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phytotechnology
[fahy-toh-tek-noh-luh-jee] *noun*

emerging field that implements solutions to scientific and engineering problems in the form of plants

Demonstrating a phytotechnological design-approach

Plant biology in stormwater remediation practice

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Jag vill tacka

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för er tid och bidrag till denna uppsats. I viss mån har detta arbete varit en projektledningsövning i vilken ni som projektdeltagare inte blivit helt informerade om er roll i projektet. Fytoteknologi kräver samarbete mellan många kompetenser och utan era bidrag hade uppsatsen inte varit genomförbar.

Tack!

ABSTRACT

In this master's thesis the field of phytotechnology is investigated. Phytotechnology is a collection of largely unexploited methods and processes that aim to employ the abilities of plants to manage contaminants in our environments. In Sweden, as well as the rest of the world, contaminated stormwater is a significant problem with negative impacts on areas such as natural and built environments, human health and recreational opportunities. This work demonstrates a phytotechnological design-approach to planning spaces with the purpose of combining management of contaminated stormwater with the enhancement of ecological, social and economic aspects of the semi-urban environment. The purpose of this thesis is to illuminate phytotechnology's potential in this regard and show how landscape architects can use it as a means of planning and designing spaces that serve as integral parts of sustainable stormwater management systems. Furthermore, the opportunities and challenges that face this endeavour are studied and discussed.

Phytotechnology is fundamentally based on the natural sciences – and plant science more specifically. My background in plant biotechnology at Umeå Plant Science Centre prior to my studies at the Swedish University of Agriculture allow this thesis to largely be devoted to this aspect. However, application of any plants and their associated infrastructure in the built environment falls within the purview of urban planning and landscape architecture. Therefore, this thesis incorporates many fields and should be viewed as an interdisciplinary effort.

A literature review covering this broad area is presented. The review describes the processes of remediation; the opportunities and the challenges that face the further development of the field and how this relates to landscape architecture and its practitioners; and why phytotechnology is not a fully accepted practice despite the fact that it rests on firm scientific grounds. The application of phytotechnology has also been demonstrated in this thesis. A design-approach developed by the landscape architects Kate Kennen and Nial Kirkwood has been employed to the construction of a site program aimed at improving the remediation capacity and the ecological, economical and social values of an existing stormwater management pond in Upplands Väsby, Sweden. The site program reveals among other the opportunity to: remediate larger amounts of contaminants and additional contaminant types; increase the areas biodiversity and ecological resilience; allow for potential economic benefits and land-value increases; sustain nationally important cultural values such as open agricultural landscapes in close proximity to urban centres; and provide improved recreational and educational areas in green environments.

The challenges that face phytotechnology are shown in the literary review and the site program. Among these challenges are: the unpredictable success that phytotechnological

systems currently have, the physical limitations of plants to reach contaminants on certain sites and the efficiency of remediation. Furthermore, difficulties with planning, maintenance and acquiring the necessary expert professionals required to complete a phytotechnological project are revealed. This is also discussed in regards to how we can use phytotechnology as landscape architects and how we can contribute to furthering the field as a whole.

One of the conclusions of this thesis is that in this era of increasingly negative anthropogenic impact on our environments – and in turn on ourselves - phytotechnology offers largely unexploited value to landscape architects, natural environments and society as a whole.

SAMMANFATTNING

Vår samtid präglas av en stadsbyggnadstrend som producerar en allt tätare och mer trångbodd urban miljö (Haaland & van Den Bosch 2015, Kyttä et al. 2013). Denna trend sker dels som en konsekvens av försök att förhindra bland annat habitatförstöring, beroende av långa transportsträckor och sociala ojämlikheter (Anguluri & Narayanan 2017, Haaland & van Den Bosch 2015, Kyttä et al. 2013). Trots dessa försök uppkommer flera problem. En tätare stad ger ofta en lägre livskvalitet, urbana värmeöar, trångboddhet och en minskning av gröna ytor (grönstruktur) (Foley et al. 2005, Goonetilleke et al. 2005). Detta leder vidare till en ökning av antalet källor till föroreningar och därmed även en ökning av mängden föroreningar i mark, vatten och luft (Anguluri & Narayanan 2017, Haaland & van Den Bosch 2015, Kyttä et al. 2013). Förutom att föroreningarna påverkar det liv som huserar i dessa miljöer, medverkar de till ett försämrat lokalt och globalt klimat, minskat ekonomiskt värde av mark, negativ påverkan på mänsklig hälsa och minskade rekreationsmöjligheter i gröna miljöer (Barbosa et al. 2012, Clark et al. 2007, Gawronski et al. 2011, Livesley et al. 2016, Naturvårdsverket 2017, Pataki et al. 2011).

Dagvatten är en källa och transportör av skadliga föroreningar både till akvatiska och terrestra miljöer. I Sverige har förorenat dagvatten lett till försämrad dricksvattenkvalitet, syrebrist i sjöar, övergödning och toxiska effekter på djurliv (inklusive människor) däribland cancerogena och hormonrubbande effekter (Naturvårdsverket 2017). Sanering av dagvatten erbjuder därmed stora möjligheter till förbättring av gröna miljöer och samhället i stort (Barbosa et al. 2012, Naturvårdsverket 2017, Naturvårdsverket 2018b, SMED 2018). I dagens Sverige finns det dock goda möjligheter att bemöta dessa problem bland annat genom de styrverk som finns. Generationsmålet med tillhörande miljömål och milstolpar erbjuder vägledning i arbetet och juridiskt stöd till delar av målen finns i bland annat Miljöbalken.

Traditionellt sett har effekterna av föroreningar hanterats genom att använda metoder som, i fallet av förorenad mark, baseras på att schakta de kontaminerade jordmassorna, transportera bort och behandla dem på annan lokal (Kennen & Kirkwood 2015 pp. 6,24). I fallet av vattenrening är nätverk av brunnar och rör som transporterar förorenat vatten till reningsverk standardiserat (Barbosa et al. 2012). Även om dessa metoder ofta fungerar bra uppstår vissa brister (Barbosa et al. 2012, Naturvårdsverket 2017). De kan vara snabba och effektiva men de kan också förstöra ekosystem, ödelägga hela landskap, vara kapitalkrävande och misslyckas att skapa mervärden utöver vattentransport och sanering (Gerhardt et al. 2017, Kennen & Kirkwood 2015 p.6). För att på ett hållbart sätt motverka de negativa konsekvenserna av den kontemporära stadsbyggnadstrenden och för att fortsätta sanera våra miljöer måste de traditionella metoderna och systemen förbättras och kompletteras (Naturvårdsverket 2017). En del av lösningen går att finna i skapandet av grönstrukturer som utnyttjar det senaste inom teknologi och vetenskap (Gulliksson & Holmgren 2015, Kennen & Kirkwood 2015, Pandey & Souza-Alonso 2019).

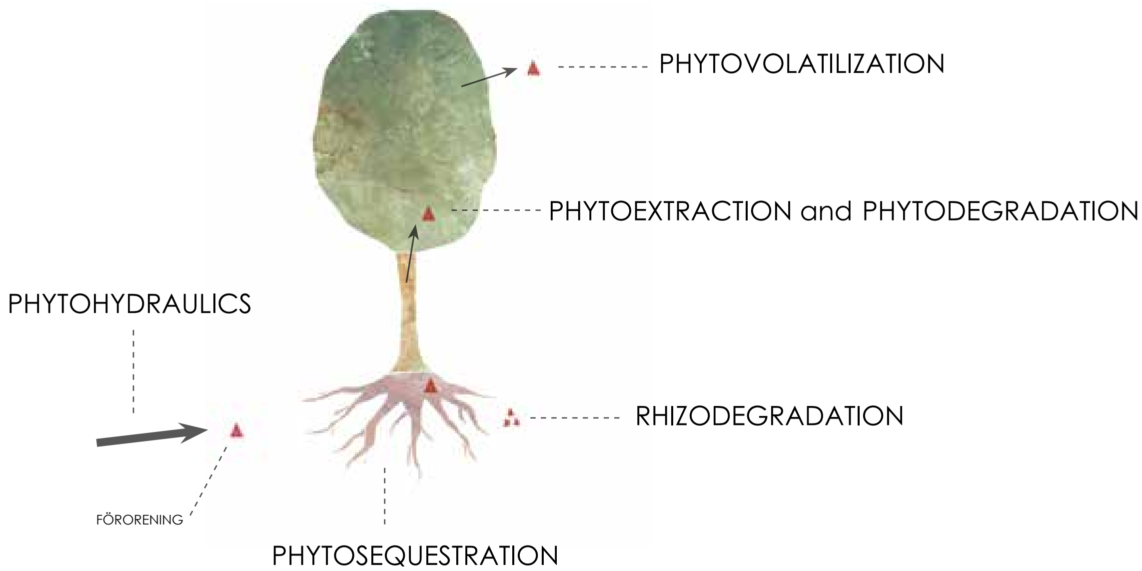
Fytosanering, eller användningen av växter för att hantera förorenade miljöer, är en av dessa teknologier (figur 1) (Ali et al. 2013, Gerhardt et al. 2017, ITRC 2009, Kennen & Kirkwood 2015). I grunden är fytosanering en naturvetenskaplig disciplin som bygger på molekylär växtbiologi. När teknologin tillämpas praktiskt behövs dock en betydligt bredare samling kompetenser (ITRC 2009, Kennen & Kirkwood 2015). Ofta är samhällsplanerare, hydrologer, ekologer, ingenjörer, agronomer och många andra experter involverade i projekten. När teknologin påverkas av andra expertområden utöver den växtbiologiska har termen fytoteknologi kommit att användas (Henry et al. 2013, ITRC 2009, Kennen & Kirkwood 2015). För att lyckas med fytoteknologiska projekt behövs således ett väl fungerade samarbete mellan experter. I detta skede kommer landskapsarkitektens kompetens väl till nytta. Landskapsarkitekten är expert på att se helhetsbilden och har en god förståelse för den potential som områden mellan byggnader kan ha (Gazvoda 2002, Thompson 2014 p. 93). Landskapsarkitekten är även väl lämpad att leda projekt av denna typ med tanke på att fältet till stor del baseras på ekologiska principer och användning av växter (Kennen &

Kirkwood 2015).

Fytoteknologi är dock ett främmande koncept för många landskapsarkitekter och är idag inte ett vanligt verktyg för miljöförbättring i någon yrkesgrupp, trots att tekniken i viss from har varit kända i närmare 40 år (Gerhardt et al. 2017, Kirkwood 2001, Todd et al. 2016). Goda exempel på dess användning finns dock. Den välrenommerade landskapsparken Landschaftspark Duisburg-Nord (figur 2) i Tyskland är ett exempel på ett projekt där landskapsarkitekter har varit involverade i skapandet av en mångfunktionell park med element som är baserade på fytosaneringsprinciper (Stilgenbauer 2005, Weilacher 2008). Området som parken ligger på idag var tidigare använd för metallraffinering och var därför på sina platser mycket förorenad. Förorenade områden stängdes av och täcktes med jord i vilken växter med fytoteknologiska egenskaper planterades (Mackay 2016). Även längs med de kanaler som löper genom området planterades växter med vattenrening i åtanke. Idag, nästan 26 år efter parkens invigning (1994), är dessa delar öppna för besökare och parken är nu mycket populär.

Fytoteknologi är i sin helhet ett mycket brett fält. I detta arbete ligger därför fokus på användningen av fytoteknologi i dagvattenhanteringssystem i den svenska semi-urbana miljön. Syftet är att både belysa metoden i stort och att demonstrera hur den kan användas av landskapsarkitekter i praktiken med utgångspunkt i dagvattenhantering. Till detta hör en diskussion och sammanfattning av den forskning som finns på ämnet och hur landskapsarkitekter kan utnyttja denna kunskapskälla, som för tillfället främst är akademisk och rotad i molekylärbiologisk naturvetenskap.

Vidare belyses fytoteknologi och dess praktiska tillämpning genom att undersöka en planerings- och gestaltningsmetod



Figur 1. De biofysiska/fytoteknologiska processer som huvudsakliga utnyttjas i fytoteknologiska sammanhang och var i en växt som föroreningar kan lokaliseras.

Figur 2. Landschaftspark Duisburg-Nord. Photo: Thomas Berns.

för fytoteknologiska projekt. Metoden är framtagen av bland andra landskapsarkitekterna Kate Kennen och Nial Kirkwood (Kennen & Kirkwood 2015) och används i denna uppsats för att ta fram ett gestaltningsprogram för ett tillägg till en befintlig dagvattendamm i Upplands Väsby. Därmed, och tillsammans med littersatursammanfattningen, besvaras uppsatsens två frågeställningar: (1) hur kan landskapsarkitekter gynnas av det rådande kunskapsläget inom fytoteknologi i dagvattenhantering? och (2) när tillämpad i skapandet av ett program för ett tillägg till en existerande dagvattendam, vilka möjligheter och utmaningar uppkommer vid ett tillvägagångssätt baserat på fytoteknologiska principer?

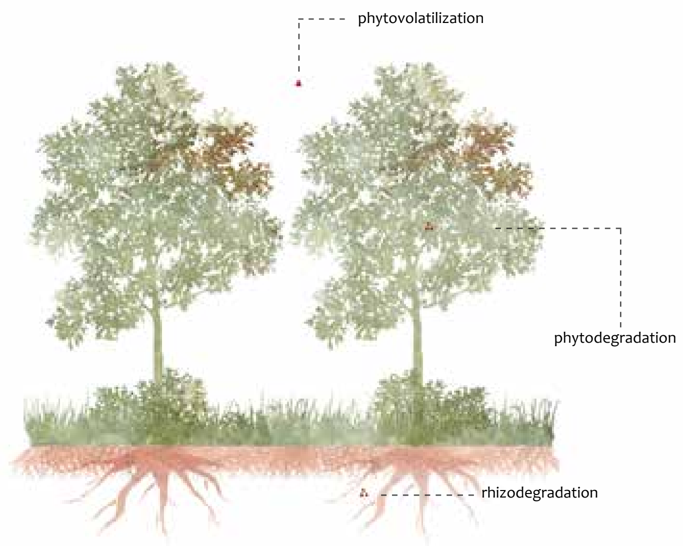
Det första steget i metoden är att identifiera vilka aspekter av dagvattendammen som kan förbättras. Kapacitet att hantera de vattenvolymer som kommer till dammen i Upplands Väsby överskrids flera gånger per år och resulterar i att 25-35% av det årliga vattnet inte renas av dammen utan leds istället ut i en intilliggande å som sedan för det förorenade vattnet vidare ut i Mälardalen (Andersson et al. 2012). Denna å är även dammens närmaste recipient och en del av de föroreningar som finns i vattnet som passerar genom dammen följer då med.

I områdets detaljplan lyfts det att dammen har estetiska och pedagogiska kvaliteter och utgör en del av ett större rekreativt stråk (Upplands Väsby kommun 2005). Området hyser även kulturella kvaliteter av nationellt intresse med dess stadsnära öppna jordbrukslandskap och närhet till en Barockträdgård norr om dammen. I kommunens vattenplan indikeras det även att en fortsatt utveckling av dammområdets rekreativa kvaliteter är önskvärt (Upplands Väsby kommun 2007). Samtliga av dessa aspekter viktas enligt Kennen & Kirkwoods metod och bidrar till det slutliga gestaltningsprogrammet.

Det andra steget i metoden består av fyra övergripande moment. Först identifieras vilka typer av föroreningar som dagvattnet innehåller. Baserat på dessa föroreningar väljs sedan ett antal lämpliga fytoteknologiska växtprocesser ut. De olika processerna är enligt metoden lämpade att användas i olika planteringstyper (s.k. fytotopologier) (figur 3). Planteringstyperna är definierade av metodens författare och används i nästa skede som mallar för ett fytoteknologiskt gestaltningsprogram där även de sociala aspekterna, som pekats ut ovan, har möjlighet att påverka.

Från litteraturen såväl som från skapandet av gestaltningsprogrammet visar detta arbete på fytoteknologins många möjligheter och utmaningar. Förutom att fytoteknologi erbjuder ytterligare reningsmöjligheter av dagvatten så möjliggör det flera andra fördelar. Ett axplock av dessa inkluderar ekologisk restaurering samtidigt som rening, kostnadseffektivitet, sanering av organiska och oorganiska föroreningar samtidigt (till skillnad från de flesta konventionella saneringsmetoderna), skapandet av multifunktionell grönstruktur, bidra till att motverka klimatförändringar samt att agera som översvämnings- och erosionsskydd (Gerhardt et al 2017, Henry et al 2013, ITRC 2009, Kennen & Kirkwood 2015, Pandey & Souza-Alonso 2019, Todd et al. 2016, Wenzel 2009).

Även teknikens begränsningar görs tydliga i detta arbete och är särskilt viktiga att poängtera om fortsatt utveckling av tekniken ska lyckas (Gerhardt et al. 2017). Ett av de mest allvarliga är att många områden inte är lämpade för fytoteknologi pga. att det exempelvis inte finns växter som kan hantera vissa föroreningar eller att det lokala klimatet inte möjliggör att växternas fytosanerande processer är tillräckligt effektiva (Cunningham et al. 1995, Gerhardt et al. 2017, Kennen & Kirkwood 2015, Mahar et al. 2016). En ytterligare begränsning är att de biofysiska processerna som är aktiva i



Figur 3. Schematisk illustration av fytotopologin Degradation Bosque med tillhörande biofysiska processer.

hanteringen av föroreningar ofta är långsamma i förhållande till konventionella saneringsmetoder (ibid.). Det finns även stora osäkerheter om specifika planteringars resultat och planering och implementering av tekniken erfordrar hög kompetens inom flera nischade områden för att maximera chansen till framgång (Gerhardt et al. 2017, Kennen & Kirkwood 2015).

Gestaltningsprogrammet i denna uppsats visar på flera saker men kan dock inte anses vara helt färdigt för projektering. Ytterligare arbete och konsultering med hydrologer, agronomer och ingenjörer behövs. Detta arbete tydliggör dock behovet av samarbete mellan flera olika kompetenser inom olika fält för att driva ett projekt av denna typ. Metoden av Kennen & Kirkwood (2015) har visats vara ett strukturerat sätt att tydliggöra vilka kompetenser som krävs i ett specifikt projekt och bidragit till att upprätta parametrar inom vilka en gestaltning av ett dagvattenhanteringssystem kan utformas. Programmet och metoden med vilket det är framställt med visar även möjligheten att använda fytoteknologi som ett tillägg till ett existerande dagvattensystem där tekniken inte bara bidrar med rening av dagvatten men även tillgodoser sociala, ekologiska och ekonomiska behov.

