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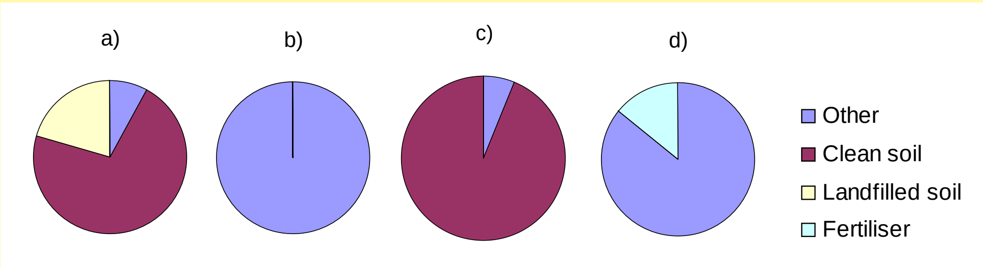

Distribution of off-site occupied land area in area × time.

Environmental impact assessment of biofuel production on contaminated land – Swedish case studies

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SUMMARY

Background
The current energy policy calls for more biofuels, and thus more land for cultivation of biofuels. There is a type of land that can be used for biofuel crops but in many cases is completely unused today: low-and medium-contaminated soil. Cultivation of biofuel leads to soils with a higher organic content and increased degradation of organic pollutants. Biocrops may, but need not, take up metals.

Rejuvenate is a joint project between r3 in England, Dechema in Germany, Bioclear in Holland and the Swedish Geotechnical Institute (SGI) in Sweden. The project examines opportunities in combining contaminated soil with different types of biofuel crops. This could be energycrops but also other crops, e.g. for the manufacture of plastics or the recycling of organic material. The project investigates global opportunities, based on national conditions, regulations and practices, potential crops for different conditions, available land, and the impact on the environment in general and carbon balance in particular. The project will include a matrix with opportunities for continued development in the UK, Germany, Sweden, Holland and in a broader European context. A number of studies underly this matrix.

This report studies the (possible) cultivation of short rotation wood (Salix Vinimalis) on two contaminated sites from an environmental perspective, through a life cycle analysis (LCA) and carbon footprint, with an outlook towards an overarching method for a qualitative or semi-quantitative analysis based on a life cycle framework.

Suitable areas
Two areas were selected as case studies: a small site where short rotation crop (Salix Vinimalis) cultivation is in progress and a large site where biofuel production is hypothetical. For the selection of suitable sites, the following aspects were considered:

- Site location and size, so that biofuel cultivation might be economically viable without a remediation bonus,
- Topography and soil conditions, so that machinery could be used for cultivation,
- Time, so that the site was not in urgent need of remediation due to environmental or human health risks, or acute exploitation requirements,
- Contamination degree, which should not be plant-toxic,
- Contamination depth,
- Assessment of optimum crop and its use.

For doubtful areas, it is especially important to analyse what the most viable option for the contaminated site is, and what bio-product could be used. For a more comprehensive analysis, which also incorporates local economic and social aspects, the decision support matrix, inter alia, described in the main report of the project Rejuvenate, is recommended.

Environmental aspects: LCA and carbon footprint

The calculation of emissions for the LCA and the carbon footprint used a German software tool for LCA of soil remediation: Umweltbilanzierung von Altlastensanierungsverfahren, by Landesanstalt für Umweltschutz Baden-Württemberg, 1999. The software includes equipment emission data published in 1995. The module ”landfarming” has been used in this study to calculate emissions from herbicide application, fertilisation, ploughing and deep-ploughing, Salix (Salix Vinimalis) harvest, harrowing etc. Since production of herbicide and Salix Vinimalis shoots were not included in the software, they were not included in the study.

The conclusions for the two sites were very similar, in spite of the large differences between the sites. The first site was small, 5000 m^2. Weeding and harvest were done manually, and the alternative was excavation of the contaminated soil followed by landfilling. The second site was 12 ha. Salix Vinimalis cultivation was assumed as entirely machine-based, and the alternative was covering the entire site with ½ m clean soil.

Transport of soil would constitute the major environmental costs for the conventional remediation alternatives (excavation or covering), and cause 60–90% of the energy use, waste, use of fossil resources, land surface occupation, global warming, acidification, photochemical smog formation, and the global human toxicity of water, soil and air. (Please note that the local increase of soil quality was not included in the assessment). Soil transports would cause 40% of water use, and less than 10% of the environmental effect on soil use, odour or local human toxicity. We calculated with clean soil transport of 30 km and a landfill 22 km from the smaller site.

Biofuel cultivation would cause a lower environmental cost for all effect categories above, even when soil transport was ignored. This was in spite of the higher fertiliser use and the increased car transport for biofuel production compared to excavation or covering. The amount of fuel needed for covering the larger area was roughly equivalent to the amount needed for the agricultural equipment for Salix Vinimalis cultivation, but the total energy need for the conventional remediation was higher. This includes e.g. the energy needed for the production of plastic groundwater wells, production of equipment, production of fertiliser etc. For more details, see Table 7 and Table 10 in the report.

Demand for arable area would increase as a result of the increasing demand for food and the increasing demand for biofuels. This spurred a detailed look at the land surface needed for the remediation alternatives.

Contaminated soil occupies surface itself, and remediation leads to the exploitation of land beyond the location as well. In this study, the surface required beyond Salix Vinimalis cultivation has been included. That is to say the land area, beyond the contaminated site, that is required by the production of materials and energy for the remediation activities. This area is largely independent of where the crop is grown.

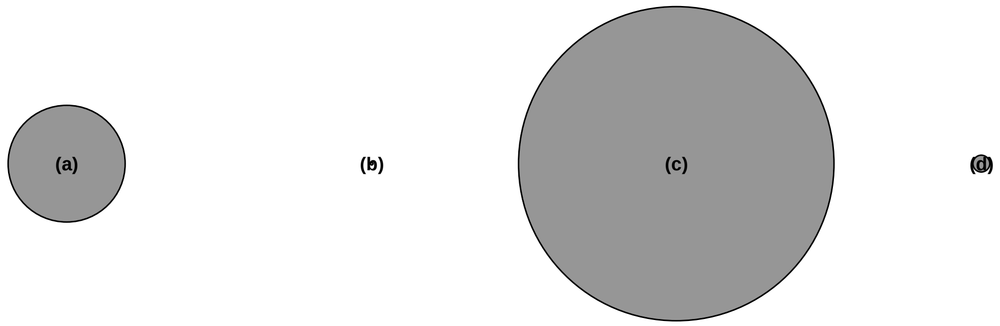

Fig. S.1: Total off-site area used by the remediation alternatives. Circle surface corresponds with square meters multiplied by years (m^2a). a) Karlstad dig-and-dump, b) Karlstad phytoremediation, c) Fagervik on site ensuring, d) Fagervik biofuel. Please note that b) is too small to be seen.

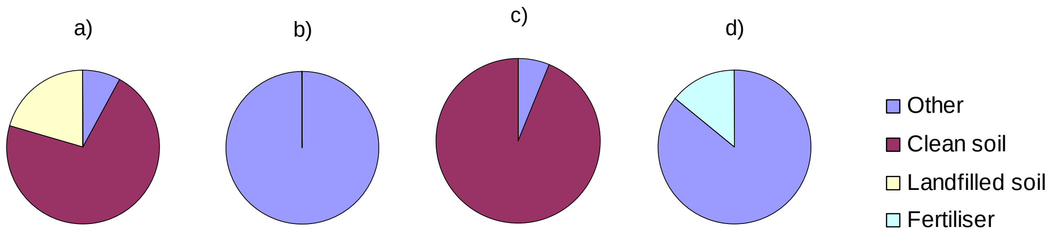

Fig. S.2: Distribution of off-site occupied land area in area × time. a,b,c and d same as in Fig. S.1. Total circle size should be as in Fig. S.1.

Remediation by excavation or by soil covering was estimated to take 20 ha for one year for the smaller site, and 140 ha for the larger site (Figure S.1). 90% of the area was due to earth masses: clean soil for refilling and covering, and contaminated soil to landfill (Figure S.2). Salix Vinimalis cultivation was estimated to require 0.02 ha × year and 0.5 ha × years excepting the site itself (small and large area respectively), see Figure S.2.

Special study of the carbon balance showed that the fate of the stubble and roots after the last harvest was crucial for the greenhouse effect (carbon footprint). During the Salix Vinimalis growth, carbon dioxide from the air is used and thereby taken up by the plant. The carbon in the roots is kept in the ground and constitute a carbon sink. Leaving the stubbles and roots in the ground will also keep the carbon in the ground. Some, however, is emitted as the roots' degrade. Storage of carbon dioxide in the roots during growth is always a positive effect, regardless of what happens to the roots afterwards.

Cultivation of biofuel on contaminated land had more net fixed carbon dioxide than cultivation on farmland, when the alternative for farmland included conventional remediation of the contaminated site. A lower harvest was presupposed for the contaminated site than for normal agricultural land, but this disadvantage in the carbon balance was offset by a wide margin because alternative treatment of the contaminated site was not necessary (the report's Table 14).

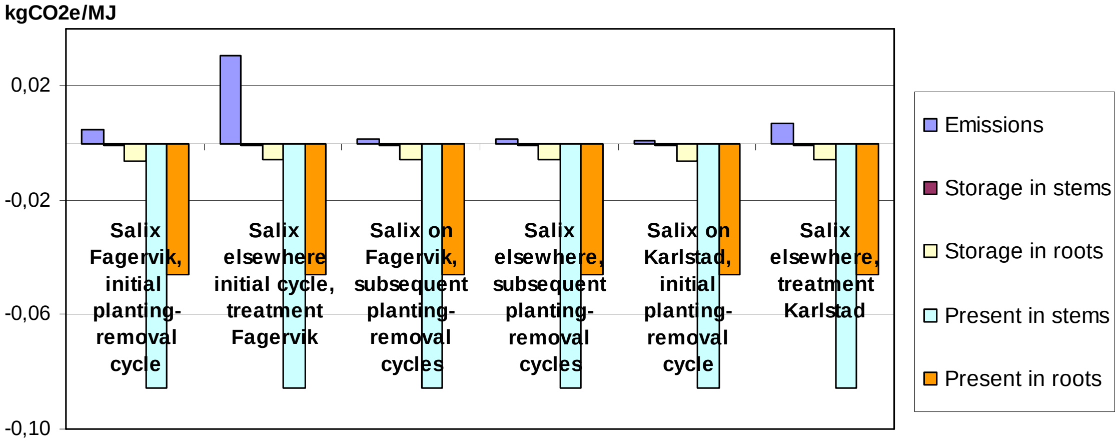

Fig S.3: Components of the carbon footprint of Salix Vinimalis cultivation at Fagervik and Karlstad, in kgCO_2e/MJ. Numbers as in Table 13. Present in roots prior to the removal of the Salix Vinimalis is shown as carbon storage, but should be divided between storage and emissions.

Life cycle analysis and carbon footprint both showed that biofuel cultivation is preferable to conventional remediation from an environmental perspective. That is to say, biofuel is a more environmentally friendly way to use the site than the other realistic remediation option in both cases.

Outlook

The studies above have been limited to remediation and do not include the subsequent use of the harvest. The harvested product may be used to increase the organic content of the soil (as in the smaller site), used as fuel in power plants, replace fossil fuel in cars, etcetera. The contaminants of the contaminated site may stay in the soil, be degraded by the cultivation, or must be managed in the harvested product. The system must be extended to include the use of the harvest in order to deal with the fate of the contaminants. A suggestion for such a system expansion is included in chapter 12.

The importance of the contaminants depends on the manner in which the harvest is used in relation to other raw materials in the production facility, and what this means for the contamination of products and waste, such as a residual sludge from car fuel production, or a wood ash from a district heating plant.

SAMMANFATTNING

Bakgrund

Den nuvarande energipolitiken kräver mer biobränsle, och därmed mer markyta till odling av biobränsle. Det finns en typ av marker som kan användas för biobränsleodling men som i många fall är helt oanvänd idag: låg- och medelförorenad mark. Odling av biobränsle leder dessutom till jordförbättring genom en högre organisk halt och ökad nedbrytning av organiska föroreningar. Biogrödor kan, men måste inte, ta upp metaller.

Rejuvenate är ett samarbetsprojekt mellan r3 i England, Dechema i Tyskland, Bioclear i Holland och Statens geotekniska institut (SGI) i Sverige. I projektet undersöks möjligheter att kombinera förorenad mark med olika typer av bioproduktion. Det kan vara energigrödor men även andra grödor t.ex. för tillverkning av plaster och andra material samt återanvändning av organiskt material. Inom projektet undersöks generella möjligheter baserat på nationella förutsättningar, regelverk och praxis, möjliga grödor för olika betingelser, tillgänglig mark, och inverkan på miljö i allmänhet samt kolbalansen i synnerhet. Projektet kommer att innefatta en ”matris” med potentiella möjligheter som är värda att gå vidare med för fortsatt utveckling i UK, Tyskland, Sverige, Holland och i ett vidare europeiskt perspektiv. För att ta fram denna matris utförs ett antal delstudier som utgör grunden och de underliggande förutsättningarna för dess innehåll.

I denna rapport har en tänkt odling av energiskog (Salix Vinimalis) på två förorenade områden studerats från ett miljöperspektiv genom livscykelanalys (LCA) och carbon footprint. Rapporten avslutar med förslag på en mer övergripande kvalitativ analys som bygger på en livscykelramverkanalys.

Urval av lämpliga platser

Två områden valdes för fallstudierna: ett litet område där Salix Vinimalisodling testas idag, och ett större område där det kanske kunde vara aktuellt. För att välja lämpliga områden användes följande kriterier:

- Områdets lokalisering och storlek

Området bör vara större än 5 hektar och produkten skall kunna användas inom ett lämpligt avstånd (förbränning, produktion av biobränsle såsom dimetyleter, etc). Om området är mindre än 5 hektar eller det är långt till närmsta kund, kan biomaterialet, som i det ena av de studerade fallen, direkt återanvändas på den förorenade marken för att binda kol och höja markens kolinnehåll.

- Föroreningsgrad

Marken får inte vara så förorenad att det inte går att odla på den.

- Tidsperspektivet

Det får inte vara akut behov av sanering, tex beroende på de risker som föreligger eller akuta exploateringskrav.

- Topografi och andra markförhållanden

Kostnaderna förknippade med att förbereda marken för odling och skörd måste vara resonabla vilket bland annat innebär att området inte kan vara alltför kuperat och geologiska förhållanden måste kunna tillåta odling och skörd.

- Föroreningsdjup

Vid odling av bioenergigröda för fytoextraktion får förorening inte ligga djupare än att växterna kan nå dem. Om växterna å andra sidan enbart skall finnas för att minska risker inom området och risker för spridning kan djupare föroreningar accepteras.

- Utredning av potentiella risker

Riskbedömning skall alltid göras och risken får inte överskrida den risk som kan accepteras av miljö- och hälsoskäl under odlingsperioden / saneringstiden.

- Bedömning av optimal gröda och dess nyttjande.

Vilken gröda och till vad man avser att använda den beror av platsspecifika förhållanden. På flera orter i Sverige finns anläggningar, t.ex. större avfallshanteringsanläggningar som producerar värme, energi och biobränsle, och pappers- och massa industrier där råvaran kan tas tillvara för energiproduktion, vilka är lämpliga för att nyttja. Förutsatt att kraven ovan är uppfyllda är det på dessa orter sannolikt förknippat med en total miljövinst att producera biobränsle (Salix Vinimalis) på det förorenade området.

På andra orter finns inte sådana anläggningar inom rimliga transportavstånd. För sådana områden är det extra viktigt att analysera vilket som är det mest hållbara alternativet för det förorenade området och till vad eventuell bioprodukt skall användas. För en sådan analys kan man för bedömning av miljöaspekter starta med ramverket som beskrivs i kapitel 12 av denna rapport. För en mer övergripande analys, som även tar med lokala ekonomiska och sociala aspekter, kan man starta sin analys genom att använda den beslutstödsmatris som bland annat beskrivs i huvudrapporten av projektet Rejuvenate.

Miljöaspekter: LCA och carbon footprint

LCA och carbon footprint-emissioner använde en tysk programvara för livscykelanalys av marksaneringar (Umweltbilanzierung von Altlastensanierungsverfahren, av Landesanstalt für Umweltschutz Baden-Württemberg, 1999). Maskinförbrukningsdata publicerades 1995. I programmet finns landfarming, där jorden bearbetas med kombinationer av plog och gödselspridare. Landfarming används i denna studie för att beskriva spridning av bekämpningsmedel, djupplöjning, maskinell Salix Vinimalisskörd, betesputsare och tallriksredskap för Salix Vinimalisodling. Eftersom produktion av bekämpningsmedel och Salix Vinimalissticklingar inte ingick i programmet har dessa inte inkluderats.

Slutsatserna för de två platserna blev mycket lika, trots att platserna var ganska olika. Det första området var liten, 5000 m^2. Rensning och skörd av Salix Vinimalisodlingen gjordes med manuellt arbete, och alternativet var utgrävning och deponering. Det andra området var 12 ha. Salix Vinimalisodling ponerades ske maskinellt, och alternativet var täckning med en halv meter ren jord.

Transporter av jord skulle orsaka huvuddelen av miljöpåverkan för de konventionella efterbehandlingsalternativ (täckning eller utgrävning), och uppgå till 60–90 % av påverkan för energianvändning, avfall, fossila resurser, ockupation av markyta, växthuseffekt, försurning, marknära ozonbildning, och den globala humantoxiciteten för vatten, jord och luft. (Observera att den lokala förbättringen av jorden pga efterbehandlingen inte ingår i modellen). Påverkan av jordtransporter orsakade 40 % av den totala vattenanvändningen, och mindre än 10 % av miljöeffekten för markanvändning, lukt och lokal humantoxicitet. Vi räknade med att ren jord skulle finnas på 30 km avstånd, och att förorenade massor från grävsaneringen skulle deponeras 22 km från platsen.

Biobränsleodlingen skulle ge mindre negativa miljöeffekter för samtliga påverkanskategorier ovan, även när jordtransporter räknas bort. Detta trots att Salix Vinimalisodlingen skulle kräva mer tillförsel av konstgödsel och mer biltransporter. För det större området motsvarade mängden bränsle som skulle behövas för Salix Vinimalisodling (lantbruksmaskinerna) ungefär mängden som skulle behövas för täckning, men det totala energibehovet för Salix Vinimalisodlingen var mindre än för täckning. I detta inräknas energikostnad för plast till grundvattenrör, tillverkning av maskinerna, tillverkning av konstgödsel m m. För mer detaljer se rapportens Table 7 och Table 10.

Efterfrågan på odlingsbar yta skulle öka som en följd av den ökande efterfrågan på mat och det ökande behovet av biobränsle. Förorenad mark tar upp yta själv, och efterbehandlingen leder också till exploatering av ytor bortanför själva platsen. I detta arbete har den yta beräknats som krävs utöver själva Salix Vinimalisodlingen. Det vill säga det markbehov, utöver själva odlingsytan, som krävs till följd av framtagning av material och energi för de aktiviteter som ingår i de olika alternativen och som redovisas i figurerna S.1 och S.2. Den ytan är oberoende av var man odlar grödan.

