Phytoremediation as Accelerator of Transformation towards Regenerative Cities

A Nature based solution for environmental pollution

Tim Grotenhuis, Lars van Vianen, Anke Wijnja & Jeroen Bruijnes

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Wageningen, July 2022

Client: Scape foundation
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The Netherlands

The Scape Foundation was founded in 2020 to enhance the biodiversity and liveability of urban communities for all living things. The foundation connects researchers, designers and developers to create sustainable and future-proof green ecosystems through open-source projects, research, data and tools.

Stadswende

Stadswende aims to contribute to a greener, more sustainable Netherlands by advising on sustainability projects of governments. This often requires a switch, a turn of the current spatial planning, to a more sustainable and circular design for the use of energy, water and raw materials in the city.

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Together with clients, partners and stakeholders, the Biodiversity & Policy team works to realize a robust, sustainable, liveable, profitable and biodiverse landscape. This on both international and local level. In our research we assume that nature offers solutions for many issues on the road to a sustainable environment.

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Civil society organizations such as citizens' initiatives, associations and interest groups, which do not have sufficient financial resources, can turn to the Wageningen Science Shop with research questions. This provides support for the realization of research projects. Applications must be in line with the work areas of Wageningen University & Research: sustainable agriculture, food and health, a liveable green space and social change processes.

Content

Preface

Our existential stability on Earth resides in the variety of life that it harbours in its natural habitats and the dynamic relationships that arise within them. Biodiversity is the reason and the prerequisite for natural life, whereas it provides clean water, fertile soil, resource-rich food, the raw materials for housing and a stable climate for all life on earth. These very same dynamics enabled the emergence of cities, through which they give rise to a plethora and crossing of cultures, emotions, ideas, and innovations.

On a very fundamental level, nature has always been the key enabler of human ingenuity; both presenting its fundamental conditions in the now, as sparking inspiration for the next. In turn and paradox, industrial evolution has led to a disconnect and degenerative relationship with nature. If we continue this patch, we will deplete essential resources beyond replenishment, destroy ecosystems on a massive scale beyond repair, and as such irreversibly destabilize the natural realm that sustains us.

Within the common realisation of this existential urgency in the last two decades of the 20th Century, we coined our own definition of sustainability. A regained environmental awareness through which we envisioned practices that reduce waste and pollution. In the first two decades of the 21st Century we further developed this into net-zero processes along circular lines of thought. Today, almost all new buildings in our urban environments employ environmentally responsible systems and strategies to lower their negative impact on our planet.

Although we are indeed steadily slowing the rate of destruction, we are yet to regain resources and repair ecosystems once lost. Instead of shifting responsibility to future generations, the time is now to truly create a future-proof built environment, based on net-positive principles and regenerative strategies.

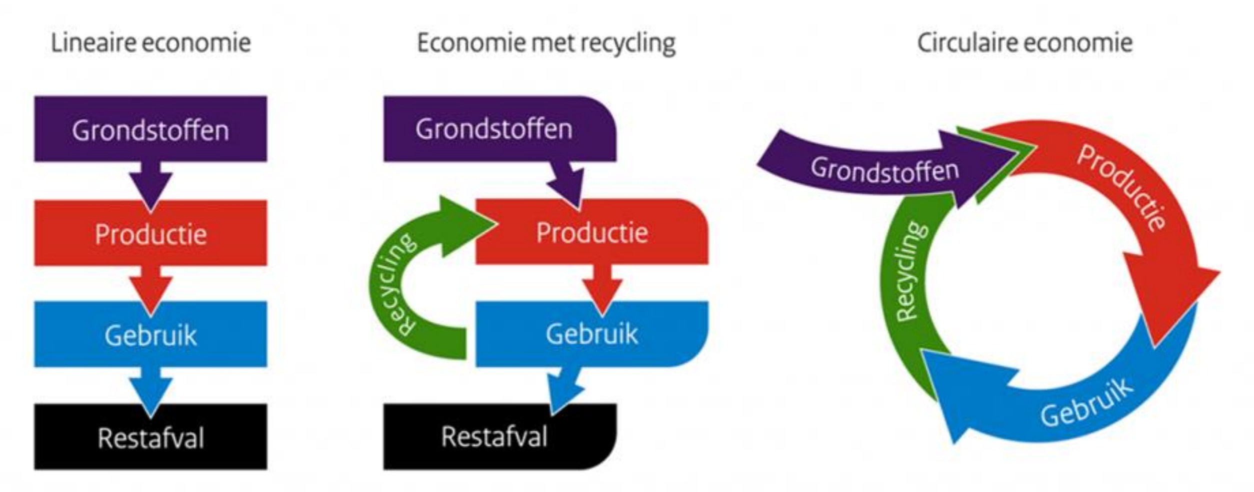

Figure 1 Concept linear economy versus circular economy (See: https://aboutcircular.nl/2019/11/18/het-verschil-tussen-een-lineaire-economie-en-een-circulaire-economie/).

The goal of regenerative design is to create net-positive actors that restore, renew, or revitalise the environment. This requires an ecological perspective on the world, in which there is a shift in focus from objects to relationships. Rather than only design the life cycle of an object, we need to design the cycle of life through an object. Buildings must not only constitute an intrinsic socioeconomic value, but actively contribute to the ecosystem services in their surroundings. Materials cannot merely be circular or biobased but must in themselves be alive to catalyse a net-positive dynamic.

Within such living design systems, in contrast to the modernist approach, a single component is never discreet, and can never be seen as independent. Regenerative design rather implies a multi-scalar approach based on Micro-Meso-Macro systems thinking, which embodies biodiversity through Meta-interdependence. A single intervention or action is always negotiated through levels of scale in order for the whole to be able to operate to life. The design and development of the built environment will therefore increasingly become scale-agnostic. If one designs a façade component on a meso-level, one must also consider the molecules that constitute it and the building it constitutes.

Now, our technological advent is such that we indeed can design on these different levels of scale in symbiosis. The domain of the meta-designer is to bend once linear processes into spiralling crossovers between emerging technology disciplines. It is in this very endeavour that regenerative design becomes a driver for innovation and a true symbiotic co-evolution of nature and technology can one again be found. Phytoremediation technologies embody this intersection – let technology become wild again!

