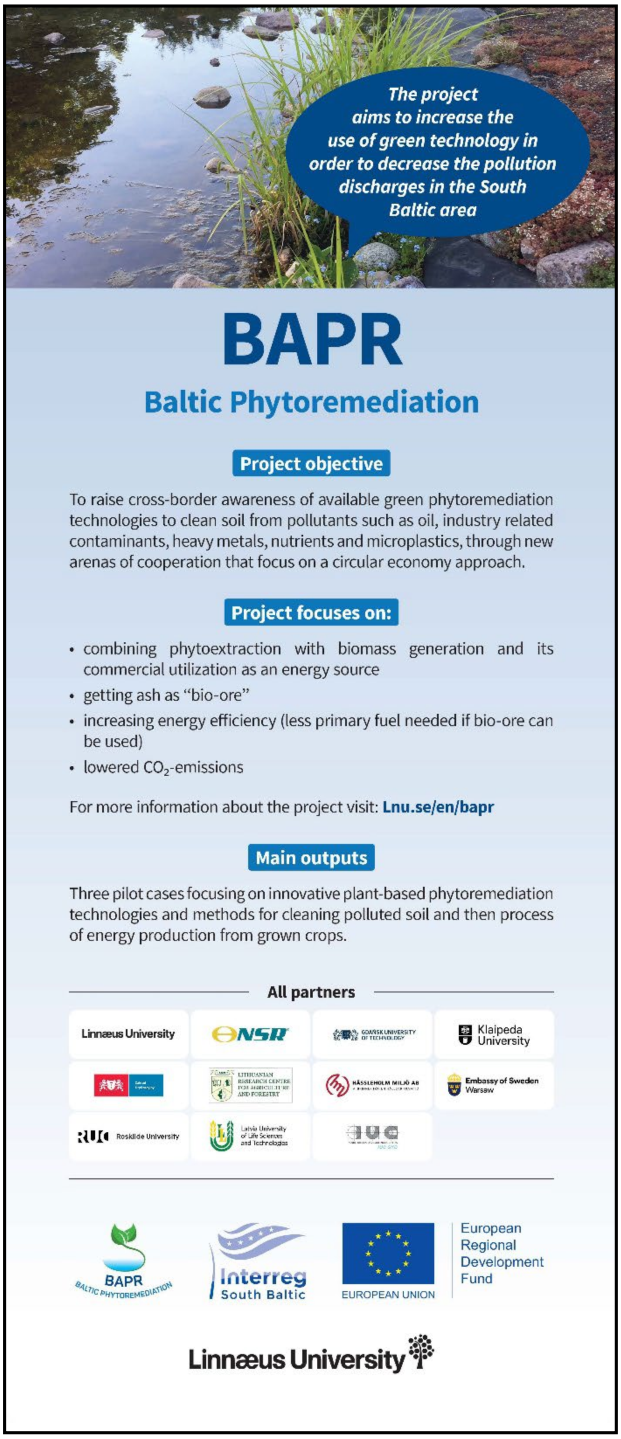
3 EXAMPLE, PROMOTIONAL MATERIAL



BAPR Baltic Phytoremediation | Interreg South Baltic | European Union European Regional Development Fund

4 POSTER

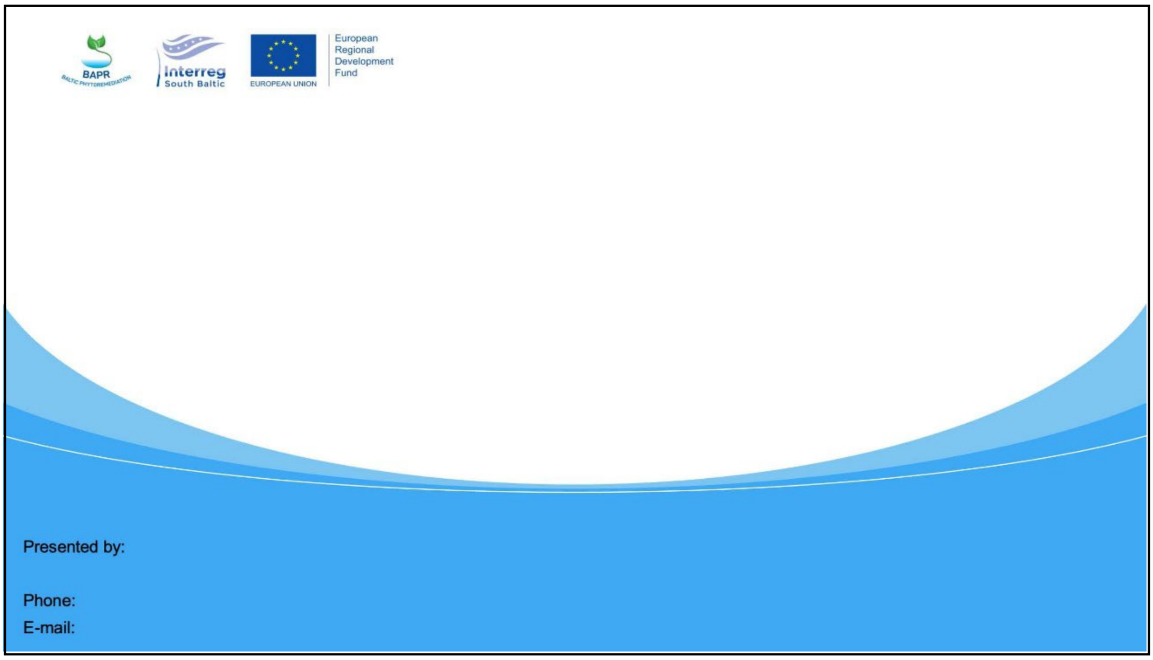
5 ROLL UP



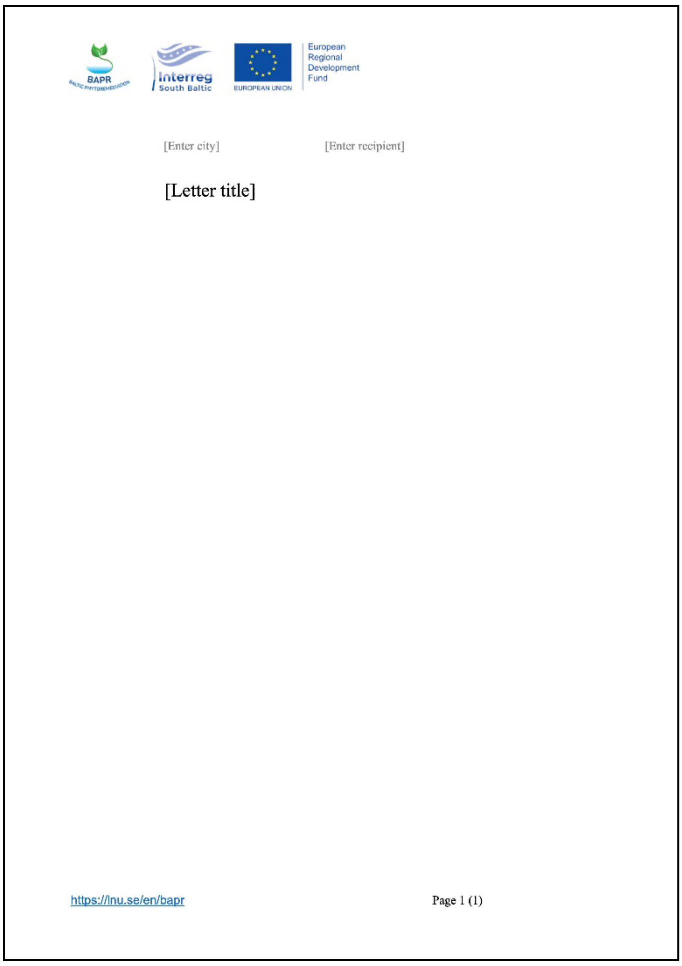
Posters should have a minimum format size of A3 and be visible to the public (e.g. entrance area of a building).

6 PRESENTATIONS TEMPLATES

Logos must be visible on all materials used.



7 A4 DOCUMENT TEMPLATES



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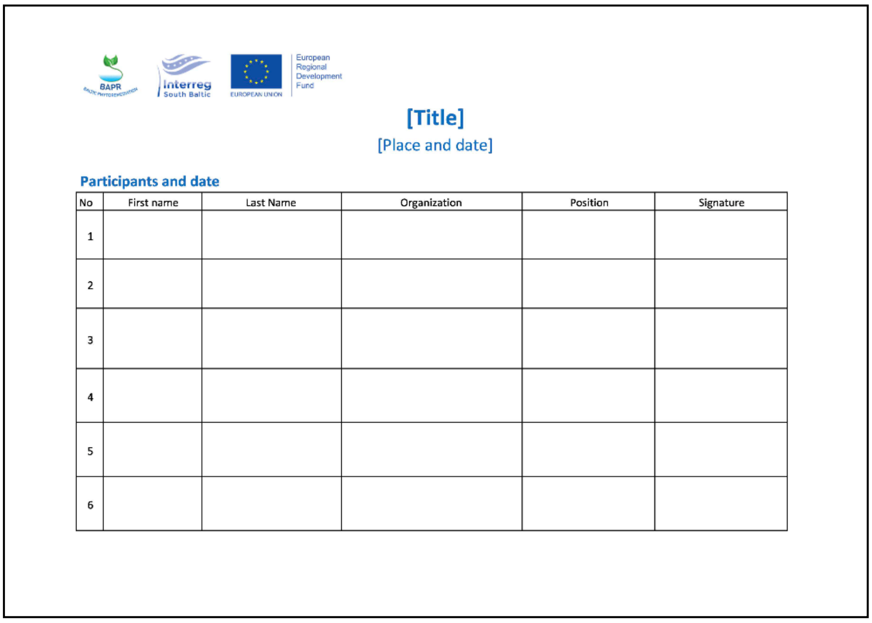
https://lnu.se/en/bapr Page 1 (1)



[Title]

[Place and date]