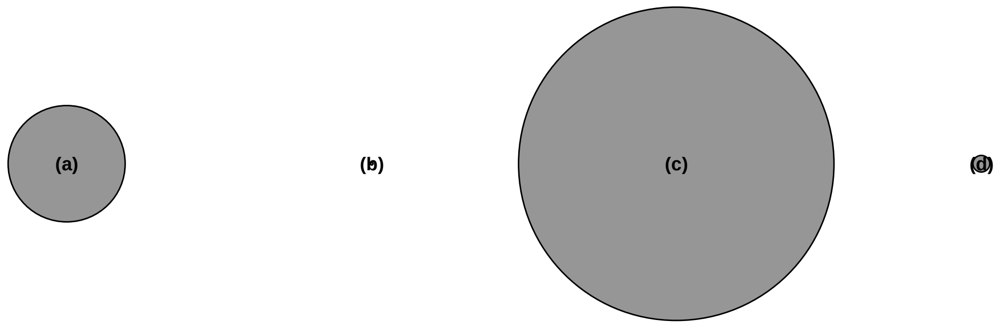

Fig S.1: Total utnyttjad markyta utanför odlingsområdet. Cirklarnas yta motsvarar antalet m^2år. a) Lilla området, grävsanering; b) Lilla området, fytosanering; c) Stora området, täckning; d) Stora området, Salix Vinimalisodling. Notera att b) är för liten för att synas.

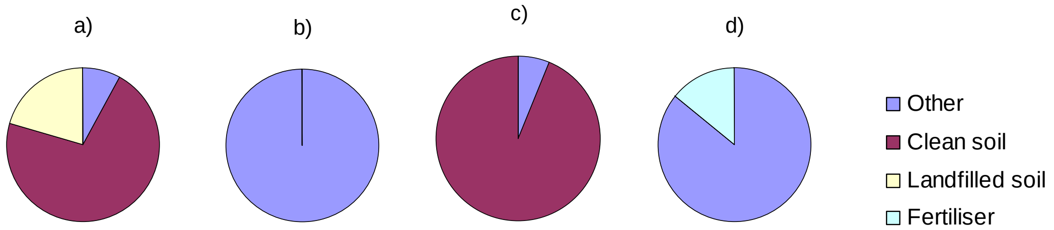

Fig S.2: Fördelningen av utnyttjad markyta (m^2år) utanför det förorenade området. Efterbehandlingsalternativ som figuren ovan. Storleken på cirklerna borde också vara som figuren ovan.

Grävnings- och täckningssaneringen beräknades ta 20 ha×år i anspråk för det lilla området, och 140 ha×år för det större (Figur S.1). 90 % av ytbehovet kunde hänföras till jordmassorna: ren jord från täckter och förorenad jord till deponi (Figure S.2). Salix Vinimalisodling beräknades ta 0,02 ha×år och 0,5 ha×år i anspråk (lilla respektive stora området), se Figur S.3.

Specialstudien av kolbalanser visade att rötter och stubbars öde efter Salix Vinimalisodling var avgörande för odlingens växthuspåverkande effekt (carbon footprint). Den koldioxid som fastläggs under Salix Vinimalistillväxten kan stanna i marken och utgör då en kolsänka. En del avgår dock till luften vid stubbarnas förruttnelse. Stubbarnas lagrade koldioxid var i samma storleksordning som den konventionella saneringsåtgärden (jämna marken och täcka med ren jord). Lagring av koldioxid i rötterna under odlingens gång utgör alltid en positiv effekt, oberoende av vad som händer med rötterna efteråt.

Odling av biobränsle på förorenad mark gav mer koldioxidfastläggning än odling på jordbruksmark. Då ingick dock att den förorenade marken skulle efterbehandlas konventionellt om den inte användes till biobränsle. En lägre skörd antogs för förorenad mark än för normal jordbruksmark, men nackdelen i kolbalansen kompenserades med råge av att marken inte skulle saneras (Rapportens Table 13).

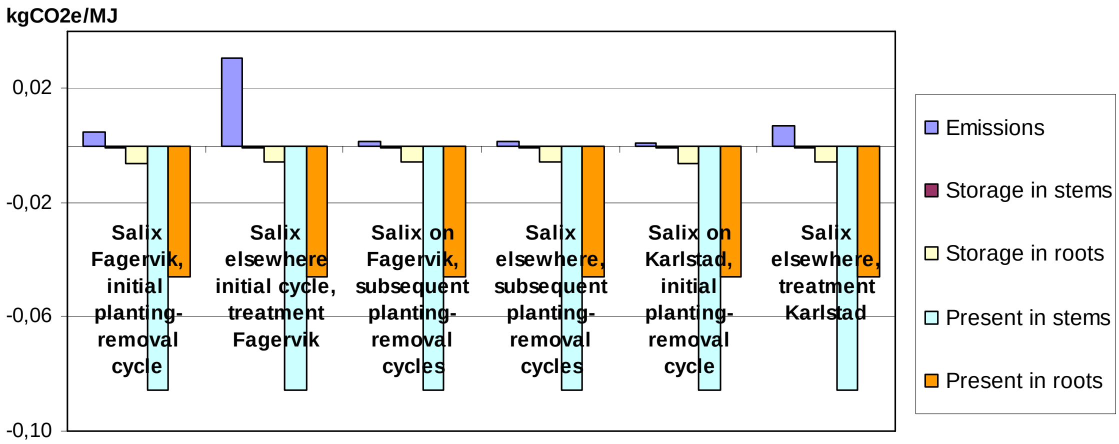

Fig S.3: Delar i en kolbalans för ett antal odlingsvarianter angivet som kg koldioxid ekvivalenter per energi enhet, d.v.s. kg CO_2e/MJ. Observera att negativa värden innebär att kolet lagras i mark eller växt istället för att återfinnas i atmosfären. Det som fanns i rötterna vid Salix Vinimalisodlingens avslutning visas här som lagring, men fördelas i verkligheten mellan lagring och utsläpp.

Livscykelanalysen av efterbehandlingsalternativen och carbon footprint av Salix Vinimalisodling visade båda att biobränsle är att föredra ur miljöperspektiv. Det vill säga biobränsle är ett mer miljövänligt sätt att sanera marken, och dessutom samtidigt nyttja den under saneringstiden, än de saneringsåtgärder som använts eller förelåg som det mest realistiska alternativet i de båda fallen.

Övriga aspekter

Studierna ovan har begränsats till själva efterbehandlingen och innefattar inte den fortsatta hanteringen av bioprodukten. Ett sätt att använda produkten är att enbart höja markens kolinnehåll, ett annat är att produkten nyttjas som biobränsle i kraftverk eller ersättning för fossila bränslen i bilar. Föroreningar kan tas upp, brytas ned, eller fortsatt finnas i jorden. För att kunna behandla frågan om upptag av föroreningar behöver systemet utökas med t ex hantering av restprodukter från olika nyttjande områden. Till exempel kan ett restslam behöva hanteras om biobränslet används vid framställning av dimetyleter, och en vedaska vid eldning av biobränslet i kraftvärmeverk. Betydelsen av föroreningar är beroende av på vilket sätt råvaran utnyttjas i förhållande till andra råvarukällor inom framställningsanläggningen, och vad det i stort innebär avseende föroreningsgrader för restprodukter av framställningen. En ansats mot hantering av denna fråga finns i kapitel 12.

1 INTRODUCTION

The total annual use of fossil fuel in Sweden is 130 TW and the European target is to replace 10 % of the fossil fuel with biofuel by 2020 [1, 2]. This could require around 30 000 km^2 land in Sweden for biofuel production [2, 3]. Biofuel production on land that is suitable for food-crops may place an increasing stress on agricultural land and food prices.

At the same time low and medium contaminated land is lying unused, but might be utilised to grow non-food crops [4]. Still very uncertain, but by a first estimate up to 750 km^2 contaminated land can be suitable for such production with regard to contaminant levels, location in relation to market and infrastructural demands, harvest capacity etc. [5, 6]. Further, in the EEA member countries 250 000 contaminated sites require clean up [7], and part of these will be suitable for biofuel production.

In addition to the significant increasing demand of biofuel there also is an increasing market for other bioproducts such as bio-based plastics and fibres and bio-feedstock [4]. Biofuel cultivation in the form of phytoremediation is suitable to prevent spreading of contaminants, to create green areas in cities, as waste water buffer, or treat small size remediation areas with diffuse spreading [8]. The growth of poplar, willow or other bio-energy products may also create a value to the landscape [9]. And if no cleaning effect is achieved, at the very least the land is usefully employed.

The use of bio-energy in place of conventional fuels or as an additive leads under many conditions results in a net gain in the energy balance and in greenhouse gases ([5] and references therein, [10]) The hypothesis of this project is that there will be a gain, and in general significant, in the energy balance when biofuel is produced on contaminated land. Alternative treatment of the soil requires energy as well. In addition even though remediation through biofuel production is low and slow, the soil quality is always improved through the organic content increase. Under some conditions the soil is further improved through contaminant degradation or plant extraction from the soil [5].

Other aspects than energy and impact on carbon dioxide (such as acidification, human health aspects and ecotoxicity) are more uncertain, less thoroughly researched, and possibly in favour of fossil fuels. These impacts are mainly caused by harvesting and processing [10], fertilizer, pesticides, and direct emissions [11]. These impacts also occur when biofuel is grown on contaminated land. In addition, there are the contaminants which may give rise to contaminated by-products in the biomass production.

This study uses a life-cycle perspective to investigate the environmental impacts of a number of scenarios for biofuel production on contaminated land. The aim has been to investigate the aspects included in life cycle assessment (LCA) and carbon footprinting and both methods have been used. Further, in part 2 of this report, the possibilities and impacts that can be regarded by the broader life cycle framework (LCF) are discussed for three potential remediation alternatives.

1.1 Life cycle assessment (LCA)

Life cycle assessment (LCA) aims to analyse the total environmental impact of an action or a product. The methodology has a general and accepted structure. The principles for LCA are given in [12] and include guidelines to establish the goal and define the scope of the analysis (i.e., define methodologies, reference condition, system boundary, etc.), to conduct the inventory analysis (i.e., collect inputs/outputs and environmental burdens associated with the processes and normalize the environmental impacts to the reference conditions), to conduct the impact assessment, and to interpret the results.

LCA is a method where both quantitative and qualitative aspects can included. In classical LCA, energy and environmental issues examined include scarce resources, such as soil and backfill, groundwater, fossil fuels such as crude oil and metals, energy consumption, greenhouse gas emissions, photochemical smog formation, acidification, and eutrophication (ISO 14040:1997, 1998, 2000a, 2000b). Today there is a development towards local aspects and also to include further aspects such as water consumption in relation to available regional water resources [13] in addition to the classical general environmental approach.

The life cycle analysis is useful to estimate the most optimal method of selected alternatives based on several environmental aspects. It is also a tool to find the most polluting, energy consuming or costly steps in the remediation process for each of those methods, and thereby useful to stimulate development towards more environmental or efficient methodologies [14].

1.2 Carbon footprint

Carbon footprinting focuses on global warming effects of the life cycle. To that end, a carbon balance is calculated. Emissions of greenhouse gases (e.g. CH_4, N_2O) are expressed as CO_2-equivalents (CO_2e), according to their impact on the greenhouse effect. Carbon dioxide uptake and storage in biomass is a benefit in this carbon balance, since stored carbon is not available to increase the greenhouse effect. The structure of the method is the same as for LCA: definitions, inventory, and impact, and the goal is to show greenhouse effect impacts over the entire life cycle (cradle to grave, or, if it must be, cradle to gate) [15, 16].

1.3 Structure of the report

This first part of the report starts with goals and a discussion of the cases: why they were selected and why several other sites were not selected. This is followed by the scope of the LCA and carbon footprint. Then come the case-specific methods and results: first the LCA for Karlstad, inventory and impact; second the inventory for Fagervik and the resulting LCA-impact. Then the results of the LCAs of both sites and various alternatives are discussed.

The inventory for Fagervik includes the emissions for both LCA and carbon footprint. Specific calculations for the carbon footprint are discussed after the LCA, followed by results and discussion of the carbon footprint.

2 GOAL

The goals of the rejuvenate project are to

- Explore possible approaches to combining risk based land management with non-food crop land-uses and organic matter reuse as appropriate.
- Identify potential opportunities worthy of further development
- Assess how verification may be carried out and identify requirements for future research, development and demonstration

The present report has a more limited goal, namely to

- Identify and explore the (environmental) usefulness of biofuel production from a remediation perspective by comparing it with other alternatives for the contaminated land.
- Investigate and compare the results of the investigation of alternative contaminated land treatment alternatives, by LCA and carbon footprint methods.

3 SELECTION OF CASES

3.1 The first case: Karlstad oil depot

Karlstad oil depot was chosen because Salix Vinimalis cultivation has been in progress since 2001, and actual data were available. The site has been used for oil storage, and this has resulted in an uncomplicated organic contamination. Excavation and landfill was considered as an alternative option in practice. We have added monitored natural attenuation (doing nothing but checking on the groundwater contamination) for the LCA study.

Karlstad oil depot is a small area (5000 m^2), and biofuel production is not in itself economically viable. Salix Vinimalis is recommended at >5 ha, and close to customers [17]. The smallness of the area makes use of harvest for biofuel uneconomical, and the harvest is left on site to fertilise and increase the organic content. It may be decided later to grind the cuttings, but also the chippings will stay on site.

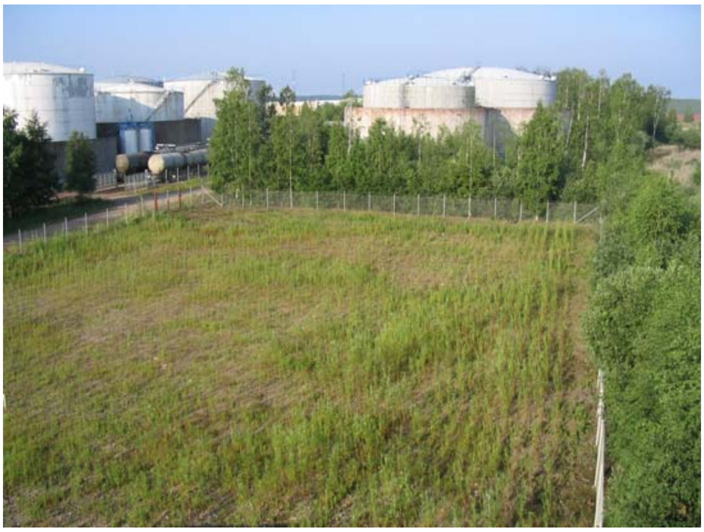

Figure 1: Salix Vinimalis cultivation at Karlstad oil depot, July 2003.

3.2 Selection of the second case

The small site at Karlstad was selected mainly because actual data for Salix Vinimalis cultivation was available. However, the site is too small for Salix Vinimalis cultivation for economical reasons. To complement this, a site with larger area (>5ha) was sought. The Karlstad site also contained mainly organic contaminants that are not expected to lead to problems in biofuel use of the Salix Vinimalis. In order to illuminate the situation where the contaminant leads to problems in the use of the harvest in a future study, a site with metal contamination was sought.

The following aspects were considered in selection of the site:

• Site location and size
The area should be larger than 5 hectares and within a suitable distance from a processing plant (energy plant, production of biofuels etc.), if the cultivation is to be economically viable [18]. For small, distant sites, non-food crops may be suitable for phytoremediation, with direct reuse of the harvest to sequester carbon and increase soil carbon, as in one of the studied cases.

• Topography and soil conditions
The costs associated with preparing land for cultivation and harvesting must be reasonable, so that the area should not be too hilly and geological conditions must be able to allow cultivation and harvesting.

• Time
The site should not be in urgent need of remediation, for example due to risks to human health. Leaching of contaminants should be limited, and there should be low demand of exploiting the area, or the costs for such a fast remediation may already have been estimated as to high compared to expected income from expected residents.

• Contamination degree
The degree of contamination should not be so high as to hinder plant growth [5, 19]

• Contamination depth
A deep contamination may not be affected by the plant roots, and in that case the bioenergy crop does not contribute to cleanup. This may still be acceptable, depending on the purpose of the bioenergy cultivation. If the plants are intended to reduce risks in the area and the risks of contaminant spreading, this is still possible.

Any action on a contaminated site should be preceeded by a risk assessment.

• Assessment of optimum crop and its use
The optimum crop should also be assessed prior to bioenergy cultivation. Salix Vinimalis was chosen in this study since there is an existing infrastructure. District heating facilities and pulp- and paper industries already use Salix Vinimalis or similar materials, and were available close to the case sites. Provided the above requirements are satisfied, it is likely associated with an overall environmental benefit to produce biofuel (Salix Vinimalis) on contaminated sites. In other places there are no such facilities within reasonable transport distance.

For doubtful areas, it is especially important to analyse what the most viable option for the contaminated site is, and what bio-product could be used. Such an analysis can start with the framework described in section 12.5. For a more comprehensive analysis which also incorporates local economic and social aspects, the decision support matrix, inter alia, described in the main report of the project Rejuvenate is recommended [20].

The Swedish current sites for remediation were reviewed, in the form of the Swedish environmental protection agency's state of the country 2007 [21]. This includes all public funded remediation projects active in 2007. Only sites where remediation was planned were considered, since this guaranties a reasonably thorough study of the contaminant situation. Unfortunately, all these sites are heavily contaminated and a risk to their environment, while biofuel production may be a more suitable alternative for low to medium contaminated sites.

A number of sites were refused. For example the (former) mining area of Bersbo was deselected, since the contamination is not concentrated to the surface. The Gusum industrial area has large parts that are so hilly that machine planting and harvest should meet with great difficulty. The Grimstorp wood treatment site leached contaminants into nearby surface water and needed a short remediation time that is not achieved by biofuel production. Byrträskbyggdens wood industry and Mjölby wood treatment sites were too small.

The Fagervik area in Timrå was selected because it is a large site (in total ca 30 ha), and about half the area could be considered for biofuel production. Contamination is superficial (1–2 m depth mostly) and mixed: mainly arsenic but with some organic compounds. The area is accessible to machinery, and remediation necessary because of human exposure to surface soil, not because of leaching.

3.3 The second case: Fagervik

Fagervik is an old industrial area in Timrå, where e.g. kies ash has been used to fill out a large area near the coast of the Baltic Sea. Kies ash is (mostly) iron oxide waste from the production of sulphuric acid through the roasting of pyrite. The kies ash contains metals in elevated concentrations. Subsequent industrial activities have added other contaminants to the site. The kies ash layer is mostly 1–2 m thick, but may be as thick as 7 m occasionally. Groundwater is at 1–2 m below the surface.

The planned remediation is a form of on-site ensuring: removal of trees and scrap metal from the site, redistribution of the soil to provide a good surface, followed by a cover of clean soil (0.5 m thick), and protection from erosion along part of the area [22]. After remediation, the area will be made into parkland. The remaining soil contamination hinders exploitation as a residential area.

Most interesting from a biofuel cultivation perspective are the connected subareas 2 and 7 (Figure 2). The other subareas have either to high contamination and exploitation pressure (1), a non-soil like structure (the landfill at 6) or lie below the water surface (4 and 5). Subareas 2 and 7 are contaminated with As, Pb, Cd, Cr, PAH (both areas), plus aliphates and PCB in subarea 2. The depth of contamination is less than 1 m for Västra vältbotten, kolbotten and koludden, 1.5 m for Östra vältbotten, 2 m for area 2, and 6 m for barktippen (between area 2 and kolbotten) ([22] Figure 7). Barktippen has been excluded from the present study, leaving a total area of 12.4 ha, divided in one large area (Västra vältbotten, kolbotten and koludden) and two smaller areas (area 2 and Östra vältbotten).

Salix Vinimalis cultivation has been chosen as the major (theoretical) phytoremediation/biofuel crop. Salix Vinimalis is used extensively in Northern Europe, and the infrastructure and acceptance in Sweden is good. In the LCF part (the second part) of the report, a crop of ferns has also been supposed, since these are the only known hyper accumulators for arsenic that grow in Sweden [23, 24].