Lars van Vianen
05-2022

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Summary

The linear use of land is informed by economic activities, often resulting in depleting or polluting characteristics, which eventually lead to land abandonment. For land use to become circular, more so regenerative, the land must be remediated in ways through which it becomes usable and useful again. Especially given the modern demands for the lands we cultivate, it becomes increasingly important to think of ways to restore and revitalise sites once contaminated. Phytoremediation is a natural process in which plants are used to remediate contamination, and therefore opens the possibility for a net-positive balance. The actual removal rate of heavy metals and other forms of pollution might be low, but the process of phytoremediation has a wide variety of benefits which can become key to accelerate the transition from contaminated sites into a new phase of land use. As an integrated ecosystem process, phytoremediation could offer a plethora of positive side-effects, by for instance improving the local biodiversity through a careful selection of plant species. Furthermore, it could prevent wind- and water-erosion and in synergy make lands useful for ecological, economic, and social activities. This paper addresses the basic soil remediation aspects of phytoremediation, whilst offering an onlook into the additional benefits of such plants within the context of ecosystem value. These key benefits of phytoremediation are subdivided into ecological, economic, social, and technical aspects. Together, these aspects make phytoremediation useful as an accelerator from contaminated site to a new phase of land use. Transforming linear land use into circular land use and contributing to sustainable land use practices.

1 Introduction

The Dutch soil is polluted at approximately 250.000 sites (RIVM, 2018). The progress of the Dutch soil remediation was reported in an annual report (Jaar verslag bodemsanering, 2009). The last report was in 2009. This changed in reporting the progress of remediation of emergency locations (spoedlocatie). Emergency locations are locations that pose an unacceptable risk to humans, ecology or the spread of contaminants in groundwater. The progress of remediation of emergency sites is slow (Figure 2) and costly. There are no recent reports on non-emergency sites. Changing the land-use of a non-emergency site could make the site an emergency location. Therefore, governments will not easily change the land-use of a contaminated site. This could create an emergency site and therefore increase the costs for remediation. This leads to many old industrial sites in the Netherlands that are not used and not remediated. The question is how can we start using these sites regeneratively instead of leaving the problem for future generation to solve.

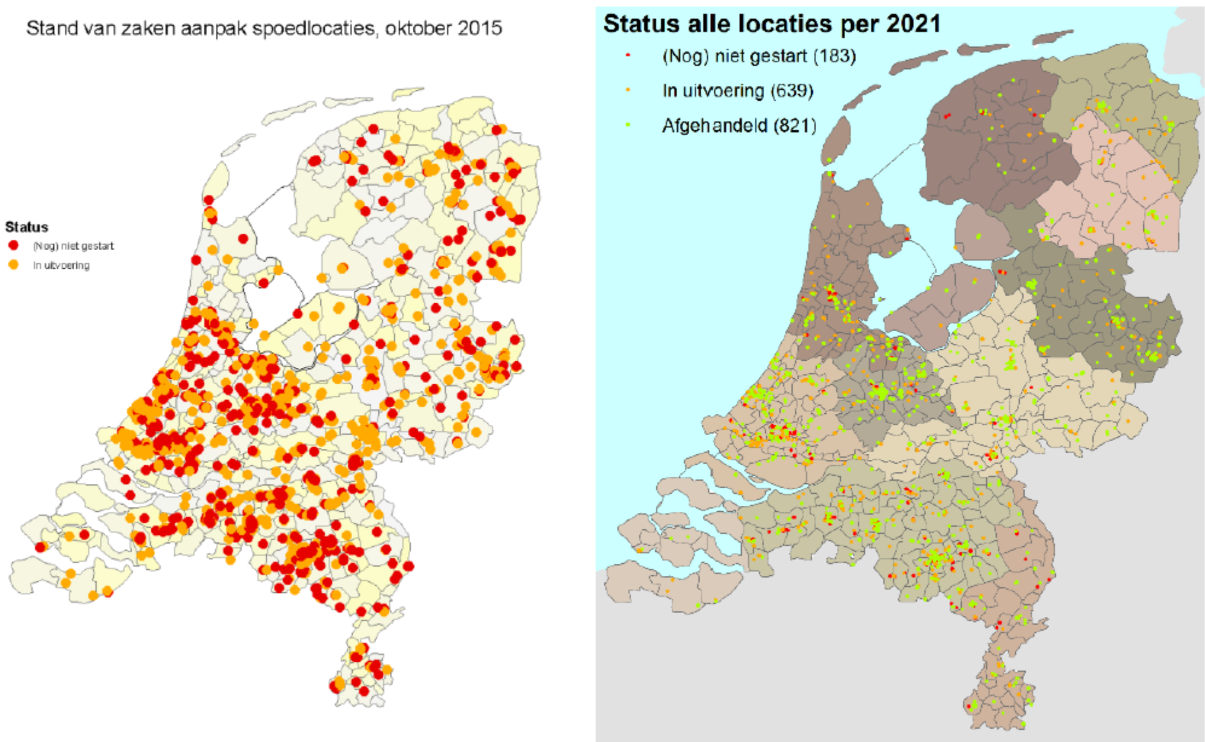

Figure 2 Progress on emergency location of soil contamination in the period 2015-2021. Source: Rijks Water Staat (RWS), 2022.

1.1 Phytoremediation

What is phytoremediation?

Phytoremediation is an umbrella of nature-based technologies that exerts the use of plants and associated micro-organisms towards the removal or breakdown of toxic environmental contaminants. For instance, the use of plants to remediated soil contaminated with heavy metals.

Phytoremediation is based on the interactions between the soil, its contaminants, its inhabiting micro-organisms and the plants that grow upon it. These interactions include the volatilization by plants, the uptake of contaminants via plant roots leading to extraction and the biodegradation by plants or in the interaction between plant roots and soil micro-organisms. An overview of the seven most common phytoremediation methods, including Phytoextraction, Phytostabilization, Phyto-immobilization, Rhizofiltration, Phytodegradation, Rhizodegradation and Phytovolatization (Trapp et al., 2001) is presented in the figure below (Figure 3).