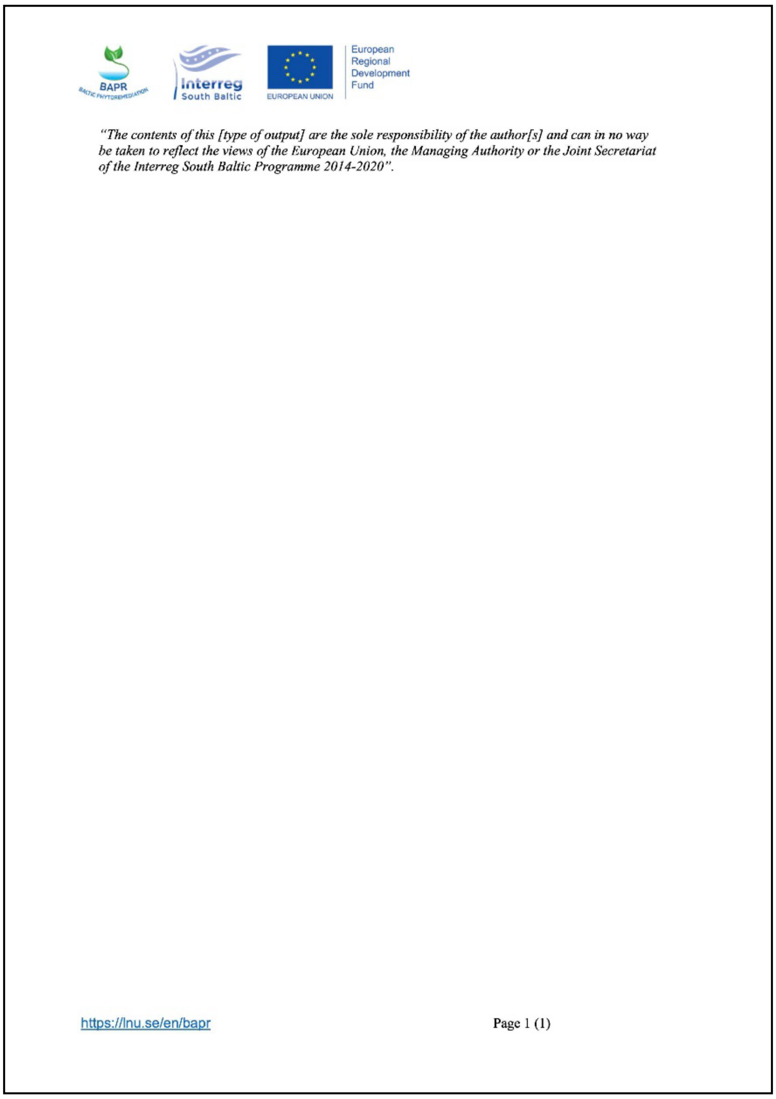
Participants and date

No	First name	Last Name	Organization	Position	Signature
1					
2					
3					
4					
5					
6					

All written outputs developed by the project must include the following disclaimer:

"The contents of this [type of output] are the sole responsibility of the author[s] and can in no way be taken to reflect the views of the European Union, the Managing Authority or the Joint Secretariat of the Interreg South Baltic Programme 2014-2020."

See example below.



"The contents of this [type of output] are the sole responsibility of the author[s] and can in no way be taken to reflect the views of the European Union, the Managing Authority or the Joint Secretariat of the Interreg South Baltic Programme 2014-2020".

https://lnu.se/en/bapr Page 1 (1)

Appendix B

Pilot Case, NSR, Sweden

The potential to reduce nutrient pollution in landfills' protective and plant layers by phytoremediation

Table of contents

1 Administrative

Evaluation report - Pilot case : THE POTENTIAL TO REDUCE NUTRIENT POLLUTION IN LANDFILLS' PROTECTIVE AND PLANT LAYERS BY PHYTOREMEDIATION - has been designed by NASR as an activity in work package 3 – Analysis and pilot case development (Activity 3:3). More administrative information can be found in Table 1.

Table 1. Administrative information

Project	Baltic Phytoremediation – BAPR Interreg South Baltic Programme STHB.02.02.00-SE-0155/18
Project Partner	PP2 NSR, registration no 556217-4580
Real estate:	Filborna 33:2
Address:	Hjortshögsvägen Helsingborg
Project manager NSR	Project leader, Angelika Blom
Project members	Environmental engineer, Samuel Svensson Environmental specialist, Anna Sorelius Financial accountant, Johan Kristiansson

2 Introduction – NSR Pilot case

2.1 Background

During the completion of the western part of the Filborna landfill (2004-2005) a mix of sludge from wastewater plants and compost from composted organic household waste was used in the topsoil layer. During the following control of the runoff water from the topsoil layer, a high level of nutrients, mainly nitrogen and phosphorus, were detected.

NSR has stated in its communication with the authorities that the capping vegetation would be "grass, shrubs, and herbs with a root depth <1 m". Today, the surface, which was once sowed with a grassland mixture, a large percentage of which was rye grass, is dominated by stinging nettle. Some years, the nettles grow tall, up to 2 m high, always completely dominating the flora (see Figure 1).

No harvest and no weed control is currently being performed on the finally capped part of the landfill.

Figure 1. Young prosperous nettles (left) and withering stock of nettles, July 2021 (right)

Originally, the runoff water was planned to be directed to the nearby water recipient (a small stream), but the high nutrient content made this impossible. Instead, the runoff water is treated at the local leachate water treatment plant. This results in lost capacity in the leachate treatment and costs associated with the treatment.

Table 2 below shows the nitrogen levels in the runoff from the protection/plant layer in two different sampling points (see Figure 2, Y7 and Y9). Nitrogen levels allowed to be released to Öresund (sea) are 15 mg/l, and a former guideline value to protect the nearby stream was 5 mg/l. From these numbers it is obvious that nitrogen is a problem that needs to be addressed.

Table 2. Nitrogen (N tot, mg/l) levels in surface water runoff. Values exceeding site specific (Öresund) emissions limit of 15 mg/l are marked in bold red text.

	Y9	**Y7**
2022-02-09	**43**	**54**
2021-11-09	9.6	
2021-09-16	14	**10**
2021-05-27	12	1.8
2021-02-09	**25**	
2020-11-24	12	**39**
2020-10-09	**22**	
2020-05-11	**43**	
2020-02-04	**63**	**88**
2019-11-06	**19**	
2019-09-16	**20**	
2019-05-08	**30**	
2019-02-08	**120**	**210**
2018-11-15	**130**	
2018-09-21	**220**	
2018-05-23	**94**	
2018-02-15	**39**	**96**
2017-12-18	**51**	**110**
2017-10-11	11	**130**

Figure 2. Finished (covered) part of the landfill dominated by nettles is marked with dashed red line. The sampling points included in the monitoring program; Y7, Y9 marked

This runoff water was originally planned to be led to the nearby clean water recipient, but the high nutrient content, up to 10 times higher than allowed, made this plan of action impossible. Instead, the runoff water is treated at the local leachate water treatment plant. This results in lost capacity in the leachate treatment and cost associated with this treatment and it is obvious that the nutrient is a problem need to be addressed.

2.1.1 Phytoremediation

Phytoremediation is a sustainable approach to remediate contaminated soils, water, and air by using plants to remove, transform, or stabilise pollutants. This technique has gained attention in recent years due to its low cost, environmental friendliness, and potential to improve soil quality. Phytoremediation involves a wide range of processes, including phytoextraction, phytostabilisation, phytodegradation, and rhizofiltration, which depend on the ability of plants to accumulate and transform contaminants in their tissues or through interactions with their root systems. However, the success of phytoremediation depends on several factors, such as the choice of plant species, the type and concentration of pollutants, soil or water properties, and environmental conditions.

Research on phytoremediation has focused on improving the efficiency and reliability of the technique, as well as exploring its integration with other remediation methods, such as bioremediation, electrokinetic remediation, and chemical oxidation (Salt et al., 1998). Various plant species, including hyperaccumulators, have been identified and tested for their ability to remediate specific pollutants, such as heavy metals, organic compounds, and radioactive elements (Baker & Reeves, 2018; Rascio & Navari-Izzo, 2011).

While phytoremediation has shown great potential as a green technology for environmental remediation, further research is needed to better understand the underlying mechanisms and optimise the use of plant species and their associated microbial communities (Tordoff et al., 2000). In addition, phytoremediation should be evaluated within the context of sustainable land management practices to ensure its long-term effectiveness and benefits (Chigbo & Batty, 2020).

2.2 Nordvästra Skånes Renhållnings AB

Nordvästra Skånes Renhållnings AB (NSR) is a waste management company owned by six municipalities in the south part of Sweden (see Figure 3).

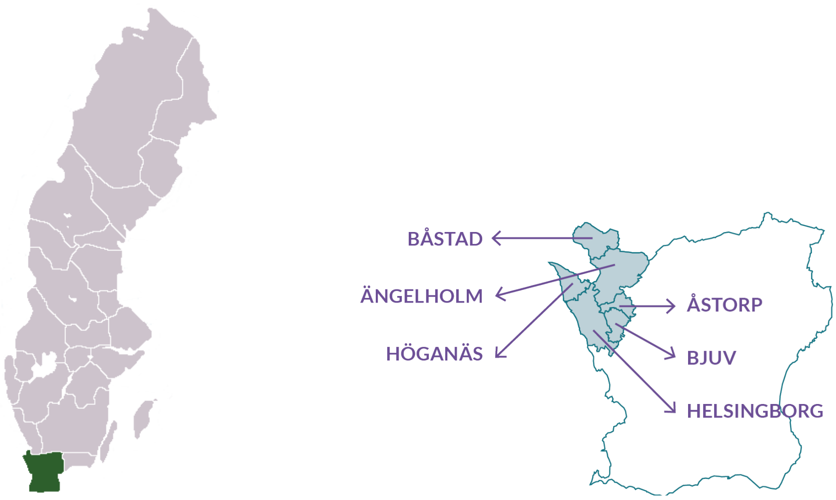


Figure 3. Sweden and the county of Scania; diagram of Scania with the six municipals which constitute NSR

NSR has one active landfill (Filborna landfill in Helsingborg) and three other recent landfills with no current disposal of waste. Svenstad (Båstad) and Åstorp landfills are finally capped and the capping process is ongoing at Tjörröd landfill in Höganäs.

Sludge mixed with food waste compost has been used in some of the plant layer of the finally capped landfills at Filborna and Tjörröd.

2.2.1 Filborna landfill, Helsingborg

The NSR Filborna landfill contains approximately 11,000,000 m^3 waste from the 1950s to the present day. The landfill consists of both municipal and industrial waste containing both organic and non-organic materials. The landfill's age and varied composition of waste types means that the leachate from the landfill contains a wide range of pollutants.