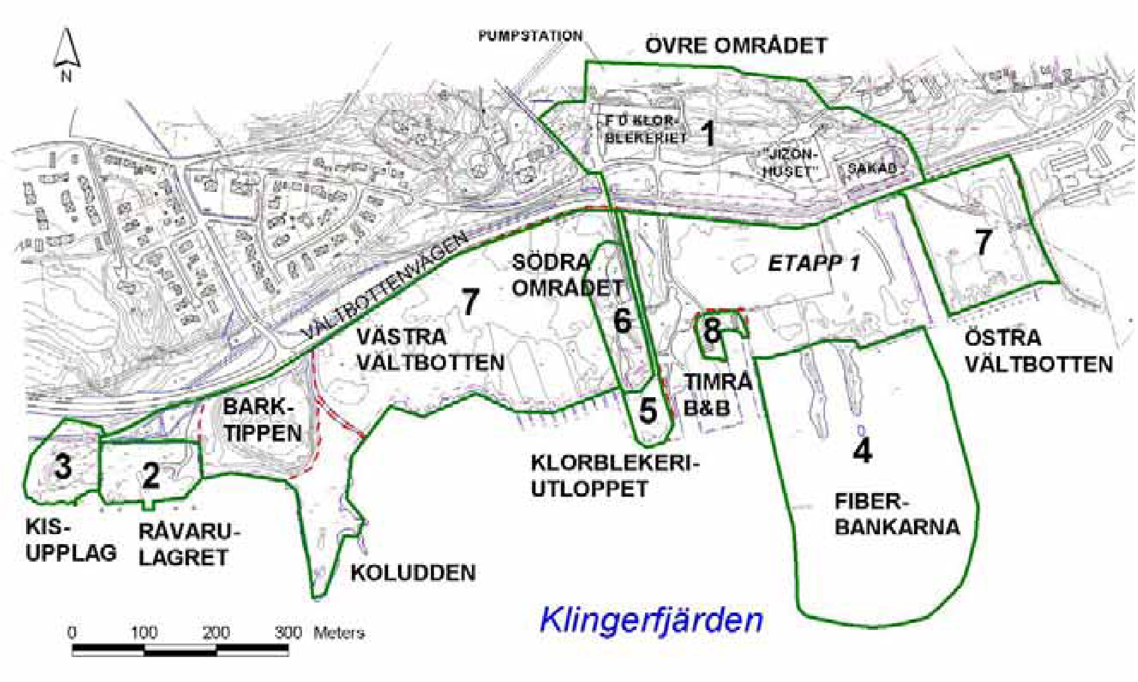

Figure 2: Sublocations from the Fagervik contaminated soil area. From [25].

4 NORMAL SWEDISH SALIX VINIMALIS CULTIVATION PROCEDURE

This chapter provides a short summary of the normal Swedish procedure for Salix Vinimalis cultivation, since Salix Vinimalis cultivation is central to the study. It is mainly based on the manual from Lantmännen Agroenergi, the biofuel part of the Swedish Farmers Co-operative [17]. Changes in the normal procedure that are expected and observed for cultivation on contaminated soil are discussed in later chapters.

Salix Vinimalis in this context is a short rotation coppice willow crop. Agricultural soil is prepared for Salix Vinimalis by removal of competing growth the year before planting. This involves herbicide application and ploughing, principally to remove perennial weeds like quitch grass. In the planting year, herbicide application is repeated if necessary. The the soil is harrowed, Salix Vinimalis shoots are planted, and herbicide is applied. Mechanical weeding may also be used. The shoots are cut at the end of the first growing season to promote a thight growth.

The Salix Vinimalis shoots are transported from Svalöv, in the south of Sweden. Agricultural equipment may be rented from the Swedish Farmers Co-operativ local offices.

After the planting year follow one or two years with fertilisation, either fertiliser, manure, or sewage sludge combined with extra nitrogen.

Salix Vinimalis is first harvested after four years, with a somewhat reduced harvest, and again every three years afterwards. In a harvest year the soil is fertilised and weeds between the rows are fought mechanically. The year after harvest is also a fertilising year. The year after that, i.e. the year prior to harvest, the Salix Vinimalis will have grown so mych that fertilisation is impractical. The Salix Vinimalis harvester chips the harvest directly and it is loaded into a container. Either the containers or the harvested chips are left at the roadside, picked up later and delivered to the end user.

The life-time of a well-handled Salix Vinimalis cultivation is estimated as more than 25 years, and 5–6 harvests. After the last harvest the roots are allowed to grow somewhat and then a herbicide is applied to kill the roots. The year after the åker is ploughed with a heavy plough and a grain crop is sown. After the grain harvest, the Salix Vinimalis roots have degraded sufficiently to allow normal agricultural cultivation on the land [18].

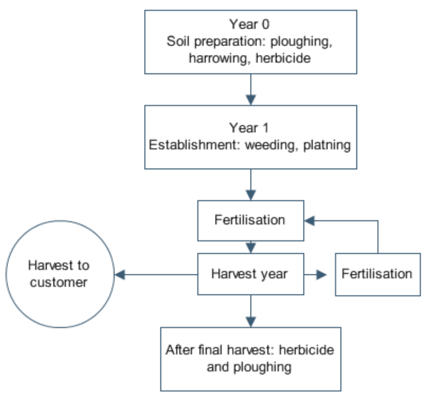

Figure 3: Schematic of normal Salix Vinimalis cultivation.

5 SCOPE: THE METHODS AND WHAT THEY MEASURE

The LCA impact of different alternatives has been calculated for two contaminated sites, the selection of the sites is discussed in chapter 3. The site in Karlstad is a small oil storage area. Phytoremediation is in progress there. This impact is compared with a dig-and-dump remediation and monitored natural attenuation (doing nothing but keeping an eye on things). The site called Fagervik is a larger area contaminated with metals and some organic compounds. The planned remediation is on-site ensuring (covering with a layer of clean soil). Here Salix Vinimalis cultivation for combustion (or other biofuel production) is the hypothetical alternative.

Carbon footprint, in addition to LCA, have been prepared for the larger site, Fagervik, where biofuel production might be economically feasible as well as useful from a remediation perspective.

5.1 Functional unit

The functional unit is used to express the results uniformly, in a unit which describes the product that is achieved by a process. The life cycle assessment (LCA) in this report centres on the contaminated land, and as standard for this type of investigations by UvA "the contaminated site" is the functional unit.

The carbon footprint is intended as a part of the assessment of biofuel production, and uses the energy contained in the harvest (MJ) as the functional unit. However, the contaminated site is included so far that if it is not used for biofuel cultivation, it must be treated, and this is a carbon footprint burden to the cultivation of Salix Vinimalis elsewhere.

5.2 System boundaries

The LCA is centred on the remediation of contaminated land, and the comparison of management alternatives (biofuel cultivation being one, the alternative that is/was considered by the land owner the other). Investigation of the land prior to use/remediation is not included. The LCA does encompass the landfilling of waste, production of clean soil from pits, the land, energy and materials used for the extraction of fossil fuel. The system ends when Salix Vinimalis has been transported to a combustion facility, or the earth-moving equipment has left the, by now treated, site.

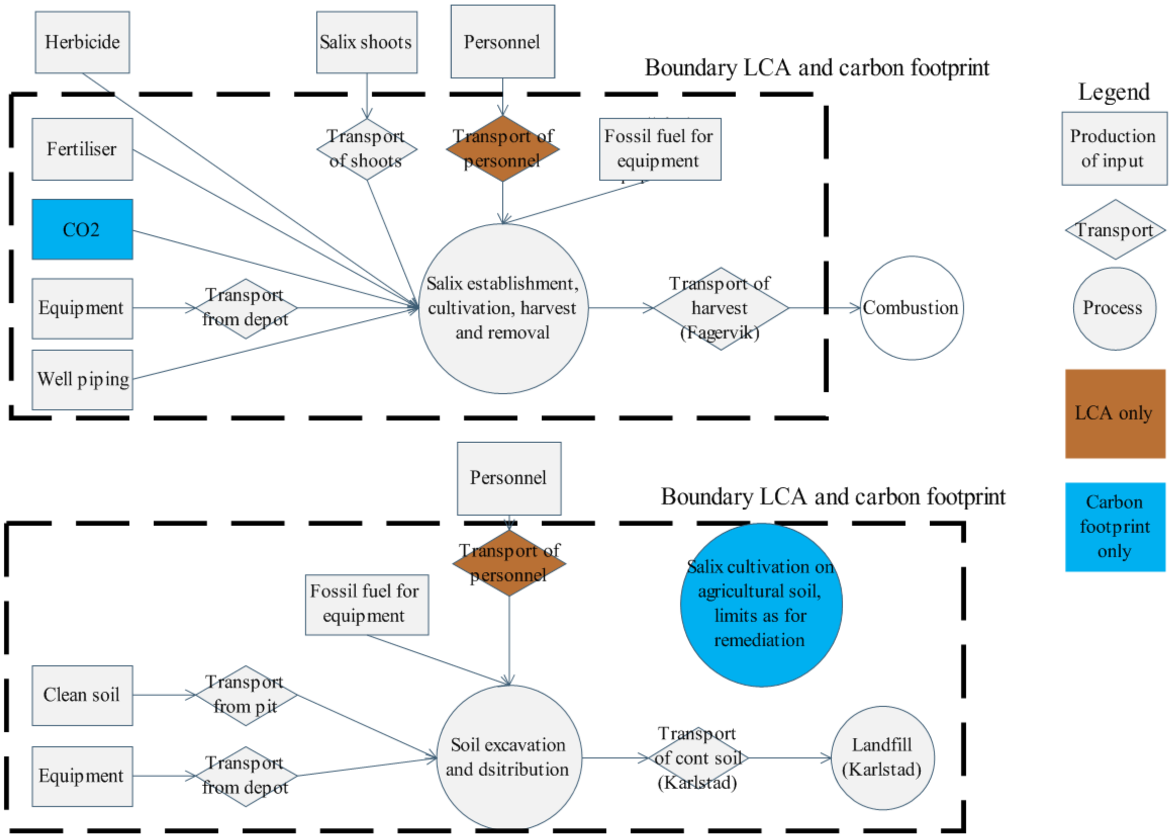

Figure 4: LCA and carbon footprint boundaries.

The carbon footprint follows the LCA closely. It stretches from the planting of Salix Vinimalis to the removal of Salix Vinimalis, and from the production of equipment to the transport of the harvest. The boundary is extended to include cultivation of Salix Vinimalis on agricultural soil to produce the same amount of short-rotation wood if the Salix Vinimalis is not produced on the contaminated site. Combustion (or other biofuel production) of the harvest is outside the boundary. This will be the same for the compared alternatives.

The system boundaries are discussed in more detail in the text of the inventory, and an outlook on the system boundaries is provided in section 12.4.

There are a number of lesser inclusions and exclusions also:

Production of **equipment** is included (in so far as the UvA database includes them), for example loading shovels, excavator etc are included. Emissions from the use of equipment are included, but the emissions from the brush saw are only sketchily included (Karlstad, see section 6.1), and the production of the brush saw is not included. The equipment used for Salix Vinimalis cultivation has been described as either a plough or a fertiliser (Fagervik, see section 8.2). In reality other equipment may be used, such as a forest plough, a harrow, and a Salix Vinimalis harvester.

The production of **materials** like fertiliser and plastic (HDPE) for groundwater wells is in included, but not the production of herbicides and Salix Vinimalis shoots for planting. In normal Salix Vinimalis production (i.e. on non-contaminated soil), fertiliser causes the major impact, whlie herbicide and shoots play a very minor role [26]. Transport from the (only) Swedish producer of Salix Vinimalis shoots in the south of Sweden (Svalöv) is included. The production of clean soil for filling and the transport of this soil are included.

The greenhouse gas N_2O is emitted from fertilised areas, such as the Salix Vinimalis field. These emissions constitute less than 1 % of the added nitrogen fertiliser [26]. This is negligeable in the study context and has been excluded.

Travel of machinery operators and on-site controllers has been included in the LCA, but not in the carbon footprint since the travel of employees to their normal place of work should not be included there [15].

Different management alternatives lead to a different **level of soil clean-up**. This environmental effect has not been included. All alternatives are assumed to achieve a satisfactory risk level at the end of their respective life-times where the LCA is concerned. The carbon footprint and the LCF do not directly take the level of soil clean-up into account.

5.3 Time scales

The LCA time scale is till remediation is completed [27], or 20 years of biofuel production. The assumption of 20 years is based on the reduced contaminant concentrations by time at the ongoing Karlstad site at which relatively little efforts have been used, the time perspective consequently can be regarded as a conservative estimate.

Two periods of 6 harvests (equivalent to around 20 years each) have been used as time scale for the carbon footprint. A low yield on the contaminated site and the burden of site preparation and treatment are allocated to the first period. The second period includes normal harvests and no land use change except new establishment of Salix Vinimalis, and removal of Salix Vinimalis at the end of the period.

Storage of carbon has been calculated as CO_2e with a time perspective of 100 years, i.e. storage of C for 20 years leads to a carbon benefit of 0.2 (20/100) times the amount of carbon stored [15].

5.4 Software: the UvA program

The inventory has been compiled and impact has been assessed using the software “Umweltbilanzierung von Altlastensanierungsverfaheren” (UvA) version 1.0 Rev. 16. The UvA program has been developed to assess the environmental impact of different remediation alternatives for a given contaminated site [28].

The UvA program consists of building blocks for different activities (e.g. transport of masses, installation of groundwater wells, landfarmning) that are combined to make an entire remediation. Site specific data are entered, such as the amount of soil to transport, the length and materials used for groundwater wells, the amounts of fertiliser applied to the land. These are combined with a set of default data in the UvA program to compile an inventory and calculate an environmental impact.

The UvA building block “landfarming” is central to biofuel cultivation, as it contains ploughing and fertilising, and has been used to represent ploughing, weeding, fertilising, herbicide application, and harvesting. In addition, transport of soil, equipment and personnel are recurring building blocks for the remediations. Installation of groundwater wells and other building blocks have been included when appropriate.

The data for emissions from construction machines was from [29], published in 1995. Production of equipment was allocated according to time of use.

6 INVENTORY KARLSTAD OIL DEPOT

Salix Vinimalis cultivation is in progress on the site of Karlstad oil depot. It is used solely as a remediation treatment, and the harvested wood is left on site to increase the organic content and soil quality. The Salix Vinimalis cultivation is expected to increase biodegradation, by creating a better environment for microorganisms [30]. This is termed phytoremediation. The considered alternatives for management of the site are excavation combined with landfilling of the contaminated soil (dig-and-dump), or monitored natural attenuation (leave the site fallow, without using the land, but with control of groundwater contaminant levels).

The volume of contaminated soil is 6560 m^3. The volume of contaminated groundwater is 5000 m^3 (groundwater table at ca ½m, contamination depth 1m of groundwater).

6.1 Phytoremediation (actual remediation)

Phytoremediation is the alternative where Salix Vinimalis is grown on the site. An overview is given in Figure 4 and Table 1. The remediation is expected to last around 20 years, of which 16 days involve activity on the site that might be disturbing to neighbours.

Table 1: Process, equipment and materials as used in the LCA calculations. In addition to these, personnel transport is included as well.

	Salix Vinimalis cultivation	***Equipment and materials***	**Groundwater control**	***Equipment and materials***
Establishment	Ploughing, planting, irrigation, cutting, weeding	*Tractor, (fertiliser), clones*	Installation groundwater wells	*Drilling rig, pipes, sand*
Running	Harvesting	*Brush saw*	Sampling groundwater	
Demobilisation	Salix Vinimalis removal not considered		Wells remain in soil	

6.1.1 Salix Vinimalis cultivation

The soil was treated with landfarming-like techniques. The soil was ploughed and 100 kg NPK (nitrogen, phosphor and potassium) fertiliser was added. Fertiliser was spread by hand, but since this was not admissible to the software, one run with fertilising machinery was included. This increased the diesel use from 12.9 to 19.35 kg diesel, i.e. 6.5 kg diesel was added in the model without corresponding resource use and emissions in reality.

On the other hand, a brush saw was used for cutting and harvesting, and caused emissions. Up to 2008 this had been done twice, another three harvests are anticipated for the following 10 years, for a total of 5 cuttings. Cutting time was assumed as 6 h, giving a total brush saw use time of 30 h. 30 h sawing would consume 32.2 kg fuel [31], which was not entered in the calculations. Additional emissions from the brush saw on the site as shown in Table 2 were entered. Noise from the brush saw was assumed negligeable for the neighbours, and personnel used appropriate protection.

Brush saw emissions are roughly 10 times the emissions for Diesel in Baumaschine included in the UvA program when expressed per kg fuel, so that the brush saw may not be represented by increased time for the fertilising machine.

Weeding was done by hand, without herbicides, and thus only caused travel of personnel and no activities in the landfarming building block.

Table 2: Brush saw emissions. Acrylate fuel, motor effect 1.674 kW. Data from [31].

	g/kWh	kg/remediation
Fuel use˜	642	32
CO	486	24
HC*	146.2	7.3
NOx	0.754	0.038

* Entered as NMVOC Nichtmethankohlenstoffe
˜ Not included so far

6.1.2 Groundwater wells

Four 0.05m plastic HDPE pipes of 2m each were installed in 0.1m diameter holes, to monitor the groundwater quality [32]. Standard assumptions were used for the drilling rig, i.e. 78 kWh motor effect and 2.5 m/h drilling speed. The space between pipe and hole-edge was in reality filled with some sand, but diameters of 0.05 m for pipes and 0.1m for holes required 93 kg sand, which was not in correspondence with reality. The sand amount was set to 1 kg.

6.1.3 Transport by car

The true vehicles are shown in Table 3, but environmental impact has been calculated as if a car was used. One control journey per year from Gothenburg has been planned in the Karlstad case, since this is a pilot project. Once users become more familiar with biofuel cultures, a local controller could take over, and decrease the travelled distance from 255 km to 10 km. Clone transport was from Svalöv, where the only producer of Salix Vinimalis clones is located.

Table 3: Transport by car for phytoremediation [32].

	Vehicle (in reality)	Number of journeys	Distance single journey (km)
Planting and clone transport	Small delivery van	1	482.7
Irrigation, cutting and weeding 2001	Light truck	1	10
Irrigation, cutting and weeding 2002	Light truck	5	10
Irrigation, cutting and weeding 2003	Light truck	5	10
Harvest after 2008	Light truck	3	10
Control	Car	17	255.2

6.1.4 Transport of equipment

The equipment used was a tractor for ploughing and a drilling rig for the installation of groundwater wells. The rig was transported 5 km (by truck). The tractor drove 10 km to arrive at the site, but is postulated as transported by truck for the impact calculations.

6.2 Dig-and-dump

In the dig-and-dump alternative, the contaminated soil is excavated and removed to a landfill. Treatment of the soil was not considered. For example composting is not a realistic treatment since this would involve adding a very large amount of manure: the soil itself has very low organic content. The contaminated soil would be replaced by an equal amount of pristine soil. The equipment and personnel journeys that were used for the model are shown in Table 4.

Table 4: Process, equipment, materials and personnel as used in the LCA calculations.

	Activities and equipment on site	***Personnel to and from the site***
Establishment and demobilisation	Transport of bulldozer, loading shovel, truck	
Excavating and soil quality control.	Excavation Control of contamination on site Reloading of contaminated soil Loading of clean soil Transport of cont soil to landfill Transport of clean soil	*Bulldozer operator* *Controller (non-local)* *Loading shovel operator, truck driver*

A dig-and-dump remediation is expected take 40 d “building technical” activity time. With brakes for weekends this would constitute 60 calendar days (total remediation time). During this time control personnel, a bulldozer operator, a loading shovel operator, and a truck driver are needed every day of the remediation. Bulldozer and truck drivers are assumed to live locally and travel by car to the site. One controller is living locally during the remediation but travels to and from Gothenburg for weekends (Table 5).