Fortsatt forskning och tillämpning är nödvändigt för att fytoteknologi ska bli lättanvänt för landskapsarkitekter. För tillfället är det svårt för landskapsarkitekter att på egen hand förstå möjligheterna och begränsningarna med tekniken och vad framsteg i grundforskningen betyder i praktiken. I viss mån innebär det begränsningar för landskapsarkitektens förmåga att vara med i framkanten av utvecklingen av fytoteknologi. Ett dilemma uppstår i och med detta eftersom att en av de viktigaste delarna för en fortsatt utveckling bygger på dess praktiska tillämpning (Gerhardt et al. 2017) där just landskapsarkitekten har en viktig, eller potentiellt avgörande, roll. Frågan är dock om landskapsarkitektens kompetens inom fytoteknologi måste fördjupas eller om samarbetet kring dess praktiska tillämpning är ett effektivare sätt att föra utvecklingen framåt. Landskapsarkitektens vetskap om tekniken är oavsett scenario viktig.

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GLOSSARY

Bioremediation: the use of biological systems for managing contaminants.

Best management practice (BMP): a more sustainable stormwater management practice that adresses the quantity and quality of stormwater.

Catchment area: the area from which a recipient recives its water.

Ecosystem service: any benefit that humans gain from ecosystems.

Endophyte: bacteria or fungus that live their entire lives or part of their lives in plants.

Eutrophication: a body of water that has an excess of plant nutrients.

Evapotranspiration: the sum of the water that evaporates and transpires from plants to the atmosphere.

Exudate: a substance extracted by plants.

Infiltration: water that runs through the top-soil.

Macronutrients: nutrients that a plant requires in the large quantites. (N, P, K, Ca, S, Mg, C, O, H)

Metabolite: a substance that is involved in the process of metabolism.

Microorganism: bacteria, fungi, algae and viruses.

PAHs: polycyclic aromatic hydrocarbons are organic compounds with adverse effects on natural environments, wildlife and humans.

Phytoremediation: the use of plants to remove, degrade, detect, prevent the spread of and detain contaminants in soil, water and air.

Phytoremediational processs/methods: include the processes of phytoextraction, phytosequestration phytovolatilization, rhizodegradation, phytodegradation and phytohydraulics. (figures 2.2. and 2.3)

Phytotechnology: umbrella term that includes all the methods by which plants can be used for puposes of managing environmental issues.

Phytotypology: planting types that make use of phytotechnological methods.

POPs: persistent organic pollutants are a set of organic compounds that are particularily difficult to remove from soil.

Recipient: body of water that receives water from another source.

Rhizosphere: the area of soil that plant roots influence.

Sedimentation: the settling of suspended particles.

Semi-urban: an area that is not overtly city nor country-side but contains a mix of elements, roughly in equal ratios of urban, suburban and rural.

Water retention: preventing uninterrupted flow of water.

PART A
Background

The first part of this thesis introduces phytotechnology and illuminates the extent of the problem associated with contaminated stormwater and how the Swedish parliament's environmental objectives serve the sustainable management of semi-urban stormwater. Traditional ways of managing stormwater are briefly covered as well as what phytoremediation and phytotechnology is more fundamentally and how it can be used in stormwater management endeavours. In closing, the aims, research questions, methods, target audience and boundaries of this thesis are formulated.

1.1 INTRODUCTION

A contemporary trend in urban planning calls for an increased densification as a means of combating adverse effects associated with urban expansion e.g. loss of biodiversity, reliance on long transport routes and social inequalities (Haaland & van den Bosch 2015, Kyttä et al. 2013). This planning approach is not without drawbacks however and increased urban density; lower quality of living, heat-island effects and over-crowding can be expected and is observed (Anguluri & Narayanan 2017, Haaland & van den Bosch 2015, Kyttä et al. 2013). More broadly, densification and urban development have led to a decrease in vegetated area (green structure) in both urban and rural environments (Foley et al. 2005, Goonetilleke et al. 2005). As a consequence, there has been an increase in local sources of pollution as well as further contamination of water, soil and air – all of which pose a significant threat to the well-being of all organisms and the environments that we inhabit (Barbosa et al. 2012, Clark et al. 2007, Gawronski et al. 2011, Livesley et al. 2016, Naturvårdsverket 2017, Pataki et al. 2011). Furthermore, detrimental effects extend to local and global climate, economic land-value, human health and recreational opportunities in natural environments (Ali et al. 2013, Foley et al. 2005, Todd et al. 2016, Ulrich 1986, Winquist et al. 2014).

The traditional ways of managing these effects have most often been to use methods that rely on excavating, moving and treating contaminated soils off-site, commonly known as "dig-and-haul"-methods, or utilizing extensive pipe infrastructure and treatment facilities to clean water (Barbosa et al. 2012, Kennen & Kirkwood 2015 pp. 6,24). Although these systems have many benefits, they also have many drawbacks (Barbosa et al. 2012, Naturvårdsverket 2017). They can be fast and thorough, but also be destructive of landscapes and ecosystems as well as being expensive (Gerhardt et al. 2017, Kennen & Kirkwood 2015 p.6). To sustainably mitigate the adverse effects of urbanism and continue to remediate contaminants in our environment, traditional remediation systems need to be improved (Naturvårdsverket 2017). Part of the solution is the design of green structure that uses state-of-the-art technology and science (Gulliksson & Holmgren 2015, Kennen & Kirkwood 2015, Pandey & Souza-Alonso 2019).

Phytoremediation, or the use of plants to manage contaminated areas, is one such technology (Ali et al. 2013, Gerhardt et al. 2017, ITRC 2009, Kennen & Kirkwood 2015). At its most fundamental, it is a field of plant biology. However, when applied outside the lab, phytoremediation practice requires the expertise of numerous different fields (ITRC 2009, Kennen & Kirkwood 2015). Projects often require close consultation with urban planners, hydrologists, ecologists, soil agronomists, civil engineers and many more professionals and when considered as a whole, the practice is known as **phytotechnology** (Henry et al. 2013, ITRC 2009, Kennen & Kirkwood 2015). To coordinate and understand what expert professionals to consult in any particular project is therefore vital to its success (Kennen & Kirkwood 2015). Leading projects of this kind is a task that is well-suited for landscape architects as they are trained in adopting a broad view of the potential that the spaces between buildings can have (Gazvoda 2002, Thompson 2014 p. 93). Additionally, since phytotechnology operates in the built environment and is based on ecological principals, it is further nestled within the purview of landscape architecture (Kennen & Kirkwood 2015).

Phytotechnology, although not a novel method, will be a foreign concept to many landscape architects and can scarcely be considered a staple of remediation practice more generally (Gerhardt et al. 2017, Kirkwood 2001, Todd et al. 2016). Despite this, notable examples of phytotechnology, and more strictly phytoremediation, do exist. The award-winning landscape park in Duisburg Germany is a prime example of landscape architects being involved and the use of *Salix spp.* in agricultural practice for purpose of phytoremediation, among others, is broadly recognized (Isebrands et al. 2014, Mackay 2016).

As a whole, the subject of phytotechnology is diverse and can be approached from numerous angles. In this thesis, the focus is on the use of phytotechnology in stormwater management systems in semi-urban environments containing a mix of rural, suburban and urban elements in approximately equal ratios (Alm et al. 2010, Meeus & Gulinck 2008).

1.2 CONTAMINATED STORMWATER

Stormwater is defined as the water that temporarily exists on the surface of the ground and the contamination of stormwater poses a threat to the environment and the organisms that inhabit them – including humans (Barbosa et al. 2012, Naturvårdsverket 2017, SMED 2018, SMHI 2018). When water runs over the types of surfaces common to semi-urban landscapes – such as roads and roofs of buildings - the contaminants on these surfaces are suspended in the water and moved downstream (Carey et al. 2013, Tsihrintzis & Hamid 1997). Roads are a particularly contaminant-rich source and the stormwater runoff from roads contain some of the most toxic heavy metals (Pb, Zn, Cu, Cr and Ni). This has well documented detrimental effects on stormwater recipients such as water bodies, groundwater and soils (SMED 2018, Tsihrintzis & Hamid 1997). It is noteworthy that although roads produce the most contaminated stormwater runoff, industrial effluents supply the bulk of the contaminants - a fact that may have implications for where to allocate the most resources for clean-up endeavours (Naturvårdsverket 2018b).

Other common contaminants include nitrogen and phosphorus that when transported via stormwater can result in eutrophication of aquatic systems (Groffman et al. 2004). There are many sources of N and P, some of which include: the atmosphere, leafs from trees, construction, wastewater, fertilizer and landfills (Carey et al. 2013, Janke, Finlay & Hobbie 2017, Smith, Tilman & Nekola 1999).

Fundamentally, stormwater often acts as a vector for numerous different substances and mitigating the detrimental effects associated with contaminated stormwater offers substantial environmental and societal benefits (Barbosa et al. 2012, Naturvårdsverket 2017, Naturvårdsverket 2018b, SMED 2018).

1.3 THE EXTENT OF THE ISSUE IN SWEDEN

Collecting data that comprehensively describes the contamination of stormwater in Sweden is difficult and at present, the data only gives a limited picture (SMED 2018). However, there are many confident indications that stormwater is a significant contributor to the spread of contaminants to recipients - despite the fact that urban areas only cover 1% of Sweden’s total area (ibid.). If stormwater is defined as the water that temporarily exists on the surfaces of urban environments and roads, the total amount of nitrogen and phosphorous that is spread via stormwater in Sweden is only 1% and 4%, respectively. Conversely, the spread of heavy metals is substantial, with amounts of some metals reaching 17% (ibid.). For a host of organic contaminants, such as polyaromatic hydrocarbons (PAHs) and polychlorinated biphenols (PCBs), there is likely also a large contribution to recipients by stormwater (ibid.). When considering individual areas there may be large variations however and the stormwater in certain areas can contribute to translocating 100% of some metals and 20-50% of macronutrients found in recipients (Naturvårdsverket 2017, SMED 2018).

The adverse effects that the stormwater-spread contaminants have in Swedish environments are many and include: deteriorated quality of drinking water, oxygen deficiency in lakes, eutrophication and toxicity to humans and non-human animals that can include cancerogenic and hormone destabilizing effects (Naturvårdsverket 2017). It is difficult however to judge how severe the effects are on one particular site and studies have at times shown contradicting results (SMED 2018).

1.4 SWEDISH ENVIRONMENTAL OBJECTIVES AND LEGAL UTILITIES

In 1999 the Swedish parliament (Miljö- och Jordbruksutskottet 1999) recognized the need for environmental protection and put forth a policy framework for handling environmental issues (Naturvårdsverket 2018). After several amendments, the policy framework now consists of three levels, divided according to degree of detail (figure 1.1). The first and least detailed level consists of an overarching statement known as the Generation goal. It is intended to "guide environmental action at every level of society" and indicate what actions need to be taken to achieve a "clean, healthy environment" in one generation - which in 1999 meant until 2020-25 (Naturvårdsverket 2018).

The second level is a collection of 16 environmental quality goals aimed at making the efforts suggested in the Generation goal more tangible (Naturvårdsverket 2018). Although many of the goals have some connection to the improvement of stormwater quality, the six most relevant ones are: **A non-toxic environment**, **Zero eutrophication**, **Good-quality groundwater**, **Thriving wetlands**, **A balanced marine environment, flourishing coastal areas and archipelago** and **A good built environment** (Naturvårdsverket 2017).

The third and final level is a further specification within each of the 16 environmental quality goals and consists of milestones specific to certain aspects of the quality goals. As an example, one such milestone, within the goal of **Zero eutrophication**, states that: atmospheric effects and land-use will not lead to substantial and long-term detrimental effects associated with eutrophication in any part of Sweden (Naturvårdsverket 2018). Also, lakes, rivers, riparian zones and groundwater should at least achieve a good status according to the decree on the maintenance of the aquatic environment's quality (SFS 2004:660).

In addition to the environmental framework above, the Swedish Environmental Code (Miljöbalken) was passed in 1999 and contains the legal tools necessary to enforce the framework, as it has no

Figure 1.1 Swedish environmental objectives are arranged in three levels according to degree of detail with the Generation goal being the broadest. Images: sverigesmiljomal.se/miljomalen/.

direct legal implications on its own. The code's tenth chapter (§10 vattentjänstlagen) states that significant contamination of an area must be remediated if it poses a threat to human health or the natural environment. It also states who is responsible for the necessary investigations and remedial actions. However, this can often be a difficult task due to the possibility of there being many parties involved (Naturvårdsverket 2017) – such as deciding who is responsible for a contaminated area that the effluents of multiple municipalities affect.

The European Union's Water Directive Framework (2000/60/EG) also produces a legal imperative on its members to protect all forms of water, restore ecosystems connected to these forms of water, decrease contaminants in all forms of water as well as guarantee sustainable use of water for individuals and companies. In Sweden, the directive was first introduced into Swedish law 2004 - 4 years after it was conceived - and is a part of the 5th chapter in the Swedish Environmental Code (§5 miljöbalken) as well as the decree on the maintenance of aquatic environments' quality (SFS 2004:660) and the decree on the instructions for county adminstrative boards of Sweden (SFS 2017:868).

1.5 STORMWATER MANAGEMENT AND CONVENTIONAL CONTAMINANT REMOVAL

The management of stormwater is a diverse topic that includes several types of management practices. What practice is implemented is highly site-specific as well as specific to the intended use of the water after it has been cleaned (Wang, Eckelman & Zimmerman 2013). For the purpose of this thesis, the most conventional stormwater management systems that primarily make use of extensive pipe infrastructure and treatment plants, aimed at either cleaning the water for human use or for expulsion into ecosystems, will not be discussed comprehensively. In many cases, these systems - often referred to as grey systems - have disadvantages in the pursuit of developing sustainable treatment methods (Barbosa et al. 2012, Naturvårdsverket 2018). For instance, they do not offer opportunities beyond the treatment of the water and can also be invasive and disruptive, and deteriorate local environments (Barbosa et al. 2012, Kennen & Kirkwood p. 6, Naturvårdsverket 2018).

In contrast, systems that focus on managing and treating stormwater using processes that more closely resemble ones in natural environments are known as green stormwater systems (Wang, Eckelman & Zimmerman 2013). They are often characterized by several treatment steps located closer to the stormwater source and, to a higher degree than grey systems, make use of processes such as: infiltration, sedimentation, filtration, evaporation, evapotranspiration and water retention (Liu et al. 2014). Naturally, plants are an integral part of systems that rest on ecological principals. Green stormwater management systems that aim to improve the quality and quantity of stormwater are also commonly known as stormwater best management practices (BMPs) (EPA 2013, Trafikverket 2018).

1.6 PLANT-BASED REMEDIATION TECHNOLOGY

Although some research was conducted as early as the 1950's, it was first in the early 1980's that research really started emerging on the ability of plants to accumulate heavy metals - and the use of these plants to remediate contaminated soils was envisioned (Kennen & Kirkwood 2015 p. 11). This novel field was termed phytoremediation and was the source of great optimism. Research continued, and subsequent findings revealed numerous applications of the technology that extend beyond the accumulation of heavy metals (Kennen & Kirkwood 2015 p. 11, ITRC 2009). However, forty years later and the technology is still not a staple of remediation practice – a development that has many explanations. Part of the explanation is given by technological limitations and an initial amount of unsubstantiated optimism as well as by difficulties with predictability, prof-of-concept and efficiency of remediation (Gerhardt et al. 2017, White & Newman 2011). As is often the case with new and promising technologies, the pendulum started by swinging high on the side of optimism (Kennen & Kirkwood 2015 p.11, Reynolds 2013). Consequently, the pendulum swung high on the opposite side and a decline in funding and research marked the field in the late 1990s (Kennen & Kirkwood 2015 p.11). Fortunately, there has been a sobering around the potential of phytoremediation in recent years and the field can demonstrate successful research and application in many areas (Ansari 2018, Gerhardt et al. 2017, Kennen & Kirkwood 2015 p. 11). In particular, the contribution of plants to stormwater management systems such as constructed wetlands is widely recognized and is the most common application of phytoremediation (Herath & Vithanage 2015, Kadlec & Wallace 2009 p.59, Redfern & Gunsch 2016). It is fair to say, however, that the technology's potential is not reflected in its frequency of application (Gerhardt et al. 2017).

There are many benefits to phytoremediation both as a stand-alone technology and in comparison to more conventional clean-up methods (Ali et al. 2013, Gerhardt et al. 2017, Henry et al. 2013, Kennen & Kirkwood 2015 pp. 7-8). An attractive and often heralded aspect of phytoremediation is its purported cost-benefits (Ali et al. 2013, Mani & Kumar 2014, Pandey & Souza-Alonso 2019, Redfern & Gunsch 2016). This is of special interest to developing countries that often are more polluted than more developed countries and have less means of dealing with the issue (Pandey & Souza-Alonso 2019). The certainty of the advantageous economic aspect in all cases, compared to conventional methods of remediation, is contested however. Gerhardt et al. (2017) suggest that there is not enough data to support this claim and they urge further research on the topic.

In the discussion of phytoremediation, it is useful to mention genetic engineering of plants and microorganisms (Gerhardt et al. 2017, Redfern & Gunsch 2016). Genetic engineering is a powerful tool and has been shown to offer significant improvements to the efficiency and range of applicability of phytotechnology (Eapen et al. 2005, Gunarathne et al. 2019, Redfern & Gunsch 2016). However, the use of genetically engineered plants in practice is wrought with difficulty. This is especially true in Sweden as regulations around genetically engineered plants are highly limiting (European Parliament and Council of the European Union 2001). Interestingly and with large consequences to the prevalence of genetically engineered plants in practice is the fact that the European Union's legislation solely concerned with the method in which an organism is produced while in the United States, the characteristics of the organism itself dictate if it can be used (Abbott 2015, Gunarathne et al. 2019).

Although phytoremediation has a roughly 40-year long scientific history, it is a relatively new concept to the field of landscape architecture. Despite the novelty, a landscape architecture firm that specializes in phytotechnologies does exist (Offshoots Productive Landscapes Inc.) and several master's and bachelor's theses in landscape architecture have been written on the subject, dating back to 2010. Additionally, a dissertation in landscape architecture (Pieterse 2017) and celebrated books on phytotechnology (Hollander et al. 2010, Kennen & Kirkwood 2015, Kirkwood 2001), authored by landscape architects, exist as well.

1.7 AIMS

This thesis aims to discuss current research on phytotechnology and the extent to which existing knowledge of the field is and can be applied to the design of stormwater BMPs in a Swedish semi-urban context. Furthermore, because the practical application of phytotechnology requires a broad range of different types of knowledge in many different fields, this thesis aims to demonstrate how the interdisciplinary approach native to landscape architecture can be beneficial in phytotechnology projects. Considering the complex nature of phytotechnology and its successful implementation, the results also aim to show the use of a structured method of designing stormwater BMPs using a phytotechnological design-approach and evaluating the usefulness of the method in designing green structure in semi-urban environments. As a result of all of the above, this work will provide a source of knowledge of phytotechnology to landscape architects and in doing so, illuminate the unrealized potential of a complex and theory-heavy technology.

