Review Articles

Aspects of Phytoremediation of Organic Pollutants

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Preamble

Biological methods for soil cleaning receive increasing attention. Not only bacteria and fungi, but also plants, possess mechanisms of detoxifying contaminants. However, biological methods are not yet used in all possible cases.

Our interest focuses on the interaction of industrial compounds with organisms in soil. Are plants and associated microorganisms able to 'consume' compounds that are toxic for us humans or are they targeted themselves? Bacteria, plants and fungi do not have a nervous system, no blood circulation, and a completely different hormonal system, if any. The metabolic pathways are quite adaptable, and are known to mineralise recalcitrant compounds in some cases.

Currently, an 'explosion' of knowledge about environmental biotechnology, including phytoremediation, is taking place. Many projects directly target field applications. Therefore, the scientific investigations are not only a chance to increase the existing knowledge about plants and pollutants, but are also of economic interest. Phytoremediation requires a detailed knowledge about plant physiology, acceptable doses, and about transport and metabolism inside plants and in the root zone.

If successful, the method will have economical and ecological advantages. So, why is phytoremediation rarely used in Europe? A major reason might be that there is insufficient experience, hence great uncertainty about this new technique. This article intends to give an overview of current developments, and an insight into methods and applications.

Abstract. Phytoremediation is a quite novel technique to clean polluted soils using plants. In theory, phytoremediation methods are cheap, are accepted by the public and, compared to physical or chemical approaches, are ecologically advantageous. Until today, however, there are only a few examples of successful applications. One reason is that the processes involved are complex, and a full clean up may require many years. Plants affect the water balance of a site, they change redox potential and pH, and stimulate microbial activity of the soil. These indirect influences may accelerate degradation in the root zone or reduce leaching of compounds to groundwater. Compounds taken up into plants may be metabolised, accumulated, or volatilised into air. Based on these processes, several phytoremediation methods have been developed: Phytoextraction, rhizofiltration, phytostabilisation, rhizo and phytodegradation, pump and tree, land farming, phytovolatilisation, hydraulic control and more. Already in use are plants (and here willow, poplar and grass) for the degradation of petroleum products, aromatic hydrocarbons (BTEX), chlorinated solvents, explosives and cyanides. However, phytotoxicity and pollutant mass balances were rarely documented. Often, the success of the projects was not controlled, and only estimates can be made about the applicability and the potential of phytoremediation. This lack of experience about possibilities and limitations seems to be a hindrance for a broader use of these techniques.

Keywords: Benzene; cyanide; metabolism; petroleum; phytoremediation; plants; pollutants; review articles; Saliceae; soil, contamination; trichloroethylene

Introduction

Phytoremediation is a technique for remediating polluted soils through the use of plants. Pollutants can be both inorganic and organic chemicals. In several European countries, biological clean-up techniques are finding interest and are supported by governments and research organizations. Phytoremediation has several benefits: It is inexpensive, it seems to be effective, it is in situ, and it is 'green' (Flathman and Lanza 1998, Schnoor et al. 1995). A special advantage of phytoremediation compared to other techniques is that soil functioning is maintained and life in soil is reactivated.

Worldwide, trees, grasses, herbs, and associated fungi and microorganisms are being used increasingly for cleaning polluted sites. In Denmark, phytoremediation projects on sites polluted with oil, PAH, BTEX and cyanides have recently been started. After "more than one decade and a half of research scrutiny", phytoremediation is "on the brink of commercialization" (Watanabe 1997), and is given a rapidly increasing market potential (Flathman and Lanza 1998). In the US, it was expected to increase from between 16.5 and 29.5 million $ in 1998 to between 214 and 370 million $ in 2005 (Watanabe 1997).

Phytoremediation has a good image and is often, but not always, more cost-effective than competing techniques. Up to now, only few scientifically sound studies have been undertaken at field scale. Although there is a commercial demand, "sufficient data do not yet exist to support its commercialization" (Watanabe 1997). This may explain why this new technique only slowly expands on the market. Another reason is that successful phytoremediation takes time, sometimes more than one decade, which makes it difficult to evaluate success in an early state. Therefore, methods are needed to evaluate the probable success via lab experiments, with simulation models and by decision support systems.