The western part of the landfill, approximately 80,000 m^2 has a final capping layer and the other part of the old landfill will get its final capping in the years leading up to 2028.

The leakage from the landfill is mixed with other polluted waters from the industries within the waste management area, for example water from pre-treatment of organic waste for biogas production (rich in nutrients and organic material), large areas for sorting waste (metals) and compost production (some metals, phosphorus) (see Figure 4). Runoff water from the capped slope is also diverted to the water treatment system because of high levels of nutrients within it.

The total amount of collected and treated water is between 300,000 and 400,000 m^3, dependent on precipitation.

The water entering the leachate treatment can roughly be divided into two separate streams – nutrient rich and nutrient poor (see Figure 5). The nutrient rich water is being treated in a specific part of the system called the CBR (Continuous Biological Reactor), in ponds 8B-9A, B, C. The process is a sequence of ponds where nutrients in the form of nitrogen, phosphorus and carbon are removed by nitrification/denitrification and post-treatment in the form of aeration and sedimentation. The system is based on microorganisms which are only active above a certain temperature in the water. This confines the systems operation season to approximately May-September.

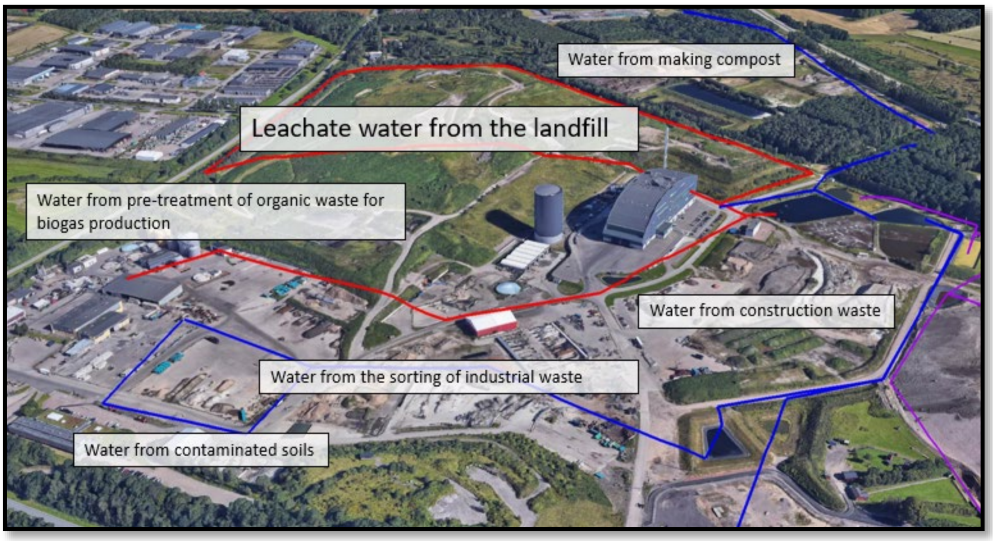


Figure 4. The layout of the Filborna area with major flows of water that effect the water characteristics

Nutrient poor waters are led around the CBR-system directly for sedimentation (in pond 10A) with the help of flocculants.

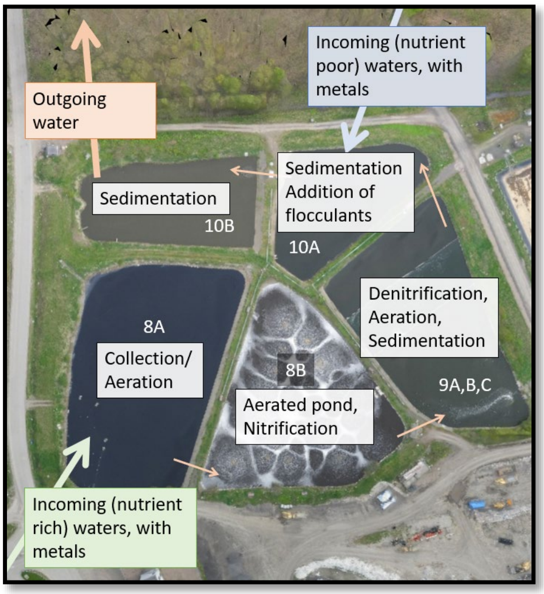


Figure 5. The water treatment system at Filborna

3 Purpose and aim/goals of NSR's pilot case

The purpose of the NSR pilot case, is to evaluate if phytoremediation could be a solution to reduce the nutrient levels in the landfill's protective and plant layers.

The long-term goal is to reduce the concentration of nutrients in runoff water to levels acceptable to the recipient. There might also be positive side-effects, for example utilisation of biomass (biochar or biogas) and positive effects related to the ecosystem.

Aim/goals for NSR's pilot case

- Identify issues associated with nutrient-rich plant layers at finally capped landfills. For example, safety measures to protect the important low permeable layer of the capping, which can limit plant selection, and the possibility of mechanically cultivating soil and crops.
- Evaluate different plant-based and phytoremediation related solutions to solve the problems associated with nutrient-rich plant layers at finally capped landfills.

The project does not have a typically academic focus but instead aims to address the practicalities of handling this type of issue at a landfill.

The purpose of the project is also to highlight the possibilities of ecosystem and environmental services that a finally capped landfill area might hold.

The knowledge of how to prevent plant nutrients in soil from leaking into water recipients is by no means new. This is something that the agricultural sector continues to work on, for example through the initiative "greppa näringen" ("Focus on nutrients"), which was initiated in Sweden in the early 2000s. It could be said, then, that NSR's pilot case is about applying old knowledge in a new context.

A lean, depleted soil has many properties beneficial to a landfill capping. The most obvious is that it leaks less nutrients but will also be easier to maintain, and lean natural meadows often present greater biodiversity. A meadow contributes flowers to our bees, butterflies, and other pollinators and flower visitors.

4 Material and methods

The pilot case consisted of two elements: one was based around the use of cultivation beds and other included the use of field trials on a larger scale. A common denominator for the two elements of the project was the selection of plants that might be suitable for phytoremediation on a landfill.

1. The purpose of the cultivation beds was to study the chemical, physical and biological conditions regarding mainly nutrients in soil and soil water under more controlled conditions. An additional purpose was to study the establishment of various plants.

2. The purpose of the field trial was to highlight the practical aspects of using plants for nutrient uptake on an existing landfill. Aspects that were included in the field trials were:

    - Soil preparation, including spread of biochar
    - Establishment
    - Maintenance
    - Harvesting
    - Biomass removal and utilisation

4.1 Method for choice of plants for the pilot case

Multi-criteria analysis (MCA) is a collective concept, the purpose of which is to consider several factors in a structured way. An MCA shows how well different measures fulfil one or more purposes. Usually, the purposes are described through a number of criteria, each of which is valued, and then weighted together for a final assessment (Rosén, et al., 2009). The assessment ultimately results in the identification of one or more suitable alternatives.

In this project, we have excluded the valuation step. The term MCA has been used in this pilot case to reflect that selected plants must deliver against more than one criterion, for example that they must not only be good at absorbing nutrients, but they must also have roots that are not too deep.

4.1.1 Plants for cultivation beds and field trials

To determine which plant criteria were important and, based on these, to select plants for the above-mentioned cultivation beds and field trials, the following were carried out:

- Internal workshop

- Dialogue with local actors, e.g. agricultural representatives and seed sellers
- Student work
- Study visit to Swedish University of Agricultural Sciences (SLU)
- Dialogue with several researchers at SLU

A study visit was made to the testbed of one of the local seed suppliers (Olssons frö) (see Figure 6) and a visit to the Swedish University of Agriculture Sciences focused on harvesting equipment and *Miscanthus giganteus* clones (see Figure 7).

Figure 6. Study visit to the testbed of Olssons frö guided by Maria (August 2020)

Figure 7. Study visit to SLU Alnarp collection of Miscanthus giganteus clones (September 2020)

With the help of Sustainalink,[1] we commissioned two students to do a literature review to find scientific publications on what has been done and published in terms of cleaning soil from nutrients with the help of plants. The results of the literature study were used to provide suggestions for suitable plants for NSR's pilot case (see Figure 8).

[1] Sustainalink runs projects where university students solve sustainability challenges faced by private and public actors. https://sustainalink.se/

Figure 8. Student presentation at NSR, August 2020

4.2 Cultivation beds – method and purpose

NSR constructed six cultivation beds in duplicate (a total of 12 boxes) of 4 m^2 (2 x2 x 1.2 m).

The cultivation beds were filled with material from the protection and plant layers of the current landfill (in the same proportions) (see Figure 9). Lysimeters were installed in the culture beds to measure mainly nutrient and occasionally metal content in the water. Lysimeters are a method of extracting soil-water that can be used over an extended period of time to provide a series of samples from the same source.

Figure 9. Cultivation beds filled with soil from the landfill top layer and with lysimeters on top, ready to be installed.

The lysimeters were installed approx. 50 cm from the corner, with an angle of about 40 degrees towards the centre. The filter part was placed about 30 cm below the surface. There was also a reference bed, directly on the landfill, full of naturally established nettles. Two lysimeters were installed in the reference bed.

Due to the pilot case's aim to determine the viability of using phytoremediation to reduce nutrient in topsoil on a landfill, focus was placed on analysis of the nutrients in the water and soil. Below is a list (see Table 3) of the parameters of focus.

Table 3. Parameters for analysis of water from lysimeters and from soil

Water (lysimeters)	Soil
Ammonium Nitrate	
Nitrate Nitrogen	
Total Nitrogen	Total Nitrogen
TOC	TOC
Phosphate Phosphorus	
Total Phosphorus	Total Phosphorus

Initially the plan was to collect water from the lysimeters every month to get a large number of samples. However, low yield of water in the lysimeters due to soil composition, the soil being too porous for the lysimeters to retain a vacuum, and greater than expected evapotranspiration, resulted in few samples. Investment was made in a mobile irrigation system to increase the chance of water extraction from cultivation beds. Unfortunately, we did not get any more water samples, even though the beds were watered several times during drier periods.

4.2.1 Biochar

In one bed, biochar was blended with the soil. The biochar was purchased from the producer, Circular Carbon, and produced at 750ºC in 20 minutes, with 30% moisture. Approx. 60 kg of biochar was added to 910 kg of soil. The particle size in the tested biochar was fine (powder), which has an impact on what methods of handling are suitable.