1.8 RESEARCH QUESTIONS

How can landscape architects benefit from the current state of phytotechnological theory and practice as it concerns stormwater management in a Swedish context?

When applied to the drafting of a site program of an addition to an existing stormwater pond, what opportunities and challenges face a phytotechnological design-approach?

1.9 METHODS

The research questions above were answered using three different methods: literary review, case study and a phytotechnological design-approach to drafting a site program aimed at improving the studied case (figure 1.2).

To aid in guiding and evaluating this thesis, a series of meetings were had with professionals in various fields. A researcher in theoretical and practical phytotechnology: Tommy Landberg at Stockholm University - who also runs the phytoremediation firm PhytoEnvitech AB - was consulted, along with a landscape architect with experience in stormwater management projects: Sofia Eskilsdotter at SLU, an agronomist specialized in water systems: Jonas Andersson at WRS, and a hydrological engineer: Kristina Wilén at WSP.

1.9.1 Literary review (Part B)

The primary sources of information on current phytotechnological research and application was Google scholar and the Swedish University of Agriculture's search engine Primo. Google's standard search engine was also used, but to a lesser extent, and was instrumental in the search for information on Swedish applications of phytotechnology and other sources of information relevant to a Swedish context.

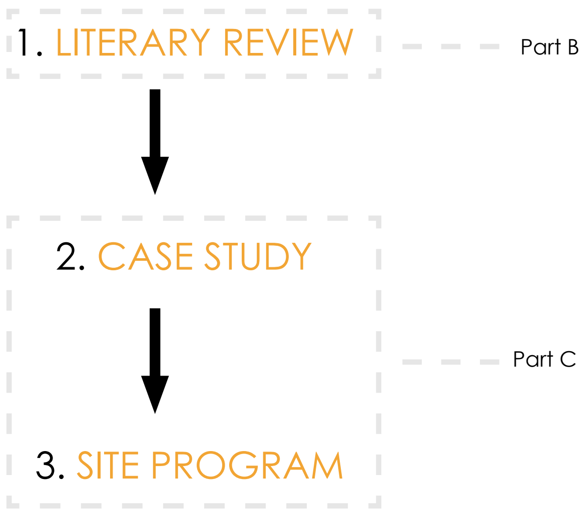

Figure 1.2 Methods used to answer research questions.

Search words are of particular interest on account of the complicated and non-standardized terminology of the field. The initial search words used were *phytoremediation* and *bioremediation* as these were familiar terms from previous education. After subsequent understanding of the sub-fields within phytoremediation, the words *phytotechnology*, *fytoremediering* and *fytosanering* were used - often in combination with more specific terms such as *phytohydraulics*, *phytoextraction* or *phytoirrigation*. Search words such as *landscape architecture*, *stormwater BMP* and *evidence-based design* were also used in concert with the above.

A large part of the literature was found by following citations of older articles in newer ones (Johansson 2016). Furthermore, articles that argue differing or opposite views were actively search for. This included using search words such as *cost-effectiveness*, *challenges* and *disadvantages*.

1.9.2 Case study (Part C)

Jonas Andersson at WRS was consulted about suitable cases for the thesis and the stormwater pond Ladbrodammen in Upplands Väsby, Sweden was chosen primarily because of the amount of research that already was available on the pond.

A case study method developed by landscape architect Mark Francis was employed in the analysis of Ladbrodammen (Francis 2001). Francis (2001) argues that "a case study is a well-documented and systematic examination of the process, decision-making and outcomes of a project, which is undertaken for the purpose of informing future practice, policy, theory and/or education" and suggests conducting case studies using a specific case study format. In the case study of Ladbrodammen, information was gathered on: location, date designed/planned, when the construction was completed, size, client, context, site analysis, role of landscape architects, photographs, user analysis, peer reviews, significance of project, limitations, general features and future issues. Additionally, the remediation potential of the plant species that are currently found in the pond was investigated.

1.9.3 Phytotechnological design (Part C)

Based on the case study of Ladbrodammen, improvements to the treatment methods of the stormwater are suggested and summarized in an illustrated site program. The design of the improvements rest on the use of phytotechnology and the methods and guidelines for this that have been developed by researchers and practitioners in the field (ITRC 2009, Kennen & Kirkwood 2015). In the book *Phyto: Principles and resources for site remediation* (Kennan & Kirkwood 2015 p.17) the authors suggest a four-part method for realising a phytotechnology project that builds on the work of Dr. David Tsao of the Interstate Technology & Regulatory Council (ITRC) (ITRC 2009). For the purposes of this thesis only the first two parts of the method were relevant: the Preplanning phase and the Phytoremediation design and protocol phase (figure 1.3), as the last two are concerned with the implementation and post-implementation stages of a project (Kennen & Kirkwood 2015 pp.17-19).

The Preplanning phase included the following: defining the project vision/aim, selecting the site, finding available data for the site, if there is economic value for the involved parties, if partnerships with stakeholders is possible and the potential to educate affected parties on phytotechnology (Kennen & Kirkwood 2015 pp.17-18). As a result, areas of possible improvement were identified.

In the Phytoremediation design and protocol phase, the two first points that were considered include the on-site remediation potential and the environmental opportunities of the site (Kennen & Kirkwood 2015 p.18). Areas of improvement to the management of the stormwater in Ladbrodammen are suggested based in part on studies of the pond completed in the Preplanning phase (Alm et al. 2010, Andersson et al. 2012). Subsequently, the contaminant types were identified in order to evaluate if phytoremediation was viable on the site (Kennen & Kirkwood 2015 p. 32). Based on the contaminant type, the most suitable phytoremediational plant processes were identified. A number of planting types, i.e. phytotypologies, were selected based on the most suitable phytoremediational plant processes as well as recreational/aesthetical, cultural and ecological values identified in the case study and the site visit (Kennen & Kirkwood 2015 p. 201). Finally, a site program and phytotechnological design was developed.

As a final step, to ensure quality and correct use, the project was reviewed by Tommy Landberg at PhytoEnvitech before publication.

1.10 THESIS BOUNDARIES

Considering how diverse and complex the field of phytotechnology is, this thesis largely focuses on one specific site rather than many. The geographical restriction and the data gathered prior to this work, allowed for more precise targeting of the design to certain contaminants and resulted in highlighting a sub-set of the many plant processes that are usable in phytotechnology projects. The results are limited to a site program and should not be viewed as a complete design ready for projecting.

Although making cost-benefit and cost-effectiveness analyses would be of great use to this research, it is a time-consuming task; dependant on many factors (Pandey & Souza-Alonso 2019). Accurately and extensively describing the economics of a specific project as well as of various remediation practices for comparison could be a thesis in and of itself and is therefore only briefly discussed.

Furthermore, this thesis does not consider the opportunities and challenges afforded by genetical engineering of plants and microorganisms due to the restrictive legislation by the European Union surrounding the use of genetically modified organisms as the potential application of transgenic organisms in phytoremediation endeavours in Sweden is unlikely in the near

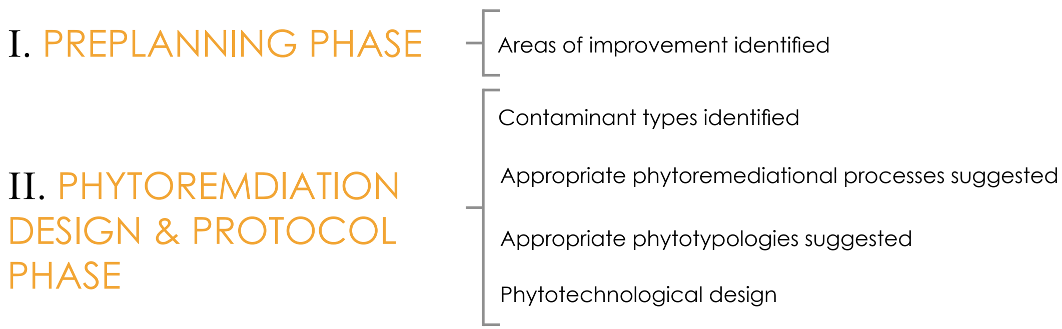

Figure 1.3 The parts of the phytotechnology project checklist by Kennen & Kirkwood (2015) used in this thesis.

future (European Parliament and Council of the European Union 2001, Pandey & Souza-Alonso 2019).

1.11 TARGET READER

The interdisciplinary nature of this thesis renders its target audience quite broad. However, the primary targets are professionals and students in landscape architecture/engineering and related fields with an interest in stormwater management and new developments within remediation practices. It may also be of interest to planners and policy makers as this paper aims to illuminate the opportunities of an under-used and somewhat novel technology.

By writing this thesis in English, rather than in Swedish, it will hopefully serve as a small encouragement to making the discussion of phytotechnology as well as the results of this thesis more accessible to a larger audience.

PART B

Literary review

The following is a review of phytotechnology. The field's somewhat convoluted terminology is initially illuminated followed by a description of the relevant plant biology, phytoremediational processes and what contaminants that can be targeted with phytotechnology. A list of the foremost opportunities and challenges that face the technology in practice is presented as well as a number of notable practical examples and a discussion on why it is not a more commonly used method.

2.1 PHYTOREMEDIATION AND PHYTOTECHNOLOGY

Using biological systems for the management of contaminants is a broad field. It includes numerous methods that take advantage of the ability of certain organisms to interact with contaminants and produce beneficial outcomes in contaminated soil, water and air (Herath & Vithanage 2015, Mani & Kumar 2014). Because of the amounts of organisms that can be used and the many possible applications of their abilities, the terminology naturally gets complicated (figure 2.1) (Gerhardt et al 2017, Kennen & Kirkwood 2015). This can lead to misunderstanding or a general lack of understanding by readers not familiar with the field or with reading scientific literature (Gerhardt et al. 2017, Kennen & Kirkwood 2015 p.34). Furthermore, definitions often vary to some degree depending on the authors, thus creating even greater confusion. However, at its most scientifically fundamental there is large agreement and the term bioremediation defines the use of biological systems for the purpose of managing contaminants (Cristaldi et al. 2017, Herath & Vithanage 2015, Mani & Kumar 2014). Depending on the organism as well as by what biological process that is taken advantage of, different terms are used to describe various sub-fields within bioremediation (Bayona et al. 2013, Herath & Vithanage 2015).

Phytoremediation (*phyto-* meaning: of plant, and *-remediation* meaning: the act of correcting) is one such field and has historically been defined as the use of plants to degrade or remove contaminants in soil, water and air (Kennen & Kirkwood 2015). Subsequent developments have led many researchers and practitioners to include systems with plants that also detect, prevent and detain contaminants (Ali et al. 2013, Gawronski et al. 2011, Gerhardt et al. 2017, ITRC 2009, Kennen & Kirkwood 2015). As with bioremediation, numerous sub-fields of phytoremediation also exist – often referred to in this text as phytoremediational processes. They are categorized by what physiological processes are used, plant types or if other organisms are used in concert with plants (Cristaldi et al. 2017, Mani & Kumar 2014). The American Interstate Technology and Regulatory Council (ITRC) is an organisation with prominent members within phytoremediation research (ITRC 2009, Kennen & Kirkwood 2015). To structure and organize the field, the ITRC defines six major sub-fields: phytosequestration, rhizodegradation, phytohydraulics, phytoextraction, phytodegradation and phytovolatilization (figures 2.1 and 2.2) (ITRC 2009). Note that other authors often use different terminology, definitions and numbers of the sub-fields (Gerhardt et al. 2017, Kennen & Kirkwood 2015, Mani & Kumar 2014).

As a means of avoiding the messy terminology, some authors suggest using the umbrella term phytotechnology to encapsulate all methods, systems and tools concerned with using plants for environmental benefits – including such broad reaches as urban planning and design tools (Henry et al. 2013, ITRC 2009, Kennen & Kirkwood 2015). Additionally, in discussing the lack of acceptance of this technology, Gerhardt et al. (2017) argue that the terminology should be standardised and perhaps simplified as a means of gaining greater acceptance within industry, with planning officials and with non-practitioners.

Although not commonly used in scientific literature, Kennen & Kirkwood (2015) postulate the term phytotypologies to describe standardized planting types that make use of different plants, plant processes and media for managing contaminants.

In the following sections, different phytotechnological processes and methods describing the pathways that a contaminant may take in a phytotechnological system are described (figures 2.2. and 2.3). Although many terms are mentioned, the most relevant ones for this thesis are: phytotechnology, phytoremediation and phytotypology as well as the processes of phytoextraction, phytosequestration and rhizodegradation (figures 2.2 and 2.3) – further described below.

2.2 CONTAMINANTS, THEIR FATES AND BASIC PLANT BIOLOGY

Contaminants in soil and water are subjected to numerous biogeochemical processes (ITRC 2009 p. 10-16, Kennen & Kirkwood 2015 p.27-59). An overview of the various fates of contaminants, and by what means the contaminants arrive there, are presented in figures 2.2. and 2.3. The following is a simplified description of these processes. Note that the fate of any particular contaminant is dependent on several other factors (Kennen & Kirkwood 2015). However, in most phytotechnological systems, among the most important factors are plant species and contaminant type (Gerhardt et al. 2017, ITRC 2009, Kennen & Kirkwood 2015).

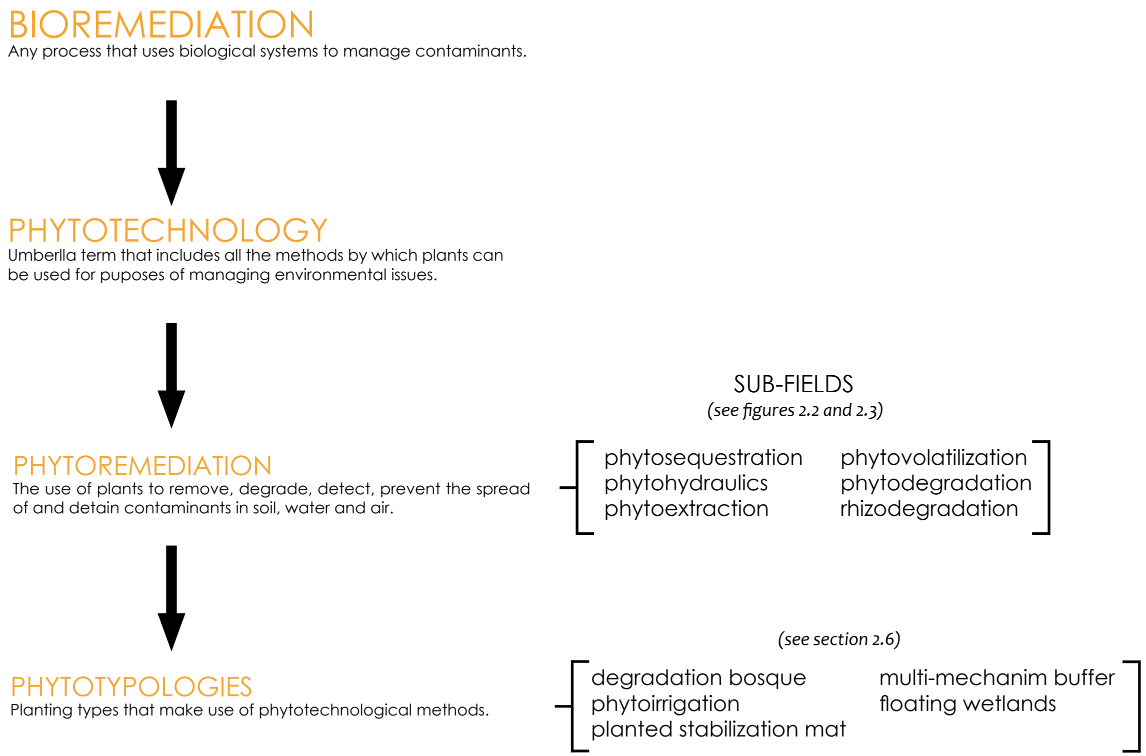

Figure 2.1 Overview of terms associated with the use of biological systems for the purpose of managing contaminants. The sub-fields of phytoremediation are often referred to as phytoremediational processes throughout this text.

Numerous lists (see references) of plant species suitable for different phytotechnological systems and different types of contaminants exists and new species are constantly being added (Gawronski et al. 2011, Gerhardt et al. 2017, Herath & Vithanage 2015, ITRC 2009, Kennen & Kirkwood 2015, Sytar et al. 2016). The lists are too vast to summarize here. Fortunately, the contaminants that can effectively be managed by plants are categorized more easily. In short, two fundamental categories can be distinguished: inorganic and organic (Kennen & Kirkwood 2015 p.61). Determining which of these groups the contaminant(s) on a specific site belongs to is the starting point for deciding what phytoremediational process to employ on that specific site (ibid.). The polluted areas often contain a mix of contaminants that can be unevenly distributed over an area. This necessitates a careful analysis of the local conditions that extends beyond calculating absolute concentrations of contaminants (Kennen & Kirkwood 2015 p. 34).

Organic contaminants are compounds, and some can therefore be broken down or degraded by plants and/or microorganisms. In soil, the remediation of organic contaminants is shown to be the most effective use of phytoremediation (Gerhardt et al. 2017, Kennen & Kirkwood 2015). Common organic contaminants in both phytoremediation practice and research include: petroleum hydrocarbons, gas condensates, crude oil, chlorinated compounds, pesticides, explosive compounds, persistent organic pollutants (POPs) such as DDT and PCBs, and other organic contaminants of concern such as ethylene and formaldehyde (Gerhardt et al. 2017, ITRC 2009 p.1, Kennen & Kirkwood 2015 p.64).

Conversely, inorganic contaminants are elements and can therefore not be broken down further. In comparison to the effectiveness of remediating organic contaminants in soils, most inorganics are less successful or practical, with the exception of plant macronutrients (Kennen & Kirkwood 2015). Despite some difficulties with extraction of contaminants, aquatic systems such as wetlands, show effective filtering and immobilizing of inorganics in the wetland soil (Herath & Vithanage 2015, Kadlec & Wallace 2009). Common inorganic contaminants in both phytoremediation practice and research include: salts, heavy metals, metalloids, radioactive materials as well as plant macronutrients (Gerhardt et al. 2017, ITRC 2009 p.1, Kennen & Kirkwood 2015 p.64).

Hydrological forces (3.).