1 Relevant Processes in Phytoremediation

Plants contribute to removing or stabilizing soil pollutants by a number of processes. Aside from the uptake of com-

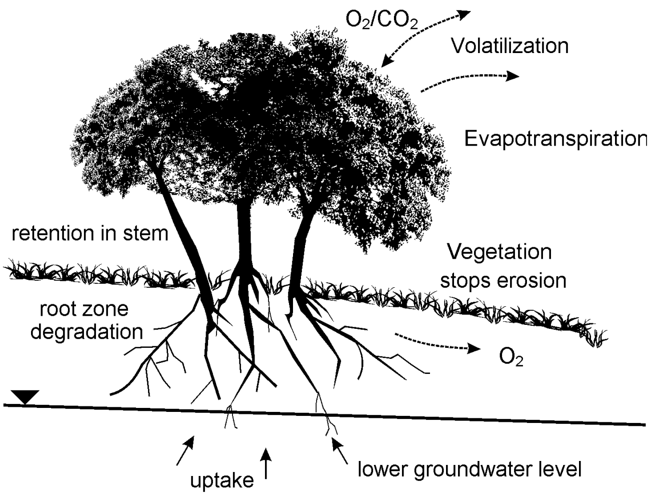

Fig. 1: Relevant processes during phytoremediation; adapted from Black (1999)

pounds with subsequent metabolism, plants frequently participate indirectly by changing the soil conditions so that soil microorganisms can degrade pollutants (Siciliano and Germida 1998). Phytoremediation is carried out by the 'team' of higher plants, bacteria and fungi, and depends on several biological, physical and chemical processes (**Fig. 1**).

1.1 Water balance

Evapotranspiration (the sum of water vaporisation from surfaces and transpiration by vegetation) is the most relevant loss process for soil water. Evapotranspiration accounts for about 2/3 of the water balance in a deciduous tree forest of the Temperate Zone, and about the same for a conifer forest (Larcher 1995). Evapotranspiration in willow stands grown in southern Sweden was between 365 and 495 mm water per year, i.e. between 60% and 85% of the mean annual precipitation (Perrson 1995). Increased transpiration means reduced infiltration of water into the subsoil and reduced transport of compounds to the groundwater. In St. Arnold, western Germany, the precipitation from 1990 to 1998 was 834 mm/a on the average. The infiltration below grass was 404 mm/a; below 8 to 11 m tall oak trees, 208 mm/a; and below 12 to 15 m high Scotch pines 134 mm/a (Klein 2000). Plants, therefore, can be considered as a solar-energy driven water pump. Furthermore, vegetation reduces erosion and stabilizes soil.

1.2 Influence of plants on soil conditions

The vicinity of plant roots is the preferred environment for soil microorganisms. Approx. 1.2 x 10^{11} cells per cm^3 live within a distance of <1 mm to the roots, whereas only 1.3 x 10^{10} at a distance of 2 cm (Paul and Clark 1989). About 5 to 10% of the root surface are covered with bacteria. Roots live in symbiosis with fungal mycorrhiza. Their mycelium is again covered with bacteria (Romantschuk et al. 2000). Growing roots may transport inoculated bacteria through soil (Karlson et al. 1995). Besides forming a habitat for microorganisms, plant roots also provide nutrients, e.g., sugars, in exchange for phosphate (fungi) or nitrogen (N_2-fixation). Mulberries *Morus rubra* L. growing at PCB-polluted sites, excrete considerable amounts of phenolic compounds, which probably support the growth of PCB-degrading bacteria (Fletcher and Hedge 1995). Roots can also exude organic compounds, which might mobilize soil-born pollutants, e.g. saponines, proteins, and enzymes. Spectacular was the finding that root and xylem exudates of zucchini (*Cucurbitaceae*) solubilize PCDD/F (Hülster et al. 1994), probably by a protein (Hülster and Marschner 1995; Neumann et al. 1996). However, plants hyperaccumulating lipophilic compounds have not yet been detected, although they might be very valuable for phytoremediation.

Physicochemical parameters of soil are also influenced by vegetation. Evapotranspiration of water means less water-filled pores, more gas-filled pores and a much faster flux of gases through soil (oxygen diffusion in gas-filled pores is about 300 000 times faster than in water filled pores). Additionally, some wetland plants, among them the basket willow *Salix viminalis*, possess a ventilation system for roots (Grosse et al. 1992, 1996). For *Phragmites*, oxygen fluxes of up to 8 g m^{-2} d^{-1} have been determined (Brix et al. 1996). For basket willow, fluxes are around 0.5 g m^{-2} d^{-1} (own calculation) and therefore only relevant in water-saturated soils.