The use of biochar has been accepted as a sustainable approach, and a promising way to improve soil quality and stabilise pollutants in the soil. Biochar has also been shown to absorb nutrients, and some research points to reduced leaching or reduced nitrification (Enell et al., 2020).

The hypothesis of blending biochar with the soil was:

- Biochar added in the correct amount would increase plant growth (and therefore reduce nutrient leakage, especially if biomass is removed).

Since biochar is like a sponge and is known to hold water (including dissolved substances like nitrogen and phosphorous), the leakage of nutrients should decrease. The biochar can hold nutrients for a while (how long is likely to be affected by the properties of the specific biochar, choice of feedstock, and temperature of the pyrolysis), and then release water and nutrients once charged.

4.3 Field trials

At the landfill, five plots (one of which is a reference area with existing plants, mainly nettles) were prepared at the top of the final part of the landfill (approx. 20 x 30 m) (see Figure 10). Prior to establishing the field trials, an overview of the section was performed where the depth of the different layers above the landfilled waste was determined, as well as the slope and levels of nutrients and other parameters in the soil.

4.3.1 Figure 10. Field trials at Filborna landfill, consisting of five plots, 1-5, and several cultivation beds Method for gathering practical experience

To gain practical experience, the following was carried out:

- Internal workshop
- Dialogue with local actors, e.g. agricultural representatives and seed sellers
- Study visit to Swedish University of Agricultural Sciences (SLU)
- Dialogue with researchers at SLU
- Visit to retailers for agricultural machines

Aspects of practical experience acquired in the field trials were:

A. Soil preparation
    a. Weed control
    b. Spreading of biochar on plot 3
    c. Ploughing
    d. Harrowing
B. Establishment
C. Maintenance
D. Harvesting
E. Biomass removal and utilisation

5 Results and discussion

The following section is divided into three parts, focusing on results from the:

1. Simplified multicriteria analysis – choice of plants
2. Analysis of water and soil from the cultivation beds
3. Practical experiences working with machines on the landfill

5.1 Simplified multicriteria analysis – choice of plants

The study visits, discussions with seed suppliers and researchers, as well as the student work, resulted in identification of conditions typical for landfills and the criteria that were assessed as critical for selection of plants for NSR's pilot case.

In this chapter, typical aspects linked to landfills that can influence the choice of plants for phytoremediation are presented and discussed, as is which criteria are crucial when choosing plants for phytoremediation in this context.

5.1.1 Conditions typical for landfill

It's well documented that some plants have a great ability to absorb nutrients from the soil, but the choice of plants is important due to the special conditions at the landfill.

There are some conditions typical of a landfill that need to be addressed. The main goal of landfill capping is to minimise infiltration of rain and runoff. The aim of the protection coverage is to protect the low permeable layer and provide a substrate to the important plant cover system which protects the protection layer from wind, water and, to some extent, temperature induced erosion. The topography of the landfill has been adapted to prevent erosion and give the slopes good stability.

The landfill should preferably be executed in such a way that protection can work passively in the long run (or be of importance and interest), so that long-term sustainable protection can be ensured.

NSR has identified five important conditions to consider when choosing plants for landfills:

1. **Slope of the landfill.** According to Swedish regulation and recommendation, the minimum slope of the sealing layer of the final cover should be 1:20 (V:H) and the maximum slope of the final cover should be 1:3.

2. **Roots of the plant species**. The roots must not risk penetrating the cover so deeply that they risk damaging the impermeable layer. Trees are generally not acceptable on finally covered landfills. When it comes to information about root systems, research often focuses on the uptake of water and nutrients (often managed by thin roots, which are not a great threat to, for example, a low

permeable layer such as a PE membrane).

3. **Plant coverage.** The distribution of greenery and the density of the root system are important to counteract erosion and reduce infiltration of precipitation.

4. **Maintenance.** Factors such as replanting, weed control and harvest are important when it comes to ensuring the function in the long run.

5. **Ability to absorb nutrients.** To reduce leakage of nutrients to the surrounding environment and recipients.

5.1.2 Identified criteria for choice of plants

The study visits, discussions with seed suppliers and researchers, as well as student work resulted in the following criteria being assessed as critical for selection of plants for NSR's pilot case:

- **Root depth**
  As mentioned in sub-chapter 5.1.1 it is important that the root system must not risk penetrating the cover so deeply that it risks damaging the low permeable layer.
- **Uptake of nutrients**
  That the plant has a high absorption of nutrients is of course prioritised for the greatest possible effect.
- **Conditions for harvesting**
  In order for phytoremediation to have an effect, it is vital that the plant can be harvested and removed, to reduce the amount of nutrients in the soil.
- **Total economy; acquisition, establishment, maintenance**
  We are looking for cost-effective solutions, which in this case could mean plants that are perennial, have good and fast establishment, do not require major efforts for irrigation and plant protection, and can be harvested with existing and available technology.
- **Use of the biomass; for biochar, biogas production or other use**
  At NSR, we work for circular solutions with a focus on reuse and recycling. Therefore, it is a priority for us to choose a plant that enables utilisation after harvest, for example through biogas and digestate production.
- **Biodiversity and other ecosystem services**
  Finally, we have looked for plants that, in addition to contributing to efficient uptake of nutrient without damaging the landfill, can offer more ecosystem services. By way of the fact that the selected plant contributes to more ecosystem services, it is our hope that this leads to an even more sustainable management of the final covered landfills, while at the same time contributing to society's goals of sustainable ecosystems, e.g. increased biological diversity.

Other important aspects included perennialism and resilience (against drought, pests and diseases). The plants chosen for the cultivation beds and field trials are presented in sub-chapter 5.1.3, and shown in Tables 4 and 5.

5.1.3 Selected plants for cultivation beds and field trials, and their establishment

In the following sub-chapters, choice of plants for cultivation beds and field trials are detailed. The establishment in both cultivation beds and at the field trials are also presented and discussed here.

5.1.3.1 Plants for cultivation beds

Table 4 below shows the plants that were selected, based on the simplified MCA, together with an overall description of each chosen plant's characteristics that are relevant for the pilot case.

Table 4. Plants for NSR's cultivation beds (footnotes are on the next page)

Bed nr	Plant	Growing information	Root		Promoted characteristics
			Type	Depth	
1	**Elephant grass** *Miscanthus giganteus*	Perennial, replanting every 15-25 years. Optimum pH is between 5.5 and 7.5	Rhizomes	70 cm[2]	Annual yield[3]: 15 tons DW per hectare. Used for heat production, production of biochar, beddings for animals or substitute for peat.
2	**Oil Radish** *Raphanus sativus Oleiformis*	Annual	Taproot with side roots	20-100 cm depth[4]	Recommended as a lush and rewarding green fodder plant, especially on lighter soils.[5]
2	**Blue tansy/purple tansy** *Phacelia tanacetifolia*	Annual Hardy to minus 28ºC Thrives in virtually any well-drained, fertile soil	Taproot with branched fibrous roots	50-80 cm in depth[6]	Spring forage source and a widely used bee crop plant, producing nectar continuously throughout the day.[7] Useful to prevent serious soil erosion.
3	**Reed canary grass** *Phalaris arundinacea*	Perennial (8-10 years) Can be grown on most soils (best on water-bearing, mulch-rich and light soils)	Thin rhizomes, form a thick impenetrable mat below the soil surface	Strong shoots 130-200 cm[8]	Energy crop; the yield is around 4-6 ton dry matter per hectare and year. Can withstand both drought and flood. Resistant to frost, coat of ice, night frosts in spring and autumn.
4	**Common chickory** *Cichorium intybus*	Perennial (3-5 years)	Strong taproot branched with side roots	150 cm[9]	Good ability if well-established growth during the autumn. Very good drought resistance (deep strong roots). Good structural improvement characteristics.
5&6	**English rye grass** *Lolium perenne* L	Perennial	Fibrous roots	30-50 cm[10]	An easily established grass, not nitrogen-fixing (perennial), with very fast growth.

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[2]. Mann, J.J., Barney, J.N., Kyser, G.B. *et al.,* 2013

Cultivation bed 1 – Elephant grass, Miscanthus giganteus

Miscanthus giganteus is an ordinary European landfill plant and is used, for example, at capped landfills in the UK with good results. According to UK experience, there is no risk of damage to the low permeable layer and protective layer (see Table 4). NSR has been in contact with one of the suppliers in the UK for practical instructions, information about the root system, and delivery of rhizomes.

Miscanthus giganteus is a C4 plant. These kinds of plants grow very fast and live a long time. Once the Miscanthus is planted, it sprouts itself every year. One may expect that the rootstock in the ground will sprout repeatedly for 20 to 25 years. *Miscanthus giganteus* does not grow seeds in Europe, its propagation is vegetative, and it is not invasive, according to the Swedish Environmental Protection Agency (2023). From dialogue with growers of *Miscanthus giganteus* in the UK and USA, we know that it is harvestable.

Miscanthus giganteus is interesting as an energy crop as it can give high yields (see Table 4) and has low requirements for fertilisation. However, its use as an energy crop can be limited by a relatively high need for water, but it binds the soil well. (Landfors and Hollsten, 2012). Miscanthus is also an interesting plant for biochar production.

The low requirement of fertilisation indicates a low uptake of nutrient, but this might be compensated through the impressive yields (DEFRA, 2001). *Miscanthus giganteus* has a long productive period, but does not grow at temperatures below a threshold of 6^{o}C (Forest Research, 2007).

In the cultivation bed trial, nine rhizomes were planted in each box, and at regular distance intervals in the boxes. Figure 11 shows the rhizomes at the time of planting – May 2020.

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[3]. https://www2.jordbruksverket.se/webdav/files/SJV/trycksaker/Pdf_ovrigt/ovr254.pdf

[4]. Scandinavium seed, Oljerättika, 2022

[5]. Jordbrukslära för skolor och självstudier (Rydberg m.fl. 1912)

[6]. Scandinavium seed, Honungsört, 2022

[7]. Phaecelia, cover crop, 2022

[8]. http://www.agrolitpa.lt/Product/organic-seeds/fodder-grasses-and-legumes/reed-canary-grass/PEDJA2/

[9]. Scandinavium Seed, Cikoria, 2022

[10]. Scandinavium seed, Engelskt rajgräs, 2022

Figure 11. Elephant grass Miscanthus giganteus rhizomes

The pictures show the establishment at both four eight months was good, despite only moderate care and maintenance.