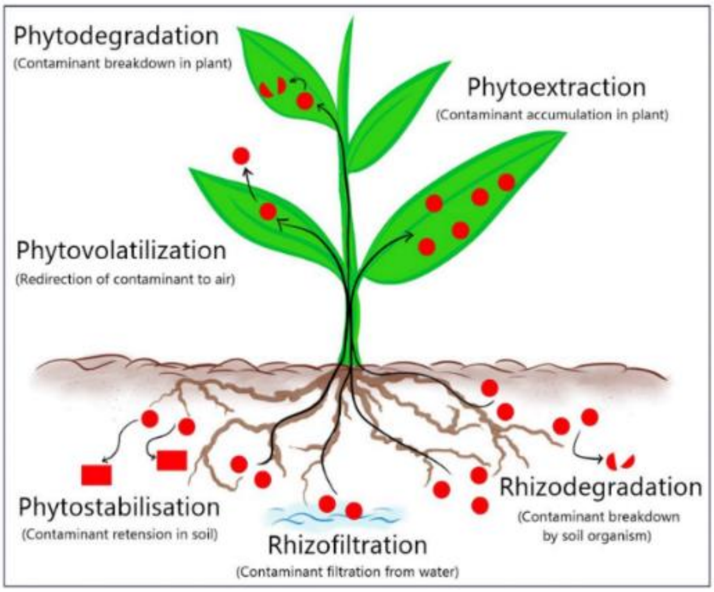

Figure 3 Different methods of phytoremediation. The contaminant (represented by the red circles) can be stabilized broken down in the rhizosphere, accumulated or degraded inside the plant biomass, or be volatilized into the atmosphere.

1.2 Land Use Cycle & Phytoremediation

Applying phytoremediation could help to transform contaminated sites. The large demand for land makes it important to redevelop sites with soil contaminants. In the concept of the Land Use Cycle (Figure 4), the goal is to create a new land use when the former land use ceased. To start with the new land use a transition from the old land use to the new land use is a necessary step. Such transition phase in the case of land with soil contaminants could be accelerated by phytoremediation. In other words, using phytoremediation as an accelerator of transformation towards regenerative cities.

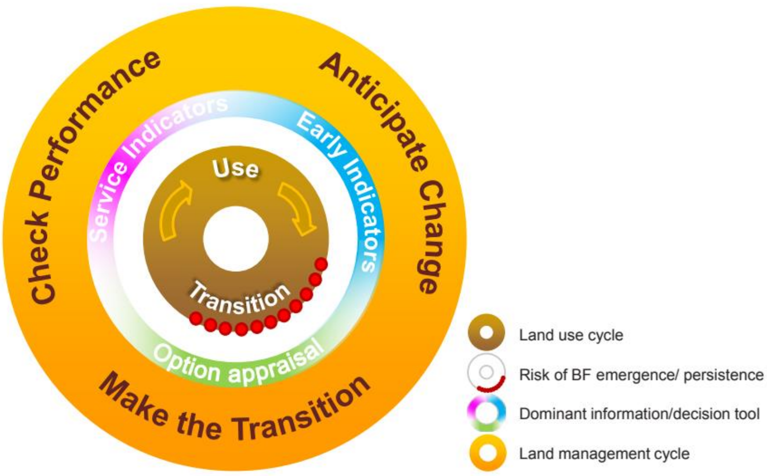

Figure 4 The Land Use Cycle (http://www.zerobrownfields.eu/content.aspx?wp=3&p=227).

1.3 Key aspects of phytoremediation

Phytoremediation is often studied from the specific perspective of soil remediation and mentioned as nature-based alternative to traditional chemical and mechanical solutions. When studied in more detail it becomes clear that the time needed for phytoremediation is long, as heavy metal pollutants in plants need aftercare and only contaminants close to the soil surface can be dealt with. However, phytoremediation could help to start the land-use-cycle and use the land regeneratively instead of starting with remediation when the land-use is formally changed, and the site becomes an emergency site. Furthermore, the use of plants also has other benefits for biodiversity and society.

The transition phase for a contaminated site into a useable site can be accelerated using plants. In order to use plants as accelerators certain key aspects need to be considered. In this report we will refer to these aspects as the key aspects of phytoremediation. The key aspects of phytoremediation are:
1. Ecological aspects
2. Economical aspects
3. Social aspects
4. Technical aspects

These key aspects could help city planners and landscape architects to start phytoremediation projects and accelerate the towards regenerative cities.

1.4 Scope

The chapters 2 to 5 describe the key aspects of phytoremediation from an ecological, economic, social and technical perspective. Chapter 6 provides a case study of De Ceuvel in Amsterdam. Chapter 7 describes how the key aspects can be used to transform an unusable site into a useable site and advice is giving to order information on a digital platform for phytoremediation.

2 Ecological aspects of phytoremediation

2.1 Introduction

Urbanization and industrialization have led to increasing levels of pollutants in the environment, especially in the soil. Heavy metals and polycyclic aromatic hydrocarbons (PAHs) are abundant in urban areas in the Netherlands and cause serious concerns about their toxicity levels in relation to plants, animals, and humans.

For city planners and landscape architects willing to work with phytoremediation, it is important to know what kind of pollutants are present in the project area, to be able to select the proper plants to implement in their designs. In principle, basic information on soil pollution is available at municipalities, however this information is hard to find for specific locations.

2.2 Soil contaminants and bioavailability

At first sight, the concentration of contaminants – most often heavy metals and PAH – is relevant information on the status of the ecologic effect to the environment. However, next to the amount or concentration of contaminants, information about the route for uptake in the ecosystem is also crucial for the effect of contaminants to the ecosystem.

In the research of the last two decades, the route and rate for uptake in the ecosystem has been studied for both heavy metals and organic compounds like PAH. An important phenomenon that determines the risks of contaminants in the soil refers to the increased binding over time of contaminants to the soil and is referred to as a lack of (bio)availability. At low availability levels, the uptake in the ecosystem is low, and environmental risks are lowered compared to those of the total free concentration of contaminants. Several science-based tools have been developed to measure the availability of metals and PAH. Such studies showed that the risk of pollutants in soil for the ecosystem and humans are in general lower compared to the total contaminant concentration levels of regulatory standards.

Although in science the bioavailability studies are well accepted, this concept is rarely integrated into regulatory standards, residents at urban redevelopment sites are in general enthusiastic about the idea that plants can be used to remediate soil contamination either by immobilization of heavy metals into the plant itself or by conversion of the contaminants. Often people have a broader interest in functions of plants, like increase of the liveability of the site, noise reduction, cooling down the urban heat island (UHI) effect, improvement of air quality by reduction of dust via adsorption to leaves and improving the biodiversity.

2.3 Increasing biodiversity

Plants can increase the green infrastructure in an urban environment and thereby improve biodiversity. In urban areas, an increase of buildings and infrastructure, leads to a loss of biodiversity. When green areas become smaller than 50 ha and isolated from other green infrastructures, the environment will lose biodiversity as survival of various species is reduced. Smart design of vegetation structures will benefit other species, while increasing the connectivity between patches by providing corridors can benefit small mammals, insects and birds. By increasing the green infrastructure, they will be able to sustain viable populations for certain species.