Table 5: Personnel transport for dig-and-dump. Return journeys are included in the LCA.

	Nr of journeys	**distance single journey (km)**
Control personnel, daily local transport	39	10
Control pers, weekend journeys home	3	255
Bulldozer operator, local to site	41	10
Loading shovel operator, local to site	41	10
Truck driver, local to site	41	10

A bulldozer and a loading shovel are moved to the site from a distance of 10 km (building block “Mobilisierung”). The contaminated soil is excavated into a temporary heap, with the work effort of the bulldozer set at 100 m^3/h (standard). Control of the contaminant level in the temporary heap is done by hand, and gives no effect on the LCA except for journeys of the controller. From the temporary heap, contaminated soil is loaded with a loading shovel into a truck (building block “Materialtransport vor Ort”), and transported 22 km to Djupdalen, the only active landfill in Karlstad.

6560 m3 contaminated soil was removed and the same volume of pristine soil is used to replace it. The clean soil is transported 30 km to the contaminated site (no specific location assumed), and distributed on the site using the loading shovel.

6.3 Monitored natural attenuation

With no action, natural attenuation is expected to decrease the contaminants to harmless levels in 50 years. After 50 years, the site is expected to be suitable for industrial purposes. There is some risk of transport by groundwater to Lake Vänern, 350m distant from the site, but this has no impact in the environmental inventory using UvA.

The only activity during these 50 years is control of the groundwater contamination levels. Disturbances at the site occur for 1d, since groundwater observation wells will need to be drilled. Installation is done in accordance with the data for phytoremediation, and 1 journey/year for control by a local (10 km) sampler has been included.

6.4 Inventory summary

A summary of the inventory for Karlstad is shown in Table 6. For the detailed inventory of Karlstad, see Appendix 1.

Table 6: summary of inventory for Karlstad.

English translation	UvA original text	Unit/ Einheit	Phyto-remediation	Dig and dump	Natural attenua-tion
Waste to remove from the site	Abfall zur Beseitigung vom	kg	0	12 000 000	0
Soil resources used	Aufbereitete Erdmaterialien	kg	1.3	12 000 000	1.3
Diesel in equipment, off site	Diesel in Baumaschine	kg	19	0	0
HDPE half fabricate	HDPE Halbzeug	kg	8.5	0	8.5
Establishment/Demobilisation	Mobilisierung/Demobilisierung	km	15	20	4.8
Local effect: Diesel in equipment on site	NF-Diesel in Baumaschine	kg	47	2 700	47
Local effect establishment	NF-Mobilisierung	km	0.5	0.5	0.25
Local effect truck transport	NF-Transport LKW	t km	0	5 900	0
Local effect car transport	NF-Transport PKW	km	16	83	25
Fertiliser	Nährstoffe	kg	9.9	0	0
Noise duration 108 dB(A)	Schalldauer 108 dB(A)	h	3.2	590	3.2
Truck transport	Transport LKW	t km	0	610 000	0
Car transport	Transport PKW	km	9 900	4 700	980

Most of the diesel use for the dig-and-dump alternative is on-site, where the soil is excavated and reloaded. The biofuel alternative, phytoremediation, causes more car transport. This is mainly transport of the controller from Gothenburg (17×255 km). If a local controller would suffice, 1600 km of car transport would remain. About half of these 1600 km were in reality driven in a light truck, not in a car as assumed in the model. The diesel amount that is used in the equipment is based on the stereotype values in the UvA program.

The model differentiated between local and non-local input. Use of equipment on the site causes emissions that are designated local effect (in e.g. Table 6 and Table 9). 0.25 km of each personnel journey, and 0.25 t km of each truckload leaving the site are also allocated to local effect.

7 LCA-IMPACT KARLSTAD OIL DEPOT

A summary of impacts is presented in Table 7 and Figure 5.

Table 7: Summary of impacts for Karlstad.

English translation	UvA original text	Unit	Phyto-remediation	Dig and dump	Monitored natural attenuation
Cumulative energy use	Kumulierter Energieaufwand	TJ	0.05	3.5	0.01
Waste (total)	Abfallentstehung gesamt	kg	580	12 000 000	71
Waste reused on site	Abfallentstehung Verwertung Standort	kg	0	0	0
Waste removed from site	Abfallentstehung Beseitigung Standort	kg	0	12 000 000	0
Fossil resources	Fossiler Ressourcenverbrauch	1/a	26	1 500	4.2
Use of water resources	Ressourcenverbrauch Wasser	m^3	27	2 600	4.5
Occupied land area off-site	Flächeninanspruchnahme	m^2 a*	190	200 000	27
Climate change	Treibhauseffekt	kg CO_2 eq	3 500	230 000	540
Acidification	Versauerung	kg SO_2 eq	25	2 600	4.8
Smog	Sommersmog	kg Ethen	10	410	1.1
Human health air-global	Humantoxizität Luft - Fernbereich	index unit	1 700	140 000	190
Human health water	Humantoxizität Wasser	index unit	0.04	2.3	0.01
Human health soil	Humantoxizität Boden	index unit	0.01	0.4	0
Odour	Geruch	index unit	120	14 000	14
Human health air – local	Humantoxizität Luft - Nahbereich	index unit	120	7 300	120
Odour - local	Geruch – Nahbereich	index unit	15	940	15

* NB: the unit for ccupied land area is square meters multiplied by years

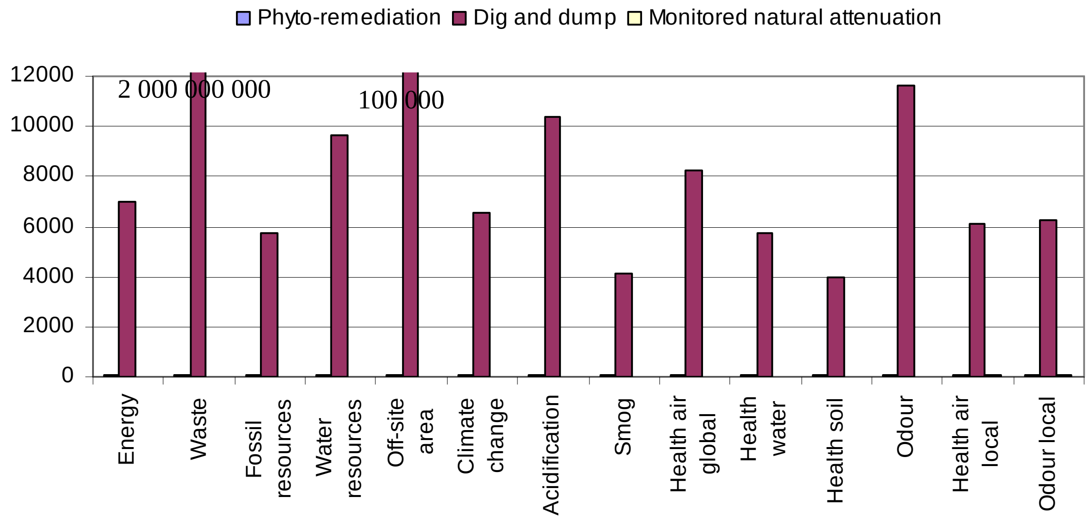

Figure 5: Impact from Table 7 in graphical form, with phytoremediation set to 100.

Dig-and-dump would have used more energy, mainly as fossil fuel for soil transport.

Waste from dig-and-dump is contaminated soil, which is landfilled. Monitored natural attenuation and phytoremediation waste is partly from drilling of groundwater pipes, partly from secondary processes. No waste was reused on the site.

Use of water resources in the LCA calculation is entirely due to the production of materials and fuel. In reality the Salix Vinimalis plantation was irrigated from a local fire post.

The occupied surface area is high for the dig-and-dump alternative. This is both area at the landfill for the contaminated soil and at the pit for pristine soil. Area needed for the production of fossil fuel is also included. All three are higher for the dig-and-dump alternative than for the other alternatives. The area of the contaminated site itself, i.e. 5000 m^2, is not included. Dig-and-dump would result in occupying the site only a short time, after which the site would be multifunctional. The phytoremediation/biofuel alternative occupies the site for a far longer period. This is further discussed in chapter 12.1.

Climate change, acidification and smog mainly come from combustion.

The health and odour impacts are shown in an indexing unit without relevance outside the study. The local effects are for the nearest residential area, health effects on workers on the site are not included.

As can be seen from Table 7 at Karlstad Oil depot the most environmentally sustainable alternative according to this investigation is monitoring natural attenuation (MNA). MNA is a realistic remediation alternative at such a small site where organic compounds such as oil products are the only contaminants since those will be.naturally remediated. The choice of remediation method depend on several site specific aspects. Of course, a risk assessment needs to be done and the risk acceptance at each site for the total time of remediation must be considered and related to other site specific aspects regarding which remediation method to be used.

In relation to the dig and dump alternative, the environmental benefits of MNA in comparison to phyto-remediation (or active use of the land) are small according to this investigation. This LCA study does not include the reuse of organic material and the carbon balance, which may reduce difference in the total environmental benefints of MNA in relation to phyto-remediation or other active use of the land under some conditions and enlarge it under other.

The total environmental benefits and costs depend on the existing natural ecosystem, what will develop under natural attenuation, and the type of bioproducts. At larger sites contaminated with only organic compounds, the use of the land while treated may be an advantage compared to MNA, not at least from economical and social aspects. Of course, the most beneficial alternative depends also on location in relation to costumers and other infrastructural conditions.

At most sites, however, there are either a mix of organic and metallic contaminants or metals are the dominating contaminants. At those sites MNA is not a realistic remediation method simply since it does not work on metals. Since the aim of the project is to investigate the costs and benefits of active use in relation to other remediation alternatives, this report will henceforth exclude the natural attenuation alternative and instead focus on active use of the land.

The impacts are further discussed in chapter 12, togheter with the results of the LCA for Fagervik.

8 INVENTORY FAGERVIK

Subareas 2 and 7 of the Fagervik industrial area are 12.4 ha (124 000 m^2). These are contaminated mainly with metals, and some organics (see section 3.3). No contamination has been found in the groundwater. Planning is underway to treat the area by on-site ensuring. The (hypothetical) alternative used in this study is the cultivation of Salix Vinimalis to be used as bio-fuel (e.g. heat, gas- or liquid fuel, electrical energy)

Erosion protection of the coast is also planned (a sand and peat filter, with stone blocks outside), but not included in this inventory. It would be necessary for either alternative, and has no bearing on the general impact from biofuel cultivation. A park will be created after the on-site ensuring. This is outside the LCA-boundary, but inside the carbon footprint.

The distance to the nearest residential area is 100 m. This is important for the expected noise and odour disturbances.

8.1 On site ensuring (planned remediation)

Levelling activities are estimated to take 50 d, during a total remediation time of 6 months. 50 local journeys (10 km) for 2 operators are included for the LCA, but not for the carbon footprint [15]. The entire area is occupied during this time. The activities are summarised in Table 8.

Table 8: Processes, equipment and personnel as used in the LCA calculations.

	Equipment and activities on site	**Personnel**
Establishment and demobilisation	Bulldozer, loading shovel	
Levelling the site	Moving earth around	Bulldozer operator, loading shovel operator
Covering with clean soil	Transport to contaminated site Loading clean soil	No personnel journeys Bulldozer operator, loading shovel operator

The site is not flat enough to allow a satisfactory soil covering as it is. Therefore it will be levelled prior to application of the pristine soil. This involves the movement of soil on site. The amount of soil is calculated as 0.5 m over the entire area, i.e. 62 000 m^3. The levelling has been described using building block “Erdaushub”, engaging an excavator and a loading shovel. The building block is identical for on site ensuring and bio-fuel cultivation.

To prevent human direct oral intake of soil, a 0.5 m thick cover of clean soil is planned, i.e. 62 000 m^3 or 110 000 tonnes. Surplus soil from elsewhere will be used if available. Clean soil is assumed to be available within 50 km [22]. For the purpose of this environmental assessment, 30 km has been used as the distance to transport the clean soil. Distribution of clean soil on the site is modelled as loading, which uses a loading shovel and a truck. Excavation of clean soil has not been included.

An excavator and a loading shovel are transported 10 km to the site to execute both levelling and covering.

Salix Vinimalis cultivation on agricultural land is included for the carbon footprint. An area of the same size and location as Fagervik is used, so that establishment, fertilisation, removal of Salix Vinimalis and planting of new shoots are the same as for Salix Vinimalis cultivation on contaminated land.

8.2 Biofuel cultivation – Salix Vinimalis

Cultivation of Salix Vinimalis has been presupposed as an alternative to on-site ensuring. A general manual for the cultivation of Salix Vinimalis [17] has been used to provide data, as well as experiences from the Karlstad case. Since the Fagervik area is larger, machinery will be assumed both for fertilising and for cutting. No groundwater observation wells are included since no contamination has been observed in the groundwater. The process is described in Figure 6.

The site is active for 56 days: 20 d for removal of scrap and levelling, 1 day each for glyphosphate application, ploughing, harrowing, irrigation, herbicide application, harvesting, and glyphosphate again, cutting shoots and ploughing down the roots respectively (the last three prior to new agricultural use), 1½ day for planting (1ha/h [33]), 5 d for mechanical weeding, 13 d for fertilising (2 out of every three years), 7 d for harvesting (once every three years). This assumes 20 years of remediation/biofuel production (minimum suggested for Salix Vinimalis).

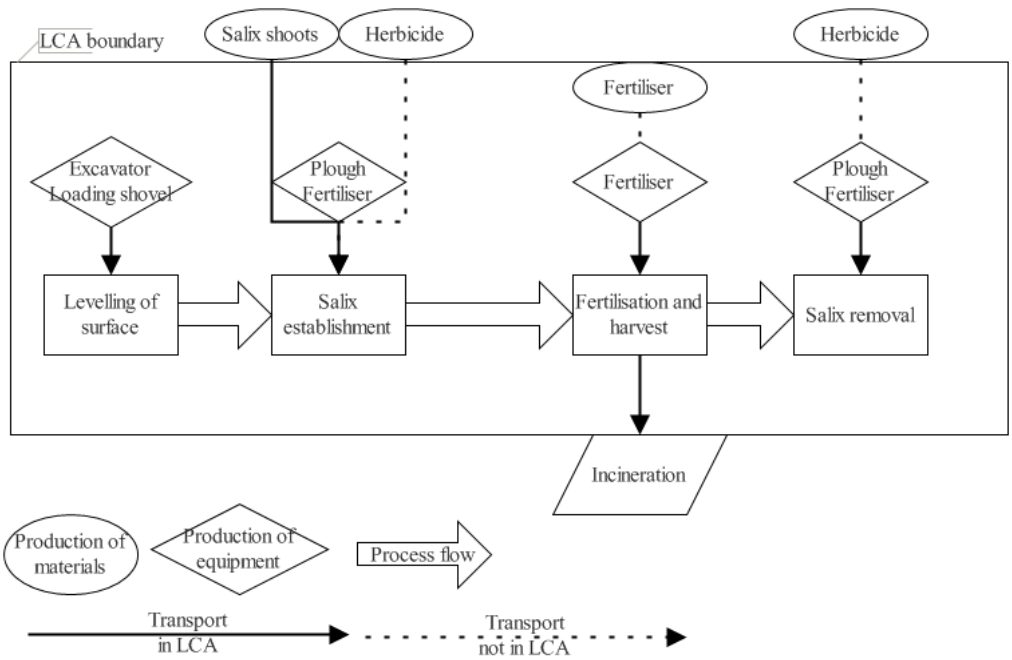

Figure 6: Schematic representation of the studies' inventory for Salix Vinimalis cultivation on Fagervik. Journeys by personnel are also included in the LCA, though not in the figure or the carbon footprint.

8.2.1 Levelling the surface

Salix Vinimalis cultivation is more efficient if the surface is smooth and standard machinery may be used to harvest. Redistribution of the soil on site has been modelled as the same as for the planned remediation (see 8.1): use of an excavator and loading shovel on 62 000 m^3 soil, for 20 days. 2 operators travel 10 km each to the site each day, and two pieces of equipment (bulldozer and loading shovel) are transported 10 km to the site.

8.2.2 Establishing Salix Vinimalis

The establishment of Salix Vinimalis requires ploughing, harrowing, and weeding. Three to six mechanical weedings are recommended during the planting year, and another two during the first year if weeds persist [17]. 1 ploughing, 1 harrowing and 5 weeding applications (total 7) have been entered as ploughing into the UvA program.

1 year old Salix Vinimalis shoots are used for planting. These are prepared during winter and kept at –4 °C (freezer) prior to planting. Planting Salix Vinimalis usually requires 2200 running metres shoots (rm)/ha. 1 box contains 5500 rm shoots, and 1 truck contains 35 boxes [18]. Planting the study area in Fagervik would require 5 boxes, possible to transport in a car. The closest source of Salix Vinimalis shoots is Weibulls in Svalöv, 951 km from Fagervik. There shoots are harvested (during winter) and frozen. They are kept frozen until just before planting. Delivery to Fagervik would either be from Svalöv, or from Agroenergy´s depot in Örebro (which in turn had received the shoots from Svalöv), by truck or by car [18]. For the purposes of this LCA, a journey by car from Svalöv to Fagervik is assumed. Other environmental effects of shoot production than that transport are not included.

Herbicide application (once prior to ploughing and once in conjunction with planting) and planting itself have been entered as 3 fertilising runs. Since fertiliser addition is required by the model, 1e-15 kg fertiliser per tonne soil is entered instead.

NB: Herbicide production and effects have not been included.

8.2.3 During Salix Vinimalis cultivation (fertilisation and harvest):

When the Salix Vinimalis has been established it needs fertilisation and harvesting. Fertiliser is spread two years out of three, and the wood is harvested every third year. This means 13 fertilisation applications and 7 harvests during a lifetime of the cultivation of 20 years. 100 kg fertiliser are applied per hectare [17], or 0.0037 kg/t, at each fertilising application, summing up to 0.049 kg fertiliser per tonne soil over the entire period. This is the standard amount of fertiliser normally applied to Salix Vinimalis cultivations on agricultural soil. The Fagervik soil may in reality need higher applications initially, due to the low quality of the soil.

Two appliances are used to harvest, a harvester and a tractor, all modelled as fertiliser applications (the choice is between ploughing and fertilising. Ploughing requires more fuel since it is the heavier work, so fertilising approaches the harvesting more closely). The wood is chipped in the harvester and filled into a container. The containers are placed at the roadside, and collected by truck for transport to the user. Alternatively, the wood chips may be placed at the side of the road and collected later [18]. The first alternative has been assumed here, and described using truck transport without reloading.

Expected harvest for Salix Vinimalis cultivation on agricultural soil is ca 25 tonne dry mass/ha and harvest [34], or 50 tonne wet weight/ha each harvest [18]. Since the Fagervik soil is initially of lower quality, the actually expected harvest is lower initially. A 50% decrease of harvest is included during the first 20 years, or ca 2000 tonne wood chips (ww)/20 a (time frame of the LCA). A full harvest of 620 tonne wet weight per harvest is used for later harvests (the carbon footprint).

A possible user of the wood chips is the paper plant using biofuel in Ortviken, 20 km S of Fagervik. Alternative energy plants are in Kvissleby (34 km) and Matfors (37 km). The nearest location, Ortviken at a distance of 20 km, has been used in this study.

8.2.4 Demobilisation of the Salix Vinimalis

When the surface is wanted for other purposes, the Salix Vinimalis is harvested (included above), treated with herbicide to kill the remaining Salix Vinimalis, followed by a shredder to remove smaller wood fragments and a plough to crush root stumps [17]. Two fertiliser runs and one ploughing run have been entered to model this, again with a fertiliser amount of 1e-15 kg/t.