Figure 12. Miscanthus giganteus, 27 August 2020 (left) and approx. four months later (right)

The root system was documented at the end of the trial after two years. It was determined that the root system did not extend further than 30 cm below ground with rhizomes in the very top layer (see Figure 13).

Figure 13. Miscanthus giganteus root system with/without soil. Mostly fine roots to 30 cm below the surface and rhizomes in the very top layer, September 2022

Cultivation bed 2 – Oil Radish, Raphanus sativus and Blue tansy, Phacelia tanacetifolia

For cultivation bed 2, oil radish and blue tansy were selected (see Table 4). Oil radish, *Raphanus sativus*, is a non-nitrogen-fixing annual cabbage plant with a large root system that has good nitrogen uptake and weed competition. In the field of agriculture, it is considered to be one of the best plants for absorbing nutrients. Recently, varieties have been developed that have a control effect against beet cyst nematodes (Scandinavium seed, Honungsört, 2022).

Phacelia Tanacetifolia is an annual cover crop, also used for green manure, growing to 0.6 m – 0.9 m. It is a richly flowering plant with lavender blue flowers in bunches (see Figure 14). Decorative in the summer flower bed, it is one of the best draft plants for bees and butterflies (Scandinavium seed, Honungsört, 2022). Both plants are nicely flowering and great as pollinators.

Due to both plants being annuals, the amount of work needed to establish them over a large period (many years) is considerably greater than for the other plants.

Figure 14. ***Blue tansy to the left and oil radish to the right.***

The establishment of both the blue tansy and the oil radish was successful, and the prevalence of pollenating insects was high.

Cultivation bed 3 – Reed canary grass Pedja, Phalaris arundinacea

Reed canary grass is a species native to Sweden. Historically, it has been grown for animal feed, and has recently been used as an energy crop and in wetlands for nutrient uptake. It reproduces by seed, by stem fragments, and by underground horizontal stems (rhizomes).

Reed canary grass is a perennial grass that grows wild over large parts of the northern hemisphere. It spreads vegetatively through creeping soil stems and with seeds that grow on bare ground. The seeds have moderate germination. The species can grow in both humid and drier conditions, which makes it a versatile plant in the context of wetlands. It has been shown to be highly effective in absorbing chloride from water (Landfors and Hollsten, 2012)

Figure 15. Reed canary grass at Olssons frö – flower and root

The plant grows slowly in the beginning until the root system has developed (see Figure 15). Weed control may be necessary during the first year. After a couple of years, the reed canary grass competes with weaker weeds and gives a full harvest from the third year onwards. A well-maintained embankment can last 10-15 years before new establishment is required. It is considered an interesting energy crop (Landfors and Hollsten, 2012). Ordinary hay harvesting machines can be used to cut and collect biomass.

An indication of the possible nutrient uptake may be obtained from the fertiliser recommendations. The Swedish Board of Agriculture recommends between 60 and 90 kg of nitrogen per hectare per year for an established cultivation.

Reed canary grass might invade other native plant communities that are under stress or have been disturbed by past farming practices.

In the pilot case, reed canary grass showed poor establishment in the beginning (mentioned as common in the literature) and therefore more seeds were added at the end of August 2021. The resulting establishment was good (see Figure 16).

Figure 16. Canary reed in cultivation bed, September 2021

Cultivation bed 4 – Chicory

Chicory is not a nitrogen-fixing perennial plant. In Sweden chicory is mainly used, in small numbers, in grassland, especially in organic farming. It’s also used as a companion crop. It is efficient at capturing soil nitrogen, as its roots penetrate further into the soil. (Scandinavium Seed, Cikoria, 2022) (see Table 4 for brief facts regarding chicory).

Chicory is a somewhat woody, perennial herbaceous plant of the daisy family, *Asteraceae*, usually with bright blue flowers (see Figure 17). It is grown as a forage crop for livestock (where the lush green young plants are harvested). It lives as a wild plant on roadsides in its native Europe.

Figure 17. Chicory flower and meadow

Chicory is a 30-100 cm tall herb that usually grows on nutrient-rich and loose soil that is dry and sunny, and it produces a lot of biomass. The leaf base is heart-like stem-wide and it has a strong root.

Experiments have shown that chicory gave the greatest yield when it was fertilised with 200 kg nitrogen / ha and that the more nitrogen given, the larger the amount of harvest, regardless of the harvest interval. ***Chicory*** can be harvested or grazed every eight weeks and the yield can be as large as 5-7 tonnes dry weight per hectare (Olsson, 2014).

The establishment was very good, with good growth and good flowering (see Figure 18).

Figure 18. Chicory, cultivation beds 4A and 4B, 2020-09-04 to the left and 2021-08-20 to the right

Cultivation Bed 5 & 6 – English rye grass + biochar

One of the most common plants used at capped landfills is short grass, such as rye grass. Usually, a mix of different types of grass is used but very often with a high percentage of rye grass.

Nutrient uptake in rye grass can be approximated with general information on nutrient uptake in grassland. Annual removal of nutrients in grassland varies between 105 and 186 kg/N per hectare (greppa näringen, 2011; Yara, 2022).

There was a good establishment as expected in cultivation beds 5 and 6. Figure 19 shows the establishment one year after sowing.

Figure 19. Good establishment in cultivation beds 5 and 6, 23 May 2021

Biochar

Biochar was added to bed 6 with the help of hand tools (shovel and rake). The dispersion in the soil was studied after the cultivation bed test was over at the end of the project (see Figure 20). The distribution of biochar in the soil was not perfect and observable layers/patches with higher levels of char were prevalent.

Figure 20. Construction of the bed's soil layer with addition of biochar, May 2020. Cultivation beds 6A and 6B with biochar and lush rye grass, October 2020. Uneven distribution of biochar, September 2022

5.1.3.2 *Plants for field trials*

Table 5 shows the plants, and their establishment, that were selected for the field trials, based on the simplified MCA, together with an overall description of each chosen plant's characteristics that were relevant for the pilot case. In the table there is also information regarding establishment in each plot.

Plot number 1 can be said to be the reference field, i.e. the alternative if we do nothing else, besides harvesting the nettles as they are. For plots 2-4, different types of energy crops were chosen; we have extensive domestic experience in growing rye grass and reeds as an agricultural and energy crop.

In plot number 5 we chose to try grass and flowering plants that could be used on a steeper slope. We chose to sow more flowering plants for an increased contribution to biodiversity and other ecosystem services.

The establishment of the plants was very good except in field 2, which was planted with *Miscanthus giganteus* plug plants. All the *Miscanthus giganteus* plants migrated during the winter. No new planting of miscanthus took place as the project was to end within six months (November 2022). In plot 5, very few flowering plants were found in the second growing season.

Table 5. Plants chosen for NSR's field trial and their establishment

Field nr	Plants chosen	Motives for choice	Establishment
1	Nettles together with thistles and other weeds	Existing vegetation. Cheapest option.	Existing vegetation. Very good establishment. Good regrowth after first harvest.
2	Miscanthus giganteus	NSR has plans to use it on another landfill. Can be used as an energy crop.	No plug plant survived the winter.
3	Rye grass and biochar	In other experiments, biochar has been shown to absorb nutrients. Ryegrass is a common plant used for final cover of landfills.	Very good establishment during the first growing season. Survived the winter.
4	Reed canary grass, timothy	Harvestable and used as an energy crop.	The establishment was above expectations in the first growing season. Good wintering.
5	Low growing grass with flowering plants	Many other ecosystem benefits. Can be used on surfaces with greater slope.	Good establishment with many flowers in the first growing season. In the second growing season, most flowering plants were outcompeted by thistles and other weeds.

5.2 Cultivation beds – water and soil analysis

To determine the feasibility of removing nutrients using the plants and the methods discussed, water and soil analysis was performed in the cultivation beds.

The results from the lab analysis should be interpreted with caution. The number of analyses is limited and the approach only allowed an insufficient number of replicates and not always in similar conditions. We see the results as an indication, and part of the overall decision basis for measures to reduce nutrient leakage.

5.2.1 Water analysis

The results from the water analysis in the cultivation beds are presented in Table 6.

The aim at the beginning of the study was to measure the nutrients in the soil water (one sample per bed, mixing water from two lysimeters) once a month over the course of one year. But the soil matrix texture was so porous that the lysimeters often lost pressure. For most of the time it was not possible to collect the soil water to analyse its nutrient content; only small amounts were collected.

In the reference bed (with nettles) placed on the fields, the inflow of water to the lysimeters was considerably higher. Since the oil radish and blue tansy were harvested in the autumn, the samples were taken from a soil with no vegetation at all.

Table 6. Analysis Soil water Lysimeter

		Ammonium nitrate (NH4-N)	Nitrate nitrogen (NO3-N)	Total nitrogen	TOC	Phosphate Phosphorous (PO4-P)	Total Phosphorous
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
1 **Miscanthus**	2020-12-02	0.0485	165	190	110	2.98	3.235
	2021-03-01	0.159	94.5	107.5	72.5	3.5	3.9
	2021-06-03	0.0345	100	66.5	110	0.89	2.05
2 **Oil radish/Blue tansy**	2020-12-02	0.17	170	190		7.9	9.2
	2021-03-01	0.4	93.5	107	85	10.25	10.15
	2021-06-03	0.0375	145	165	140	0.75	2.9
3 **Reed canary grass**	2020-12-02	0.0655	109.5	130	130	12.35	11.55
	2021-03-01	0.28	125	140	140	11.35	15.7
4 **Chicory**	2020-12-02	0.11	175	200	145	7.8	8.9
	2021-03-01	0.35	126	140	149.5	8.65	9.05
	2021-06-03	0.385	140	165	155	7.35	8.45
5 **Rye grass**	2020-12-02	0.075	69.5	83.5	115	12.5	11
	2021-03-01	0.205	60.5	67	66.5	8.5	8.65
6 **Rye grass + biochar**	2020-12-02	0.0795	53.5	66	120	13.5	12
	2021-03-01	0.22	25	28.5	68	13.5	18.5
Reference (nettles)	2020-12-16	0.0925	97	109.5	170	12.5	15
	2021-03-08	0.33	47	57	123.5	21.5	20.5

The nitrate-nitrogen levels differ considerably, with the lowest concentration in beds with rye grass and rye grass + biochar. The material in the cultivation beds was taken from the same area so the difference in the initial nitrate nitrogen levels is unknown.