In addition to redox potential, all soil organisms influence the pH by respiration (CO_2), the membrane-located proton pump, and eventually by excretion of organic acids (Larcher 1995). In buffered ISO 8692 nutrient solutions, willows can lower the pH from 7.5 to 6.7 within a few hours (own observation). Schnoor et al. (1995) observed that Hornwort increased the pH from 3 to 7.

1.3 Root zone degradation

The described processes may explain the high metabolic activity of the root zone. There are some examples that the interaction with bacteria allows plants to survive in highly polluted soils.

Four years after the Gulf war and the oil spill in Kuwait, wild flowers (mainly Compositae, e.g. *Senecio glaucus*) were growing in sand polluted with up to 10% petroleum. Roots of these plants were associated with millions of oil-degrading bacteria (*Arthrobacter*), which took up and detoxified alkanes and aromatic hydrocarbons. The roots were practically free from oil (Radwan et al. 1995).

Galega orientalis is a nitrogen-fixing legume. When inoculated with the bacterial symbiont *Rhizobium galageae* and toluene-degrading *Pseudomonas* bacteria, *Galega* plants could withstand up to ten-fold higher toluate concentrations than non-inoculated plants (Suominen et al. 2000).

The number of BTEX-degrading bacteria was significantly higher in the rhizosphere of hybrid poplars than in neighbouring agricultural soils. Atrazine-degrading species were found only in the poplar rhizosphere. It was concluded that poplars stimulate microbial communities capable of degrading organic pollutants (Jordahl et al. 1997).

Trichoroethylene, TCE, can be degraded bacterially by cometabolic oxidation. Nonetheless, it is rather persistent in the environment. Under anaerobic conditions, reductive dehalogenation is accompanied by the formation of the carcinogenic metabolite vinyl chloride. TCE degradation has been shown for several plant species, among them poplars (Newman et al. 1997). In laboratory experiments with 35 cm tall poplar cuttings, fast uptake was observed, but the main fate process was volatilization from leaves (Burken and Schnoor 1998). However, in field-scale experiments with three-year old poplars of 6 m height, the main fraction of TCE was mineralized in the root zone. Up to 99% of TCE added with artificially contaminated groundwater were removed, and less than 9% escaped to the atmosphere (Newman et al. 1999).

The average rooting depth of trees is 1-2 m, which is much less than usually expected, and almost 90% of tree roots are found in <0.6m depth. Poor aeration will lead to a smaller root density. Poplars root to a depth between 0.8 and 2.43 m (Dobson and Moffat 1995). Although willows survive permanent flooding and water saturated soils, the roots will not grow deep into the groundwater (Larcher 1995). However, there are techniques to force the trees to go deeper, e.g. coverage of the soil (which leads to drought in the upper soil layer), or wrapping of cuttings with plastic tape before planting (Lars C. Larsen, Hedeselskabet, personal communication).

1.4 Uptake into plants

Plants are known to take up many pollutants, in particular weak electrolytes and compounds with intermediate lipophilicity (Briggs et al. 1982, Briggs et al. 1987, Trapp 2000). Very polar compounds have difficulties crossing biomembranes, and therefore are subject to limited uptake. Very lipophilic compounds quickly cross biomembranes, but then sorb to the roots. Therefore, compounds with intermediate lipophilicity are best translocated to upper plant parts, which explains the bell-shaped relation between log K_{OW} and the transpiration stream concentration factor (TSCF, concentration ratio between xylem solution and external solution) (Briggs et al. 1982, Burken and Schnoor 1998, Trapp 2000). Sorption to soil matrix limits the bioavailability of lipophilic compounds, hence generally compounds with a log K_{OW} between 0.5 and 3 are taken up best. Many pollutants are dissociating, e.g. phenols, amines, benzoates, tributyl tin, some detergents and most herbicides. Metabolites of neutral parent compounds are frequently weak electrolytes, e.g. when hydroxy, acid or amino-groups were formed. Uptake of weak electrolytes depends on the pKa, log K_{OW} and valency of the molecule, on the soil pH, on the pH in cytoplasma (7 to 7.5), vacuole and xylem (5.5), and on the electrical potential of the cell membrane (-80 to -120 mV) (Trapp 2000). Best uptake is shown by weak acids from acidic soils and weak bases from basic soils. The accumulation is due to the so-called 'ion trap': neutral molecules quickly pass the biomembrane, dissociate inside the cell and only slowly diffuse back. Anions rarely sorb to the soil matrix and therefore accumulate best. Cations (positively charged) may strongly sorb to clay (negatively charged), which limits uptake.