Literature study showed that in urban spaces, the species richness and diversity are generally lower for animals like birds and arthropods than in natural areas. There are efforts in some areas that attempt to reconstruct the natural vegetation prior to urbanization of the area to restore native biodiversity, increase vegetation heterogeneity, and enhance overall biodiversity. The discussion about restoration of biodiversity in cities is also linked to the choice of plants for phytoremediation.

For the choice of plants, several aspects play a role, such as: native versus non-native species, hyper accumulators versus normal plants, food crops versus non-food plants, interaction of plant roots with soil fungi and soil micro-organisms, as well as even more complex interactions of plants with contaminants and the environment.

2.4 Choice of plants

At contaminated sites, non-native species are often chosen for their contaminant removal capacity. However, these species may have a negative long-term effect on biodiversity, as they may outcompete native plants or are not suitable for native insects and pollinators.

Some researchers search for hyper accumulating plants, which can accumulate heavy metals form the soil in high concentrations in their biomass. However, from the point of view of removal of metals by such plants the yearly produced biomass is often small. Furthermore, such hyperaccumulating plants only grow in specific extreme environments. In some cases, it can be more effective to select plants that accumulate relative low amounts of heavy metals in there biomass but grow relatively fast. Because of the growth rate these plants could be more effective than hyperaccumulators.

Heavy metals cannot be biodegraded, as they are per definition non-degradable. However, such metals can be translocated in the plant, meaning that metals will be transported from roots to shoots or even fruits (See: Figure 1). Especially translocation to fruits increases the risk for uptake in the food chain. Therefore, many scientists recommend using non-food crops for phytoremediation.

A general advantage of plants is that they interact in the rootzone with all kinds of microbiota in the soil, that help in biodegrading contaminants. In literature widespread information can be found about *Rhizobia* bacteria that live in symbiotic relation with specific plants. For instance, Legumes (*Fabaceae*) contain bacteria that fix nitrogen from the atmosphere after becoming established inside the root nodules. Furthermore, plants can stimulate bacterial growth by exudates, compounds excreted by plant roots. Therefore, plants can also stimulate a wide variety of bacteria in soil.

2.5 Plants decrease erosion

In urban areas with soil contamination, wasteland with bare soil often occurs in locations, such as: former gas work sites, former harbours, industrial sites, dumpsites and at demolition businesses. On these sites, bare soil can lead to wind and water erosion and the spread of contaminants in the environment. Planting these sites helps to decrease the effects of wind and water erosion and reducing the negative impact of the contaminated sites on the environment.

3 Economical aspects of phytoremediation

3.1 Introduction

Economic aspects of phytoremediation include a variety of topics. Many of these topics were investigated in more detail in the student report upon the values of phytoremediation (De meerwaarde van fytoremediatie, UvA, 2022). In this section the key aspects are addressed: circularity, soil, biomass, environmental quality and spatial and temporal scales.

3.2 From linear to circular

At present, economy is seen as a linear process in which resources are converted into products and end as waste. Since the start of environmental technology, about 50 years ago, it is aimed at closing cycles by converting waste into resources again, as in biological cycles. In the last 10 years, it has become clear in a large part of society that more attention is needed for a new approach to design, which is not focused on the product and its use, but on the whole life cycle. In such circular economical thinking, the focus is on converting waste into raw materials so they can be reused. Such circular economy would ideally be driven by sustainable energy.

Several theoretical models are under development for circular economy in which stages in the development from linear to circular economy can be recognized as in the schematic figure below (Kirchherr et al., 2017).

As phytoremediation is done by plants and thereby organic, it can be expected that the products of phytoremediation can fit to the circular economy. In the sections below various attempts to increase circularity are discussed.

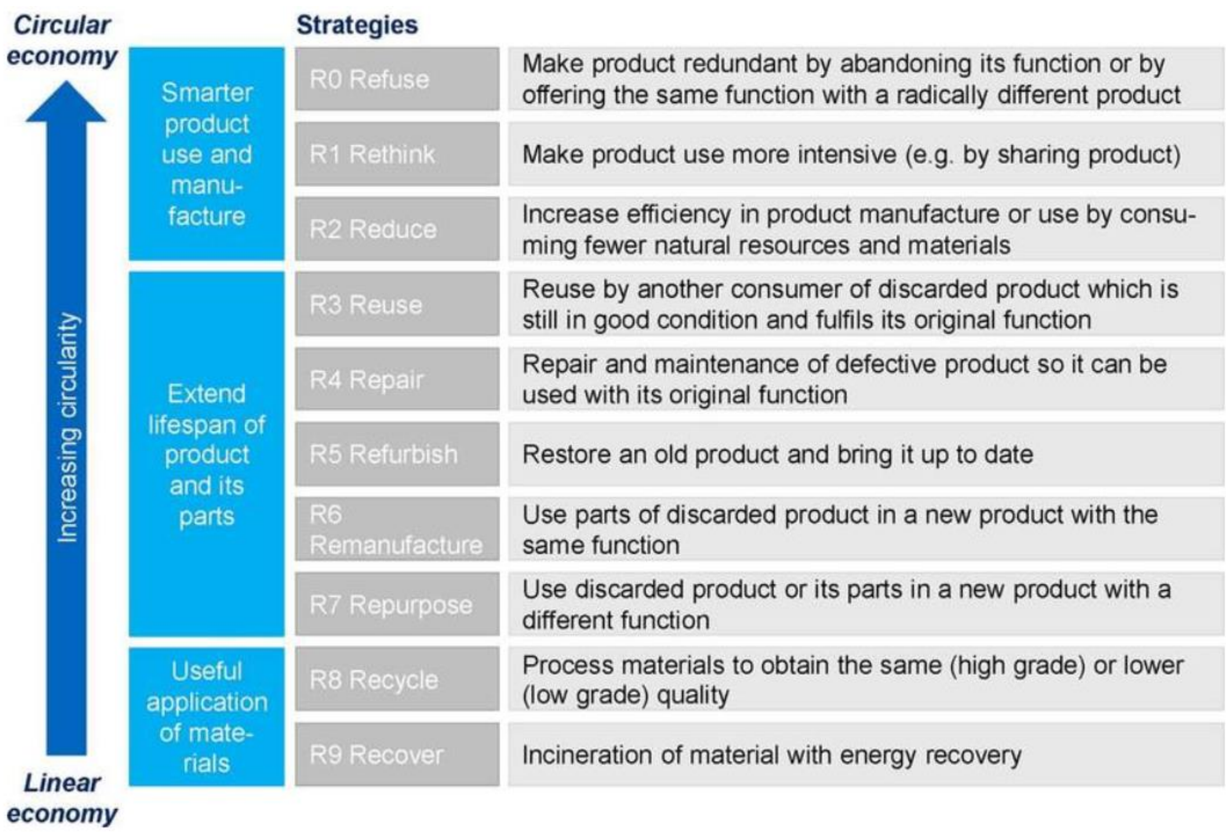

Figure 5 The 9R Framework (Kirchherr et al. 2017).