The total nitrogen levels are also lowest in the cultivation beds with rye grass and in particular rye grass + biochar. Except for reed canary grass, the general trend is lower nitrogen levels in the succeeding sampling points, with the highest levels during the first sample. This indicates a lowering of nutrients in the soil over time, however, it is not possible to distinguish if the reduction is due to uptake or natural annual variation.

5.2.2 Soil analysis

Despite the short period of time, an attempt to study the nitrogen balance in the soil was made and the nutrients analysed. Focus was placed on nitrogen and phosphorus.

The greatest fraction of nitrogen in the soil belongs to its organic matter, but soil contains other fractions such as nitrate, and nitrite and ammonia. Total nitrogen measures the total amount of nitrogen and includes ammonium, nitrate and organically bound nitrogen.

Nitrogen can become available for plant use from organic nitrogen sources. Before these organic sources are available to plants (or present in the soil pore water), they must be converted to inorganic forms (mineralisation process, controlled by bacteria). Nitrogen is available to plants as either ammonium (NH_4^+-N) or nitrate (NO_3^--N).

Ammonium nitrogen (NH_4^+) is adsorbed (binds on the surface) to the soil's colloids (clay and humus), which causes it to move slowly in the soil. Nitrate (NO_3^-) is mobile in the soil, which makes it easily accessible to plants and effective as a fertiliser. On light soils and in heavy rainfall, nitrate nitrogen can be leached.

The results are based on a low number of samples but show a consistent decrease in both nitrogen (total) and phosphorus (total) levels in the soil for all cultivation beds from the 2020-08-18 to 2022-02-08. The decrease varied between -15% to -37% for nitrogen, and -28% to -44% for phosphorus (see Table 7).

Table 7. Total amount of nitrogen and phosphorous in soil (kg/ton)

Pot nr/plant species	Nitrogen (total)				Phosphorus (total)			
	Kg/ton				Kg/ton			
	2020-08-18	2021-10-22	2022-02-08	Decrease/ increase in %	2020-08-18	2021-10-22	2022-02-08	Decrease/ increase in %
1: Miscanthus 2020-05-04 - Harvest spring 2021	6.8	7.0	5.75	-15%	12	9.5	8.8	-27%
2: Fodder radish 2020-07-10 Harvested Oct 2021 and Oct 2022	9.75	6.7	6.1	-37%	20.5	12	11.5	-44%
3: Reed canary grass 2020-07-10 No harvest. Lush vegetation	8.0	6.2	5.7	-29%	16.5	10	10.75	-35%
4: Chicory 2020-07-10 Harvested Oct 2021 and Oct 2022	8.15	6.0	5.85	-28%	14.5	11	10.4	-28%
5: Rye grass 2020-07-10 Harvested Oct 2022	8.45	6.9	6.2	-26%	15.5	12	9.6	-38%
6: Rye grass + biochar 2020-07-10 Harvested Oct 2022	7.75	6.6	4.9	-37%	13	9.3	7.4	-43%

5.3 Practical experience from the field trails, including spreading of biochar

Presentation of the practical experiences of using phytoremediation at a landfill will be made in the following order:

A. Soil preparation
   a. Weed control
   b. Spreading of biochar
   c. Ploughing
   d. Harrowing
B. Establishment
C. Maintenance
D. Harvesting
E. Biomass removal and utilisation

In the section below, each segment will be commented on regarding implementation and the correlating practical experience from the field trails.

A. Soil preparation

a) Weed control

In April 2021, all established vegetation, mainly nettles and thistles, was controlled by spraying with Roundup. The control was carried out on all five surfaces, using a ramp spreader (see Figure 21). We chose to do this in mid-April for the best effect on small plants. This was successful and the nettles wilted.

Figure 21. Weed control performed with a ramp spreader and Roundup, April 2021

b) Spreading of biochar
Biochar amendment improves soil quality by increasing pH, moisture-holding capacity, cation-exchange capacity, and microbial flora (Enell et al., 2020).

The most important aspect for the purpose of reducing nutrient leakage might be the increasing ability to retain moisture (with dissolved nutrients), and it has often been shown that this, together with biochar, increases growth and yield (especially in permeable soils with a low content of organic matter).

Amendment of biochar can have a positive effect on the availability of nitrogen as the nitrogen remains in the soil instead of being lost through leaching.

Biochar was spread on plot 3. This is not common practice yet, and a trial-and-error type of approach was used. First, a limestone spreader was used (see Figure 22). This solution did not turn out well due to problems with evenly distributing the biochar along the spreader and subsequently over the trial plots.

Figure 22. Limestone-spreading agricultural equipment

Secondly, a low rotation spinning disc fertiliser was tested, with good results (see Figure 23). In total, approx. 6 tonnes were spread, i.e. approx. 10 kg/m2. The biochar content is then about 3.3% by weight. The day after spreading, the biochar was tamped down about 5-20 cm by ploughing.

Figure 23. Rear-discharge manure-spreading agricultural equipment. Low rotation on spinning disc to prevent the biochar from spreading too much with the wind

Figure 24 and Table 8 show the dispersion of total organic carbon (TOC) indicating biochar in the soil. Both the sample pit and the calculation are indications of an even dispersion of biochar in the soil.

Figure 24. The dispersion of TOC indicating biochar in the soil

Table 8. Field trial. TOC (calculated) in soil at different levels under soil surface (under the thick root system)

	Depth	Dry matter	TOC
	m	%	
Test pit 1	0-0.05	56.6	17
	0.05-0.1	43.6	20
	0.1-0.15	43.9	22
	0.15-0.20	50.6	17
Test pit 2	0-0.05	58.2	15
	0.05-0.1	50.1	19
	0.1-0.15	46.5	20
	0.15-0.20	53.9	17
Test pit 3	0-0.05	54.9	17
	0.05-0.1	42.7	21
	0.1-0.15	49.6	19
	0.15-0.20	53.4	15

c) Ploughing
Approximately 14 days after the control of nettles, the test fields were ploughed. In connection with the ploughing, the biochar was turned into the soil. Ploughing was done using conventional agricultural technology. This worked well, but unfortunately some debris was exposed. This type of debris should not be in this type of topsoil.

d) Harrowing

After ploughing the fields, plots 2-4 were harrowed to prepare for sowing. The photograph shows this being done on the plot where biochar had been spread (see Figure 25).

Figure 25. Harrowing at the field trial plots, May 2021

There was no problem harrowing at the landfill using conventional agriculture techniques. The biggest challenge was all the debris found at the surface that got stuck in the harrowing tines.

B) Establishment
Plots 3-5 were sown three days after harrowing (see Figure 26). The areas were sown using conventional agricultural technology. See Table 5 for establishment results.

Overall, sowing with this technique worked, but it would have been preferable to use smaller machines as the number of seeds for each plot was extremely small. The set-up time for each test area was therefore long.

Figure 26. Sowing seed in plot 4, mid-May 2021

Field number 2 was planted with *Miscanthus giganteus* plug plants in September 2021 (see Figure 27). We chose to plant two plants/m2. All planting was done by hand (see Figure 27). No irrigation took place after planting.

Figure 27. Miscanthus giganteus plug plants and planting, September 2021

C) Maintenance

Experience is lacking as no maintenance was carried out on any of the field surfaces. No irrigation was performed, or weed control.

D) Harvest

During the project, harvest was performed twice. Once in August 2021 and again in June 2022. On the first occasion, a machine used for park and garden management was used, an Amazon profit hopper (see Figure 28) and only field 1 with nettles was harvested. One year later we tested the use of a conventional agricultural techniques (see Figure 29). At this time all five fields were harvested. A week later the harvest was baled (see Figure 30).

Figure 28. Harvest of nettles with an Amazon profit hopper, August 2021

Figure 29. Harvest of nettles using side-mounted harvester, June 2022

Figure 30. Equipment for baling the harvest, June 2022

The practical experiences showed that harvesting with both techniques worked. However, the park machine's efficiency was too low to be relevant for regular operation of the landfill, while the agricultural machinery was too large and unwieldy for the borders, and poorly adapted for harvesting on the steepest slopes. The agricultural machines were limited to driving straight up and down and needed the ability to turn at the bottom and top, which was not possible due to the shape of the actual slope.

E) Use of biomass

During the field trials, the harvested biomass was treated by composting. From previous projects that NSR participated in (Blom et al., 2020), we know that anaerobic digestion plants have different requirement specifications for receiving "green biomass", e.g. grass clippings from parks and sports fields, energy grass, long grass from natural pastures and meadows, etc. One of the most important requirements is that the straw/blade of grass from the biomass, e.g. rye grass or reed canary grass should have a length of around 3 cm with a maximum of 5 cm. Some dry digestion plants can accept up to 10 cm.

Requirements for cleanliness, i.e. freedom from visible contamination, apply regardless of the facility type. The green biomass should also meet the criteria for approved substrates according to SPCR 120 for the biogas plant to be interested in receiving the green biomass.

In the future, the biomass could maybe be utilised at a biochar plant. NSR is building a biochar plant that will be go into operation in spring 2023. However, this plant has been built to treat twigs and branches which will not be accepted as energy grass.

5.4 Summative discussion

In this sub-chapter we discuss the connections of the results to identified conditions for phytoremediation at landfills, criteria for choice of plants, and our practical experiences, including the spreading of biochar.

5.4.1 Choice of plants

In general

It is important to choose non-nitrogen fixing plants with a high yield and preferably green and growing during the main part of the year. It is also important to choose a covering crop with a dense and lush root system. A base with a well composed mix of grass is probably a good basic solution to many covered landfills, e.g. rye grass with the addition of a grass that spread via spurs (to “self-repair” any damage to the rye grass lawn). Red fescue (*Festuca rubra*) and meadow (blue) grass (Poa pratensis) would be a good complement to rye grass.

Worth noting is that basically no flowering plants were left in field trial plot E in season two. These were probably outcompeted by plants that could better use the nutrient-rich soil, such as rye grass, nettles and thistles.