NB: Herbicide production and effects have not been included

8.2.5 Transport of equipment and personnel for Salix Vinimalis cultivation

Agricultural equipment (tractor, fertiliser, and harvester) is assumed to come from Lantmännens nearest office, in Sundsvall. This means 11.2 km single journey. The agricultural equipment is transported to the site for each application, and two appliances are transported for each harvest. The operators of the equipment will usually accompany the equipment and no separate journeys for personnel are envisaged.

8.3 Inventory summary LCA

A summary of the inventory is presented in Table 9. For the detailed inventory of Fagervik, see Appendix 2.

Table 9: Summary of LCA inventory for Fagervik.

English translation	UvA original text	Unit/ inheit	Biofuel - Salix Vinimalis	On site ensuring
Used clean soil materials	Aufbereitete Erdmaterialien	kg	0	110 000 000
Diesel in equipment	Diesel in Baumaschine	kg	7 700	0
Establishment/Demobilisation	Mobilisierung/Demobilisierung	km	510	20
Fertiliser	Nährstoffe	kg	17 000	0
Local effect: Diesel in equipment	NF-Diesel in Baumaschine	kg	7 600	16 000
Local effect establishment	NF-Mobilisierung	km	12	0.5
Local effect truck transport	NF-Transport LKW	t km	500	28 000
Local effect car transport	NF-Transport PKW	km	21	50
Noise duration 108 dB(A)	Schalldauer 108 dB(A)	h	620	1 900
Truck transport	Transport LKW	t km	40 000	3 300 000
Car transport	Transport PKW	km	2 700	2 000

The total amount of diesel in equipment is similar for the biofuel alternative and on-site ensuring. The emissions from the agricultural part of Salix Vinimalis cultivation are not tied to the site by the model. The emissions from levelling of the area and from the soil cover are all designated local.

The truck transport for the biofuel alternative comprises wood chips, and for the on-site ensuring alternative soil transport. Transport of equipment is found under establishment/demobilisation. The local effect of truck transport is tied to the number of journeys, since 0.25 km of each journey are designated local. The car transport is higher for the biofuel alternative due to the journey of the Salix Vinimalis shoots (1902 km, since the return journey is included).

8.4 Exploration of the Fagervik LCA-model

The model described above was run with a few adjusted parameters in order to assess the impact of various activities. The following adjustments were made to investigate the effect on land occupation:

- Soil raw material was set to 0 for on site ensuring
- Fertiliser amount was set to 0 for biofuel cultivation

And to investigate the effect on environmental impact in general:

- Soil transport was set to 0 for on site ensuring
- Fertiliser amount was doubled for biofuel cultivation
- The number of weeding runs was doubled for biofuel cultivation
- The distance to a wood chip facility was multiplied by 10, to 200 km.

The results are discussed in chapter 12.

9 LCA-IMPACT FAGERVIK

The summary of impacts is presented in Table 10 and Figure 7. Biofuel cultivation had a lower impact on the environment for all categories.

Table 10: Summary of impact for Fagervik.

English translation	UvA original heading	Unit	Biofuel – Salix Vinimalis	On site ensuring
Cumulative energy use	Kumulierter Energieaufwand	TJ	1.4	19
Waste (total)	Abfallentstehung gesamt	kg	8 600	330 000
Waste reused on site	Abfallentst. Verwertung Standort	kg	0	0
Waste removed from site	Abfallentst. Beseitigung Standort	kg	0	0
Fossil resources	Fossiler Ressourcenverbrauch	1/a	630	8 200
Use of water resources	Ressourcenverbrauch Wasser	m^3	840	14 000
Occupied land area	Flächeninanspruchnahme	m^2 a*	3 500	1 400 000
Climate change	Treibhauseffekt	kg CO2	86 000	1 200 000
Acidification	Versauerung	kg SO2	1 000	14 000
Smog	Sommersmog	kg Ethen	180	2 300
Human health air- global	Humantoxizität Luft – Fernbereich	10^6 m^3	32 000	570 000
Human health water	Humantoxizität Wasser	10^6 m^3	0.9	13
Human health soil	Humantoxizität Boden	10^3 kg	0.1	1.9
Odour	Geruch	10^6 m^3	4 600	78 000
Human health air – local	Humantoxizität Luft – Nahbereich	10^6 m^3	19 000	44 000
Odour - local	Geruch – Nahbereich	10^6 m^3	2 400	5 600

* NB: the unit for ccupied land area is square meters multiplied by years.

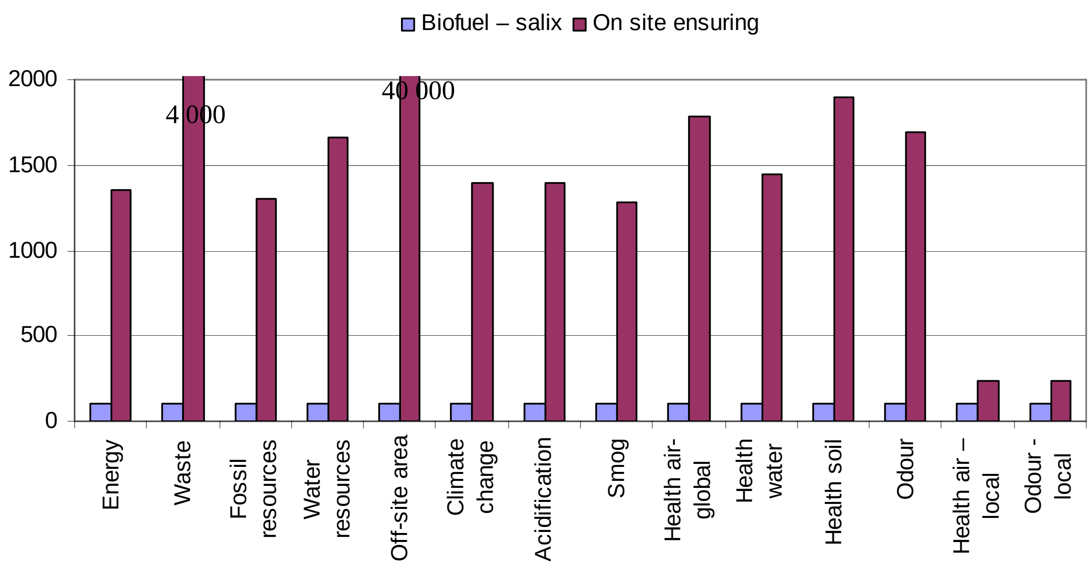

Figure 7: Impact from Table 10 in graphical form, with biofuel-Salix Vinimalis set to 100.

The occupied land area is due to the excavation of minerals and the production of fuels and fertiliser for the biofuel alternative. The clean soil production is added to this in the case of on-site ensuring. Please note that “human health soil” and the occupied land area in Table 10 allude to off-site land occupation, caused e.g. by oil production. It is not concerned with the contaminated site.

The fuel use for construction and agricultural equipment was similar for the two alternatives (section 8.3). However, transport of clean soil for covering the site caused a large additional fuel use, which has a number of negative environmental impacts. The impact of the use of fertiliser, which is negative for biofuel and non-existent for on-site ensuring, does not balance the soil transport impact.

The impacts are further discussed in chapter 12, togheter with the results of the LCA for Karlstad.

10 CARBON FOOTPRINT CALCULATIONS

10.1 Carbon footprint Fagervik

The major differences between the carbon footprint model and the LCA model is for personnel journeys (excluded instead of included) and the inclusion of Salix Vinimalis cultivation on agricultural land (Figure 4).

In addition the carbon footprint used the functional unit of MJ energy instead of “treated site”. Therefore the inventory has been broken down into a number of processes that are the building blocks of Salix Vinimalis cultivation. Their carbon emissions are shown in Table 11.

Production of equipment is included, although it should not have been according to [15] The dinitrogen oxide (N) emissions of Salix Vinimalis during growth are probably limited since fertilisation only needs to replace the N-amounts lost by harvest [35].

A Salix Vinimalis cultivation is expected to last at least 5–6 harvests [17]. For the purpose of the carbon footprint, each rotation of planting and removal has been assumed to last 6 harvests during 22 years.

The total greenhouse gas emissions from the change in land use are assumed to be released in equal annual amounts for 20 years [16]. The Fagervik site needs to be prepared (levelling) for the land change from inaction to short rotation wood. The associated emissions have been spread out over the 6 harvests of the first Salix Vinimalis rotation from planting to removal. Thus the first 22 years of Salix Vinimalis cultivation are burdened by both a low harvest on the contaminated site and the emissions from the site preparation.

The alternative use of the site (on site ensuring followed by parkland) is similarly a burden to the Salix Vinimalis cultivation on agricultural soil. The emissions from on site ensuring have been taken from the UvA model. This includes levelling and covering the site with clean soil. The landscaping needed for creation of a park on the site has not been included, and neither have the emissions from use and maintenance of the park

Table 11: Carbon emissions and storage for sub-processes of Salix Vinimalis cultivation on Fagervik.

Identifier	Unit process, usually 1 year	Greenhouse effect according to UvA Cfootprint model (kg CO2e/site[&])	Remarks
O	On site ensuring	1 200 000	First 6 harvests, Salix Vinimalis elsewhere
L	Levelling prior to Salix Vinimalis cultivation	30 000	First 6 harvests, Salix Vinimalis Fagervik
P	1 planting of Salix Vinimalis	12 000	1 allocated to every 6 harvests
F	1 fertilisation application	1 700	2 allocated to every harvest
Hn	1 harvest of Salix Vinimalis, normal	4 200	
Hi	1 harvest during the first 20 years, on contaminated soil	2 700	Lower emissions due to lower transport, because of lower yield
Hi1	Very first harvest on contaminated soil[*]	1300	Lower emissions due to no transport, because of lower yield
Hn1	First harvest of Salix Vinimalis, normal[*]	3000	Lower emissions due to lower transport, because of lower yield
R	1 removal of roots and stubs	2 600	1 allocated to every 6 harvests

[*] Please note that the 40% reduction in yield for the first harvest after planting only has been included for the carbon footprint. It has not been included in the LCA.
[&] The global warming impact of the UvA model writes $kgCO_2$ as output unit, but includes the CO_2 equivalents for the most common greenhouse gases (e.g. CH_4, N_2O) [28].

A normal harvest is expected for every hectare to yield 50 tonne wet weight [18], or 30–35 tonne dry matter wood chips [36]. The first harvest after planting yields only 60% of this, normally 20–25 tonne dry mass [37]. The very first harvest on Fagervik has been assumed to be left on site to improve the soil, and not utilised for energy production.

The yield reduction in the first harvest of every new Salix Vinimalis cycle leads to higher emissions per MJ energy. This is a form of land-use change emissions, similar to planting itsself, and a prerequisite for the following harvests. Therefore the emissions have been allocated over the Salix Vinimalis produced during the entire 20-year period.

Formulae for calculation of the carbon emissions are shown in Table 12, together with the results.

Table 12: Calculation of carbon emissions per MJ Salix Vinimalis energy.

	Formula for calculation	Emissions
		$kgCO_2e/MJ$
Salix Vinimalis on Fagervik, first 22 years or 6 harvests:	[L + P + 2×F+Hi1 + 5 × (2×F+Hi) + R] / Y / E	0.0049
Salix Vinimalis on agricultural soil, first 22 years or 6 harvests:	[O + P + 2×F+Hn1 + 5 × (2×F+Hn) + R] / Y / E	0.030
Salix Vinimalis on Fagervik, later harvests:	[P + 2×F+Hn1 + 5 × (2×F+Hn) + R] / Y / E	0.0013
Salix Vinimalis on agricultural soil, later than 20 years after Fagerviks remediation:	[P + 2×F+Hn1 + 5 × (2×F+Hn) + R] / Y / E	0.0013

Y=total yield during period. E=Energy content, 19.2 MJ/kg Salix Vinimalis dry weight [37] or 19200 MJ/tonne dry mass The other symbols as in Table 11

10.1.1Carbon in harvested shoots

The Salix Vinimalis takes up carbon dioxide during growth, which is emitted during combustion. This storage effect is not included in Table 12. With a carbon content of 50% dry weight [38], the carbon thus stored would amount to 15 tonne C, or 50 tonne CO_2, for a normal harvest of 30 tonne dry mass Salix Vinimalis/ha, or about 0.086 kg CO_2/MJ.

This carbon is released during combustion, and the consequent emissions are part of the carbon footprint of the combustion step. Combustion usually occurs in a short time from harvesting, and usually well within the year. Therefore the storage for last years growth should not be counted as carbon storage when these results are used for a carbon footprint of combustion [15]. But growth occurs during 3–4 years before harvest and combustion, and this carbon should be accredited as carbon storage. The magnitude would be around 0.0009 $kgCO_2e$/MJ in a 100 year perspective.

10.1.2 Carbon in belowground biomass

The Salix Vinimalis also stores carbon in the roots of the plants. This is stored between planting and removal, for a period between 1–20 years. At the removal of the Salix Vinimalis cultivation the roots remain in the soil. Part of the root rots (emission of CO_2) and part contributes to soil-carbon (longer storage of CO_2). Willow root biomass may be equal to, or greater then, the total aboveground biomass (Porter et al, 1993 in [35]). Clone selection for biofuel production has increased the proportion of stem over root biomass. Rytter found that 33–40% of the net primary production occurred belowground for (well fertilised and well watered) willows in lysimeters during year 2 and 3 of their growth [39].

The root carbon increase has been calculated for Fagervik as 35% of the total production, or for a normal Salix Vinimalis cultivation to (35/65)×8 tonnes/ha/year. The growth of roots has been adjusted to lower initial yields on contaminated soil and to lower growth the first three years after planting, in agreement with the yield calculations for the harvest. At the end of a Salix Vinimalis rotation, prior to removal of the roots, this gives a carbon amount belowground corresponding to 75 tonne CO_2 for the Fagervik site during the first Salix Vinimalis rotation, and 150 tonne CO_2 for a normal growth rotation of 6 harvests, or 0.05 kg CO_2/MJ. These 75 resp 150 tonne CO_2 are either emitted to the atmosphere (carbon emission) or remain in the soil carbon pool (carbon storage).

The carbon in the belowground biomass is stored prior to the Salix Vinimalis removal, independent of its faith afterwards. To express this in CO2e on a hundred year bases in accordance with [15], each years carbon storage has been multiplied with the number of years it is expected to be in the ground (22-years since planting) and divided by 100. Total carbon storage would be 18 CO_2e for the entire site at normal harvest, and 9 CO_2e for half harvest (the initial Salix Vinimalis rotation on contaminated soil). Divided by the energy contained in the shoots, this corresponds to 0.006 kgCO_2e/MJ.

10.2 Carbon footprint Karlstad

A carbon footprint was calculated using the LCA inventory for the Karlstad site as well. Personnel journeys were removed from the model, in accordance with [15]. The alternative is comprised of excavation and landfilling of the soil at Karlstad, together with biofuel cultivation elsewhere. Salix Vinimalis cultivation elsewhere would be on a larger, mechanised scale. Therefore the same data as for the Fagervik case have been used for comparison.

The distance from the site to a combustion facility (Heden, Karlstad) is 5 km. Truck transport of a first harvest of 10 ton wet weight (½ of 20 tonne dry mass/ha; water content 50%; 0.5 ha for the site) and five following harvests of 15 tonne wet weight (½ of 30 tonne dry mass/ha) have been added to the LCA model.

The amounts of carbon in roots and shoots is the same per MJ energy as in the Fagervik case.

11 CARBON FOOTPRINT RESULTS

The CO_2 equivalent emissions are summarised in Table 13. In the first column are the emissions that occur during cultivation, transport, production of equipment and production of fuel and fertiliser, calculated with the UvA program. The following columns present carbon storage in stems and roots prior to harvest (carbon storage of known duration), and after harvest (carbon storage of unknown duration). The carbon present in the stems and roots after the final harvest may be liberated during combustion (stems) or decay (roots). Part of the roots remains in the soil as part of the soil carbon pool.

Table 13: Summary of carbon footprint for one Salix Vinimalis cultivation cycle. Unit: kgCO_2e/MJ. The first five columns are also shown in Figure 8. Negative numbers are storage benefits, positive numbers are emissions.

	Emis-sions	Storage in stems	Stor-age in roots	Present in stems	Present in roots	Total, all root-C emitted	Total, all root-C stays in soil
Salix Vinimalis Fagervik, first period	0.0049	-0.0009	-0.006	-0.09	+ or - 0.05	-0.042	-0.13
Salix Vinimalis elsewhere, treatment Fagervik	0.031	-0.0009	-0.006	-0.09	+ or - 0.05	-0.016	-0.11
Salix Vinimalis on Fagervik, later	0.0013	-0.0009	-0.006	-0.09	+ or - 0.05	-0.045	-0.14
Salix Vinimalis elsewhere, later	0.0013	-0.0009	-0.006	-0.09	+ or - 0.05	-0.045	-0.14
Salix Vinimalis on Karlstad, first period	0.0009	-0.0009	-0.006	-0.09	+ or - 0.05	-0.046	-0.14
Salix Vinimalis elsewhere, treatment Karlstad	0.0071	-0.0009	-0.006	-0.09	+ or - 0.05	-0.039	-0.13

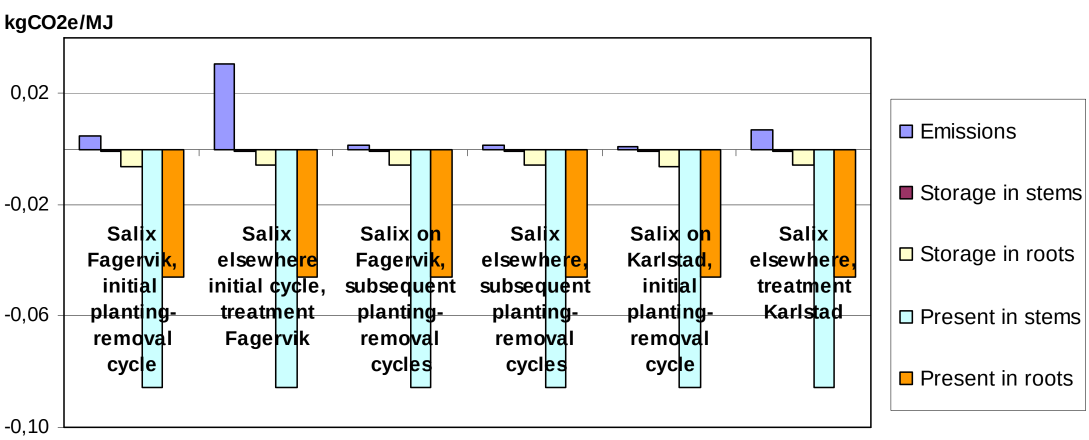

Figure 8: Components of the carbon footprint of Salix Vinimalis cultivation at Fagervik and Karlstad, in kgCO_2e/MJ. Numbers as in Table 13. Present in roots prior to the removal of the Salix Vinimalis is shown as carbon storage, but should be divided between storage and emissions (see text).

When these emissions are summarised according to [15], the net CO_2equivalent emissions on a 100 year basis per MJ energy in the Salix Vinimalis is between –0.02 and –0.1 kgCO_2e/MJ (Table 13). The carbon emissions are negative for the studied system, i.e. a net carbon storage occurs. However, this is largely an effect of the system boundary: the emissions of the combustion were not included and the entire harvest is counted as storage while it in reality is an emission waiting to happen.

The faith of the roots is very important to the magnitude of the carbon balance. The estimate of the carbon contained in the roots prior to removal of the Salix Vinimalis is coarse, and could easily be double, or half, of the amount in Table 13 and Figure 8. The carbon balance has been calculated in Table 13 both with the roots as an emission (decay causing CO_2 emissions to the air) and as a storage (the entire root remains part of the soil-C pool). These are two extremes and the truth lies somewhere in the middle. Précising it is unfortunately beyond the means of the present study. The actual fate of the carbon in the roots after Salix Vinimalis cultivation are not well known, though Salix Vinimalis cultivation does increase the C-pool in the soil, at least for low carbon soils [40].