The uptake of three non-dissociating compounds by barley on sandy soil, and by wheat on loamy soil, was simulated (Matthies and Behrendt 1995). The result for carbofuran, a systemic insecticide with a log K_{OW} of 1.82, was 20% uptake into barley within one vegetation period. Uptake from loamy soil into wheat was >10%. Only 3% of terbuthylazin, a herbicide with a log K_{OW} of 3.06, were taken up from both soils. Almost complete uptake from soil would require decades in the latter example.

However, most model calculations only consider uptake with water and neglect the fact that fast metabolism inside cells, e.g. in root cells, establishes a permanent concentration gradient. This concentration gradient may lead to diffusive uptake, which is fast for compounds that can move in the soil gas phase, i.e. which have a high partition coefficient between gas phase and soil matrix (Trapp 1995).

1.5 Metabolism inside plants

Compared to other life forms, plants have the largest genomes, with some species exceeding 10^{11} base pairs (bacteria $<10^{8}$) (Voet et al. 1998). This corresponds to the very complex secondary metabolism of plants. More than 80000 secondary metabolites are known today, with many more to be identified (Richter 1998). Basically, plant metabolism resembles more the reactions in the animal liver than the bacterial metabolism (Sandermann 1994). For the detoxification of xenobiotics, such as herbicides, cytochrome P-450 monooxygenases and glutathione-S-transferases (GST) seem to be the most important enzyme types (Pflugmacher and Schröder 1995, Barret 1995). P-450 enzymes catalyse phase I transformation reactions, frequently hydroxylation, but also sulfoxidation, and *N*-and *O*-dealkylation. GST are responsible for phase II conjugation reactions, which play a central role in the detoxification of herbicides in plants. Unlike animals, plants cannot excrete conjugates formed via urine. Instead, phase III of plant xenobiotic metabolism involves storage and compartmentation of soluble conjugates in the vacuole and of insoluble conjugates in the cell wall (Komossa et al. 1995). This may lead to so-called 'bound residues'.

Transformation of xenobiotics may occur outside the plant in the rhizosphere, inside the plant and sorbed to the leaf surface (photolysis). Often, the differentiation between metabolism by fungi or bacteria living on and in plants and metabolism by plant cells is not possible. However, some reactions are more common in eukaryotes or higher plants than in bacteria. Examples relevant for phytoremediation are the oxidation of chlorinated solvents (trichloroethylene, Newman et al. 1997) and the conversion of cyanide to the amino-acid asparagine, which occurs in vascular plants (Trapp et al. 2001a, b).

1.6 Phytotoxicity

Uptake of compounds into plants may lead to phytotoxic effects, causing phytoremediation to fail. Plants may tolerate higher pollutant concentrations than soil microbiota, which means that they can still be used for bioremediation purposes when non-degrader bacteria cannot survive anymore (Schnoor et al. 1995). This also means that in these cases the microbial component of phytoremediation relies solely on adapted (specialized degrader) microbiota. Most phytotoxicity data were

Table 1: EC_{50} (50% reduced transpiration) measured for tree cuttings; if not stated otherwise, uptake from solution

Compound	Species	EC_{50} (mg/l)	Period (d)	Reference
trichloroethene	hybrid poplar	131	14	Dietz and Schnoor 1995
perchloroethylene	hybrid poplar	38	14	Dietz and Schnoor 1995
diesel oil	basket willow hybrid	3910 mg/kg (soil)	12	Trapp et al. 2001
free cyanide (HCN)	basket willow	4.47	3	Trapp et al. 2001a
ferro ferricyanide (Prussian blue)	balsam poplar	>1000	19	Trapp et al. 2001a
MTBE	basket willow	approx. 1000	3	Trapp, Zhang and Miglioranza, non-published
TNT	hybrid poplar	<5	20	Thompson et al. 1998
3,5-dichlorophenol	basket willow hybrid	5.9-7.8	3	Trapp et al. 2000