Root depth

Practical experience from cultivation beds regarding root depth confirms the literature, that there is no risk of damaging the impermeable layer with the studied plants. Although the chicory's root system is said to be 150 cm deep, the majority of this consists of small, thin roots. The same applies to elephant grass.

Uptake of nutrients

A focus on plants with a documented high uptake of nutrients was the initial plan but during the work with the MCA the importance of this factor was lowered, and a focus was placed on ease of the practical aspects. This was due to it being hard to determine the uptake from specific plants and uncertainties regarding how much of the removal of nutrients would be derived from actual uptake and from microbial processes in the soil/roots.

Harvesting

As expected, the field trials showed successful harvesting and baling of nettles, rye grass, ragwort and low-growing yarrow with a XXX and a YYY. Unfortunately, we lack practical experience of harvesting *Miscanthus giganteus*, as no plants survived the winter. However, there is considerable experience of this worldwide, for example at landfills in England.

A challenge is to find harvesting equipment of the appropriate size to suit the challenging environment of a landfill, e.g. slopes, piecemeal small roundings, gas collectors, etc.

Total economy

Each facility has its specific conditions, which must be weighed up in the analysis of whether the necessary machinery is to be owned outright, or whether the service is to be bought in, for all or parts of the work steps.

It could be more economical to buy in the services that occur once or only a few times, such as possible land preparation and sowing/establishment. Recurring work steps, such as harvesting and removal, which take place on average one to three times per year for 10-20 years, could be handled in-house with our own machines, especially if you can benefit from the work vehicle (e.g. tractor) for other work within your business.

Establishing miscanthus through plug plants was not economical in this pilot case, as no plant survived the winter. The miscanthus planted with rhizomes had 100% establishment and survival, despite moderate care.

Use of biomass

The experience from the practical trials in this pilot case is that the simplest option for utilising the harvested biomass is through composting. The less woody plants could be digested in an anaerobic digester, but this places higher demands on the harvested material (length, purity). A dry digestion facility often has better conditions for receiving plant material than wet digestion facilities, which often have narrower requirement specifications. Biochar production may be an option in the future, depending on the type of biochar plant, e.g. *Miscanthus giganteus* or reed canary grass.

When choosing the plants, the possibility of using the harvested material, for example biochar or energy production, should be taken into account. High yield plants like *Miscanthus giganteus* have been shown to be suitable for use on landfills in Great Britain and could be combined with other uses. This could improve the chance of a maintenance program being followed over a longer period of time due to the economic and environmental benefits associated with the use of biomass.

Biodiversity and other ecosystem services

Dividing the landfill area into different zones adapted to conditions that prevail at the site (slope, latitude, etc.) and with a focus on different ecosystem services, might be the best overall solution. Based on the results of this pilot case, there is a draft final cover for another landfill owned by NSR, where among many other factors taken into account, ecosystem services are included (biodiversity, recreation, energy production, water management, etc.)

When working with phytoremediation on landfills, one should take a holistic approach and look at ecosystem services in general to highlight the benefits of working with plant-based solutions. A well-thought-out application of phytoremediation can lead to increased biodiversity, value-creating biomass, increased recreational value in the form of beautiful natural environments, protection zones to minimise the transport of pollutants, etc.

Water and soil analysis

The results from the water and soil samples indicate a decrease in nutrients in both soil (15% to 37% for nitrogen and 27 to 44% for phosphorus) and water over two years. The number of individual samples stretches well beyond 100 but the sampling would need to be conducted over a longer period with more focus put on identifying seasonal variations due to natural changes to get a firm grasp on the nutrient uptake. How the decrease will change over time when the nutrient levels reduce is an important factor to consider when evaluating the efficiency of the process. Lastly, how the decrease of nutrients in soil and pore water will affect the nutrient levels in the actual runoff is another open question.

5.4.2 Practical experiences including spreading of biochar

Common to the efforts linked to soil preparation was that it works, but that it is cumbersome to work with large agricultural machines on a landfill. The surface is uneven, the areas are small in places, the slopes large, there may be hidden waste under the existing vegetation, and a close eye has to be kept on any gas wells. However, soil preparation prior to establishment should hopefully be carried out only once the perennial plants are chosen. Good preparation is essential for successful soil preparation.

One of the recurring problems with working on the surface of a landfill, especially a partly active one, is the presence of debris (see Figure 31), which generally means significantly more maintenance work.

Figure 31. Test field after ploughing, unfortunately with debris on surface(left). Maintenance work due to debris (right), May 2021

The practical aspects of the field trials showed difficulty in finding a suitable machine adapted to the conditions that can prevail in a landfill. In our case, machines designed for park maintenance had a low capacity when harvesting, while the agricultural machines were perceived to be on the verge of being too large and unwieldy.

Larger machines generally need to approach driving on the landfill up and down, without the possibility to turn on the slopes. This creates the need for a substantial area at the top (usually not a problem) and bottom of the landfill for turning. Common practice is to use diches to collect surface runoff at the base of the landfill, which may interfere with the possibility of creating room for turning and therefore the use of larger machines.

If the landfill is large enough to merit the use of larger machines to maintain the plants, the need for the machinery to turn should be taken into consideration when designing the landfill.

5.4.2.1 *Amendment of biochar*

The test at NSR indicates a positive impact (biochar in combination with rye grass) with less leakage of nitrogen.

It is important to consider that biochar is not a single homogenous type of product. The type of biochar produced depends mostly on two variables: the biomass being used and the temperature and rate of heating. Pyrolysis at low temperature (<550ºC) gives a biochar that has an amorphous carbon structure with a lower aromaticity than the biochar produced at high temperature.

In order to see the positive effects of biochar, the biochar must be mixed well with the soil in the plant layer. Since this is a fairly new application, there are no standard methods. Type of biochar (size and water content of the char) affect how well it is dispersed on the soil.

NSR’s field trial showed that spreading with a low rotation spinning disc fertiliser followed by ploughing provided an even distribution of biochar in the soil.

5.4.2.2 Maintenance

All plants need maintenance to fulfil the purpose of the planting on the landfill as a protective layer and to prevent the plants from becoming outcompeted. A thorough maintenance plan is essential.

If not properly harvested and maintained, the risk is that other plants such as nettles will outcompete chosen plants in the case of nutrient rich soils.

The plants evaluated at NSR's site could all be harvested with the same type of equipment. Note: on steep slopes, tillage and harvesting must take place across the elevation curves and it must be possible for the machines to turn at the bottom of the landfill and at the top.

However, municipal waste management actors lack experience of using energy crops on landfills to remove nutrients. Municipal waste management is also inexperienced in caring for vegetation on landfills with the aim of making use of the removed biomass, for example for bioenergy production.

5.4.2.3 Choice of soil substrate to the plant layer of the capping

The excess of sewage sludge is a problem for many municipalities and using the material for capping of landfills is a tempting solution. It might be acceptable in some conditions and with some safety measurement; however, experiences from the Filborna landfill are that spreading sewage sludge as a major part of the top plant layer is problematic due to excessive leaching of nutrients.

Use of dystrophic soil in areas where maintenance is difficult, for example on steeper parts of the landfill (gradient of 1:5 or more), is preferable due to it being easier to maintain.

6 Conclusions

The most obvious conclusion from the experiences, experiments and literature studies is that overly nutritious plant layers at landfills should be avoided and that the maintenance of the plant layer is of crucial importance in removing and reducing high nutrient levels in the topsoil.

1. The results from the pilot case indicate that phytoremediation is a feasible method to reduce plant nutrients on a final covered landfill, both from a theoretical and a practical perspective.
2. It is possible to identify and establish plants suitable for landfills with nutrient-rich plant layers.
3. Both park and agricultural machinery is needed, but it can be challenging to find machine sizes that are optimal for landfills.
4. If plants are to be regularly harvested and maintained on a landfill after (or during) finalisation, this should be considered as early as possible in the planning or construction process, and provisions, such as turning zones, should be taken into account.
5. Before establishing a specific plant, a plan for the use of the harvested material should be in place. Specifics like the size of the harvested material limit its use, for example composting, biogas, or biochar production.
6. Achieving an even spread and integration of biochar (with fine particle size) in the plant layer works with existing methods, such as disk fertiliser spreaders and ploughs.
7. The results indicate a low risk of jeopardising the impermeable layer with the root system of the plants discussed.

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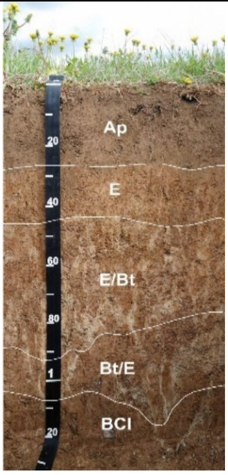
Appendix C
LAMMC, Lithuanian pilot case – additional tables and characteristics

Annex 3.1.1.1.

Soil profile structure and main characteristics

Soil profile view	Horizons	Depth, cm	Soil indicators		
			pH_{KCl}	Corg. %	Mobile Al. mg kg^{-1}
	Ap	0-30	4.32	1.42	35.9
	E	30-40	3.89	0.47	99.8
	E/Bt	40-70	3.71	0.18	142.0
	Bt/E	70-100	3.44	0.11	150.8
	BCl	100-153	3.46	0.08	211.5

Annex 3.3.1.2.

Amount of nutrients and organic matter in sewage sludge used in pilot case

Total nitrogen, g kg^{-1}	**Total phosphorus, g kg^{-1}**	**Organic matter, %**	**pH_{KCl}**
JSC Klaipėdos vanduo			
54.6	40.0	65.8	7.20
JSC Šilutės vandenys			
33.4	5.02	64.97	5.56

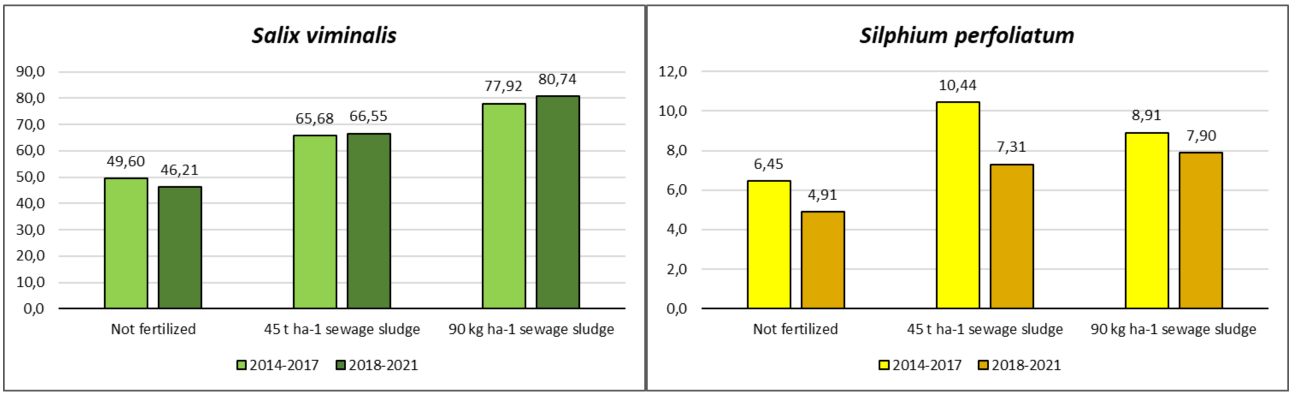
Annex 3.3.1.3.