Some plants can produce such great pull, or turgor pressure, that they can alter the flow of groundwater (3.1) (Kennen & Kirkwood 2009 p.39). If the groundwater is contaminated and has a negative impact on downstream environments, the groundwater plume can be redirected to a location that poses less of a threat. Depending on the type of contaminant, the microbiome and the plant species, the contaminant may also be subject to the mechanisms in fates 1. and 2. (Kennen & Kirkwood 2015 p.39).

Plants' above-ground tissues can intercept enough water that contaminants in the soil will not leach as readily (Bayona et al. 2013 p.79, ITRC 2009 p.13). Coupled with the plant evapotranspiration, stemming from root absorption, the movement of contaminant-rich water through soil can be mitigated (3.2) (ibid.).

Enters plant (1.).

Plants can accumulate contaminants via their roots. Once the contaminant is inside the plant it can either be stored in root cells' waste organelle: the vacuole (1.2 phytosequestration) or transported via the xylem to the shoots and leaves (1.1) where one of several mechanisms can occur – including storage in shoot and leaf vacuoles (1.1.3). If the contaminant is a metabolite, the plant can metabolize and nullify the environmental threat that the contaminant first posed and, in the process, benefit from it (1.1.1). Some contaminants may also be broken down into volatile compounds that can be released via the leaf stomata into the atmosphere (1.1.2). The gaseous product may still be harmful to the environment but, when compared to the threat that the contaminant posed while in the soil/water, it is on balance an environmental improvement (Kennen & Kirkwood 2015).

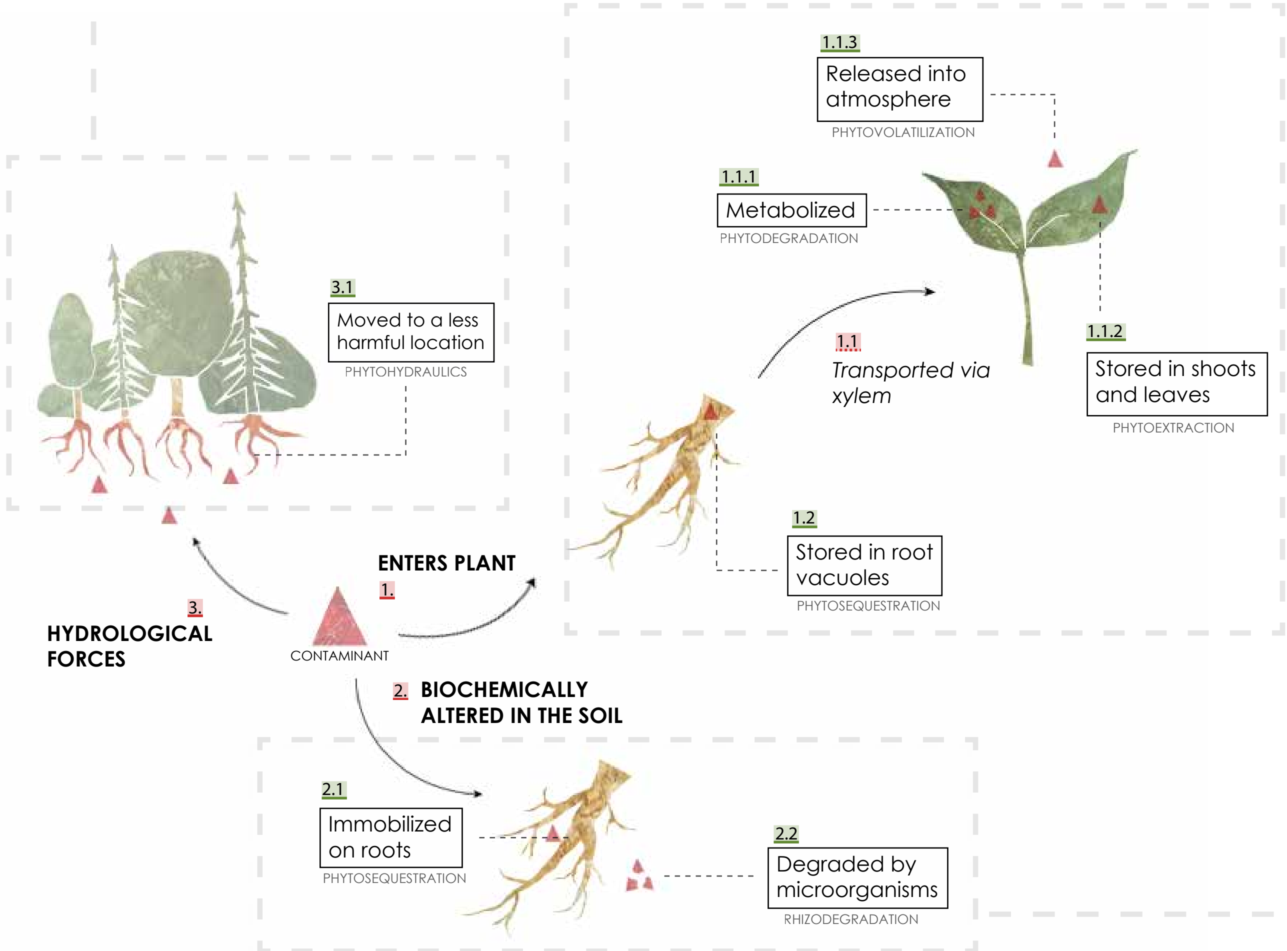

Figure 2.2. Common fates of contaminants in phytotechnological systems.

Biochemically altered in the soil (2.).

Plant roots produce various exudates that can facilitate the adherence of contaminants to the surface of the roots; thus, immobilizing and reducing their bioavailability and downstream environmental threat (2.2). Some exudates also stimulate the growth of microorganisms whose activity serve many functions both outside and inside the plant (Redfern & Gunsch 2016, Reynolds et al. 1999). Microorganisms can: transport contaminants into the plant (1.) (Redfern & Gunsch 2016), degrade the contaminants into compounds that are easier for the plant to accumulate (2.1 followed by 1.) or break down the contaminants into less harmful compounds or elements in the soil or in the plant (2.1) (Redfern & Gunsch 2016). Additionally, the microorganisms can immobilize contaminants by facilitating their adherence to soil particles (2.1) (Dary et al. 2010, Redfern & Gunsch 2016).

2.3 PHYTOREMEDIATIONAL PROCESSES

Many phytoremediational processes, or sub-fields, of phytoremediation exist. Any of these processes can be applied to numerous different situations to achieve a wide range of desired effects. Phytoextraction, phytosequestration and rhizodegradation are presented below because of their relevance to the case of Ladbrodammen in Part C. Other phytoremediational processes that are commonly used include phytodegradation, phytovolatilization and phytohydraulics but will not be described extensivly.

2.3.1 Phytoextraction

Phytoextraction is the use of so-called accumulator and hyper-accumulator plants to extract contaminants – often heavy metals – from soil or water (Kennen & Kirkwood 2015, Mahar et al. 2016, Mani & Kumar 2014). It was the first phytoremediational process discovered and is likely what most people that are only somewhat familiar with the field think of as phytoremediation. In phytoextraction, contaminants are taken up via the roots and translocated and stored in the above-ground plant tissue (figure 2.3) (ibid.). In practice, this necessitates harvesting the contaminant-rich plants after they have had time to accumulate the contaminants (tens of years in many cases) (ibid.).

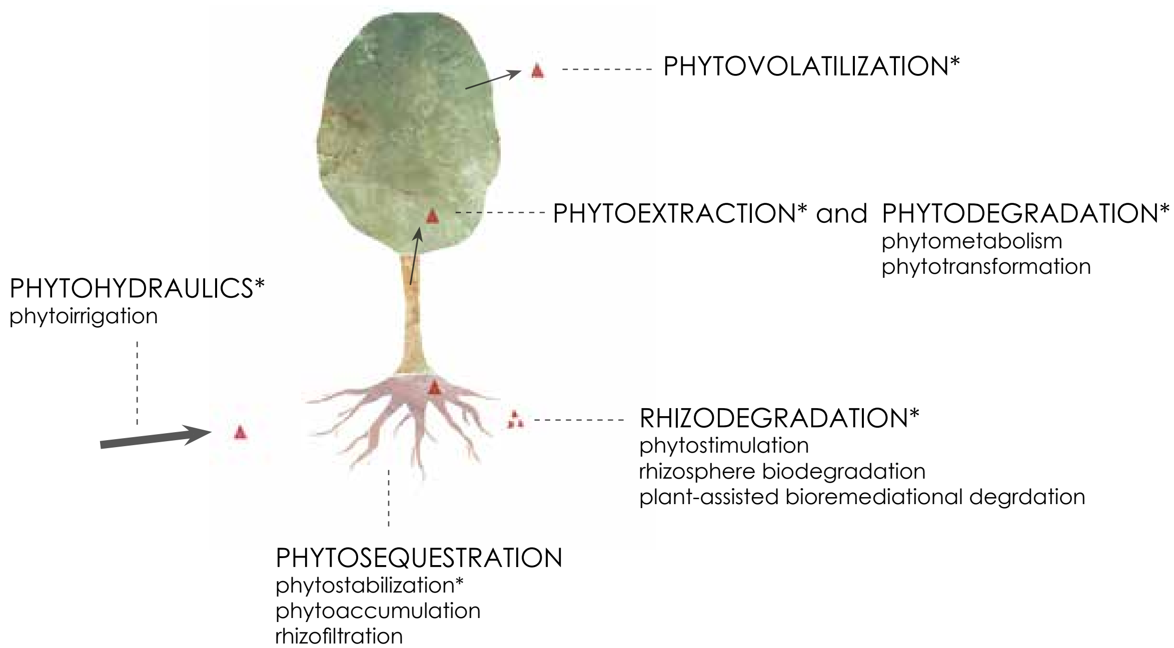

Figure 2.3. Phytoremediational processes and their locations in the plant and its proximity. *Defined as a sub-field by Kennen & Kirkwood (2015).

However, if degradation processes such as phytodegradation or phytovolatilization are coupled with phytoextraction, some contaminants can be broken down and metabolized within the plant (Kennen & Kirkwood 2015 p.38) or degraded into volatile compounds that can be released into the air (ITRC 2009), thus avoiding the necessity of harvesting.

Systems that promote phytoextraction can be commercially viable (Ali et al. 2013, Pandey & Souza-Alonso 2019) with many hyper-accumulator plant species showing effective phytoremediation of certain heavy metals - with metal concentrations in above-ground tissue 100 times greater than comparable non-accumulator plants (Chaney et al. 2007, Cristaldi et al. 2017). However, concerns about the practicality of using phytoextraction for most heavy metal remediation have been voiced and further development and improvement of the method is urged (Kennen & Kirkwood 2015, Mahar et al. 2016).

2.3.2 Phytosequestration

Phytosequestration is often referred to by different names, such as phytostabilization or rhizofiltration, but in essence it is the processes of using plants to immobilize contaminants found in soil, water and air (ITRC 2009, Kennen & Kirkwood 2015 p.39). Immobilization can be achieved by three different plant processes (ITRC 2009): (1) root exudates can be released that immobilize the contaminants in the rhizosphere, (2) the contaminants can be immobilized on the surface of the roots and (3) transport proteins allow for the absorption and storage of contaminants in the roots. Additionally, plant-microorganism interactions can be utilized to enhance phytosequestration (Cristaldi et al. 2017, Mani & Kumar 2014, Redfern & Gunsch 2016).

As with phytoextraction, hyper-accumulator and accumulator plants that take advantage of the absorption of contaminants are also of interest to applications of phytosequestration (Mahar et al. 2016). In contrast to phytoextraction, however, phytosequestration can offer greater aesthetical and ecological benefits due to the simple fact that plants do not need to be harvested (ibid.). Furthermore, these benefits can extend to include positive social effects such as providing attractive building blocks for constructing meeting places and recreational areas.

2.3.3 Rhizodegradation

Rhizodegradation (*rhizo-* meaning: relating to roots) is a phytoremediational process that heavily rests on the symbiotic relationship between plants and microorganisms present in the rhizosphere (Gawronski et al. 2011, Kennen & Kirkwood 2015 p. 35, ITRC 2009). Microorganisms such as bacteria, yeast and fungi use certain contaminants as energy sources and by degrading, metabolizing and/or mineralizing the contaminants they are rendered harmless or less harmful (Cristaldi et al 2017, ITRC 2009, Mani & Kumar 2014, Winquist et al. 2014). The plants' primary role in a rhizodegradation system is to release compounds, or exudates, into the rhizosphere that aid in creating a favorable environment for the microorganisms as well as provide an additional source of energy (ITRC 2009, Mani & Kumar 2014). These processes occur in all vegetated soils and rhizodegradation can be viewed as an enhancement of these processes (ITRC 2009). Plant root exudates vary depending on species and thus, different plant species also attract different species of microorganisms that may be better suited for degrading different contaminant types (Kennen & Kirkwood 2015, Mani & Kumar 2014). Therefore, when implementing a rhizodegradation system, plant species' root exudates and associated microorganisms should be considered (Kennen & Kirkwood 2015).

Like phytosequestration, rhizodegradation offers aesthetical, ecological and social benefits that phytoremediational methods that rely on harvesting don't provide. Furthermore, rhizodegradation is a best-case scenario for most phytotechnology projects since it has the potential to completely nullify the threat of many contaminants (Kennen & Kirkwood 2015 p. 36).

2.4 PLANT TRAITS FOR PHYTOREMEDIATION

The fundamental engines of phytotechnology are plants and there are many factors to consider when selecting the appropriate species for a site (Gerhardt et al. 2017, Kennen & Kirkwood 2015 p. 42). In broad terms, fast growing plants that produce large amounts of biomass while being able to tolerate high concentrations of contaminants should be considered for phytoremediation (Gawronski et al. 2011). More comprehensively, Kennen and Kirkwood (2015 pp. 42-50) present ten plant-specific characteristics and installation considerations as well as two more fundamental considerations for phytotechnology projects. According to the authors, the two first and most crucial things to consider are: (1) if the plants can tolerate the concentration of the contaminant and thus grow on the site and (2) if the depth at which the contaminants are located can be reached by plant roots (Kennen & Kirkwood 2015). Given that the first two are fulfilled, the following plant characteristics and installation consideration can be explored:

- drought-tolerance of species
- use of plants with roots that consistently are in contact with water
- use of planting techniques that allow roots to reach deeper than when unaided
- increase root-surface area by using species with fibrous root zones
- high biomass-producing species
- high evapotranspiration-rate species
- hybrid species
- contaminant concentration and soil amendments
- winter dormancy and climate
- plant spacing

Note that the appropriate focus on any of these characteristics is dependent on site-specifics and the appropriate emphasis on particular points can vary widely depending on local conditions and opportunities (ITRC 2009, Kennen & Kirkwood 2015).

2.5 CONTAMINANT TYPE AND PLANT TRAITS

The types of contaminants that are present on a site largely dictates what plants to use (Gawronski et al. 2011, Gerhardt et al 2017, Kennen & Kirkwood 2015). A substantial amount of research exists on phytoremediation of many specific contaminants (Ali et al. 2013, Cristaldi et al. 2017, Kennen & Kirkwood 2015 p.61) and the ones described below are relevant to the case of Ladbrodammen, presented in Part C.

2.5.1 Petrolium hydrocarbons

Petroleum hydrocarbons such as polycyclic aromatic hydrocarbons (PAHs) are organic compounds and can be managed by phytotechnological systems (Cristaldi et al. 2017, Kennen & Kirkwood 2015). Many petroleum hydrocarbons are among the most promising targets for phytoremediation. Although promising research and practical applications exist, PAHs are considered more difficult to manage than other petroleum hydrocarbons (Kennen & Kirkwood 2015 p. p.67). For targeting PAHs, the most suitable phytoremediational process is currently rhizodegradation (Kennen & Kirkwood 2015 p. 69). It is therefore important to select plants species that promote a rich rhizospheric environment where microorganisms can thrive as well as select plant species that produce root exudates that promote the growth of specific microorganisms that degrade PAHs (Gawronski et al. 2011, Pilon-Smits 2005, Reynolds et al. 1999, Winquist et al. 2014, White & Newman 2011). Plant species commonly used often happen to be deep-rooted grasses (Cook and Hesterberg 2013, Kaimi et al. 2011).

2.5.2 Persistent organic pollutants (POPs)

Phytoremediation of POPs such as PCBs has had some limited success but the significant mechanisms behind the successes in the few examples that exist are poorly understood (Kennen

& Kirkwood 2015 p.119). One of the obstacles to effectively degrading and extracting POPs is that they tend to bind tightly to soil particles - as is also often the case with PAHs. This makes it difficult for plants to affect the contaminants (ibid.). However, POPs can spread if the soil they are bound in is transported by erosion or dust mobilization. Because phytoextraction or degradation and sequestration processes are not yet viable methods for managing POPs, plants that can tolerate the contaminants and grow well on the contaminated area should be chosen as they aid in minimizing the spread of the contaminants.

2.5.3 Heavy metals

Compared to other contaminant types, phytoremediation of inorganic heavy metals, such as zinc and copper, is a rather well-studied area with many experiments that show successful phytoextraction of different heavy metals by a host of different plant species (Ali et al. 2013, Cristaldi et al. 2017). Many authors promote phytoextraction as a promising application of phytoremediation (Cristaldi et al. 2017). However, all do not agree. Many of these studies are only greenhouse or short-term studies and make unjustified extrapolations from the results (Dickinson et al. 2009, Kennen & Kirkwood 2015, Pandry & Souza-Alonso 2019). Kennen & Kirkwood (2015 p.139, 167) even discourage the use of methods that employ phytoextraction for most heavy metals and suggest caution when reading studies on phytoextraction of heavy metals as many of them have not been verified by field-trials or have been shown to be ineffective in the field. Consequently, phytosequestration is often better suited for phytoremediation of most heavy metals (Kennen & Kirkwood 2015 pp.152, 170, Mahar et al. 2016). When selecting plant species for sites that contain heavy metals such as Zn and Cu, root exudates that alter the soil chemistry should be considered. Changes in soil chemistry can greatly affect the bioavailability of heavy metals that then can be mineralized and/or immobilized. Despite the fact that phytosequestration has many advantages over other phytoremediational methods, when applied to heavy metal contaminated media, it does not present a permanent solution to the contamination issue and further actions will need to be taken at a later stage (Ali et al. 2013).