3.3 Mining metals from contaminated soil using plants

In phytoremediation of soils, heavy metals can be concentrated in plants, whereas organic contaminants like PAH are most often converted into harmless products. It is relevant to know where heavy metals end up in the plant. For example, when the contaminants accumulate in the fruits or edible parts of plants, it is recommended not to use such plants to avoid uptake of contaminants. For this reason, it will be more economic feasible to use phytoremediation plants as biofuel, resulting in ashes with very high concentrations of heavy metal. Although this sounds attractive, extra handling will be needed to harvest the plants and transport them to an incinerator for energy production and thereafter collect the highly contaminated heavy metal ashes. In most cases the mix of heavy metals in the ashes is hard to use for mining metals, as for mining the concentrations are often too low and the mix of metals is too complex to be economically feasible. Furthermore, it became clear that incineration of biomass has a negative impact on air quality. After the incineration of biomass, the ash that is left over will contain the metals. Such ashes must be stored in a special dumpsite. Experiments showed that although metal concentrations of ashes are high, they are not fit for mining, as the composition of the ashes is too complex for economical use.

3.4 Economic use of plants

During the process of phytoremediation plants can be harvested for use of the biomass in all kinds of products. Also, when the seeds are not affected by the contaminants, they can be economically used e.g., rapeseed. Other plants like hemp are used as isolation materials in buildings. Also, experiments were done with willow trees and elephant grass (*Miscanthus)* as these plants grow fast their production per hectare can be high with a relative low concentration of contaminants. In contrast some plants show a high percentage of metals in the dry matter (so called hyper accumulators) but have a low biomass yield. Native species like willow are well known for their applications in various tools and have a relatively large yield.

Fruit bearing plants and trees can be used to create woods or parcs for picking fruits (voedselbos). However, care with plant selection is needed to avoid uptake of contaminants in the fruits which otherwise will result in uptake in the food chain.

Allotment gardens can deliver social coherence and therefore be of economic impact, however consumption of home-grown food in contaminated areas led in the past on the ban for consumption of these products. In such cases ornamental gardens impose less risk, as there is lower chance of uptake of contaminants via plants.

3.5 Environmental quality

A green urban environment is often recognized as valuable by inhabitants. An example is Griftpark in Utrecht, that has a long history due to the former gas works, which belongs now adays to the most popular parcs of the city. Although phytoremediation is not applied at Griftpark, the quality of a green environment is highly appreciated by the public. Such parc has many functions varying from children’s farm to festival area.

Other aspects include the catchment of dust to improve air quality, noise reduction as well as the lowering of the temperature leading to a substantial reduction of the urban heat island effect. In all green areas, but especially at larger areas like parcs the water bearing capacity can help to reduce flooding.

The appreciation of a good environmental quality can lead to a higher value of the soil and the surrounding area. As phytoremediation reduces the concentrations of contaminants an increase of soil prices is expected. This price increase is mainly due to the lift upon the ban of soil uses, caused by the former soil pollution. Especially when soil becomes fit for building of houses the soil prices increase.

By phytoremediation a chain of subsequent activities may result in the direction of a liveable and sustainable city. In the land use cycle (Figure 3) old industrial areas with contaminated soils, can be remediated by phytoremediation leading to a cleaner and greener environment. Such green environment is appreciated for its good environmental quality, leading to a new phase in the land use cycle.

3.6 Spatial and temporal scales

In phytoremediation plants can take up contaminants from the upper layer of the soil, however the uptake rate is slow. Therefore, phytoremediation will take more than a decade to realize a significant lowering of contaminants in the upper 1 m of the soil.

To be a successful strategy from economic perspective, a plan on the long-term is needed as well as a relatively large site of application. Sites smaller than 1 ha are not feasible from an economic perspective. Therefore in e.g., the case study of Havenstad in Amsterdam, where building activities will only start after 2029 and an area fit to house over 100.000 people phytoremediation can become economic feasible when it will start on short-term.

4 Social aspects of phytoremediation

4.1 Introduction

In the UvA student report 'De meerwaarde van fytoremediatie' the social impact of phytoremediation showed that the well-being of individual people and even the social coherence in a neighbourhood can improve. The key social aspects are discussed below.

4.2 Health

When trees and large plants are used for phytoremediation, it is proven that people attach to this green environment, especially when it has the minimum scale of a park. Even increase of mental health is reported when there is a view on green environment. However, it did not become clear whether aesthetics of the plants can improve the mental health of people.

4.3 Environmental quality

Plants can improve the liveability of people. Except the direct effect of phytoremediation on soil contaminants, plants also result in other improvements of environmental quality, like reduction of noise, smog and temperature. Due to wind and the physical barrier by the leaves of plants, noise pollution will be masked and reduced. Dust particles will stick to the leaves and will be thereafter washed away by rain to the soil surface. Larger plants and trees create shade and will reduce the temperature increase in summertime to create a more liveable environment. Due to this temperature lowering less ozone production occurs, leading to less smog formation.

All these physical interactions of plants with the environment improve the liveability of people, leading to a better social climate.

4.4 Education

In interviews with residents, it became clear that the awareness of people increases when they were involved in phytoremediation projects about environmental pollution. This was not only limited to awareness about soil contaminants in their environment, but also in broader sense, people became more aware upon the connection of individual choices and environmental quality, climate change and interest in the importance of biodiversity.