The Salix Vinimalis would improve the soil quality. If the roots are left in the soil, they contribute to soil carbon and increase degradation of organic contaminants. Metal contaminants also concentrate in the biomass, and it may be advantageous to remove the roots after the Salix Vinimalis cycle to remove the metals stored in the roots.

To grow Salix Vinimalis on the contaminated sites was more advantageous then to grow it elsewhere, on agricultural soil. After the initial land use change burden is worked off, the two alternatives are the same (‘later’ in Table 13). The land use change involves the planned treatment on the contaminated site, on site ensuring or excavation and landfill, when Salix Vinimalis is grown elsewhere. For Salix Vinimalis on Fagervik, it involves only levelling the site. In spite of the halved harvest that was supposed for the contaminated sites, it is still the more advantageous alternative.

12 DISCUSSION AND INTERPRETATION

The aspects included in the LCA investigations of the two contaminated sites and their treatment include scarce resources such as groundwater, soil and backfull, fossil fuels and metals, energy consumption, green house gas emissions and emissions contributing to photochemical smog formation, acidification, eutrophication and occupation of land area. The carbon footprint included global warming, and accounted for CO_2 storage in stems and roots that were ignored for the LCA.

At both sites the cultivation of Salix Vinimalis is environmentally favourable based on this investigation than the two serious alternatives, i.e. dig and dump for Karlstad Oil depot and the establishment of a park at Fagervik. The conclusion was similar for the two sites, despite their differences. Fagerwik is large, the alternative is covering, and Salix Vinimalis cultivation machine-run. Karlstad is small, the alternative is excavation, and Salix Vinimalis cultivation has a large manual component.

For Karstad Oil depot every single investigated category is in favour of Salix Vinimalis cultivation instead of excavation. In general the benefit is around 50 times, varying from 40 times less impact regarding the local health aspects and contribution to photochemical smog to infinitive regarding the waste transported from the site and more than 20 000 regarding waste production in general. In this investigation the difference between the two alternatives is of an order of magnitude, so that small deviations in parameters have no impact on the comparison. Since all environmental aspects work in the same direction regarding the most favourable alternative there also are no need of making any priorities among the different environmental aspects. Based on environmental aspects the choice should be cultivation of Salix Vinimalis instead of dig and dump. In the real case the economical aspects were also in favour of the Salix Vinimalis cultivation alternative.

In the Fagervik case the total environmental and most of the individual impacts investigated were in favour of Salix Vinimalis cultivation as well. Here the magnitude in favour varies from being equal (for example the diesel used in equipment) to 80 times higher for truck driving in the on site ensuring case. The distance driven by truck is 3000 million km for on site ensuring and 40 million km for Salix Vinimalis cultivation. All other transport and machines in use are hundreds of magnitudes less than the trucks. The use of trucks, other vehicles and machines leads to air emissions (including greenhouse gases, particles and species contribution to photochemical smog and acidification), use of fossil fuel and occupation of land [41, 42].

12.1 Occupied land surface

The occupied land area is a critical parameter for the study and is therefore discussed in more detail.

The on-site occupied land area and the total off-site occupied land area are shown in Table 14. The on-site area includes the assumption that biofuel cultivation is considered as occupying the site and not as otherwise useful land use (which is correct for Karlstad but directly misleading in the Fagervik case since the harvest would be utilised).

Table 14: On and off-site occupied land area in hectares multiplied by years (ha×a) as calculated by the UvA program.

	Karlstad phytoremediation	Fagervik biofuel	Karlstad dig-and-dump	Fagervik on site ensuring
On site land area	8.5	250	0.55	6.2
Off-site land area	0.02	0.45	20	140

The area occupied by the remediation was smaller for the biofuel alternatives than for the others when the site itself was not considered (Figure 9 and Table 14). Most of the area that will be needed is due to the soil. Clean soil corresponded to 70 and 90% of the occupied land area (Figure 10), due mainly to the quarry and sieving areas. The other large contributor is soil to landfill in the Karlstad case: 20%.

The numbers used in this report are the general land occupation from the UvA program, unless otherwise specified. This includes landfilling and soil pits as well as the area occupied for oil production and others. Most of those land demanding activities, apart from the landfill and the area used for the pristine soil, are only temporary. The production of clean soil caused occupation for a higher surface × time (21 m^2 anually per m^3 soil) than the same amount of landfilled soil (6 m^2 anually per m^3 soil). This may be caused by a lower height of the pit: if the occupation time 20 years then the soil quarry is one m high, or by a longer duration: if the soil quarry is 20 m high, then the occupied time is 400 years.

The landfilled masses from dig-and-dump remediation in Karlstad would in reality have been landfilled at the nearest landfill, Djupdalen. Djupdalen will have a height of approximately 20 m when it is filled [43], so that the removed soil volume, 6560 m^3, corresponds to 330 m^2 of a 20 m high pillar. The landfilled soil factor from the Uva, 6 m^2 anually per m^3 soil, corrresponds to a 20 m high pillar for 123 years.

Fertiliser may also be a significant contributor, but accords for less than 10% (Figure10). The UvA program models all fertiliser as sodium nitrate, since this is the major consumer of energy, so that phosphate with accompanying mining is not included. The remainder of the (of-site) occupied land area is likely due to the extraction and refining of fuel.

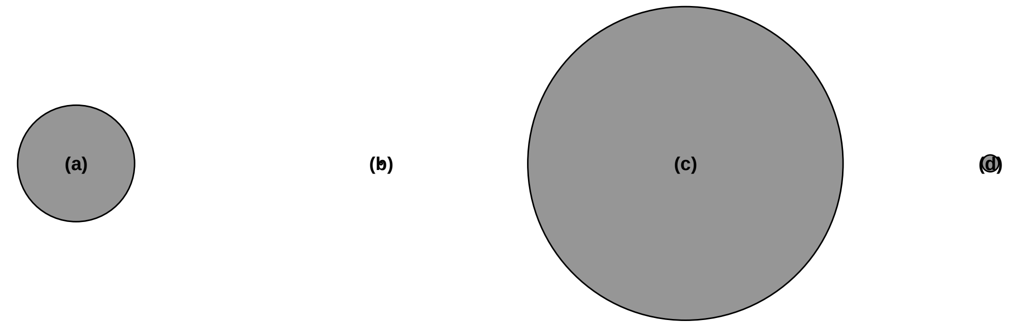

Figure 9: Total off-site used area of the remediation alternatives. Circle surface corresponds to square meters multiplied by years (m^2a). a) Karlstad dig-and-dump, b) Karlstad phytoremediation, c) Fagervik on site ensuring, , d) Fagervik biofuel. Please note that b) is too small to be seen.

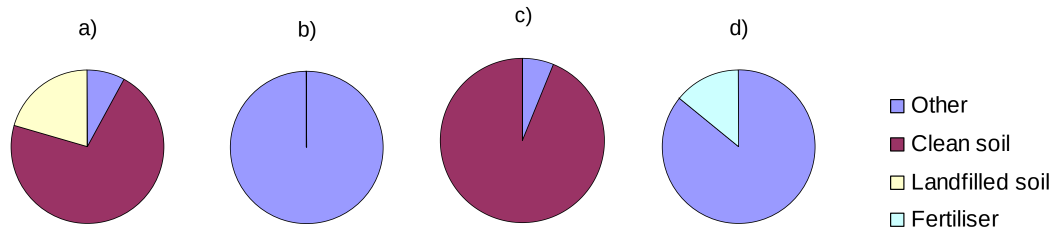

Figure 10: Distribution of off-site occupied land area in area × time. a,b,c and d same as in Figure 9. Total circle size should be as in Figure 9.

Cleaning soil by biofuel cultivation is a longer term project, and occupies the site for longer than conventional remediation. Incidentally, biofuel was assumed to clean the soil in approx. 20 years. This has not been included in the study as the time perspective has not been regarded from this point of view.

The land use time perspective, i.e. what is regarded as occupying and useful, depends on local demands and conditions and includes both economical and social aspects. From a LCA based environmental perspective the use of land for biocrops may be beneficial in comparison with other land use alternatives despite the further fate of the crop according to this investigation. Using the biocrop to replace fossil fuel will further contribute to a positive environmental impact, where an additional advantage is that the biocrops need not be grown on forest land or land that can be used for food production.

This aspect of land use is not addressed in the LCA investigation and only partly in the carbon footprint (section 10 and 11). Section 12.4 includes some remarks on a method to include a broader perspective.

12.2 Other important inventory and impact aspects

Soil transport constituted 60–90% (Fagervik) or 60–75% (Karlstad) of most impact categories for on site ensuring and excavation alternatives (excepting water resources 40%; land use, odour and human toxicity near the site <10%). The biofuel alternative had lower environmental impact for all categories even when soil transport was discounted.

The use of fertiliser is the single activity in Salix Vinimalis cultivation that has no corresponding activity in the on site ensuring alternative. The impact, however, is not significant in relation to the other aspects (see Table 10 and Appendix 2).

The local health effects for both sites were in favour of biofuel (effects on workers were not included). Excavation and soil covering emissions are moreover concentrated to a short period of time, which would accentuate the acute toxicity effects on human health. Since the sites did not pose an acute health risk prior to remediation unless the soil was ingested, the net effect of the fast remediations may be to increase the health and environmental risks related to air emissions, definitely globally but even locally.

12.3 Uncertainties and reliability

It has to be noted that the data base used in the investigations was last updated 1995. Since then there has been a development towards less emissions per km driven from cars. The development of trucks and working machines are, however, not expected to have followed the same development. In the investigations here, the major emissions are due to trucks or working machineries and therefore the emissions used are assumed to be relevant also in this study. During the nearest decade and decades the emission are expected to be both changed and reduced also from those types of vehicles and updates in data basis for environmental assessments shall be done accordingly. Also already in this investigation, the total emissions and use of fossil fuel may be lower than calculated here. But even if the total environmental impacts will be less than calculated here for all alternatives and scenarios, the relative relation between the remediation alternatives will still be in favour of the Salix Vinimalis cultivation alternative.

In theory, there may be sites where the environmental benefits are less pronounced and less clear than in the investigated examples here. In such cases, it is important to find which are the most important factors and to find more certain information about those aspects for the realistic alternatives investigated. Under conditions where the two most favourable alternatives are of equal environmental impact it is also recommended to include the next phase of the products and activities on the site. It can under such conditions also be relevant to use other methods for estimating the environmental impact such as carbon footprint.

12.4 System boundaries: expansion for Fagervik

12.4.1 Introduction

The LCA of this study focused on the contaminated site. The system boundaries of the carbon footprint were somewhat wider, since Salix Vinimalis cultivation elsewhere were included. The cleaning effect of biofuel production was simply assumed, and the focus was on the negative environmental and health impacts of the activities on the contaminated site.

But the cultivation of biofuels as a remediation alternative causes a number of other issues. Wether metal contamination is taken up into the harvest depends largely on the choice of crop and clone. Salix Vinimalis clones may be selected for high or low cadmium or zinc uptake [44, 45]. The faith of metals in the stems in the production chain *after* the harvest has environmentally relevant consequences [5]. These have not been included in the study so far, and different system boundaries are necessary to study this issue.

12.4.2 Possible alternative cases and system boundaries

When Salix Vinimalis or ferns are cultivated on Fagervik, land elsewhere is available for agriculture. Arsenic is not taken up to a large extent by Salix Vinimalis [45], so that the soil will not be cleaned effectively. Zinc and cadmium may be taken up, depending on the Salix Vinimalis clone, and found in the by-products. Six alternative cases are shown in and discussed below.

a) The harvest is converted to DME. Some metals would be found in the sludge from the gasification. The sludge would be suitable for limited recycling, for example back to Fagervik.
b) In alternative b the Salix Vinimalis is used for combustion and heat production. The resulting ashes with some metals could be useful for road construction. The Salix Vinimalis cultivation will then need some more fertiliser.

The majority of ferns do hyperaccumulate arsenic [23]. Cultivation of ferns has the potential to clean the Fagervik soil completely.

c) The fern harvest could be used for DME production. The resulting sludge could contain high metal contents and might need to be landfilled.
d) The fern harvest could alternatively be used for combustion, for example in a district heat system. Arsenic will be concentrated in the bottom and filter ashes [46]. If the metal concentrations are sufficiently high, recovery of the metals could be possible and leave a clean ash and useful metals.

The last alternative, e), corresponds most closely to the present-day situation.

e) Biofuel (Salix Vinimalis) is cultivated elsewhere, and used for either combustion or biofuel production. The by-products (ash or sludge) do not contain threatening concentrations of heavy metals and are recycled to the same or another Salix Vinimalis field. The Fagervik area is covered with a 0.5 m thick layer of clean soil, while the contaminants remain in the soil [22].

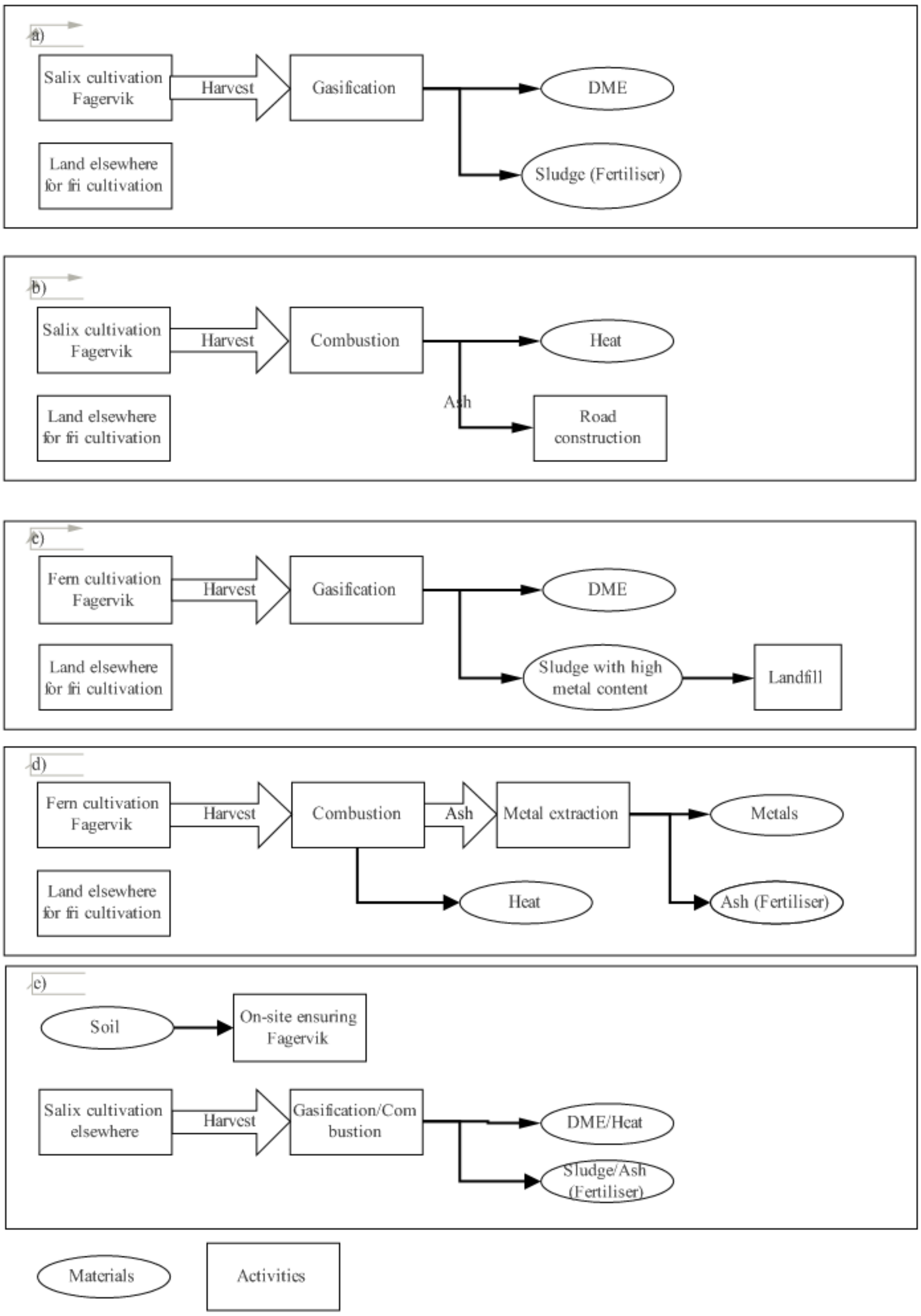

Figure 11: Possible alternatives for the remediation of Fagervik and the production of bioenergy.

Discussion

The suggested system boundaries in Figure 11 make the assessment of the entire chain of biofuel production possible. The main difference compared to LCA of biofuel production like in [11, 26, 47] is that the energy cost of soil remediation is included. The use of by-products from metal-extracting biofuels is an interesting further issue that may become realistic (Karlfeldt, 2006).

12.5 Outlook: a possible decision support tool

Building a LCA, even for screening, is a labour-intensive project, and this is usually not convenient prior to a decision. And at the same time an LCA can only answer certain questions. In the present study the LCA included two contaminated sites and their treatment included scarce resources, energy consumption, green house gas emissions, acidification, eutrophication etc. A special effort has been made for the occupation of land area, on and off site. The carbon footprint naturally dealt exclusively with global warming, and accounted for CO_2 storage in stems and roots that were ignored for the LCA. But other important impacts, such as the improvement of the land or the accessibility for neighbours walking their dogs were not addressed. Introduction of entirely new impacts in an LCA is also a daunting task.

The environmental competence of the deciding people is often fair. But they are not environmental experts and hesitate to take a stand on environmental issues, which consequently are left out of the decision process. (Compare this to economics, where everyone is sufficiently sure of himself to make some judgement). Diamond et al. have suggested a life cycle framework to make a broader assessment of soil remediation alternatives. The life cycle framework is semi-quantitative based on expert judgement of level of concern for all inventory items [48]. A similar, but simplified tool could be helpful also in the case of biofuel on contaminated land.

A matrix of inventory items (rows) and likely impacts (columns) is shown in Table 16. The matrix is three dimensional: the extended system boundaries and alternative treatments of section 12.4 and Figure 11 are considered for every cell. The impacts were selected from [11, 48, 49], grouped into global, local and resources impacts (Table 16). The local/regional impacts are mainly concerned with the quality of the environment, while the resources are concerned with the quantity of renewable resources.

Table 15: Considered impacts for the life cycle framework.

Global/International impacts (in meteorology referred to semi regional to regional and up to global scale)	*Global warming*	
	Ozone layer	
	Ground-level ozone	
	Acidification	
	Long distance transportation of air, water or animal borne primary emissions(e.g. bio accumulating substances)	
Local/Regional (in meteorology local to semi regional scale) impacts	*Air quality*	Health risks related to gas contaminants, deposition toxic airborne substances, particles, eutrophication
	Surface water quality	Contamination of metals, organic species or other non particle bound chemicals through emissions for example through spill or leaching, or local sources of air borne deposition, particles, eutrophication
	Groundwater quality	Dissolved or dispersed contamination through leaching or spill , particle bound contaminants, eutrophication
	Soil quality	Contamination of metals, organic compounds, particles, bioaccumulating compounds, eutrophication
	Social environment quality	Cultural environment, landscape, noise, smell, accessibility, exploitation, recreation
Resources	*Land quantity*	Multifunctionality, biodiversity, compaction, erosion
(present	*Water quantity*	Drinking water, recreation, water storage
<-> alternative	*Renewable resources*	Hydroelectric power, forest, wind power, solar power
<-> future use)	*Non-renewable resources*	Clean soil, rock, minerals, fossil fuels

The matrix in Table 16 gives a simplified but comprehensive overview of environmental aspects that should influence the decision on use of the site. The work of constructing the matrix guaranties broader consideration than usual. At this stage, the values presented in Table 16 are first suggestions and have not been tested, communicated or validated. They are only given as examples of what a relevant matrix for changes in land use by bio fuel cultivation can contain and look like. The completion of the matrix shall be done as a process where a group of key stake holders participates. The members and the size of the group depend on the size of the site and other specific demands in the project [14]. Some of the impacts are general and may also be more adequately estimated by experts, for example the environmental impacts of some of the activities on different scales. For those, guiding pre assessed estimates would be convenient to have available, especially for small site stake holder based assessments. To fill the matrix completely is likely overly labour intensive, and implication of this in decision practice needs to be further studied, especially with regard to key stakeholders and participation. This concept is further developed in [50].