2.5.4 Macronutrients

Phytoremediation of macronutrients such as nitrogen and phosphorous, can be very efficient (Kennen & Kirkwood 2015). For phytoextraction of N, plants species with high evapotranspiration rates and very high growth rates are the most effective. N present in soil or water can also be converted into gaseous form by denitrifying microorganisms. To promote this mechanism plants that produce soil zones with high concentrations of sugars, oxygen and other beneficial root exudates should be chosen. For P, phytosequestration is preferable although some work indicates that phytoextraction could be viable as well (Kennen & Kirkwood 2015 p.132). Muir et al. (2004) demonstrate successful phytoextraction of P but unlike N, the amounts extracted are rarely at a practical rate and is dependent on the removal of above ground plant tissue. For the phytosequestration of P, stormwater ponds are effective at producing phosphorous-rich sediments that can be removed from site or left and slowly allowed to naturally dissolve (Kadlec & Wallace 2009, Kennen & Kirkwood 2015 p.132). In soils that have high concentrations of P, immobilization by adsorption to soil particles can be promoted. This occurs in soils without vegetation as well but at a certain point the soil will be saturated with P. By using plants that have dense, thick root systems and high growth rates, saturation can be prevented (Kennen & Kirkwood 2015 p.133).

2.6 IMPLEMENTING PHYTOTECHNOLOGY

When considering the implementation of phytotechnology on a site there is a substantial number of variables to consider (Gerhardt et al. 2017, ITRC 2009, Kennen & Kirkwood 2015). Kennen & Kirkwood (2015 p. 201) suggest selecting among 18 different planting types, i.e. phytotypologies, that aim to serve as initial design-aids in the process. The phytotypologies described by the authors are adaptable and combinable and are defined by several variables that render them suitable for different projects depending on site-specifics and project goals. Kennen & Kirkwood (2015) also offer various design considerations for each typology that take into account suitable characteristics of plant species, ecosystem services, numerous abiotic factors, seasonality and more. The following is a description of five phytotypologies that are relevant to the case of Ladbrodammen presented and later discussed in Part C. Additionally, further considerations – such as selecting plant species based on specific contaminants – are discussed at appropriate sections in the site program, also in Part C.

2.6.1 Degradation Bosque

A Degradation Bosque (figure 2.4) is an area planted with deep-rooted trees and shrubs and is primarily designed to target the contaminants: petroleum, chlorinated solvents, pesticides and nitrogen (Sleegers & Hisle 2018, Kennen & Kirkwood 2015). The aim of this phytotypology is to stabilize, volatilize, metabolize and/or degrade contaminants without the need of harvesting plants (Kennen & Kirkwood 2015 p. 218). The most efficient phytoremediational processes at work are: rhizodegradation, phytodegradation, and phytovolatilization (ibid).

In selecting plant species, the fundamental design considerations are degradation-capability and root-depth (Kennen & Kirkwood 2015 p. 218). Plant species should also be selected based on what root-exudates and associated microorganisms the plants have, the plants' root-lengths as well as contamination-depth (ibid.).

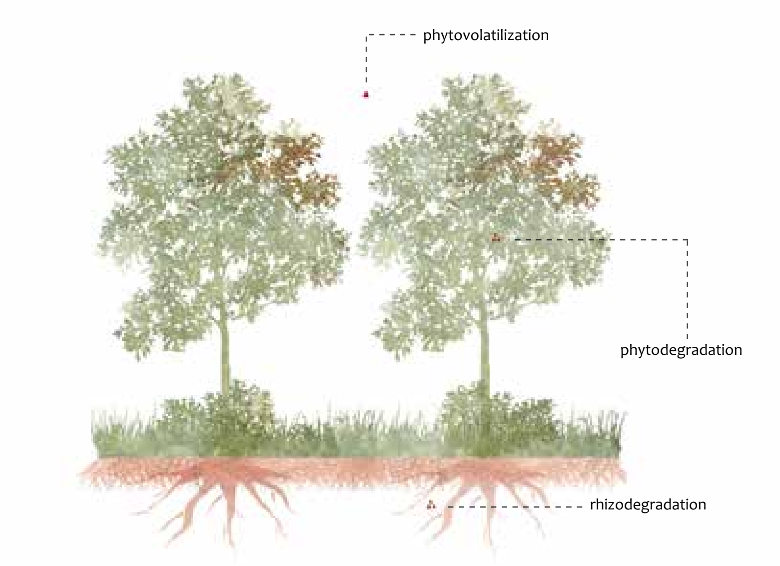

Figure 2.4. Schematic illustration of a Degradation Bosque showing the most active phytoremediational processes at work.

2.6.2 Phytoirrigation

In phytoirrigation systems (figure 2.5), contaminated water is irrigated onto planted areas where carefully selected plants degrade or volatilize nitrogen, chlorinated solvents, petroleum, selenium and tritium (Smesrud et al. 2012, Sleegers & Hisle 2018, Kennen & Kirkwood 2015 p.207). The primary phytoremediational processes used in these typologies are rhizodegradation, phytodegradation and phytovolatilization (Kennen & Kirkwood 2015 p.207).

Plants should be selected based on the maximization of water volume irrigated (Kennen & Kirkwood 2015 p.207). This also means selecting plants that can tolerate large amounts of water. Nitrogen degradation should also be considered when selecting plant species. High-biomass species are correlated with the greatest amount of nitrogen removal by incorporation of nitrogen into the plant as well as the plant's ability to create large root-zones that promote denitrification of nitrogen by microorganisms (ITRC 2009). Furthermore, plant species with high evapotranspiration rates are preferable in phytoirrigation systems as studies show that they are the most effective at volatilizing and degrading chlorinated solvents, petroleum, selenium and tritium (Kennen & Kirkwood 2015 p.207).

Kennen & Kirkwood (2015 pp.209-210) also suggest doing mass water balance calculations in the design. This will ensure that the plants use all the water that is irrigated onto the area. If it is possible to control, the concentration of contaminants in the irrigated water should be investigated and a maximum concentration should be chosen based on the tolerance of the plant species. Finally, the seasonal changes on the site should be considered. The area should only be irrigated during the growing season.

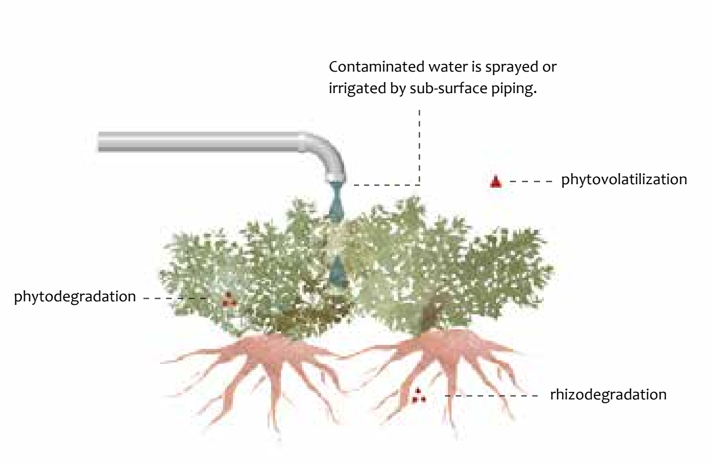

Figure 2.5. Schematic illustrations of a Phytoirrigation system. Note that many different irrigation mechanisms are applicable.

2.6.3 Planted Stabilization Mat

A Planted Stabilization Mat is a typology that is characterized by low vegetation (figure 2.6). It is designed to immobilize contaminants while allowing water to run through the soil (Sleegers & Hisle 2018, Kennen & Kirkwood 2015 p. 202).

The major plant phytoremediational process at work is phytosequestration and the primary contaminants targeted are: metals, POPs and salts. However, all contaminant types can be target to some degree (Kennen & Kirkwood 2015 p. 202).

When considering plant species, Kennen & Kirkwood (2015 p. 204) suggest selecting plants that can tolerate high concentrations of harmful contaminants, plants that release root exudates that reduce the mobility of the contaminant as well as selecting plants that effectively cover the soil and eliminates erosion by wind and water.

Careful consideration of the soil chemistry should also be made as abiotic factors can sometimes influence the mobility of contaminants even more than plants (Kennen & Kirkwood 2015 p. 204). The addition of a soil buffer, consisting of a thin cap of clean soil on top of the contaminated soil, could be considered if the exposure needs to be minimized quickly. A change in the topography may also be appropriate when aiming to direct potentially contaminant rich water away from more vulnerable areas (ibid.). The concentrations of the contaminants may be of vital importance as some plants simply can not survive at high contamination levels (Cunningham et al. 1995, Gerhardt et al. 2017).

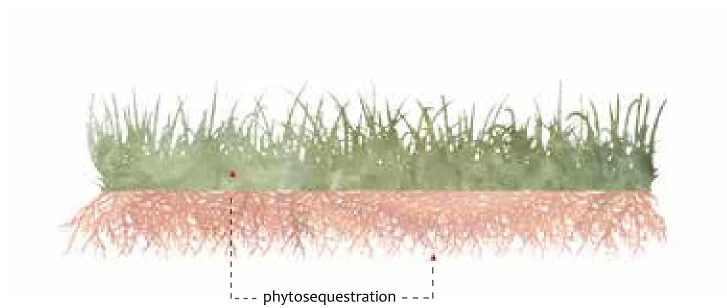

Figure 2.6. Schematic illustration of a Planted Stabilization Mat.

2.6.4 Multi-Mechanism Buffer

Minimizing exposure-risk is at the heart of Multi-Mechanism Buffer typologies (figure 2.7) (Kennen & Kirkwood 2015 p.234). By using all available phytotechnological means, this phytotypology targets all types of contaminants and the details of its design is strongly influenced by the type of contaminants present on the site of interest. This allows for a large amount of plants and plant types in the design and factors other than phytoremediation can easily be incorporated in the design.

Kennen & Kirkwood (2015 p.235) suggest considering ecosystem services when designing a Multi-Mechanism Buffer – most notable among them: preventing erosion, habitat creation and enhancement, carbon sequestration, increase of property value and opportunity for enhanced recreational value and aesthetics.

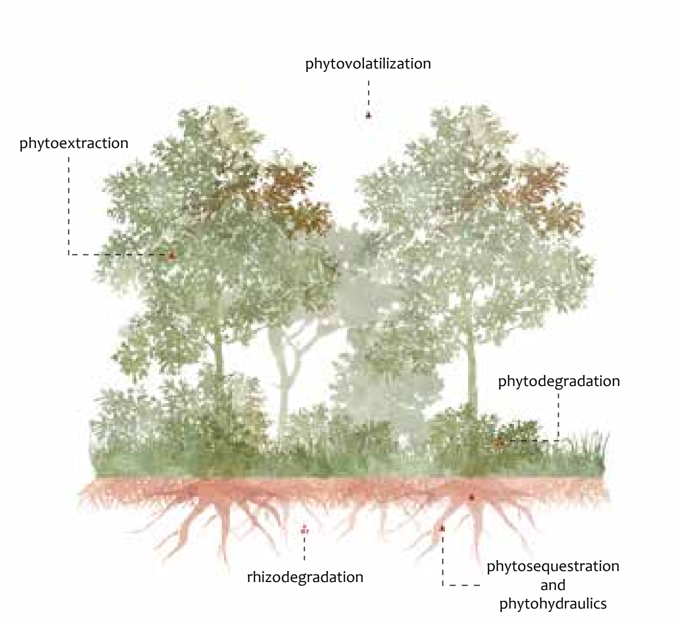

Figure 2.7. The Multi-Mechanism Buffer targets all contaminants using all phytoremediational means availabale. Note that these processes can occur in several locations in the phytotypology as well as in the individual plants themselves.

2.6.5 Floating wetlands

Floating wetlands (figure 2.8) are natural or artificial floating platforms planted with vegetation that promote various phytoremediational processes (Headley & Tanner 2008, Kennen & Kirkwood 2015 p. 242, Rechman et al. 2018). Although the phytoremediational capability of floating wetlands is extensive, the primary process at work is phytosequestration (Kennen & Kirkwood 2015 p. 242). Depending on the plant species composition and the associated microorganisms, many contaminant types can be managed. Nitrogen, petroleum, chlorinated solvents and pesticides can be degraded and/ or removed; explosives, metals, phosphorous and POPs can be immobilized in the soil or in the plants; and some metals, phosphorous and nitrogen can slowly be extracted, if the plants are harvested (Kennen & Kirkwood 2015 p. 243, Srivastava et al. 2017).

When selecting plant species for floating wetlands; contaminant type, water tolerance, pH preference and good growth without the need of maintenance, should be considered (Kennen & Kirkwood 2015 p.244). If the aim is to degrade organic contaminants from the water, plant species that grow fast and acquire large amounts of biomass increase contaminant degradation and removal (ibid.). Coupling this with a large species diversity also aid in creating favorable conditions for beneficial microorganisms that aid in the degradation process. Plant-microorganism interactions are of large consequence to the success of floating wetlands and should be carefully evaluated when considering implementing this phytotypology (Srivastava et al. 2017, Stewart et al. 2008).

Floating wetlands can also be a rich habitat for animals by acting as an additional food source as well as providing cover for fish, insects and birds (Kennen & Kirkwood 2015 p.244, Stewart et al. 2008, Vegtech AB 2019).

Floating wetlands are now commercially available on the Swedish market (Vegtech AB 2019). They are modular and can be customized according to the above-mentioned criteria, depending on site-specifics of a particular project. In terms of phytotechnological capabilities, the manufacturer broadly claims that the system can improve water quality, improve the landscape image, reduce the risk of algal bloom, regenerate wetlands and lakes as well as provide an erosional barrier in bodies of water (Vegtech AB 2019).

The literature on the phytoremediational capability of plants in aquatic systems such as floating wetlands is extensive (Kadlec & Wallace 2009, Kennen & Kirkwood 2015, Srivastava et al. 2017) and the description given above presents only a very brief overview of the wealth of knowledge that exists.

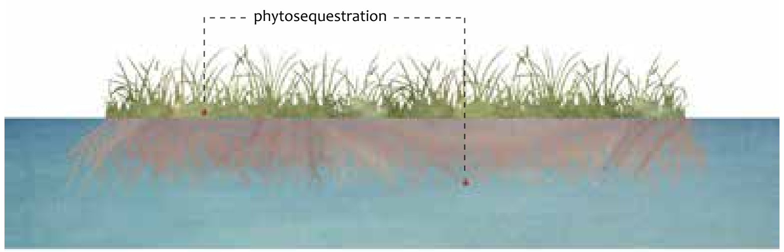

Figure 2.8. Schematic illustration of Floating wetlands.

2.7 OPPORTUNITIES AND CHALLENGES OF PHYTOTECHNOLOGY

Plant-based remediation methods offer many opportunities for sustainable remediation practice along with an additional number of ancillary benefits (Gerhardt et al. 2017, Kennen & Kirkwood 2015, ITRC 2009, Redfern & Gunsch 2016). However, many obstacles do exist when considering implementing phytotechnology and the careful consideration of these is of paramount importance for the success of any project (Gerhardt et al. 2017, Kennen & Kirkwood 2015). In general, large sites with a low to moderate concentration of contaminants are best suited for phytoremediation (Gerhadt et al. 2017). The opportunities and challenges are presented in no particular order of importance in the followng two lists.

The foremost opportunities are:

- The diversity of plants and their different physiological mechanism offer a wide spectrum of application to different landscapes (Kennen & Kirkwood 2015 p.7);
- For most applications, the technology is primarily solar driven (Cunningham et al. 1995, ITRC 2009 , Kennen & Kirkwood 2015);
- Ecological regeneration of the site is possible with plant-based methods as is not the case with many conventional methods of remediation that often render soils barren (Gerhardt et al. 2017, ITRC 2009, Kennen & Kirkwood 2015, Wenzel 2009);
- It is perceived as an attractive technology to many groups as it provides common goals for scientists, engineers and designers (Kennen & Kirkwood 2015, Kirkwood 2001). The public acceptance has also been shown to be high, especially when used close to residential areas (Ali et al 2013, Kennen & Kirkwood 2015);
- Phytoremediation is generally viewed as a cost-efficient way of managing contaminated areas (Gerhardt et al. 2017, ITRC 2009, Kennen & Kirkwood 2015, Pandey & Souza-Alonso 2019). Some studies show a cost-reduction of up to 50 % of conventional remediation methods (Gerhardt et al. 2017). Others claim a possible reduction of 80% and even 95% in some instances (Prasad 2003);

- Phytotechnology can be integrated with other vegetation and landscape designs – particularly for post-industrial sites (Kirkwood 2001). This is dependent on the foresight and knowledge among planners. Landscape architects knowledgeable about phytotechnology are in a key position to achieve this (Kennen & Kirkwood 2015);
- In addition to being a tool for remediating contaminants, phytotechnology can also be used in preventative measures (ITRC 2009, Kennen & Kirkwood 2015). Plantings can act as buffer zones for potential contamination and environmental degradation of landscapes;
- Specific vegetation planted in strategic locations can be used as indicators of ecosystem health and contaminant presence (ITRC 2009, Kennen & Kirkwood 2015). In many cases, contamination can be assessed more easily with plants than conventional methods (Burken et al. 2011, Kennen & Kirkwood 2015 pp.21-23);
- In contrast to most conventional remediation techniques, phytoremediation can simultaneously remediate both organic and inorganic contaminants using only one system (ITRC 2009 p.29); and
- Apart from addressing issues concerning contaminants, phytotechnology also provides other services including: community and educational use, habitat creation, biomass production, climate change mitigation, it offers benefits to agricultural systems as well as controls erosion, infiltration, runoff and dust emissions (Henry et al. 2013, ITRC 2009 p.30, Kennen & Kirkwood 2015 p.8, Todd et al. 2016).