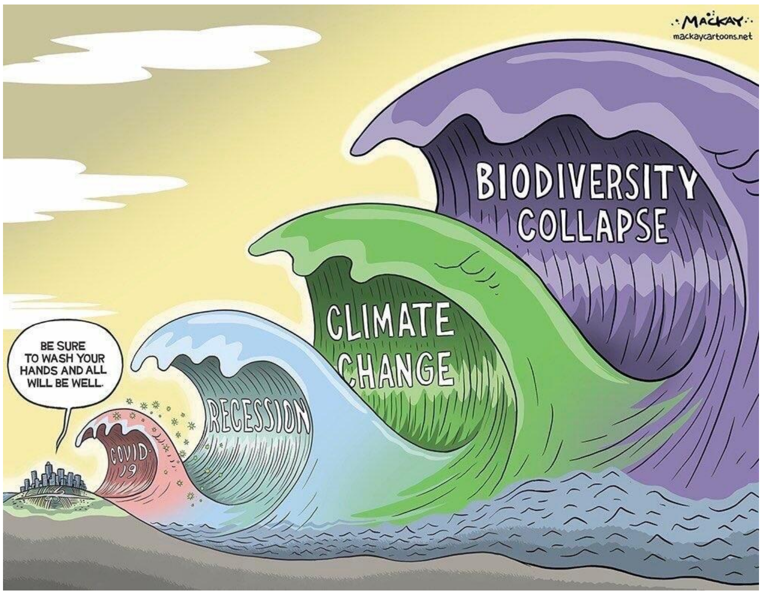

Figure 5 Image of the crises that humanity face (mackaycartoons.net) (https://www.google.nl/search?q=cartoon+covid+biodiversity+collapse&source=lnms&tbm=isch&sa=X&ved=2ahUKEwjXy8Tjzqn2AhWB76QKHZ6DBl8Q_AUoAXoECAEQAw&biw=1280&bih=569&dpr=1.5#imgrc=mN-L_0QgdSsjKM).

4.5 Social coherence

When residents are participating in the decision-making process of phytoremediation, the social coherence in a contaminated area is increasing. This is not only realized by the formal process of the planning and organization of phytoremediation project, but is also strengthened by increasing informal interactions between residents when people are enjoying the public green environment and stay for longer time to have a drink, lunch etc.

Phytoremediation can strengthen the social coherence in a neighbourhood, however it is still unclear how to design and create a qualitative good environment including improvement of the social aspects.

4.6 Safety

Trees and shrubs can also make people feel unsafe. This is because trees and shrubs can block the view and provide spaces for people to hide in. The unsafe feeling near greenery is more present in women than men and occurs more often in urban areas. The safety of greenery can be improved by regular pruning of trees and shrubs in a way that they do not block the view or provide spaces to hide in.

5 Technical aspects of phytoremediation

5.1 Introduction

In this section the technical aspects of phytoremediation are addressed that are involved in the removal of contaminants from soil – what happens in the plants and the root zone, where do contaminants go in plants and after the plant is harvested what to do with plant residues?

5.2 Interaction plants with soil and contaminants

Soil contaminants can only harm the health of people when they are taken up by them. Therefore, plants can also function as a pure physical barrier between soil contaminants and people. In scientific papers this approach is known as the source-path-receptor approach in which the receptor (people) is protected when the source of the contaminants is removed or the path to the receptor is blocked. In the case of plants as physical barrier, you can think of a plant with thorns, such as a rose that avoids people or children to start digging in contaminated soil.

Most phytoremediation projects are aiming at the removal of contaminants, thus removing the source of contamination. A major problem is the limited depth of the root system of the plants leading to only the removal of contaminants in about the upper 2 meters of the soil. Contaminants in deeper soil layers cannot be reached by plants. This is an important limiting factor of phytoremediation, however, most people are not in contact with contaminants deeper than 2 meter and therefore risks for uptake are limited by contaminants in deeper soil layers.

Although chemical analysis may prove soils are contaminated, the chance for uptake by people, as well as plants and bacteria, is limited which is caused by a process that is known as ageing. Due to ageing the binding of contaminants to soils increases over time (decades). In science this phenomenon is defined as limited bioavailability, which is dependent upon many factors and therefore cannot be predicted by modelling. Several methods have been developed for measuring the bioavailability for heavy metals as well as for organic compounds like PAH and Total Petroleum Hydrocarbons.

The negative side of limited bioavailability is that the contaminants cannot be removed from soils. The positive side is, that uptake by people of these strongly bound compounds is unlikely to happen and therefore the uptake risk of aged contaminants is minimal, which opens the route to apply phytoremediation also at concentrations above intervention value at limited risk.

5.3 The time it takes to phytoremediate

Full removal of soil contaminants from the upper soil layers requires quite some time. As metals are elements and therefore not biodegradable, the only way to remove metals from the environment is uptake by plants. Therefore, the metals that are moved from the soil to the plants must be harvested yearly. Agricultural crops can produce about 10 ton of dry plant material per hectare on yearly basis. Such agricultural plants have a nutrient content of about 1% and much lower concentrations of metals. These plants can remove 100 kg of nutrients per hectare per year at most. For a soil with 1 gram of metals per kilogram soil it can be calculated that at a constant removal rate by these plants it will take 200 years to remove all metals.

To speed up this process several scientists selected plants that can accumulate metals up to 10% of their dry weight. Unfortunately, these plants grow slow and the maximum yield per ha per year is lower. If you assume a yield of 1-ton dry weight per hectare per year, it will still take 20 years to remove all metals.

Another aspect is the limited depth of the roots to reach the contaminants as discussed above.
To reach a significant remediating effect of the upper soil layers of contaminated soil a period of about 10 years looks realistic from a technical point of view. In the transition of former industrial areas or old harbour areas to residential areas the time frame for spatial planning of about 10 years can be realistic to apply phytoremediation as intermediate use.

5.4 Fate of contaminants

In phytoremediation it is relevant to know what happens to the contamination after uptake.
For heavy metals it is known that they end in the stem, branches or leaves of the plant.
Organic compounds can be biodegraded in the root zone of the plant. Scientists have proven that microbes near the roots can be stimulated in their activity by compounds from the plants that have a positive effect upon the growth of the microbes. Unfortunately, evaporation of volatile organic compounds may lead to the transport of contaminants from soil to air, known as phytovolatilization. This process is not likely for heavier compounds as PAHs. In general, the organic contaminants can be biodegraded to harmless minerals as CO_2 and water.

In contrast to organic contaminants the heavy metals will stay in the plants, until they are used e.g., as energy source.

5.5 Concluding remarks

The technical aspects show that at least 10 years is needed to reach a significant removal of contaminants from soil. In the land use cycle, the intermediate use of plants in the transition from contaminated areas to residential areas or other destinations, might well work.

The technical perspective is rather narrow and as stated above except for the action of removal of contaminants as well as the physical blocking of the path of contaminants has a positive effect to reduce risks for humans. The technical aspects together with ecological, economic and social aspects, make phytoremediation useful as an accelerator from contaminated site to a new form of land use.