Table 16: Life cycle framwork for Fagervik. The table is partly filled in, to illustrate the procedure. This is not intended as an actual LCF of Fagervik.

Legend:
0 of negligeable concern
- small concern + small positiv impact
-- medium concern++ medium positiv impact
-- great concern +++ great positiv impact

a) Salix Vinimalis on Fagervik, DME
b) Salix Vinimalis on Fagervik, heat
c) Ferns on Fagervik, DME
d) Ferns on Fagervik, combustion and ash-metal extraction
e) Salix Vinimalis elsewhere

		Global/International impacts																			
		Global warming					*Ozone layer*					*Ground-level ozon*					*Acidification*				
	Case:	a	b	c	d	e	a	b	c	d	e	a	b	c	d	e	a	b	c	d	e
Inventory categories	**Inventory list**																				
Materials input (NB	Nutrients	0	-	-	-	0	0	-	-	-	0	0	-	-	-	0	0	0	0	0	0
Incl transport	Salix/fern shoots	-	-	0	0	-	-	-	0	0	-	-	-	0	0	-	-	-	0	0	-
	Irrigation water	0	0	-	-	0	0	0	-	-	0	0	0	0	0	0	0	0	0	0	0
	Herbicides	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Soil	na	na	na	na	--					--					--					--
Materials distributi	Harvest	-	-	0	0	-	-	-	0	0	-	-	-	0	0	-	-	-	0	0	-
=transport	Sludge (to reuse)																				
	Ash (to reuse)																				
Materials output (Ot	Ash (to byproduct use or landfill)																				
Incl transport	Sludge (to byproduct use or landfill)																				
	Metals	na	na	na	0	na				0					0					0	
Processes (Obs ev. tr	Cultivation	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Incl transport of equip	Irrigation																				
	Gasification																				
	Combustion																				
	Metal extraction (d)	na	na	na	-	na				-					-					-	
	Soil movement (e)	na	na	na	na	--					--					--					--

		Local/Regional impacts																								
		Contamination, particles, acidification, overfertilisation					Contamination, particles, acidification, overfertilisation					Contamination, particles, acidification, overfertilisation					Contamination, particles, acidification, overfertilisation					Cultural environment, landscape, noise, smell, accessability				
		Air quality					*Surface water qual*					*Groundwater quali*					*Soil quality*					*Social environmen*				
	Case:	a	b	c	d	e	a	b	c	d	e	a	b	c	d	e	a	b	c	d	e	a	b	c	d	e
Inventory categories	**Inventory list**																									
Materials input (NB	Nutrients	0	-	-	-	0	-	-	-	-	-	0	0	0	0	0	0	+	+	+	0	0	0	0	0	0
Incl transport	Salix/fern shoots	-	-	0	0	-	-	-	0	0	-	-	-	0	0	-	0	0	0	0	0	-	-	0	0	-
	Irrigation water	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Herbicides	0	0	0	0	0	-	-	?	?	-	--	--	?	?	--	-	-	0	0	-	0	0	0	0	0
	Soil					--					0					0					0					0
Materials distributi	Harvest	-	-	0	0	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
=transport	Sludge (to reuse)																									
	Ash (to reuse)																									
Materials output (Ot	Ash (to byproduct use or landfill)																									
Incl transport	Sludge (to byproduct use or landfill)																									
	Metals				0					0					0					0					0	
Processes (Obs ev. tr	Cultivation	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	++	++	0	-	-	+	+	++
Incl transport of equip	Irrigation																									
	Gasification																									
	Combustion																									
	Metal extraction (d)				-					0					0					0					0	
	Soil movement (e)					--					0					0					0					--

		Resources (present <-> alternative <-> future use)																			
		Biodiversity, exploatation (irreversable?), compaction, erosion,					Drinking water, rekreation, water storage					Hydroelectric power, forest, windpower, solar power					Clean soil, rock, minerals, fossil fuels				
		Land quantity					*Water quantity*					*Renewable resourc*					*Non-renewable reso*				
	Case:	a	b	c	d	e	a	b	c	d	e	a	b	c	d	e	a	b	c	d	e
Inventory categories	**Inventory list**																				
Materials input (NB	Nutrients	0	-	-	-	0	0	0	0	0	0	-	0	0	0	-	0	-	-	-	0
Incl transport	Salix/fern shoots	-	-	0	0	-	0	0	0	0	0	0	0	0	0	0	-	-	0	0	-
	Irrigation water	0	0	0	0	0	0	0	-	-	0	0	0	0	0	0	0	0	-	-	0
	Herbicides	0	0	0	0	0	0	0	0	0	0	-	-	?	?	-	-	-	?	?	-
	Soil					---					0					0					---
Materials distributi	Harvest	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	--	--	-	-	--
=transport	Sludge (to reuse)																				
	Ash (to reuse)																				
Materials output (Ot	Ash (to byproduct use or landfill)																				
Incl transport	Sludge (to byproduct use or landfill)																				
	Metals				0					0					0					++	
Processes (Obs ev. tr	Cultivation	+	+	+	+	0	0	0	0	0	0	-	-	-	-	-	--	--	--	--	---
Incl transport of equip	Irrigation													-	-						
	Gasification											++		++		++					
	Combustion												++		++	++					
	Metal extraction (d)				0					0					-					-	
	Soil movement (e)					0					0					0					---

long transport

Salix hinders view

Electricity to pump

13 CONCLUSIONS

The cultivation of Salix Vinimalis, instead of dig and dump or establishing a park, is environmentally favourable despite the need for transport for further treatment. The study does not include the subsequent use of the Salix Vinimalis. The subsequent use can be as an alternative to fossil fuel for energy, e.g. district heating by combustion or biofuel production. It could also be as reuse on the site, to increase the carbon content, or production of other biomaterials. Other biomaterials can for example be plastics where otherwise fossil fuel would have been used or fibre materials where cotton would have been used. The environmental benefits would then be even higher than estimated here. To what degree, however, depend on the subsequent use combined with local specific conditions.

This investigation indicates that the cultivation of biomaterial can be environmentally favourable in relation to more traditional remediation methods. It has to be noted, however, that under some conditions this may still not be the most optimal treatment or use of the site:

- The risks at the site have to be assessed prior decision, i.e. the risks during the cultivation or remediation period must be acceptable otherwise faster remediation methods are to be used.

- The choice of crop and its subsequent use depend on site specific conditions. At most locations in Sweden there are facilities where the materials can be used, such as waste treatment facilities (producing district heat and energy, sometimes combined with biofuel production) and pulp- and paper industries. At such sites the cultivation of Salix Vinimalis for bioenergy production is likely among the most environmentally beneficial alternatives. When such facilities are not available within reasonable transport distance it is important to start with an overview analysis of the most sustainable site treatments and the potential customers for non food crops. For such an environmental analysis, the method (LCF) described in section 12 in this report can be used. If also social and economic aspects are to be included, the decision matrix presented in the main report of the project Rejuvenate [20] can be the basis for the analysis. These two methods are of relevance for all contaminated sites prior to decision of treatment. The results from such analysis may show that more thorough environmental investigations, such as life cycle assessment or carbon footprint, are necessary.

14 REFERENCES

1. Commission of the European communities, *Impact assessment. Document accompanying the package of implementation measures for the EU's objectives on climate change and renewable energy for 2020. Proposals for Directive of the European parliament and of the council amending Directive 2003/87/EC so as to improve and extend the EU greenhouse gas emission allowance trading system*. 2008, Commission staff. Available from: http://ec.europa.eu/energy/climate_actions/doc/2008_res_ia_en.pdf.
2. Rydberg, T., *Dagens analysmetoder skapar övertro på bioenergi (in Swedish)*. Formas fokuserar, 2008: p. 137-154.
3. Semelsberger, T.A., R.L. Borup and H.L. Greene, *Dimethyl ether (DME) as an alternative fuel*. Journal of Power Sources, 2006. 156(2): p. 497-511.
4. Bardos, P., Y. Andersson-Sköld, S. Keuning, Pachon, T. Track, Wagelmans, Cundy, P. McDaniel and Mahoney. *Special session 1: Brownfields, Bioenergy and Biofeedstocks & Special session 2: Green Remediation*. in *ConSoil 2008*. 2008. Milano, Italy: F&U confirm.
5. Andersson-Sköld, Y., S. Blom, T. Rihm, A. Angelbratt, P. Bardos, T. Track, S. Keuning and O. Wik, *Biofuel and other biomass based products from contaminated sites - Potentials and barriers from Swedish perspectives*. 2009.
6. Enell, A., O. Wik and Y. Andersson-Sköld, *Arable area of potential contaminated sites in Sweden*. 2009, Swedish Geotechnical Institute.
7. EEA, E.E.A. *Progress in management of contaminated sites (CSI 015) - Assessment published Aug 2007*. 2007 [cited 2008 November]; Available from: http://themes.eea.europa.eu/IMS/IMS/ISpecs/ISpecification20041007131746/IAssessment1152619898983/view_content.
8. McCutcheon, S.C. and J.L. Schnoor, eds. *Phytoremediation: transformation and control of contaminants*. 2003, Wiley-Interscience.
9. Aronsson, P., M. Weih and I. Åhmna, *Salix Vinimalisodling ger mervärden - förutom energi. In: Bioenergi - till vad och hur mycket? (In Swedish)*. Formas fokuserar, 2007: p. 247-260.
10. von Blottnitz, H. and M.A. Curran, *A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective*. Journal of Cleaner Production, 2007. 15(7): p. 607-619.
11. Zah, R., H. Böni, M. Gauch, R. Hischier, M. Lehmann and P. Wäger, *Life Cycle Assessment of Energy Products: Environmental Impact Assessment of Biofuels Executive Summary of Ökobalanz von Energiprodukten: Ökologishe Bewertung von Biotriebstoffe*. 2007, Empa: Bern. Available from: http://www.bfe.admin.ch/themen/00490/00496/index.html?%20lang=en&dossier_id=01273 http://www.bfe.admin.ch/dokumentation/energieforschung/index.html?lang=en&project=100653#suchergebnisse.
12. ISO 14040, *Environmental management -- Life cycle assessment -- Principles and framework*. 2006.
13. Frischknecht, R., *Notions on the design and use of an ideal regional or global LCA database*. International Journal of Life Cycle Assessment, 2006. 11: p. 40-48.
14. Andersson-Sköld, Y., J. Norrman and K. Kockum, *Survey of risk assessment methodologies for sustainable remediation*, in *VALDOR (Values in decisions on risk)*. 2006: Stockholm, Sweden. p. 135-142.
15. PAS 2050:2008, *Specification for the assessment of the life cycle greenhouse gas emissions of goods and services*, in *Publicly Available Specification*, BSI.

16. BSI, *Guide to PAS 2050 - How to assess the carbon footprint of goods and services*, in *Publicly Available Specification*. 2008, BSI.
17. Lantmännen, J. Gustafsson, S. Larsson and N.-E. Nordh, *Manual för Salix Vinimalisodlare*. 2007, Örebro: Lantmännen Agroenergi AB/Salix Vinimalis.
18. Lindblad, G., *Personal communication.* 2008-10-09 and 2008-12-15
19. Andersson, Å. and M. Persson, *Fytoremediering - Att rena mark och vatten med växter*, in *Ecosystemtechnology*. 2007, Lund University.
20. P. Bardos, Y. Andersson-Sköld, S., Keunig, M. Polland, P. Suer, T. Track, *Preliminary title: Decision matrix for non-food crop cultivation on marginal contaminated land.* In preparation, 2009.
21. Börjesson, E., *Lägesbeskrivning av efterbehandlingsarbetet i landet 2007*, Swedish Environmental Protection Agency, Editor. 2008-02-21, Naturvårdsverket: Stockholm. p. Appendix 8. Available from: http://www.naturvardsverket.se/sv/Nedre-meny/Nyheter/Laget-for-fororenade-omraden/.
22. Envipro, P. Östlund and M. Pyyny, *Fagerviks industriområde - Kompletteringar och kostnadsrevidering av åtgärder*. 2006. Available from: http://www.timra.se/templates/Page.aspx?id=4502.
23. Meharg, A.A., *Variation in arsenic accumulation - hyperaccumulation in ferns and their allies.* New Phytologist, 2003. 157(1): p. 25-31.
24. Jacks, G., *Personal communication.* 2008-10-17
25. Envipro, P. Östlund and M. Pyyny, *Fagerviks industriområde - Ramberättelse - genomförda undersökningar och värderingar samt reviderat åtgärdsförslag*. 2005, Envipro Miljöteknik. Available from: http://www.timra.se/templates/Page.aspx?id=4502&epslanguage=EN.
26. Börjesson, P., *Livscykelanalys av Salix Vinimalisproduktion*, in *IMES/EESS*. 2006, Dept of Environmental and Energy System Studies, Lund University: Lund.
27. Volkwein, S., H.-W. Hurtig and W. Klöpffer, *Life cycle assessment of contaminated sites remediation.* Int. J. LCA, 1999. 4(5): p. 263-274.
28. Landesanstalt für Umweltschutz Baden-Württemberg, *Umweltbilanzierung von Altlastensanierungsverfahren*. 1999, Landesanstalt für Umweltschutz Baden-Württemberg.
29. Frischknecht, R., P. Hofstetter, I. Knoepfel, R. Dones and E. Zollinger, *Ökoinventare für Energiesysteme.*, B.f. Energiewirtschaft, Editor. 1995, Bundesamt für Energiewirtschaft: Bern.
30. Spriggs, T., M.K. Banks and P. Schwab, *Phytoremediation of polycyclic aromatic hydrocarbons in manufactured gas plant-impacted soil.* Journal of Environmental Quality, 2005. 34(5): p. 1755-1762.
31. SMP, *Jämförande emissionsmätningar av tvåtaktsbränslen*. 2005, Svensk Maskingprovning AB.
32. Blom, S., *Personal communication.*
33. Lantmännen Agroenergi. *Plantering av Salix Vinimalis*. 2006 [cited 2008 2008-09-16]; Available from: http://www.agrobransle.se/Salix Vinimalis/odla/plantering.
34. Lantmännen Agroenergi. *Skörderekommendationer*. 2006 [cited 2008 2008-12-12]; Available from: http://www.agrobransle.se/Salix Vinimalis/skorda/rekommendationer.
35. Karp, A. and I. Shield, *Bioenergy from plants and the sustainable yield challenge.* New Phytologist, 2008. 179(1): p. 15-32.
36. Lantmännen Agroenergi. *Att skörda Salix Vinimalis*. 2006 [cited 2008 2008-09-16]; Available from: http://www.agrobransle.se/Salix Vinimalis/skorda.
37. Lantmännen Agroenergi. *Att elda Salix Vinimalis*. 2006 [cited 2008 2008-12-12]; Available from: http://www.agrobransle.se/Salix Vinimalis/elda/effektivt.

38. Ragland, K.W., D.J. Aerts and A.J. Baker, *Properties of wood for combustion analysis.* Bioresource Technology, 1991. 37(2): p. 161-168.

39. Rytter, R.M., *Biomass production and allocation, including fine-root turnover, and annual N uptake in lysimeter-grown basket willows.* Forest Ecology and Management, 2001. 140(2-3): p. 177-192.

40. de Neergaard, A., J.R. Porter and A. Gorissen, *Distribution of assimilated carbon in plants and rhizosphere soil of basket willow (Salix Vinimalis viminalis L.).* Plant and Soil, 2002. 245(2): p. 307-314.

41. Suer, P., Y. Andersson-Sköld and J. Andersson, *Local gain, global loss - the environmental cost of action*, in *Advances in applied bioremediation (in print)*, Ajay Singh, Editor. 2009, Springer.

42. Suer, P., S. Nilsson-Påledal and J. Norrman, *LCA for site remediation: A literature review.* Soil and Sediment Contamination: an International Journal, 2004. 13(4): p. 415-425.

43. Månsson, A., *Personal communication.* 2008-10-09

44. Padmavathiamma, P.K. and L.Y. Li, *Phytoremediation technology: Hyper-accumulation metals in plants.* Water Air and Soil Pollution, 2007. 184(1-4): p. 105-126.

45. Tlustos, P., J. Szakova, M. Vyslouzilova, D. Pavlikova, J. Weger and H. Javorska, *Variation in the uptake of Arsenic, Cadmium, Lead, and Zinc by different species of willows Salix Vinimalis spp. grown in contaminated soils.* Central European Journal of Biology, 2007. 2(2): p. 254-275.

46. Chandler, A.J., T.T. Eighmy, J. Hartlén, O. Hjelmar, D.S. Kosson, S.E. Sawell, H.A.v.d. Sloot and J. Vehlow, *Municipal solid waste incinerator residues*. Studies in Environmental Science 67. 1997: Elsevier.

47. Jungbluth, N., S. Büsser, R. Frischknecht and M. Tuchschmid, *Ökobilanz von Energieprodukten: Life Cycle Assessment of bio-mass to liquid fuels, Final Report*. 2008, Bundesamt für Energie BFE, ESU-Services Ltd: Uster, Switzerland. Available from: http://www.bfe.admin.ch/dokumentation/energieforschung/index.html?lang=en&project=100653#suchergebnisse.

48. Diamond, M.L., C.A. Page, M. Campbell, S. McKenna and R. Lall, *Life-cycle framework for assessment of site remediation options: Method and generic survey.* Environmental Toxicology and Chemistry, 1999. 18(4): p. 788-800.

49. Miljömålsrådet, *Miljömålen i korthet ... och en sammanfattning av miljömålsrådets utvärdering*. 2008, Miljömålsrådet.

50. Andersson-Sköld, Y., P. Suer and H. Helgesson, *Preliminary title: Holistic sustainable decisions on the agenda - a tool structure.* Manuscript, 2009.