The principal challenges that face phytotechnology are:

- Many sites are not suitable for phytotechnology due to: types of contaminants that plants are not able to process, poor media characteristics for plant growth due to high concentrations of contaminants or nutrient deficiencies and climatic regions that have short growing seasons or for other reasons have an unfavorable climate for plant growth. (Cunningham et al. 1995, Gerhardt et al. 2017, Kennen & Kirkwood 2015, Mahar et al. 2016);
- A major limitation of phytoremediation is the depth at which the contaminants exist as the applicability of the technology is dependent on root length (Gerhardt et al. 2017, Kennen & Kirkwood 2015). This is also dependent on climate zone and the adaptability of the plants to a site's local conditions (ITRC 2009, Kennen & Kirkwood 2015, Mahar et al. 2016);
- The time-frame between planting and maturity of plants, and the desired efficiency of remediation, is long (often 3 years or more) and requires that the land-owner adopts a long-term strategy that may include a commitment to specific maintenance of the site (Cunningham et al. 1995, Gerhardt et al. 2017, Kennen & Kirkwood 2015, Mahar et al. 2016). This is especially true if the site contains strongly competing plant species. Additionally, the time-frame is of great importance if the contaminated area poses an imminent threat to human health and in such cases, phytotechnology is not viable (Gerhardt et al. 2017);
- There may be large uncertainty of the outcome of any phytoremediation technology in practice due to variable weather, animal impact, disease and insect

infestations (Gerhardt et al. 2017, Kennen & Kirkwood 2015);

- Proper implementation requires a high degree of expertise in many fields. This creates a risk of improper applications and design flaws (Gerhardt et al. 2017, Kennen & Kirkwood 2015);
- In temperate regions the efficiency is lower due to the shorter length of the growing season (Kennen & Kirkwood 2015);
- Some remediation methods that utilize phytoextraction - where the contaminants are stored in the above ground plant tissue - are dependent on the harvesting of plants. This can be labour intensive, costly and energy intensive (Mahar et al. 2016, Kennen & Kirkwood 2015);
- Contaminants stored in the above ground tissues or volatilized and released into the atmosphere may constitute a greater threat to organisms as the risk of exposure potentially becomes greater when compared to if the contaminant was limited to the soil or water (Kennen & Kirkwood 2015);
- The use of plants can alter the bioavailability of certain contaminants in the media, for instance by changing its pH and/or increasing amounts of organic compounds, and thus increasing risk of exposure to previously unexposed food-chains (Gerhardt et al. 2017);
- Maintenance and monitoring of the progress of plantings may be costly and may require expert knowledge (Kennen & Kirkwood 2015);
- Suitable species may not be available for purchase within a reasonable proximity of the site (Kennen & Kirkwood 2015); and
- The planning constraints concerning legal, regulatory and economic conditions may be difficult to understand and convey to officials and thus the potential of the technology might be overlooked (Gerhardt et al. 2017, Kennen & Kirkwood 2015).

2.8 NOTABLE EXAMPLES OF PHYTOTECHNOLOGY IN PRACTICE

There are numerous examples of successfully using phytotechnology for many different applications in different parts of the world (Greger & Landberg 2015, Isebrands & Richardson 2014, Mirck et al. 2005). In Sweden, the use of *Salix spp.* and *Populus spp.* in agricultural landscapes is relatively common (figure 2.9. a)(ibid.). These species are often sowed for the purpose of energy production or for the plant's positive effects on species diversity as well as for various phytotechnological purposes, including aesthetical reasons (Hjulfors & Hjerpe 2013, Isebrands 2014). The Swedish Board of Agriculture suggest using *Salix spp.* and *Populus spp.* for phytoremediation of macronutrients in stormwater runoff, for phytoextraction of heavy metals, such as Cd, Cu and Zn, as well as for phytodegradation and rhizodegradation of some organic compounds, such as the explosive trinitrotoluene and the gasoline additive methyl tertiary butyl ether (Hjulfors & Hjerpe 2013). An internationally recognized example of this is the thermal power plant in Enköping (ENA Energi AB, Isebrands et al. 2014). Plantings of *Salix sp.* are irrigated with sewage wastewater and the plants extract nitrogen, phosphorous and cadmium (Isebrands et al. 2014). The plants are regularly harvested and used in thermal reactors for energy production (ENA Energi AB 2019, Isebrands et al. 2014). Apart from producing energy, the system also mitigates the contamination of receiving water bodies – most notably by preventing eutrophication of Mälaren (ibid.). Many more similar examples of using *Salix spp.* and *Populus spp.* for phytoremediation of many contaminant types exist in countries such as Australia, Belgium, Canada, Estonia, Italy, Korea, New Zealand and the UK (Isebrands et al. 2014).

Another common use of phytotechnology is as part of constructed wetlands (Ansari 2018, Kadlec & Wallace 2009, Kennen & Kirkwood 2015). A case that demonstrates both phytoremediation and public utility is the Willow Lake Water

Figure 2.9. (a) Salix sp. in an agricultural landscape. A common application of phytotechnology in agricultural practice in Sweden. Photo: Nils-Erik Nordh. *(b)* and *(c)* Grorudparken in Oslo is Norway's first park with elements that make use of phytotechnology. Photos: Tomas Majewski *(d)* The creative use of floating wetlands in Pontonparken, Malmö. Photo: Ulrica Carlberg *(e)* Willow Lake Water Pollution Control Facility in Oregon, USA, demonstrates how phytotechnology projects can combine remediation with recreational opportunities. Photo: GoogleMaps.

Pollution Control Facility in Salem (Oregon), USA (figure 2.9e). The facility is designed to remediate macronutrients while also acting as a recreational area. Successful remediation of macronutrients has been achieved and the facility is frequently used by the public for recreation and wildlife viewing (Kennen & Kirkwood 2015 pp.133-135). Similarly, the landscape architecture firm Berg & Dahl, among other actors, designed a small floating park in Malmö, Sweden, that integrates floating wetlands with a small system of docks (figure 2.9 d) (Vegtech AB 2019).

The firm LINK Arkitektur used phytoremediation in part of their design of the celebrated Grorudparken in Oslo, Norway (figures 2.9 b and c). It was a project with many technical difficulties concerning contaminated stormwater and poor water quality in the park's pond (LINK Arkitektur 2019). The project was finished in 2013 and was the first use of phytoremediation in Norway. *Salix viminalis* was planted in the park but the success of the phytoremediation on the site has not been investigated.

Remediation of petroleum compounds has been successfully demonstrated in many cases (Kennen & Kirkwood 2015). The US Coast Guard Former Fuel Storage Facility is one such case and has shown efficient remediation with contaminant reductions of up to 99% for some petroleum compounds (Cook et al. 2010, Guthrie et al. 2014).

The use of phytotechnology on abandoned industrial sites, known as brownfields, is one of the more popular applications (Hollander et al. 2010, Kirkwood 2001). A famous example is Landschaftpark Duisburg-Nord in Germany (figures 2.10 and 2.11) (Stilgenbauer 2005, Weilacher 2008). The award-winning park was designed by the landscape architect firm Latz+partner and is a redesign of a disused metallurgical plant and its surroundings into a large park. The first parts of the park were opened in 1994 and it has since become very popular; even attracting visitors from abroad. The design combines industrial elements with planted areas - some of which are designed with phytoremediation in mind - and provides an abundance of opportunities for recreational activities such as concerts, climbing walls, food stalls, scuba diving and more (Duisburg kontor 2019). In the initial stages, some parts of the site had such high concentrations of contaminants that they were sealed off from public use and covered with a layer of soil in which contaminant tolerant plants were planted (Mackay 2016). Later, after the contaminant levels had dropped, the public was invited back to these areas. Multiple channels with contaminated water run through the park as well and adjacent plantings also aid in the

Figure 2.10. Integration of disused industrial structures within a park that also has phytotechnological elements in Duisburg Germany. Photo: Thomas Berns.

Figure 2.11. Concert in Lantschaftspark Duisburg-Nord. Photo: Thomas Berns.

remediation process (ibid).

2.9 NOT YET A FULLY ACCEPTED PRACTICE

The use of phytotechnology varies in different parts of the world. In North America phytotechnological practices are a lot more common than in Europe and in many Asian countries there is a growing interest (Gerhardt et al. 2017, Kennen & Kirkwood 2015, Pandey & Souza-Alonso 2019). As much research indicates, the technology could be employed more frequently and should be encouraged further (Gerhardt et al. 2017, Kennen & Kirkwood 2015, Pandey & Souza-Alonso 2019, Todd et al. 2016). The impediments to greater acceptance are many but fundamentally lack of knowledge is at its core (Cunningham et al. 1995, Gerhardt et al. 2017, Kennen & Kirkwood 2015 p.23). Furthermore, the limitations to the technology are due to physical boundaries such as plants' root depth or contaminant tolerance, as was outlined in section 2.4. However, additional reasons do exist. The field has a history of using "plant and pray"-methods that have failed to investigate crucial aspects of a site before planting; the result of which has been a collection of failed field-trials that poorly reflect the potential of the technology (Gerhardt et al. 2017). In addition, there is a lack of large-scale field trials that both investigate the technology and clearly outline its associated costs (Gerhardt et al. 2017, Kennen & Kirkwood 2015). As a consequence, it is harder for planners to confidently promote the method and more economically safe methods with less uncertain outcomes are routinely chosen (Gerhardt et al 2017).

Overselling of phytoremediation as well as negative misconceptions have been detriments to the field as well (Gerhardt et al. 2017, Kennen & Kirkwood 2015 p.23). If the technology is to be appropriately accepted in future, the opportunities and limitations of any individual project needs to be made clear (ibid.). Additionally, much is still not known about the mechanisms that drive certain outcomes or what outcomes are possible. In order to advance the field, it needs to be made clear what phytotechnology designs and plant mechanisms have been successful (Kennen & Kirkwood 2015 p.23).

Systems that promote phytoextraction can be commercially viable (Ali et al. 2013, Pandey & Souza-Alonso 2019) with many hyper-accumulator plant species showing effective phytoremediation of certain heavy metals - with metal concentrations in above-ground tissue 100 times greater than comparable non-accumulator plants (Chaney et al. 2007, Cristaldi et al. 2017). However, concerns about the practicality of using phytoextraction for most heavy metal remediation have been voiced and further development and improvement of the method is urged (Kennen & Kirkwood 2015, Mahar et al. 2016).

PART C
Case study and Site program

Part C contains a case study of the stormwater pond Ladbrodammen as well as a graphically represented site program that outlines the implementation of a number of phytotechnological improvements to the pond. Areas of improvement and contaminant types present on the site are first identified. Following this, a number of appropriate phytoremediational processes and phytotypologies are suggested. Finally, the site program is presented along with a schematic illustration of a design resulting from the site program.

3.1 CASE STUDY LADBRODAMMEN

Ladbrodammen is a stormwater pond, or constructed wetland, located approximately 1.2 km north of the town center of Upplands Väsby between a road (Ladbrovägen) and a small river (Väsbyån) (figures 3.1 and 3.2). The pond has been in use since 2003 and is the recipient of stormwater from a semi-urban catchment area that includes a wide array of land uses such as residential, town centre, industrial, forest and fields (Andersson et al. 2012). The catchment area is large (approx. 200 ha) in comparison to the size of the pond (projected area of 5 500 m^2) and receives 70% of catchment area's stormwater (Alm et al. 2010 p.24, Kadlec & Wallace 2009). The outlet leads the stormwater into Väsbyån where it is carried downstream to the lake Oxundasjön and later into Mälaren.

The pond is divided into three sections with varying depths and functions – all separated by a continuous mound of macadam (figure 3.2). The stormwater is first pumped into a smaller pre-pond (1.3 m deep) before running through a barrier of macadam to both a main pond (0.8-1.3 m deep) and a section of wetland (Alm et al. 2010). Although only one section is a specifically designated wetland area, with a wetland water depth of 20 cm, the pre-pond and the main pond have perimeters of wetland with depths of 20 and 80 cm respectively (ibid.).

The pre-pond is designed to slow down the flow of water in order to encourage sedimentation of contaminants. Alm et al. (2010) write that contaminant removal in the wetland areas is facilitated by microbial degradation and "uptake" by plants but it is not specified by what means this is achieved.

Most of the water that reaches the pond area is released into Väsbyån via the outlet located in the main pond's northern end. However, 25-35% of the water that is directed towards the pond annually, by-passes Ladbrodammen and is directly fed into Väsbyån as a means of preventing overflooding (Andersson et al. 2012). Conversely, during dry periods water is pumped into the

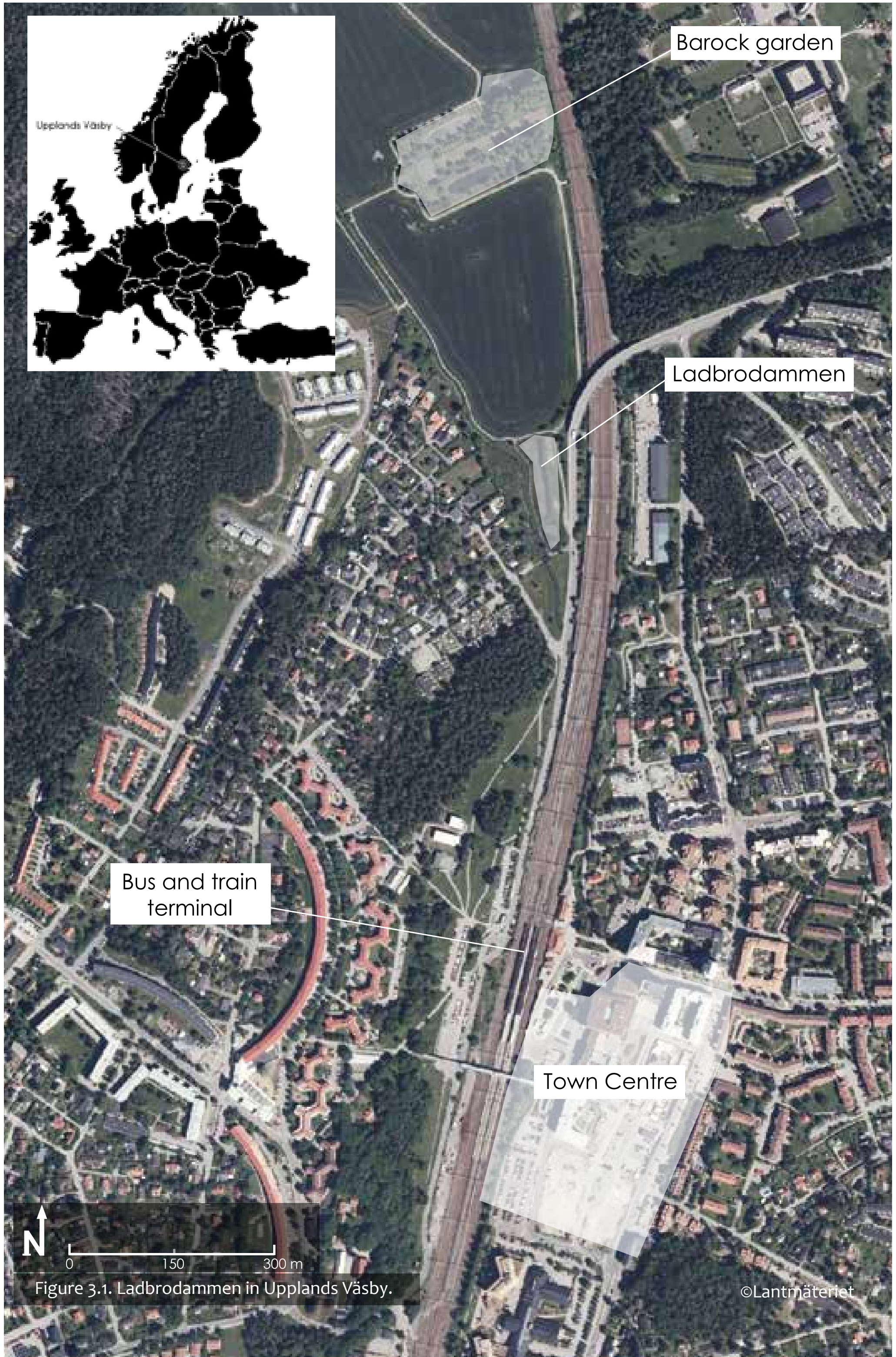

Figure 3.1. Ladbrodammen in Upplands Väsby.

Figure 3.2. The layout of Ladbrodammen.

pre-pond.
Ladbrodammen was part of a follow-up study focused on 5 stormwater ponds around Mälaren that started in 2006 (Andersson et al. 2012). Data on contaminant levels, the catchment area's qualities and more now exist. Additionally, Ladbrodammen has been the subject of several theses that have supplied additional data on ecological structure and function, water chemistry and various hydrological metrics. Landscape architects have not been involved in any follow-up studies or in the design.

North of the pond, large open fields stretch out into a recreational area that includes numerous pathways through agricultural land and wooded areas as well as a baroque garden (figure 3.1). The baroque garden as well as a smaller area 100 m south of the pond are classified as areas of ecological importance. On the standardized scale of ecological importance used for inventory of biodiversity in Swedish landscapes (SIS/TK 555 2014), both areas are given class 2-status (out of three classes) which denotes high ecological value (Upplands Väsby kommun 2018). In the detailed development plan of Ladbrodammen, the pond is characterized as an aesthetical and educational attraction along a recreational path that connects the two lakes Edssjön and Oxundasjön. (Upplands Väsby kommun 2005) Additionally, the area is categorized as culturally significant and of national importance. (ibid.) The municipality's water plan document states that a further development of the recreational pathway, starting with Ladbrodammen, is desired. (Upplands Väsby kommun 2007 p. 82)

3.2 CONTAMINATION

In a report by Alm et al. (2010), the concentrations of several contaminants were measured in both the inlet to Ladbrodammen as well as the outlet. The report indicates that Ladbrodammen can clean many contaminants from the stormwater; achieving concentrations below environmental target values. (Alm et al. 2010) However, target values do not exist for all contaminants and, due to the fact that 25-35% of the stormwater by-passes the pond, total cleaning of the stormwater is not achieved or accurately measured (Alm et al. 2010). In total, the concentration of 28 contaminants that exceed environmental target values were found in the inlet of the pond (table 3.1). However, Alm et al. (2010) note that it is difficult to know if all of these values are high or not due to the absence of reference values.

A study by SWECO (2012) shows that Ladbrodammen cleans 17% of the P and 48% of the N that enters the system. A recent report on a development project for a school within the catchment area suggests that measures should be taken to minimize the contaminant load on Ladbrodammen (SWECO 2018).

3.3 POND VEGETATION

During the construction of the pond, 16 000 plants of 35 different species were planted in the shallower parts of the pond (Andersson et al. 2012). The report by Andersson et al. (2012) shows that the species diversity was maintained since the initial construction. However, the head groundskeeper* reports that most of the species in the pond have migrated in from surrounding land and are of a different species to the original plants. The species inventory by Andersson et al. (2012) is presented in table 3.2 along with the phytoremediation potential of each plant species.

Table 3.1. Contaminants present in concentrations above environmental target values in the inlet of Ladbrodammen (Alm et al. 2010). *Also found in the outlet in concentratioins above environmental target values.

PAHs	POPs	Petroleum compounds	Other organic contaminants	Heavy metals	Macronutrients	Other
Bens(a)anthracene	4-nonylphenol*	MTBE*	DEHP*	Cu	N	Susepended solids
Bens(b)phluorantene	4-tert-oktylphenol	DTBE*	krysene	Zn	P*	
Bens(k)phluorantene	PCB 28					
Bens(a)pyrene	PCB 52					
Benso(ghi)perylene	PCB 101					
indeno(123cd)pyrene	PCB 118					
PAH 16	PCB 138					
PAH cancerogenic	PCB 153					
PAH other	PCB 180					
Phluoranten						
Pyrene						

*Nils Odén, landscape architect, personal telephone communication 2019-02-11.

Tabel 3.2. Inventoried vegetation in Ladbrodammen 2012 and associated phytoremediational potential (Andersson et al. 2012, ITRC 2009, Kennen & Kirkwood 2015).