6 Case study the Ceuvel Amsterdam

6.1 Intro

De Ceuvel is a temporary incubator in Amsterdam Noord, where creative people and small businesses - working on social or environmental sustainability - find an inspiring and affordable workplace. The site of De Ceuvel is a classic “Brown Field”: for the last century it was home to a bustling shipyard that, when closed down, left the area contaminated. The contamination that occurred consists mainly of PAHs and heavy metals including lead, zinc, cadmium and copper. During the 10 years of loaning the land, The Ceuvel tries to clean up the land during its use. The site has semi-public access and is a popular green oasis for many city dwellers in summer and spring.

6.2 Ecological aspects

Lesson 1: Working with nature rather than against it
For phytoextraction, the starting plan was a more traditional ‘planting scheme’: mono planting in different zones, assuming a kind of ‘blank’ start. That turned out not to be feasible: the otherwise unworked soil was so full of strong, wild seeds that the plants planted and sown had no chance. The intensive management required for its implementation was not within our capabilities. It also felt contradictory - putting in so much energy to create a monoculture, while a mix of plants creates biodiversity and does more with the mix of pollution.

From the third year onwards, we have therefore been fully ‘collaborating’ with nature: we identify spontaneously emerging plants and through literature study we examine them for phytoremediation properties. Unmentioned promising plants with a lot of biomass - like Arctium lappa - we test ourselves. The spontaneously emerging plants are supplemented with hyperaccumulators for extra intake. This turns out to be much more effective: it is feasible, and it yields a lot of biomass of accumulating plants.

Lesson 2: The benefits of ‘rewilding’
To our surprise, the polluted soil is not ‘dead’. It is actually very much alive and able to grow a lush green wilderness. Meanwhile during the project, we discovered that only part of the acclaimed polluted land was really polluted. That is why we decided to let most of the terrain rewild: to give room to spontaneously grown, mostly indigenous plants. We do maintain, but mainly to increase biodiversity (e.g., bramble and nettle easily take over). We deliberately leave denser, prickly shrubbery in place for the benefit of birds, small mammals and insects. The result is a small wilderness with a great diversity of nesting birds (e.g., wren, robin and chiffchaff) buzzing insects and some small mammals like hedgehogs.

Lesson 3: The possible wealth of a green oasis on polluted soil
Although hoped for, we never expected to be able to grow such a wonderful green oasis on this polluted soil in just a few years. The poplars - planted to break down PAHs - tower over the boats and provide fine shade even on the hottest day. Because we almost never leave the ground uncovered, it remains moist even in the driest spring and cool for a long time in hot summers. The aforementioned advantages - cooling, water buffering, filtering of noise and air, but also the visible presence of greenery and animals - mean that the terrain is experienced as very pleasant. Because the terrain is semi-public, not only do we Ceuvelers enjoy it, but it has also become an important green attraction for Amsterdam Noord.

6.3 Economical aspects

Lesson 4: Ability to really use a Brownfield while cleaning is going on
The Ceuvel is a good example of how to put a brownfield into use responsibly without having to remediate it in a traditional way first. The soil remains intact - including the accompanying microspheres - and is cleaned up during use. Meanwhile, valuable workspace, hospitality, hotel, meeting places and a green outdoor space have been created.

Lesson 5: Value increase of surrounding area
Very soon after the opening of De Ceuvel, the surrounding neighborhood became notedly more attractive. Lousy garages were bought up by hip creative businesses and new restaurants, housing prices rose.

Lesson 6: The cost of phytoremediation varies greatly by choice of phytotechnique
We work on a small budget, with a lot of DIY and volunteers. One of the goals of the phyto-project was to see if it is at all feasible in such a case. It turns out that it matters a lot which phytotechnique you use or can use (depending on your type of contamination). Phytodegradation - used for the degradation of PAHs - is very doable. It requires targeted planting and then only limited maintenance. However, testing the soil for PAH, to monitor progress, is pricey because it can only be done in a laboratory. This must be taken into account.

Phytoextraction - used to remove the heavy metals - is much more difficult. It requires continuous attention in sowing and harvesting the material. Therefore, with a low budget, it requires a good volunteer network from the beginning. You also need to provide seeds and gardening tools. Finally, the harvest itself also poses a problem at the moment (see next bullet). Testing the soil is very affordable via the emerging HXRF technique.

Lesson 7: How to bring the harvest to use
When you use the technique of phytoextraction, you create a harvest with a higher heavy metal contamination. We tried to find techniques to put this harvest to use. One of the most promising once was pyrolysis, in which the harvest is burned in a controlled way. This process produces some useful by-products such as biogas and wood vinegar. The pollutants end up in the ash and in a kind of slurry, with the mass greatly reduced. Although a test showed that this process was successful and feasible, we cannot currently process it in this way in practice: the available machine only works with pellets, and we have not been able to find a pellet manufacturer willing to work with contaminated crops. If more phyto-extraction projects emerge, it might make sense to make a jointly run processing point working through pyrolysis.

Another harvest every year is willow shoots. We cut them to stimulate the roots and therefore stimulating the degradation of PAH's. Since willow shoots can be reused for different purposes, we have managed to distribute them to people in the neighborhood who can use them. This doesn't generate money, but it does generate social cohesion.

6.4 Social aspects

Lesson 8: It's powerful to make it visible
The Ceuvel attracts many visitors every year. Through tours, but also spontaneously. We notice that making the possibilities of a brownfield like us visible is inspiring. The phytoremediation, but also working in green, having meetings outside, seeing volunteers working together, etcetera. The semi-accessible nature of the project means that the message spreads quickly.

Lesson 9: Transferring knowledge is important but takes time
Since we all work voluntarily, it is sometimes difficult to fulfill all needs of more information on what we do. We didn't think about that beforehand - we just started remediating. That also means that we don't always get to it properly, which is a pity. A platform such as Phytosync would be a great help to projects like ours.

Lesson 10: Becoming a social hub has it side effects
We have deliberately chosen to be semi-public, so that people can observe what we do. This is very enriching, and results in a very lively, thriving place. The disadvantage is that visitors sometimes appropriate the space (loitering, loud music, temporary housing under the scaffolding) or do not care for it as we do (pollution, walking through seedlings, etc.). If you want to become (semi)public a good contact with the local authorities is very important to be able to act jointly...