APPENDIX 1: DETAILED INVENTORY FOR KARLSTAD OIL DEPOT

Sachbilanzen

Umweltbilanz von Altlastensanierungsverfahren
V1.0 Rev.16 / Datenversion 1.03

Projekt: Rejuvenate

Nah-und Fernbereich

Sachbilanzposition		Einheit	phytoremediation Wert	dig and dump Wert	natural attenuation Wert
Energie	E erneuerbar	TJ	5,01E-04	7,66E-02	7,97E-05
Energie	E nuklear	TJ	2,68E-03	3,87E-01	4,44E-04
Energie	E fossil	TJ	5,09E-02	3,07E+00	8,24E-03
Energie	E gesamt	TJ	5,41E-02	3,53E+00	8,76E-03
Abfall	Inertabfall	kg	4,93E+02	5,48E+04	5,77E+01
Abfall	Hausmüllähnlicher Abfall	kg	1,02E+00	1,43E+02	1,82E-01
Abfall	Abfall zur Verwertung vom Standort	kg	0,00E+00	0,00E+00	0,00E+00
Abfall	Abfall zur Beseitung vom Standort	kg	0,00E+00	1,18E+07	0,00E+00
Abfall	Sonderabfall	kg	8,53E+01	1,18E+07	1,33E+01
Abfall	Abfall gesamt	kg	5,79E+02	1,19E+07	7,12E+01
Transport	LKW Massentransport Straße	tkm	3,19E+02	6,26E+05	7,58E+01
Transport	Zug Massentransport Schiene	tkm	3,38E+02	2,47E+04	5,44E+01
Transport	Schiff Massentransport Binnenschiff	tkm	2,47E+02	1,38E+04	3,85E+01
Transport	PKW Personentransport Straße	km	9,93E+03	4,31E+04	1,00E+03
Ressourcen	Erdöl	kg	9,60E+02	5,28E+04	1,56E+02
Ressourcen	Erdgas	kg	3,51E+01	2,40E+03	4,96E+00
Ressourcen	Rohfördersteinkohle vor Aufbereitung	kg	1,39E+02	1,63E+04	2,18E+01
Ressourcen	Rohbraunkohle vor Förderung	kg	9,13E+01	1,30E+04	1,70E+01
Ressourcen	Erdölgas	kg	4,06E+01	2,23E+03	6,58E+00
Ressourcen	Grubengas (Methan)	kg	1,06E+00	1,13E+02	1,67E-01
Ressourcen	Uran ab Erz	kg	6,23E-03	9,00E-01	1,03E-03
Ressourcen	Holz	kg	3,70E+00	7,99E+02	6,33E-01
Ressourcen	Grundwasser	m³	0,00E+00	0,00E+00	0,00E+00
Ressourcen	Wasser	m³	2,72E+01	2,58E+03	4,52E+00
Abwasser	Abwasser	m³	0,00E+00	0,00E+00	0,00E+00
Fläche	Flächeninanspruchnahme kultiviert	m² a	1,09E+02	1,42E+05	1,68E+01
Fläche	Flächeninanspruchnahme bebaut	m² a	8,48E+01	5,35E+04	9,94E+00
Fläche	Flächeninanspruchnahme gesamt	m² a	1,93E+02	1,96E+05	2,67E+01
Luft	CO2 Kohlendioxid	kg	3,31E+03	2,19E+05	5,17E+02
Luft	CO Kohlenmonoxid	kg	8,63E+01	8,04E+02	7,08E+00
Luft	CN Cyanide	kg	2,86E-06	1,50E-04	4,11E-07
Luft	NOx Stickoxide	kg	1,72E+01	2,66E+03	4,52E+00
Luft	NH3 Ammoniak	kg	6,46E-03	1,51E-01	2,29E-04
Luft	N2O Distickstoffoxid	kg	9,54E-02	5,28E+00	1,42E-02
Luft	P und Phosphate als P	kg	8,40E-04	3,05E+00	2,56E-04
Luft	SO2 Schwefeldioxid	kg	1,24E+01	4,93E+02	1,63E+00
Luft	H2S Sulfan	kg	2,11E-03	1,21E-01	3,01E-04
Luft	HF Fluorwasserstoff	kg	6,71E-03	4,92E-01	9,95E-04
Luft	HCl Chlorwasserstoff	kg	1,23E-01	2,96E+02	3,17E-02
Luft	Brom	kg	3,83E-03	1,51E+01	1,22E-03
Luft	I Iod	kg	2,25E-04	5,12E-01	5,72E-05
Luft	CH4 Methan	kg	5,42E+00	4,30E+02	8,52E-01
Luft	Alkane	kg	2,19E+00	2,15E+01	2,41E-01
Luft	Alkene	kg	2,36E-01	8,14E-01	2,45E-02

Sachbilanzposition		Einheit	phytoremediation Wert	dig and dump Wert	natural attenuation Wert
Luft	Alkanole	kg	8,38E-04	9,09E-02	1,28E-04
Luft	Alkanal (Methanal)	kg	3,26E-03	3,44E-01	4,20E-04
Luft	Alkansäuren	kg	9,30E-04	1,04E-01	1,45E-04
Luft	C6H6 Benzol	kg	6,59E-01	9,03E-01	6,76E-02
Luft	BTX Aromaten	kg	6,76E-02	2,29E+00	8,20E-03
Luft	C20H12 Benzo[def]chrysen Benzo(a)pyren	kg	3,41E-05	3,26E-04	3,70E-06
Luft	PAK Polycyclische aromatische Kohlenst-offe	kg	1,80E-05	1,95E-03	2,90E-06
Luft	Aromaten	kg	2,27E-02	2,31E-02	2,29E-03
Luft	C6H6O Phenol	kg	1,29E-06	1,11E-04	2,01E-07
Luft	NMVOC Nichtmethankohlenstoffe	kg	2,03E+01	9,51E+02	2,32E+00
Luft	C2ClH3 Chlorethen (Vinylchlorid)	kg	3,40E-05	3,08E-03	6,14E-06
Luft	PCDD/F chlorierte Dibenzodioxine und -furane	kg	1,39E-11	1,74E-09	2,28E-12
Luft	Cancerogene Chlororganika ((CClH2)2)	kg	5,96E-05	5,40E-03	1,07E-05
Luft	Chlororganika []	kg	0,00E+00	0,00E+00	0,00E+00
Luft	CF4 Tetrafluormethan	kg	4,72E-03	1,81E-01	5,06E-04
Luft	C2F6 Hexafluorethan	kg	5,89E-04	2,27E-02	6,33E-05
Luft	BrCF3 Bromtrifluormethan 1301	kg	2,29E-04	1,26E-02	3,72E-05
Luft	Organika (Aldehyde, Ketone, Alkine, Ether)	kg	6,25E-02	8,91E-02	6,33E-03
Luft	Ruß, Dieselruß	kg	4,04E-01	3,83E+01	9,33E-02
Luft	Partikel	kg	6,11E+00	3,12E+03	8,39E-01
Luft	As Arsen	kg	2,71E-04	8,85E-03	3,04E-05
Luft	Be Beryllium	kg	8,23E-07	9,38E-05	1,22E-07
Luft	Cd Cadmium	kg	1,62E-04	6,55E-03	2,04E-05
Luft	Cr Chrom	kg	1,91E-04	1,40E-02	2,73E-05
Luft	Cu Kupfer	kg	2,21E-03	1,90E-01	2,71E-04
Luft	Hg Quecksilber	kg	2,18E-05	2,43E-03	3,11E-06
Luft	Pb Blei	kg	8,17E-02	1,47E-01	8,28E-03
Luft	U Uran	kg	1,89E-06	2,53E-04	2,90E-07
Luft	Zn Zink	kg	1,08E-01	4,08E+00	1,12E-02
Luft	Radioaktive Strahlung	kBq	5,42E+05	7,83E+07	8,98E+04
Wasser	Mineralöl (Alkane)	kg	6,24E-03	3,44E-01	1,01E-03
Wasser	C6H6 Benzol	kg	6,34E-03	3,48E-01	1,03E-03
Wasser	BTX Aromaten	kg	1,14E-02	6,27E-01	1,85E-03
Wasser	PAK Polycyclische aromatische Kohlenst-offe	kg	6,27E-04	3,45E-02	1,02E-04
Wasser	Aromatische Kohlenstoffe	kg	2,89E-02	1,59E+00	4,69E-03
Wasser	Phenole	kg	7,10E-03	3,84E-01	1,15E-03
Wasser	Cancerogene Chlororganika ((CClH2)2)	kg	2,98E-05	2,70E-03	5,38E-06
Wasser	Chlororganika (CCl2H2, C2Cl3H, C6ClH5,	kg	1,19E-04	5,59E-03	1,71E-05
Wasser	AOX Adsorbierbare Halogenorganika	kg	1,79E-04	9,95E-03	2,92E-05
Wasser	BSB5 Biologischer Sauerstoffbedarf	kg	6,39E-03	3,12E-01	9,06E-04
Wasser	COD Chemischer Sauerstoffbedarf	kg	3,77E-01	1,75E+01	4,83E-02
Wasser	Tributylzinn	kg	7,73E-05	4,58E-03	1,23E-05
Wasser	Organika (Fette, Säuren, Alkene, Ether, KWS,	kg	1,15E+00	6,33E+01	1,87E-01
Wasser	Al Aluminium	kg	2,24E-01	2,63E+01	3,54E-02
Wasser	As Arsen	kg	4,88E-04	5,47E-02	7,69E-05
Wasser	Cd Cadmium	kg	6,83E-05	4,52E-03	1,10E-05
Wasser	Cr(VI) Chrom(VI)	kg	4,59E-07	4,47E-05	6,56E-08
Wasser	Cr Chrom	kg	2,92E-03	2,97E-01	4,56E-04
Wasser	Cu Kupfer	kg	1,24E-03	1,38E-01	1,96E-04
Wasser	Hg Quecksilber	kg	7,72E-07	6,39E-05	1,49E-07
Wasser	Ni Nickel	kg	1,37E-03	1,45E-01	2,15E-04
Wasser	Pb Blei	kg	2,86E-03	2,33E-01	4,34E-04

Sachbilanzposition		Einheit	phytoremediation Wert	dig and dump Wert	natural attenuation Wert
Wasser	Se Selen	kg	1,16E-03	1,34E-01	1,83E-04
Wasser	Sn Zinn	kg	1,55E-06	2,19E-04	2,97E-07
Wasser	Zn Zink	kg	3,56E-03	3,31E-01	5,52E-04
Wasser	Säuren als H+	kg	4,10E-04	2,14E-02	5,88E-05
Wasser	NH3 Ammoniak als N	kg	7,95E-02	4,35E+00	1,28E-02
Wasser	NO3- Nitrat	kg	3,28E-02	2,06E+00	5,41E-03
Wasser	F- Fluoride	kg	6,93E-03	3,76E-01	1,01E-03
Wasser	CN- Cyanide	kg	6,42E-04	3,30E-02	9,57E-05
Wasser	Rakioaktive Strahlung	kBq	5,01E+03	7,21E+05	8,30E+02
Boden	Mineralöl	kg	2,30E-03	1,39E-01	3,73E-04
Schall	Schallemissionsdauer 80 dB(A)	h	0,00E+00	0,00E+00	0,00E+00
Schall	Schallemissionsdauer 108 dB(A)	h	3,24E+00	5,90E+02	3,24E+00
Schall	Schallemissionsdauer 114 dB(A)	h	0,00E+00	0,00E+00	0,00E+00

den 16 december 2008

APPENDIX 2: DETAILED INVENTORY FOR FAGERVIK

Sachbilanzen

Umweltbilanz von Altlastensanierungsverfahren
V1.0 Rev.16 / Datenversion 1.03

Projekt: Rejuvenate

Nah-und Fernbereich

Sachbilanzposition		Einheit	Biofuel - Salix Vinimalis Wert	On site ensuring Wert
Energie	E erneuerbar	TJ	1,58E-02	4,06E-01
Energie	E nuklear	TJ	8,87E-02	2,06E+00
Energie	E fossil	TJ	1,27E+00	1,65E+01
Energie	E gesamt	TJ	1,38E+00	1,90E+01
Abfall	Inertabfall	kg	6,54E+03	2,95E+05
Abfall	Hausmüllähnlicher Abfall	kg	2,01E+01	7,61E+02
Abfall	Abfall zur Verwertung vom Standort	kg	0,00E+00	0,00E+00
Abfall	Abfall zur Beseitung vom Standort	kg	0,00E+00	0,00E+00
Abfall	Sonderabfall	kg	2,04E+03	3,94E+04
Abfall	Abfall gesamt	kg	8,60E+03	3,35E+05
Transport	LKW Massentransport Straße	tkm	4,95E+04	3,41E+06
Transport	Zug Massentransport Schiene	tkm	9,75E+03	1,18E+05
Transport	Schiff Massentransport Binnenschiff	tkm	5,79E+03	7,66E+04
Transport	PKW Personentransport Straße	km	5,52E+03	2,11E+05
Ressourcen	Erdöl	kg	2,09E+04	2,91E+05
Ressourcen	Erdgas	kg	3,96E+03	1,26E+04
Ressourcen	Rohfördersteinkohle vor Aufbereitung	kg	3,55E+03	7,13E+04
Ressourcen	Rohbraunkohle vor Förderung	kg	3,01E+03	6,93E+04
Ressourcen	Erdölgas	kg	8,85E+02	1,23E+04
Ressourcen	Grubengas (Methan)	kg	2,65E+01	5,24E+02
Ressourcen	Uran ab Erz	kg	2,06E-01	4,79E+00
Ressourcen	Holz	kg	1,13E+02	4,18E+03
Ressourcen	Grundwasser	m³	0,00E+00	0,00E+00
Ressourcen	Wasser	m³	8,40E+02	1,37E+04
Abwasser	Abwasser	m³	0,00E+00	0,00E+00
Fläche	Flächeninanspruchnahme kultiviert	m² a	2,50E+03	1,05E+06
Fläche	Flächeninanspruchnahme bebaut	m² a	1,04E+03	3,53E+05
Fläche	Flächeninanspruchnahme gesamt	m² a	3,53E+03	1,41E+06
Luft	CO2 Kohlendioxid	kg	8,22E+04	1,10E+06
Luft	CO Kohlenmonoxid	kg	3,92E+02	4,37E+03
Luft	CN Cyanide	kg	5,41E-05	8,23E-04
Luft	NOx Stickoxide	kg	1,19E+03	1,47E+04
Luft	NH3 Ammoniak	kg	8,47E+00	7,91E-01
Luft	N2O Distickstoffoxid	kg	2,00E+00	2,90E+01
Luft	P und Phosphate als P	kg	2,26E-01	1,67E+01
Luft	SO2 Schwefeldioxid	kg	1,64E+02	2,57E+03
Luft	H2S Sulfan	kg	1,03E-01	6,52E-01
Luft	HF Fluorwasserstoff	kg	1,54E-01	2,58E+00
Luft	HCl Chlorwasserstoff	kg	2,29E+01	1,62E+03
Luft	Brom	kg	1,12E+00	8,26E+01
Luft	I Iod	kg	4,04E-02	2,79E+00
Luft	CH4 Methan	kg	1,41E+02	2,26E+03
Luft	Alkane	kg	8,77E+00	1,13E+02
Luft	Alkene	kg	3,04E-01	3,90E+00
Luft	Alkanole	kg	2,53E-02	4,85E-01
Luft	Alkanal (Methanal)	kg	5,85E-02	1,85E+00
Luft	Alkansäuren	kg	3,34E-02	5,55E-01
Luft	C6H6 Benzol	kg	3,86E-01	3,36E+00
Luft	BTX Aromaten	kg	5,83E-01	1,23E+01
Luft	C20H12 Benzo[def]chrysen Benzo(a)pyren	kg	1,22E-04	1,60E-03
Luft	PAK Polycyclische aromatische Kohlenstoffe	kg	7,87E-04	1,04E-02
Luft	Aromaten	kg	8,50E-03	7,02E-02
Luft	C6H6O Phenol	kg	3,21E-05	5,83E-04
Luft	NMVOC Nichtmethankohlenstoffe	kg	4,19E+02	5,30E+03
Luft	C2ClH3 Chlorethen (Vinylchlorid)	kg	6,66E-04	1,64E-02
Luft	PCDD/F chlorierte Dibenzodioxine und -furane	kg	4,02E-10	9,28E-09
Luft	Cancerogene Chlororganika ((CClH2)2)	kg	1,16E-03	2,86E-02
Luft	Chlororganika []	kg	0,00E+00	0,00E+00
Luft	CF4 Tetrafluormethan	kg	2,18E-02	9,75E-01
Luft	C2F6 Hexafluorethan	kg	2,73E-03	1,22E-01
Luft	BrCF3 Bromtrifluormethan 1301	kg	5,00E-03	6,96E-02
Luft	Organika (Aldehyde, Ketone, Alkine, Ether)	kg	3,18E-02	3,27E-01
Luft	Ruß, Dieselruß	kg	2,19E+01	2,09E+02

Sachbilanzen

Umweltbilanz von Altlastensanierungsverfahren
V1.0 Rev.16 / Datenversion 1.03

Projekt: Rejuvenate

Nah-und Fernbereich

Sachbilanzposition		Einheit	Biofuel - Salix Vinimalis Wert	On site ensuring Wert
Luft	Partikel	kg	1,11E+02	2,70E+03
Luft	As Arsen	kg	1,50E-03	4,56E-02
Luft	Be Beryllium	kg	2,42E-05	4,98E-04
Luft	Cd Cadmium	kg	1,30E-03	2,57E-02
Luft	Cr Chrom	kg	3,55E-03	6,29E-02
Luft	Cu Kupfer	kg	2,91E-02	1,01E+00
Luft	Hg Quecksilber	kg	4,10E-04	8,33E-03
Luft	Pb Blei	kg	4,29E-02	5,75E-01
Luft	U Uran	kg	6,08E-05	1,34E-03
Luft	Zn Zink	kg	3,60E-01	2,19E+01
Luft	Radioaktive Strahlung	kBq	1,79E+07	4,17E+08
Wasser	Mineralöl (Alkane)	kg	1,37E-01	1,89E+00
Wasser	C6H6 Benzol	kg	1,39E-01	1,92E+00
Wasser	BTX Aromaten	kg	2,49E-01	3,46E+00
Wasser	PAK Polycyclische aromatische Kohlenstoffe	kg	1,37E-02	1,90E-01
Wasser	Aromatische Kohlenstoffe	kg	6,37E-01	8,78E+00
Wasser	Phenole	kg	1,52E-01	2,12E+00
Wasser	Cancerogene Chlororganika ((CClH2)2)	kg	5,83E-04	1,43E-02
Wasser	Chlororganika (CCl2H2, C2Cl3H, C6ClH5,	kg	1,71E-03	3,02E-02
Wasser	AOX Adsorbierbare Halogenorganika	kg	4,06E-03	5,50E-02
Wasser	BSB5 Biologischer Sauerstoffbedarf	kg	1,18E-01	1,71E+00
Wasser	COD Chemischer Sauerstoffbedarf	kg	4,51E+00	9,63E+01
Wasser	Tributylzinn	kg	1,65E-03	2,40E-02
Wasser	Organika (Fette, Säuren, Alkene, Ether, KWS,	kg	2,53E+01	3,49E+02
Wasser	Al Aluminium	kg	5,74E+00	1,15E+02
Wasser	As Arsen	kg	1,24E-02	2,43E-01
Wasser	Cd Cadmium	kg	1,56E-03	2,34E-02
Wasser	Cr(VI) Chrom(VI)	kg	1,09E-05	2,37E-04
Wasser	Cr Chrom	kg	7,12E-02	1,34E+00
Wasser	Cu Kupfer	kg	3,15E-02	6,10E-01
Wasser	Hg Quecksilber	kg	3,79E-05	3,40E-04
Wasser	Ni Nickel	kg	3,40E-02	6,50E-01
Wasser	Pb Blei	kg	1,12E-01	1,13E+00
Wasser	Se Selen	kg	2,96E-02	5,89E-01
Wasser	Sn Zinn	kg	5,06E-05	1,16E-03
Wasser	Zn Zink	kg	8,42E-02	1,53E+00
Wasser	Säuren als H+	kg	7,73E-03	1,18E-01
Wasser	NH3 Ammoniak als N	kg	1,79E+00	2,41E+01
Wasser	NO3- Nitrat	kg	7,67E-01	1,13E+01
Wasser	F- Fluoride	kg	1,36E-01	2,04E+00
Wasser	CN- Cyanide	kg	1,28E-02	1,82E-01
Wasser	Rakioaktive Strahlung	kBq	1,66E+05	3,84E+06
Boden	Mineralöl	kg	5,08E-02	7,63E-01
Schall	Schallemissionsdauer 80 dB(A)	h	0,00E+00	0,00E+00
Schall	Schallemissionsdauer 108 dB(A)	h	6,20E+02	1,86E+03
Schall	Schallemissionsdauer 114 dB(A)	h	0,00E+00	0,00E+00

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