measured with standard algae tests. These data are not representative for vascular plants, which grow in soil and have a more complex organism (Fletcher 1990). Recently, toxicity tests with poplar or willow cuttings have been developed to measure acute phytotoxicity on trees (Thompson et al. 1998, Trapp et al. 2000). Toxic endpoints are transpiration, growth and water use efficiency. A reduction in transpiration of 50% (EC_{50}) seems to occur at a similar level where growth is zero (Dietz and Schnoor 2001). Measured EC_{50}, mainly for uptake from solution, indicates a high tolerance of trees for organic compounds (**Table 1**). Tolerable levels in soil should generally be higher, due to reduced bioavailability.

2 Techniques Used

In summary, phytoremediation may be successful by an influence of the vegetation on the physical (water balance, transport processes), the chemical (enzymes, redox potential, pH, complexing agents) and the biological (roots, microbes, mycorrhiza) factors in soil. Based on these processes, several phytoremediation techniques have been developed (EPA 2000, Flathman and Lanza 1998): Phytoextraction, rhizofiltration, phytostabilization, rhizodegradation, phytodegradation, phytovolatilization, hydraulic control, vegetation cover and buffer stripes.

Phytoextraction

Phytoextraction signifies the uptake, translocation and accumulation of pollutants in plants. Harvest products, which concentrate the pollutants, may be used or disposed of. The technique is preferably used for heavy metals.

Rhizofiltration

Rhizofiltration is the sorption of contaminants to roots or other plant parts, or the precipitation in the root zone. E.g. heavy metals or lipophilic compounds can be extracted from water by this technique.

Phytostabilization

Phytostabilization is the immobilization of compounds in soil, or the stabilizing of soil itself to prevent erosion. In the first case, pollutants are transferred from a soluble form into a non-soluble form by the redox milieu in the root zone.

Rhizo and phytodegradation

Phytodegradation is the degradation of pollutants by plants. Rhizodegradation is the degradation of contaminants in the root zone, either due to microbial activity or by roots, or by both. In the root zone, several processes accelerate degradation of some compounds (see above). Phyto and rhizodegradation are frequently used for the remediation of organic contaminations, among them petroleum, PAH, BTEX, TNT, chlorinated solvents and pesticides (EPA 2000).

'Pump and Tree'

One of the common remediation techniques for groundwater pollution is 'pump and treat', pumping of water with subsequent technical cleaning (stripping, adsorption, bioreactor, etc.). A new idea is to use pumped water during times of negative water balance (summer) for irrigation, e.g. of forests. One ha *Salix* stand can transpire up to 3000 m^3 water in July (Larcher 1995). Forest soils have a high metabolic capacity and might degrade many compounds quickly. At least a part of the pumped water should be treatable by trees. Chemicals to be treated by this method are organic solvents (trichloroethene), MTBE, petroleum products, nutrients and perhaps some others. Some questions are not yet solved, e.g. the optimal dosage (avoiding phytotoxicity). In vegetation growing on a plume contaminated with trichloroethene, the toxic metabolite trichloroacetic acid accumulated in the leaves of oaks and other plants (Doucette et al. 1998). In a field study, heavy rainfall pressed the contaminated water (tetrachlorocarbon CCl_4) below the root zone (cf. Strand, personal communication, boats trip Roskilde Fjord).

Land farming

Another treatment method based on root zone degradation is 'land farming'. The method is, e.g., used for oil-polluted sludge: The sludge is ploughed into topsoil, the field is fertilized and alfalfa or grass (usually rye) is sewed out. In the rooted, aerated and fertilized topsoil, oil is degraded quickly.

Phytovolatilization

In phytovolatilization, plants are used for extraction and subsequent out-gassing of compounds from soil. The process was shown to be relevant for *m*-xylene (Trapp and Christiansen, non-published), chlorobenzene (Baeder-Bederski et al. 1999), trichloroethene (Orchard et al. 2000) and other volatile compounds (Burken and Schnoor 1998), but also for organically bound mercury (EPA 2000). The technique is relevant for all compounds that are quickly translocated (log K_{OW} <3.5) and have a high vapour pressure or a high Henry's Law constant (dim. less K_{AW} >>10^{-5}). Gassing out only removes the pollution problem from one environmental medium to the other and is therefore seen as an unwanted by-process. However, translocation, and therefore volatilization, occur mainly when the sun is shining – this makes photolysis likely.