6.5 Technical aspects

Lesson 11: Know the location of your contamination – traditional soil testing often gives an unduly broad picture
We started the project following the official tests of the site, which indicated that the entire area was contaminated. It would have saved us a lot of money, time and effort if we had done soil tests at more points immediately. Because traditional soil testing often combines several samples and only has a few lab tests done, it only gives a very rough picture of the site. If you want to apply phytoremediation, you can work much more effectively if you have a more refined picture of where the contamination is. Also, if you want to make use of the space in some other way during phytoremediation, it becomes even more important! In our case, it turns out that only 3 areas in the site above the residential standard are polluted. The other areas are not. Had we known this when we designed the site, we could have adjusted the design of De Ceuvel accordingly.

Lesson 12: There's a big difference in feasibility per phytoremediation technique
In some cases, your contamination determines which phytotechnique to use. But often there is a choice. For us, we experience a big difference in the practical feasibility of the phytodegradation of the PAHs and the phytoextraction of the heavy metals.

Phytodegradation is easy to set up, easy to maintain, and produces measurable reductions in pollution after only a few years. Phytoextraction is about as easy to set up yet requires continuous maintenance, produces a harvest flow that we are not yet able to process and even after 7 years still no measurable difference in soil contamination. It does work - through measurements on the plants we see that they do take in quite a lot - but it goes very, very slowly. Perhaps it would make more sense for a permanent location to work with stabilization when there is heavy metal pollution.

Lesson 13: Distancing people from the contamination through the jetty works
At De Ceuvel the decision was made to create a physical distance between the visitors/users and the polluted soil by means of a raised boardwalk. This appears to work very well - even when it is very busy, most people stay on the jetty and leave not only the soil but also the plants alone.

7 Phytoremediaton platform

7.1 Introduction

The knowledge about phytoremediation technologies, their underlying principles and their application in urban environments is fragmented. From a researcher's perspective, there is currently no central international dataset available of plant species with phytoremediative properties (hyperaccumulators). Moreover, there is a growing incentive amongst city planners to design and develop with biological information, such as the phytoremediative effect of plants. However, these developers of urban space apply phytoremediation only sporadically in their work because information is not accessible in an unambiguous way, nor are there means to easily integrate phytoremediation into their daily practice. The main aim of this project is to bring this knowledge and data together in a public and accessible platform that bridges the environmental research, spatial design and urban development disciplines.

This chapter will give insight into the possibilities of a phytoremediation platform (working title: PhytoSync) and the ways in which it can be implemented in a diverse co-creating community.

7.2 Ambition and audience

The platform aims to create common possibilities and transdisciplinary potentials for people that are involved with soil remediation. The platform will give these people the tools that they need like: plant information, soil information, implementation strategies, cost insights, temporal aspects, etc.

Although the platform aims to bring these different backgrounds together within a single ecosystem, it must be acknowledged that its diverse set of users are best served through tailormade multichannel information and communication formats.

During this project, we have conducted various interactions, such as questionnaires and workgroups, with the potential target audience of the platform. These showed that there is a clear division between a large group of potential users who are mainly looking for general information about phytoremediation and a more specific group of professionals who are looking for support in the application of phytoremediation.

7.3 Components

The frontend of the online platform will be structured into different sections, pages and flows to get users to the designated information as quickly as possible. To know what kind of flows are important, we need to look at the specific needs of the people using the platform. In terms of functionality, the most profound there will be separate sections, tools as you will, for professional and personal users.

To give insight in the information that will be available on the platform one of the most important is the flow of the database. The way people are guided through the platform is one of the main reasons of use. If the platform is unorganized people will not use it due to disconnect. Guiding people and helping them find what they need to find the easiest way possible stimulates the use of the platform and therefore the implementation of phytoremediation.

Positive Plant Encyclopaedia

The application of phytoremediation – like the word itself – is a complex convergence of processes and disciplines. As the previous process has shown, there is a great need from a target group - with no previous knowledge of the subject – to apply phytoremediation.

Personal users will be served information through a modern version of an illustrated plant encyclopaedia. The encyclopaedia consists of two main sections. The first section serves as an illustrated introduction to phytoremediation using interactive diagrams. These visuals will explain the core principles of phytoremediation technologies and the ways one can apply and validate them in a simple manner.

The second section is the encyclopaedia itself, which functions as an interface to the phytoremediative plant database. The project and the datasets will initially be framed into native phytoremediative plant species. However, we found that this user group, ranging from home gardeners to community gardeners, embraces phytoremediation as part of wider set of gardening strategies geared towards a healthy living environment. Therefore, at a later stage, the encyclopaedia, the database and its interface will also include other positive plant properties, such as bioremediative species (mycoremediation, air purification, etc.), water and air filtration, and possibly biodiversity enhancers, such as pollinators.

Phytoremediation Planning Atlas

The needs of the professional user group can be spliced into multiple demands, such as: basic information, project specific information, plant specific information and soil contaminate specific information. These different sorts of information will be the starting point of their 'user journey' using a three-dimensional map-based interface. Within this interface they can search for a project location and input its contamination information from for instance soil reports. The project will then be supplemented with open data, such as climate, soil layer and surface elevation data.

In the database these parts of information are indexed and will communicate between each other through queries and will find the needed information for the user. Therefore, in the future this database could be used by stakeholders outside of academics and should also include other relevant indicators. Certain physical properties of the plants, such as growth height, colour and flowering period(s) can for example be pivotal for designers in the integration of phytoremediative plants in urban developments.

Once the data is loaded, one can start designing with phytoremediative plants in a 3d environment. Plant selection suggestions will be made based on the input data, whilst one is able to download planning drawings and is given feedback on possible planting strategies and their eventual effectiveness. Combined, this platform should enable researchers, designers, and planners to initiate new projects and explore the possibilities for its use independently and in collaboration.

References

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, conservation and recycling*, *127*, 221-232.

RIVM, 2018, https://www.rivm.nl/bodemsanering, consulted on 20-05-2022

RWS, 2022. Voortgang aanpak bodemverontreiniging met onaanvaardbare risico's 2021 | 11 april 2022

The Land Use Cycle (http://www.zerobrownfields.eu/content.aspx?wp=3&p=227), consulted on 10-05-2022

Trapp, S., & Karlson, U. (2001). Aspects of phytoremediation of organic pollutants. *Journal of Soils and Sediments, 1*(1), 37-43

Veeger, M., Bouzidi, T., Hanum, S., van Berkel, P., & Pranandita Putra, P. (2018). *Cleaning the soil with nature: A framework for the implementation of phytoremediation*. Wageningen University and Research.

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