Amount (mg/kg^{-1}) of heavy metals in sewage sludge

Zn	**Cu**	**Cr**	**Pb**	**Ni**	**Cd**	**Hg**
JSC Klaipėdos vanduo						
780	251	42.8	21.9	27.2	1.4	0.34
JSC Šilutės vandenys						
287	47.8	11.51	14.47	8.22	0.44	0.96

Annex 3.3.5.1.

Aboveground biomass dry matter (DM) yield of plants, depending on sewage sludge fertilization



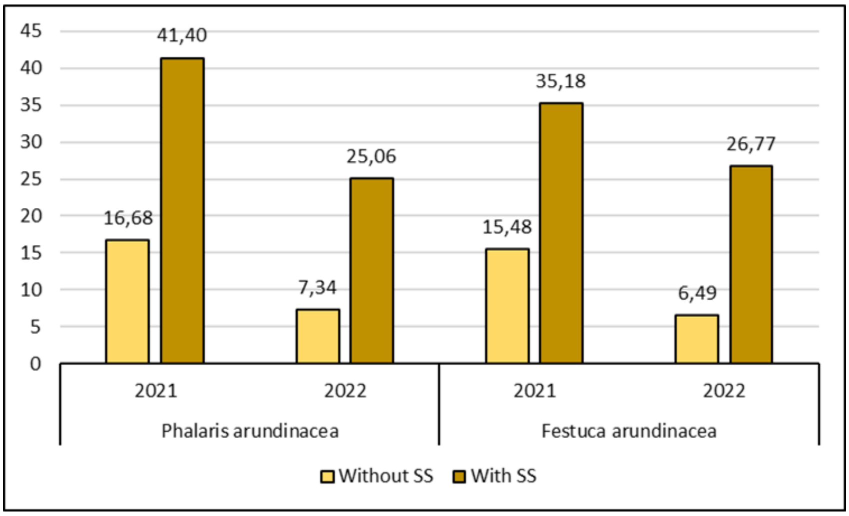
Annex 3.3.5.2.

The average annual (2014-2021) accumulation of heavy metals in tested plants' biomass (g ha^{-1})

Treatment	Cd	Cr	Ni	Pb	Cu	Zn	Hg
	Salix viminalis L.						
Unfertilized	36.21	7.09	22.17	25.90	229.2	2462	>1
45 t ha^{-1} SS	28.31	9.92	31.84	31.59	**278.6**	**3500**	>1
90 t ha^{-1} SS	**48.06**	14.07	**75.60**	**49.38**	**342.8**	**4173**	>1
	Silphium perfoliatum L.						
Unfertilized	0.371	1.034	2.615	1.636	28.12	99.99	0.04
45 t ha^{-1} SS	0.629	1.594	**6.039**	2.118	**62.35**	**149.29**	0.07
90 t ha^{-1} SS	0.872	2.045	**10.695**	3.618	**47.50**	**231.84**	0.09

Annex 3.3.5.3.

Aboveground biomass dry matter (DM) yield of perennial grasses, depending on sewage sludge fertilization



Annex 3.3.5.4

Heavy metals accumulation in *Miscanthus giganteus* and *Artemisia dubia* aboveground biomass (g ha^{-1})

Crop species	Without (-) and with SS	**Heavy metals**					
	- /+*SS*	**Cd**	**Cr**	**Ni**	**Pb**	**Cu**	**Zn**
Miscanthus giganteus	-	0.03	42.41	32.79	0.04	33.79	78.03
	+SS	0.04	63.40	29.09	0.05	55.05	106.55
Artemisia dubia (cutting (in July)	-	0.03	21.55	18.06	0.70	33.74	135.40
	+SS	0.06	51.35	57.17	0.91	95.280	504.17
Artemisia dubia (cutting in October)	-	0.05	66.55	17.75	0.07	40.30	165.31
	+SS	0.09	**135.38**	**145.84**	0.13	**118.32**	**309.29**

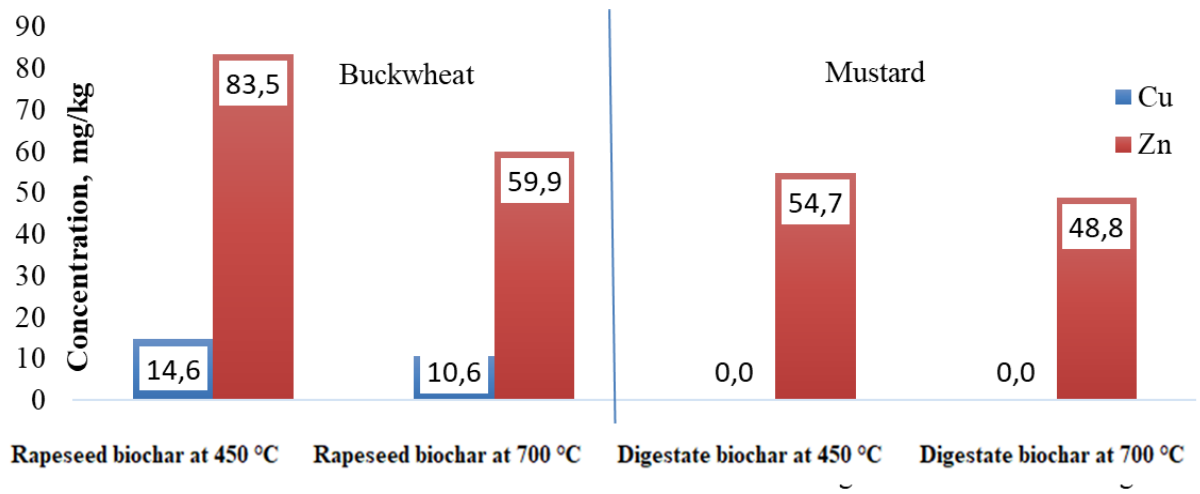
Annex 3.3.5.5

Heavy metals accumulation in *annual crops* aboveground biomass (g ha^{-1})

Crop species	Without (-) and with SS	Heavy metals					
	- / +*SS*	**Cd**	**Cr**	**Ni**	**Pb**	**Cu**	**Zn**
Helianthus annuus	-	0.12	7.75	207.95	0.17	314.72	760.43
	+SS	**0.20**	**172.00**	**589.29**	**0.29**	**336.11**	**1191.16**
Zea mays	-	0.11	95.09	181.10	0.15	170.75	172.58
	+SS	**0.25**	**275.99**	**406.44**	**0.36**	**448.17**	**1409.72**
Fagopyrum	-	0.02	10.95	17.73	0.02	22.47	70.80
	+SS	0.01	9.11	20.05	0.02	20.14	94.14

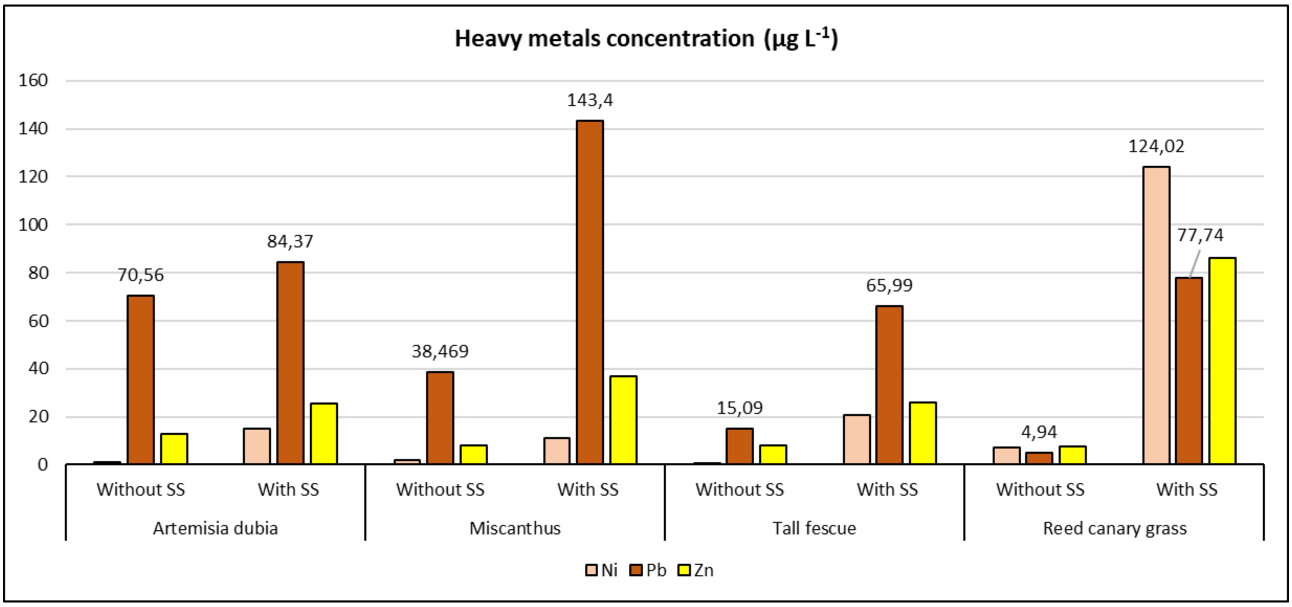
Annex 3.3.5.6

Heavy metals concentrations in the aboveground sections of plants



Annex 3.3.5.7

Heavy metals concentration in lysimeter water in perennial crops growing site



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