Hydraulic control

Very often, water is pumped to prevent leaching or movement of pollutants. Hydraulic control may be done partly or completely by trees or other plants, saving costs. In principle, this method can be applied for all contaminants, as long as the plants have no contact with the toxicants. The harvest products can be used without limitation. The main purpose of this technique is to combine it with mechanical pumping to reduce energy consumption and costs.

Vegetation cover

Waste deposits are frequently planted with grass, simply because it looks better, but also to avoid erosion. Some other aspects are beneficial: The infiltration of water is reduced, small amounts of escaping gas are adsorbed by plants (higher amounts may be toxic, EPA 2000). In only a few cases, planting trees on landfills is accepted by authorities, although trees transpire more and are aesthetically even more pleasing than grasses. But it is feared that roots could go through the coverage and damage it. According to Dobson and Moffat (1995), these fears have no basis.

Buffer stripes

The planting of trees, e.g. poplars, along rivers is surely nothing new. It is also known that these stripes provide barriers for the run-off of nutrients from fields. Recently it was found that poplars can reduce the herbicidal load (atrazine) of creeks (Burken and Schnoor 1996).

Application of genetically modified organisms

The goal of using genetic modifications in phytoremediation is a better degradation of pollutants. At the University of Washington, the human gene that encodes cytochrome P450 IIE1 was introduced into tobacco. Cytochrome P 450 oxidizes several halogenated organic compounds, among them TCE, ethylene bromide, tetrachlorocarbon, chloroform and vinyl chloride. Transgenic tobacco degraded TCE 640 times faster than non-modified plants (Doty et al. 2000).

Genetic modifications are probably not necessary: only a very small part of all plants (about 400000 vascular plants are known today) has been screened for their metabolic ability to degrade pollutants. The secondary metabolism of plants differs from family to family, species to species and even within races (Frohne and Jensen 1985) and possesses a tremendous amount of enzymes. It can be expected that, as soon as more plants are investigated, more applicable species for phytoremediation will be found.

3 Field Projects

The recent US-EPA report (EPA 2000) lists 166 ongoing projects, many of them for research or demonstration. The main pollutants treated are summarized in **Fig. 2**. For petroleum products, phytoremediation seems well established. For many other chemical classes, research is going on.

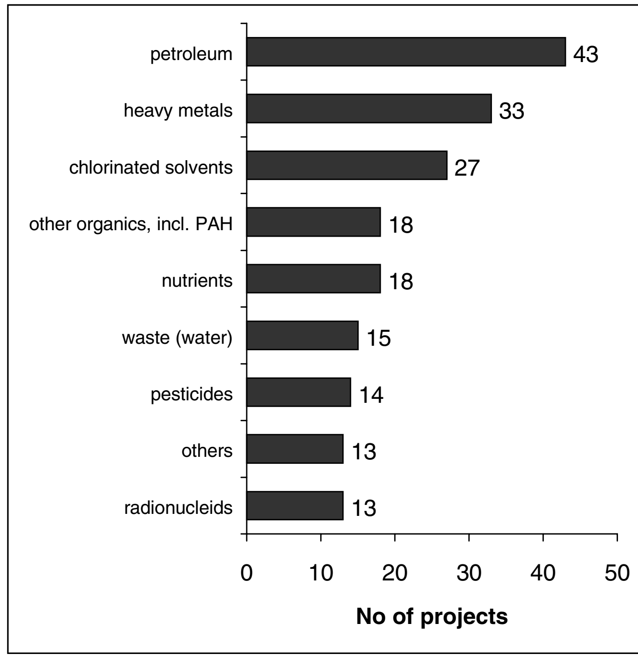

Fig. 2: Projects listed in the recent EPA report (EPA 2000)

In 1999, an in-situ phytoremediation was started at a former gas filling station in Axelved near Rønnede, Denmark. The gas station had operated from 1956 to 1990. The polluted site, in total 1400 m^2, is located in an area with importance for drinking water supply. The soil is polluted with up to 20000 mg/kg gasoline and diesel compounds to a depth of 3 m. The area was fertilized with chicken manure, before 2500 willow (*Salix schwerinii x viminalis*) and 500 poplar (*Populus trichocarpa*) cuttings were planted out in April 1999. The costs of preparing the site and planting the cuttings were below 200 000 DKK (27 000 €). The costs for the next cheapest alternative technique, excavating the soil with subsequent composting, would have been about 1.2 million DKK (160 000 €). The site is used as phytoremediation test site, and some additional costs are due to accompanying scientific investigations. These investigations address the following questions:

- how is the hydrological cycle influenced by planting trees,
- how do plants affect the microbial breakdown of oil and gasoline,
- what final concentration can be obtained by the phytoremediation,
- what are the relevant processes,
- what is the time horizon of a plant-based remediation,
- how can the technology be optimised?

Phytotoxicity was evaluated in Trapp et al. (2001). More results are to be expected in a few years.

The former municipal gas-work site in Holte, Søllerød, Denmark (6000 m^2), is contaminated with high levels of cyanide, mainly in iron-complexed form, but also with BTEX, PAH and oil. Lab and field investigations showed that willow and poplar trees, but also black elderberries grew well in cyanide-polluted soils from the site with up to almost 1000 mg/kg total CN (Trapp et al. 2001a,b) and could metabolise cyanide very rapidly (Trapp et al. 2001b). Willows grew wild on soils contaminated with up to 932 mg/kg complexed CN and 95 mg/kg easy liberatable CN. The roots showed high contents of CN (411 mg/kg complexed and 199 mg/kg easy liberatable CN), but CN contents in leaves did not differ from controls. The area is converted into a public park with about 2500 poplar trees (1000 *Populus trichocarpa x maximoviczii*, 500 *P. canescens* and 1000 *P. robusta*). In order to control leaching into the aquifer, water is pumped from wells and purified through ion-exchange filters when necessary, before entering five ponds, which discharge into a local stream. The whole area is covered with FiberTex®, which again is covered with 10 cm wood chips. The idea is to restrict ingestion of polluted soil and to keep away weed. During and after the remediation, the site (which is situated in the centre of the town) can be used by the public. The total costs (including scientific investigations) were 11.3 million DKK (1.5 million €), which is about half of conventional treatment (Andersen 2000).

4 When is Phytoremediation Successful?

Given the variety of techniques, positive laboratory and pilot project results and economical, ecological and aesthetical advantages, one may ask why phytoremediation is so rarely used. Lou Licht, president of the phytoremediation company Ecolotree in Iowa sees a large untouched market "because many people are ignorant about what phytoremediation can do" (Black 1999).

One reason might be that the technique is new. The time for remediation needs several years or even decades. There cannot be many successful applications, because the majority of projects started in recent years. Also, costs have not been evaluated finally, although some data, compared to conventional treatment, are available (EPA 1998). For metals, the costs of phytoremediation are about 1/3 of those for conventional techniques, for lead <1/20, for petroleum <1/10 (EPA 1998). More than half of the costs of phytoremediation are due to monitoring of soil, groundwater and vegetation. A decision support system for phytoremediation, the 'Phytoremediation Decision Tree' (ITRC 1999) may be of use in considering its applicability. **Table 2** lists some advantages and disadvantages.

In many cases, phytotoxicity, uptake into plant, metabolism and residues need to be measured. This requires laboratory experiments. To come to a fast answer, we use a four-step test. It includes an uptake and a toxicity test for trees (willows or poplars) on polluted soil or solution (Trapp et al. 2000), a ^{14}C-metabolism test, and a model for long-term prognosis of pollutants fate (Trapp et al. 1994, modified).

Table 2: Advantages and disadvantages of phytoremediation (EPA 1998, 2000)

Advantage	Disadvantage
good image, high public acceptance	few practical experience
inexpensive	long-lasting
in situ	only few uses of area possible
maintains soil and stimulates soil life	phyto and ecotoxicity
can be combined with other methods	not applicable for all compounds
solar driven	metabolites eventually problematic

Schnoor and co-workers evaluated applicability of Phytoremediation (Schnoor et al. 1995, Schnoor 1997). They found that the technique is most successful when the topsoil is polluted with chemicals being either degraded in the rhizosphere or effectively taken up by plants. For too high pollutant concentrations, toxic effects may occur, and phytoremediation therefore is restricted to lower to medium contamination levels. Therefore, phytoremediation might be better used in combination with an alternative treatment method for hot spots.

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