PRE-POND	Phytoremediation	**MAIN POND**	Phytoremediation	**WETLANDS**	Phytoremediation
Alisma plantago-aquatica	n/a	*Alisma plantago-aquatica*	n/a	*Juncus spp.*	PAHs Macronutrients: P
Carex spp.	PAHs: (*C. cephalophora*) POPs: (*C. aquatica*)	*Carex riparia*	n/a	*Phragmites australis*	n/a
Iris pseudacorus	n/a	*Eleocharis palustris*	n/a	*Schoenoplectus lacustris*	Petrolium compounds Heavy metals: Cu
Juncus conglomeratus	Macronutrients: P	*Juncus spp.*	PAHs Macronutrients: P	*Scirpus sylvaticus*	POPs SS
Juncus effusus	PAHs Macronutrients: P	*Phragmites australis*	Petrolium compounds Heavy metals: Cu	*Typha latifolia*	POPs Heavy metals: Cu SS
Lysimachia vulgaris	n/a	*Potamogeton natans*	n/a	n/a	n/a
Mentha aquatica	n/a	*Salix spp.*	PAHs POPs: (*S. caprea*) Metal accumulation: Cd, Zn	n/a	n/a
Phalaris arundinacea	PAHs	*Scirpus sylvaticus*	POPs SS	n/a	n/a
Phragmites australis	Petrolium compounds Heavy metals: Cu	*Schoenoplectus lacustris*	n/a	n/a	n/a
Potamogeton natans	n/a	*Typha angustifolia*	POPs Heavy metals: Cu SS	n/a	n/a
Scirpus silváticus	POPs SS	*Typha latifolia*	POPs Heavy metals: Cu SS	n/a	n/a

3.4 ENVIRONMENTAL GOALS ASSOCIATED WITH LADBRODAMMEN

Oxunda vattenverksamhet is a cooperation between municipalities that share the watershed area for Oxundaån of which Ladbrodammen is a part of. In the stormwater policy drawn up by Oxunda vattenverksamhet (Oxunda 2019) the stated goals are: sustain a natural water balance and level stormwater flows (promote infiltration en-route), reduce amounts of contaminants in water (treat at the source, treat on the way to the recipient) and enrich the built environment (stormwater as a resource).

Figure 4.1. Areas of improvement.

4.1 SITE PROGRAM

The following chapter contains an analysis of the pond and its immediate surroundings as well as suggestions to a site program (figures 4.5-4.9). Two areas of the pond that could be improved by phytotechnology are identified. Based on the contaminants in these areas three phytoremediational processes are then targeted and suitable phytotechnological planting types, i.e. phytotypologies, are suggested. Note that the phytotypologies are based on remediation ability as well as recreational/aesthetical, cultural and ecological considerations outlined in the site program as well as in the proceeding sections.

4.2 IDENTIFYING AREAS OF IMPROVEMENT

From the case study it was concluded that Ladbrodammen, in many respects, functions well as a stormwater pond aimed primarily at cleaning stormwater. Most of the contaminants are reduced from environmentally hazardous concentrations in the inlet to concentrations below environmental target values in the outlet (Andersson et al. 2012). Despite the success of the pond itself there are a number of aspects that warrant further attention.

Firstly, due to the fact that 25-35% of the annual stormwater does not reach the pond but is led directly into Väsbyån it is assumed that significant amounts of contaminants reach the recipient. Secondly, some contaminants are difficult to measure as they exist in such small concentrations and the knowledge of how they affect the environment is currently unknown (Andersson et al. 2012). Thirdly, new development within the catchment area may cause additional contaminant loads on the pond (SWECO 2018). And finally, it can be argued that the pond as a whole does not provide the larger recreational area with a suitable entrance as is wished by the municipality.

Based on the above, two areas that could benefit from the addition of phytotechnology have been identified and named:

The Southern field and The Open water (figure 4.1). If irrigated with the 25-35% of the annual stormwater that does not reach Ladbrodammen, The Southern field could act as a 1200 m^2 area suitable for phytotechnology. The pond's remediating capacity can also be improved and The Open water offers space for phytotechnological additions as well.

4.3 SUITABLE PHYTOREMEDIATIONAL PROCESSES

As suggested by Kennen & Kirkwood (2015 p. 32), the initial step of evaluating if phytotechnology is a viable method for a particular site is to identify the types of contaminants present. In the water that reaches Ladbrodammen there are 28 different contaminants that exist in concentrations that exceed environmental targets (Alm et al. 2010). The most environmentally hazardous contaminants types and groups are:

- 11 PAHs
- 9 POPs
- 2 petroleum hydrocarbons
- 2 other organic contaminants
- The macronutrients N and P
- The heavy metals Cu and Zn
- Suspended solids

Based on the contaminants listed above, phytoremediational processes that may be applicable to the areas of improvement identified on the site (section 4.1) are suggested below.

4.3.1 Phytoremediation on the Southern field

The area could be irrigated using the pump that supplies Ladbrodammen with water. However, the existing pump will likely not have a sufficient pumping capacity and additional pumps will likely need to be added (Wilén 2019).

PAHs: It could be possible to effectively degrade the PAHs deposited in the soil using phytotechnology. The main phytoremediational process that can be utilized for these contaminants is rhizodegradation (Kennen & Kirkwood 2015 p. 68).

POPs: Like the PAHs, the various POPs also bind tightly to the soil particles but are usually difficult to remediate with most phytotechnologies (White & Newman 2011). Using phytoextraction and rhizodegradation is possible but due to a higher likelihood of success, phytosequestration is suggested as this would prevent spreading of the contaminant by erosion or dust mobilization (Kennen & Kirkwood 2015 p.119).

Macronutrients: All plants take up nitrogen and phosphorus but at different rates and a phytotechnological design that considers this is suitable on the Southern field. Nitrogen can likely be effectively phytoextracted as well as volatilized by microorganisms associated with plants. For phosphorous, phytoextraction is less effective (Kennen & Kirkwood 2015 p.132) and phytostabilization is suggested. In soils that have high concentrations of P, immobilization by adsorption to soil particles should be promoted (Kennen & Kirkwood 2015 p.127). Additional consideration is taken to prevent erosion and dust mobilization by using plant species that entirely cover the soil (ibid.). This is especially true for the Southern field as it is exposed to winds primarily from the north.

Heavy metals: For the treatment of Zn and Cu, phytosequestration is suitable as this phytoremediational process has the strongest evidence behind it (Kennen & Kirkwood 2015 pp.152,170). Although substantial amounts of research exist on phytoextraction of these metals, they are most often solely greenhouse and short-term studies (Dickinson et al. 2009). Therefore phytoextraction has not been prioritized for the Southern field.

In summary, using methods that promote rhizodegradation (for PAHs) and phytosequestration (for: POPs, Cu, Zn, N and P) has the highest chance of succeeding in mitigating the spread of contaminants into Väsbyån while at the same time degrading some of the contaminants.

4.3.2 Phytoremediation on the Open water

Many of the same phytoremediational processes identified on the Southern field are suitable for the Open water as well. However, because the pond is effective in cleaning the stormwater from most contaminants, special efforts should be made to target the contaminants that are not remediated – presented below.

- 1 PAH: indeno(123cd)pyrene
- 1 POP: 4-nonylphenol
- 2 petroleum compounds: MBT and DBT
- 1 other organic contaminant: DEHP
- 1 macronutrient: phosphorous

4.4 SITE VISIT

The site was visited mid-day on the 2nd of April 2019 in sunny and windy weather and on the 14th of May 2019 in sunny and warm weather. The visits revealed a number of additional factors to consider in the site program. A sense of the visual and auditory impact of the road Ladbrovägen on the pond and its immediate surroundings was gained and was deemed to be detrimental to the recreational and aesthetic quality of the area (figure 4.3). Ladbrovägen was experienced as busy with frequent busses and cars passing – likely a consequence of the pond's close proximity to Upplands Väsby's central buss and train terminal. Considering the municipality's aim of making the pond an entrance to a larger recreational area in a green environmnet as well as being an important part of a recreational pathway, Ladbrovägen was judged to impact this negatively, from an experiential point-of-view (Upplands Väsby kommun 2018, Upplands Väsby kommun 2005). Additionally, visitors get a clear view of the large buildings in Upplands Väsby's town centre from the pond and this creates a stark intersection between the more natural landscape of the pond and the open fields that stretch northwards from the pond, and the urban landscape of the town centre to the south. The obstruction of this view, to the benefit of an entrance with a more natural character, or the enhancement of this meeting of urban and rural is an aesthetical consideration and could be used to achieve different aesthetically superior ends.

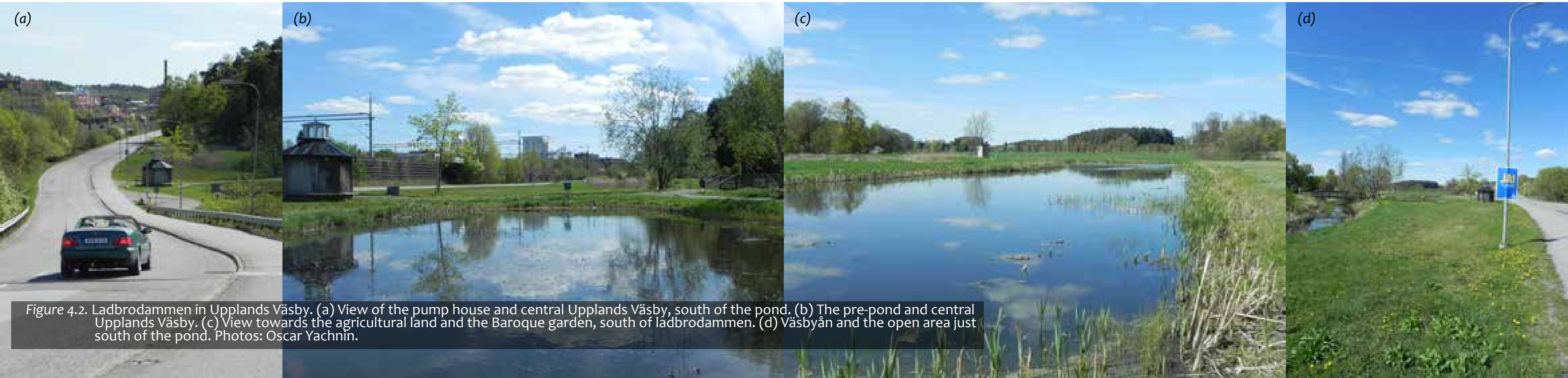

Figure 4.2. Ladbrodammen in Upplands Väsby. (a) View of the pump house and central Upplands Väsby, south of the pond. (b) The pre-pond and central Upplands Väsby. (c) View towards the agricultural land and the Baroque garden, south of ladbrodammen. (d) Väsbyån and the open area just south of the pond. Photos: Oscar Yachnin.

The site was first visited during the early spring and a full inventory of the flora was therefore not possible. However, two *Acer platanoides* and three *Salix caprea* were identified around the pond. The lack of species diversity in the open grass area just south of the pond was also noted. On the second visit, the plant species *Prunella vulgaris*, *Galium sp.* and *Taraxacum officinale* were found in the open grass area.

4.5 SUITABLE PHYTOTYPOLOGIES AND SITE PROGRAM

Based on the phytoremediational processes identified in section 4.2, suitable phytotypologies were chosen. Site-specific design considerations of recreational/aesthetical, cultural and ecological aspects have been evaluated and a final site program is presented for the Southern field (figures 4.4-4.7) and the Open water (Figure 4.8). Finally, figure 4.9 shows how the site program could be implemented in a design of the Southern field.

4.5.1 The Southern field

The primary consideration for the phytoremediation of contaminants on the Southern field was: to prevent further contamination of Väsbyån and its recipients by immobilizing and degrading contaminants using rhizodegradation and phytosequestration. The primary recreational/aesthetical considerations were: the openness of the area, the site as an entrance, the views and the traffic from the Ladbrovägen. Similarly, the cultural considerations took into account the open nature of the area as well as the views towards the Baroque garden. The opportunity to provide a habitat for insects and birds while improving the plant species richness were the ecological considerations taken into account when producing the site program. Concerning the choice to keep the area open or not, it has been judged that blocking the view of the buildings in

Figure 4.3. Inventory and analysis plan.

central Upplands Väsby and the busy road Ladbrovägen with vegetation will raise the recreational value of the area by making it visually calmer, give it a more natural character, provide more opportunities for phytoremediation and have positive aesthetic effects on the recreational path and areas north of the pond.

An expansion of the pond itself or the use of one of the many forms of stormwater filters, e.g. rain-garden, bio-swale, vegetated filter strips, would likely be a good choice but is not suggested due to the likelihood of higher costs as well as the comparatively extensive construction work needed.

Kennen & Kirkwood (2015) suggest several different phytotypologies based on the phytoremediational processes identified in section 4.3. With consideration of the suitable processes, the site-specific variables identified in the case study of Ladbrodammen and the site visit, the phytotypologies suggested for the Southern field are: Degradation Bosque, Phytoirrigation, Planted Stabilization Mat and Multi-Mechanism Buffer (figures 4.4-4.7). These figures of the phytotypologies act as graphical bullet-points for the site program.

A design based on the site program is shown in figure 4.9. In the design, along the eastern edge of Ladbrovägen a narrow area of the field is used to create an irrigated Degradation Bosque. The Degradation Bosque and the Phytoirrigation areas are thus combined in the sense that the stormwater is redirected and spread out over a large area that includes the plants in the Degradation Bosque. The central area of the Southern field consists of a Planted Stabilization Mat. In between the Planted Stabilization Mat and Väsbyån, an area that stretches along the small river is planted as a Multi-Mechanism Buffer.

Alternatively, the whole Southern field could be irrigated - as opposed to only the Degradation Bosque. Which way of irrigating the area is best suited for maximizing contaminant up-take should be discussed with hydrologists.

4.5.2 The open water

A plausible way of improving the remediation capability of the pond is to use the phytotypology Floating wetlands (figure 4.8) in order to manage the contaminants that the pond is not currently able to. This can be done by primarily promoting phytosequestration. However, some nitrogen degradation can be expected as well as slow extraction of phosphorous, nitrogen and some metals. Considering ecological opportunities, Floating wetlands can contribute to habitat creation for birds, insects and fish that also provide recreational/aesthetical benefits associated with wildlife viewing.

PLANTED STABILIZATION MAT

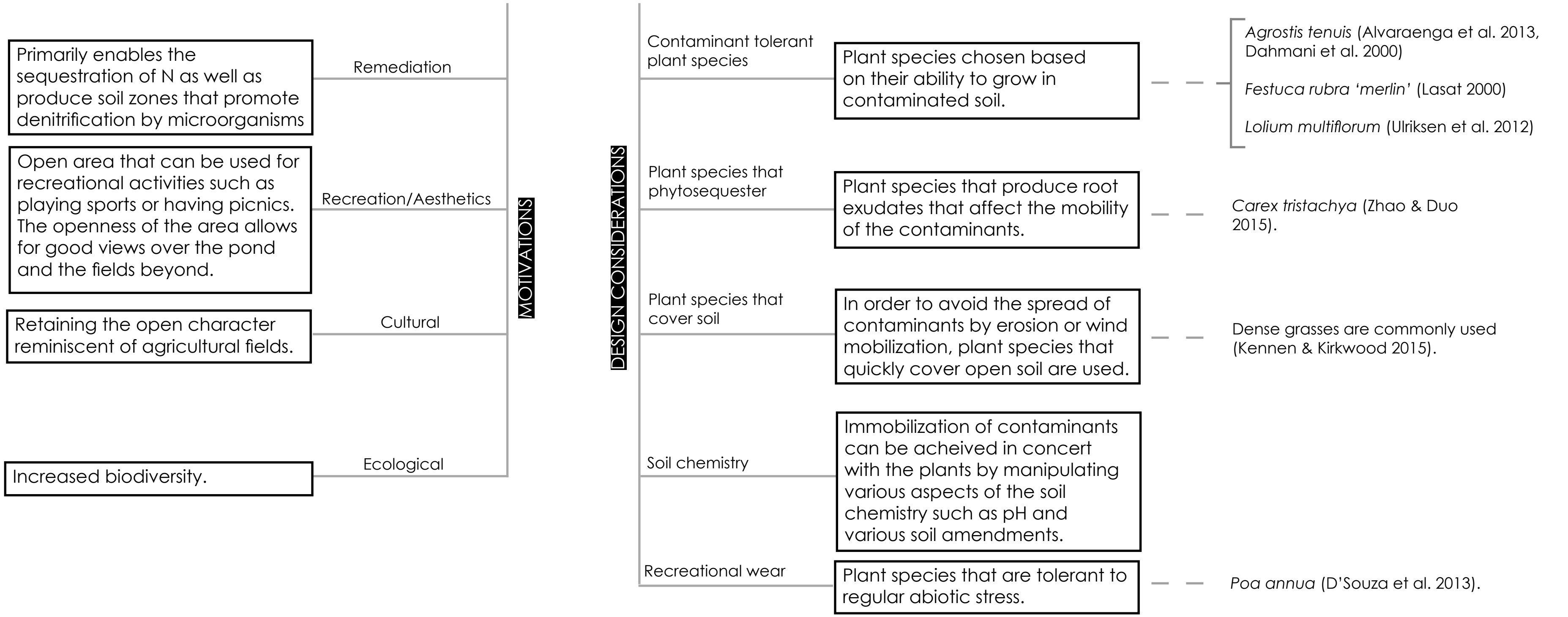

Figure 4.4. Motivations and design considerations for implementing Planted Stabilization Mat on *the Southern field*. Note that the plant species suggested are examples of some potential candidates and that further investigation into other design considerations may render certain species less suitable or not applicable.

PHYTOIRRIGATION

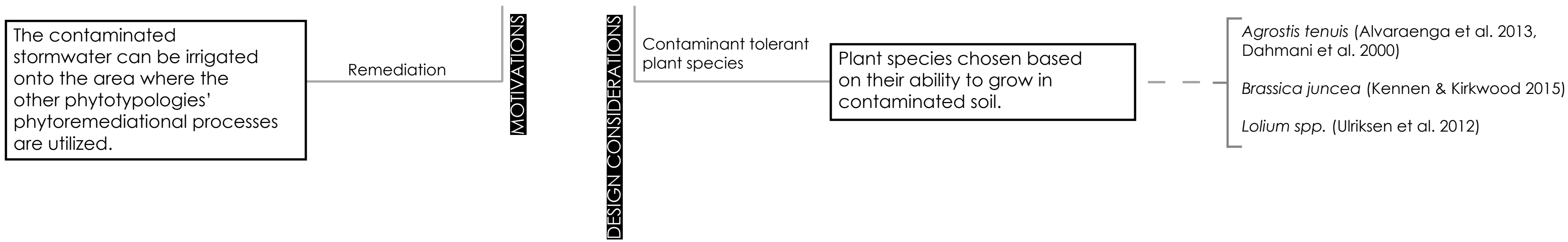

Figure 4.5. Motivations and design considerations for implementing Phytoirrigation on *the Southern field*. Note that the plant species suggested are examples of some potential candidates and that further investigation into other design considerations may render certain species less suitable or not applicable.

MULTI-MECHANISM BUFFER

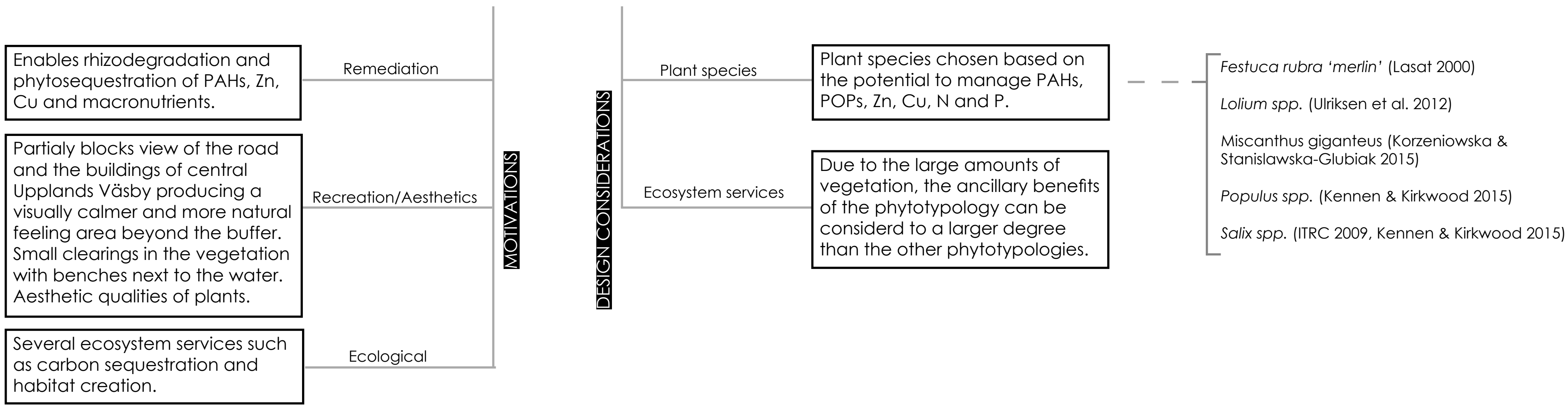

Figure 4.6. Motivations and design considerations for implementing Multi-mechanism Buffer on *the Southern field*. Note that the plant species suggested are examples of some potential candidates and that further investigation into other design considerations may render certain species less suitable or not applicable.

DEGRADATION BOSQUE

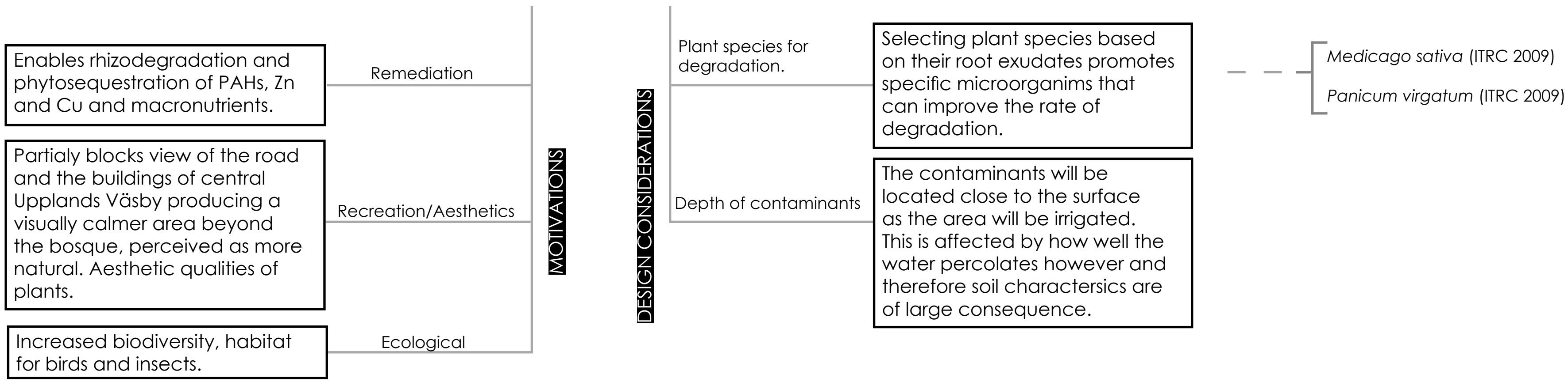

Figure 4.7. Motivations and design considerations for implementing Degradation bosque on *the Southern field*.

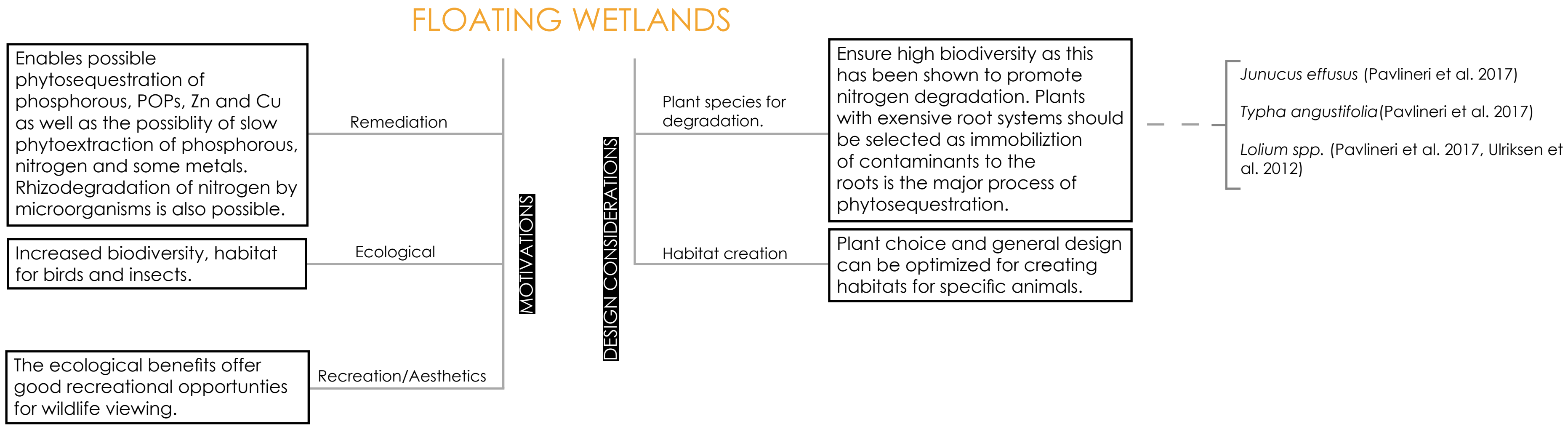

Figure 4.8. Motivations and design considerations for implementing Floating wetlands on *the Open water*. Note that the plant species suggested are examples of some potential candidates and that further investigation into other design considerations may render certain species less suitable or not applicable.

Figure 4.9. Plan progam for Ladbrodammen and surrounding area.

Figure 4.9. Military perspective illustrating *the Southern field*. Note that the proportions, layout and the inclusion of specific details are a representation of what the site program (figures 4.4-4.7) can result in.

PART D
Conclusions and Discussion

In the final part of this thesis the utility of phytotechnology to landscape architecture is discussed and the implications that current phytotechnology research has for designing stormwater BMP. The conclusions and lessons from the work with the site program for Ladbrodammen are also discussed as well as future prospects of this work and the field of phytotechnology in general.

5.1 PHYTOTECHNOLOGY IN AND AROUND LADBRODAMMEN

Tommy Landberg (2019) at PhytoEnvitech AB/Stockholm University was consulted about the plausibility of the site program and it was judged positively. However, the phytoirrigation of *the Southern field* is in need of further investigation before a final design can confidently be suggested. Further consultation with soil chemists, hydrologists, site managers and engineers is necessary. Also, the design, location and plant composition of the Floating wetlands on *the Open water* need to be investigated further. However, because of the possibility of using commercialy available floating wetlands modules, there is less need of in-depth analysis - and professional assitance in planning for its implementation is easily attained. Despite the remaining work needed to suggest a complete program and design, the site program and the work leading up to it does show the complex planning needed to effectively implement the technology as well as highlighting important aspects to consider in plant-based stormwater remediation practice.

Many of the opportunities stated by the authors referred to in the review (section 2.4) have been observed in the process of developing the site program. The applicability of phytotechnology to both *the Open water* of Ladbrodammen and to treat the irrigated soil on *the Southern field* demonstrates the technology's diversity of application. Also, by using different phytotypologies that target specific contaminant types, and selecting plant species thereafter, the technology's range of use and adaptability to site-specific variables is further demonstrated.

If no additional pumps need to be added - which is possible if only the floating wetlands are implemented and construction and maintenance is excluded - the additional energy required to improve the management capacity of the pond can be considered entirely derived from solar.

The suggestions for Ladbrodammen also demonstrate how phytotechnology can be retrofitted to an existing stormwater BMP. The opportunity for the phytotechnological systems to both manage contaminated stormwater while also contributing to the area's aesthetical/recreational, cultural and ecological value is shown in the site program.

Regarding aesthetical and recreational opportunities, the Southern field provides an opportunity to create a clear entrance to a larger recreational area, a visual blocking of the road and the large buildings of central Upplands Väsby for the benefit of a calmer sub-urban area in a natural environment and may also increase its use by providing an aesthetically pleasing area in close proximity to homes and public transport. The use of the Planted stabilization mat demonstrates the ability of the phytotechnological design-approach to consider cultural values by retaining the open character of the area that includes the view towards the baroque garden.

The ecological opportunities that the phytotechnological additions to the site provide are also clear; with habitat creation for birds, insects and other animals; greater floral and associated faunal biodiversity; and an additional source of food for animals.

Some of the principal challenges that commonly face a phytotechnological system have also been demonstrated in this work - especially the uncertain outcome and the need for a high degree of expertise in many fields. Although research and examples of using phytoremediation to target the contaminant types that are present in the stormwater that comes to Ladbrodammen exist, the many site-specific variables – such as contaminant type composition, pH, soil type, climate and more – have made it difficult to predict how well the suggested systems will work. Additionally, to acquire consultation with experts knowledgable about phytotechnology was difficult.

Further investigation into what plant species can degrade specific contaminants rather than targeting PAHs and POPs as groups of contaminants would likely yield a better potential remediation capability and the expected results of the system would be more predictable - although this depends on the chemical similarities of the compounds within the groups. If they are sufficiently similar in structure, they will likely also be affected by phytoremediational processes similarly. Furthermore, examining the contaminant concentration tolerance of the suggested plant species more closely would also be of benefit. On *the Southern field* the volume of contaminated water that is irrigated onto the area can easily be regulated and errors in plant choice can be compensated by irrigating less water. However, as suggested by Kennen & Kirkwood (2015), mass water balance calculations and plant species selection based on contaminant tolerance should be optimized in order to achieve the best possible outcome.

Although the economic figures are difficult to calculate, and in this work are based on literary review of similar projects, it is likely that the cost of implementing the suggested changes may be smaller than comparable methods such as expanding the pond's volume. If the work required to plan and design the phytotechnological additions are factored in, it might change the economic advantage however.

5.2 PHYTOTECHNOLOGY AND LANDSCAPE ARCHITECTURE

From the literary review in this thesis it can be concluded that phytotechnology is a growing and increasingly popular remediation technology that can have broad societal benefits. As more examples and more research shows how it can be applied in practice, how the technology works at a fundamental level, what plant species are suitable and what contaminants it can be applied to, it will likely be of growing use to landscape architects. Currently however, it is difficult for a landscape architect to acquire the necessary knowledge to suggest planning and/or designing an efficient phytotechnological system without the close collaboration with phytotechnology professionals. Most literature on the subject is often complex and requires a deep understanding of natural sciences such as biology and chemistry to judge its merits and limitations adequately (Kirkwood 2001). Conversely, if the technology is to be more readily accepted as a complement to stormwater management systems in semi-urban environments and its potential reached, non-landscape architects promoting phytoremediation could benefit from consulting landscape architects. Landscape architects can in-hand contribute with knowledge of the effects that green structure can have on aspects that are not commonly discussed in the natural sciences, such as aesthetics and human well-being beyond the toxic effects of contaminants, as well as planning practice and its associated regulations and laws. For non-landscape architects this provides a chance to apply the technology in more practical situations to likely greater acceptance and for landscape architects it provides further justification for the usefulness of designed green structure. Furthermore, with the aid of phytotechnology, the tangible utility of plants can be more easily expressed in terms of amounts of contaminants remediated and resources saved. With an increased understanding of the important site-specific variables and more data on different types of sites surface, there will be less uncertainty that a landscape architect needs to factor into a decision-making process. Consequently, phytotechnology will be an easier tool to use. Not using plants to manage contaminants can also be viewed as a missed opportunity that landscape architects, that make decisions about what plant species exist in the built environment, are unaware of.

Alternativly, it may be that landscape architects do not need to be more knowledgeable about the science behind phytotechnology but rather that the team-work around remediation projects needs to improve. This is likely true for larger projects where the site is highly contaminated and there is a directed effort to manage the contamination. If on the other hand, the aim is to improve the common use of plants for remediation of less contaminated areas it may be worthwhile for landscape architects to have the relevant knowledge. In these cases, it becomes a matter of judgement. How much resources is it appropriate to spend on selecting plants for phytotechnology compared to other plant or planting qualities such as aesthetics or size of plants and plantings.

5.3 EVALUATING THE PHYTOTECHNOLOGICAL DESIGN-APPROACH

From the work in this thesis it is difficult to judge how well the method suggested by Kennen & Kirkwood (2015) works for realizing a phytotechnology project. To confidently draw conclusions, long-term studies with implementation and follow-ups that focus on a narrow set of variables need to be made. However, to the extent that it is applied in this thesis, the method does illustrate how current knowledge of phytotechnology - such as careful consideration of contaminant type or cautious reading of articles on phytoextraction - can be used in, or have an impact on, the planning and design phases of a phytotechnology project.

This work relies largley on Kennen & Kirkwood's (2015) book in informing the review of phytotechnology as well as being the source of the method of design being investigated. A bias towards the authors' recommendations for certain phytoremediational processes should be noted. Naturally, other sources have been used and compared but in some cases it is more difficult to judge the validity of certain claims than others. Phytoextraction of heavy metals is one such. Kennen & Kirkwood (2015) downplay the utility of phytoextraction of most heavy metals whereas many other authors promote it as one of the most promising aspects of phytoremediation. For the purpose of this thesis, and with consideration of the time able to be spent on the literary review, a heavier reliance on Kennen and Kirkwood's interpretation of the many aspects of phytoremediation and phytotechnology is understandable. Although not explicitly stated in the book, the downplay of phytoextraction might also have been done by the authors on account of the phytoremediational process' applicability to phytotechnology - which considers aspects of landscape architecture more than pure phytoremediational approaches. For instance, the necessity of harvesting plants that extract heavy metals may have less aesthetical and recreational benefits than other methods such as phytosequestration. However, phytosequestration, or other phytoremediational processes that target heavy metals, does not solve the contamination problem permanently as the contaminants, although less harmful in the immobilized state, still remain on-site.

5.4 TERMINOLOGY

As claimed by Gerhardt et al. (2017) and Kennen & Kirkwood (2015), the complicated terminology has likely been a detriment to the field. To aid in clearing up the mess, this thesis presents a compilation of several different sources of terms for many different aspects of phytotechnology and presents a categorization based on significant phytotechnology work. Although the compilation does not include all existing terms, it does present the more well-used ones and the variations and synonyms that often appear in the literature. The field is however naturally complicated and because it can be applied to so many different situations, there is utility in being able to communicate this. How to adapt the language to different audiences in order to as effectively as possible communicate ideas may however be a better approach - rather than changing the nomenclature.

5.5 ALTERNATIVE APPROACHES AND FUTURE STUDY

Considering the aims of this work, as they relate to investigating the applicability of phytotechnology to Ladbrodammen and the contaminated stormwater in the catchment area, an alternative approach might have been used. Instead of narrowly focusing on implementing plant systems in and around the stormwater pond it would have been interesting to evaluate if several smaller plantings closer to the contaminant sources within the catchment area could achieve different results. A possible advantage of this approach would be that the likelyhood of the contaminant concentration in the stormwater would be smaller and therefore better suited for phytotechnology - due to the more advantageous growing conditions for the plants. Planning several smaller plantings over a large area containing multiple landowners might however be difficult to coordinate in practice. Alternativly, it would perhaps sufice to alter the plant species in plantings that already exist within the catchment area - a task that in practice would be feasible if the municipality, or some other larger landowner, was in charge. Perhaps most significantly is the fact that the solutions suggested for Ladbrodammen mostly rely on a pump system. This is not common practice nor is it a sustainable way of designing most stormwater BMPs. The alternative approach suggested here does not have to consider pumping stormwater and would therefore be a better representation of phytotechnology and the planning and designing that is required.

A comparison of this alternative approach and the one used in this thesis would be of interest perhaps yielding results about ease of planning, phytoremediational capacity, aesthetical alterations and possibilities, ecologcial effects, ability to affect social and cultural needs and wants among others.

Gerhardt et al. (2017), Kennen & Kirkwood (2015) among other authors have stressed the need for the study of more practical applications of phytotechnology as a means of furthering the field. This work has been an attempt at providing a demonstration of how landscape architects may apply phytotechnology in practice and what the opportunties and challenges that this poses. A number of examples of existing practical applications have briefly been discussed in the litterary review. However, a deeper study of these examples would contribute to the furthering of the field such as Gerhardt et al. (2017) and Kennen & Kirkwood (2015) suggest and is further encouraged here.

In the analysis of Ladbrodammen the existing plant species was inventoried and literature on their phytoremediational capacity was investigated. This type of analysis could perhaps be a way of judging if a planting not specifically designed with contaminant management in mind has significant phytoremediational capacity. This relates to the issue of the amont of work needed to plan and design a phytotechnological planting discussed earlier. As a topic for future study, it would be interesting to investigate how often a planting that has been designed without the expressed goal of managing contaminants actually produces significant phytoremediational results - if any. In some sense it will also be a quantification of the capability of the “plant-and-pray method“ that Gerhardt et al. (2017) have identified by acting as a control study.

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