

**Annotated Bibliography on Phytoremediation**

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## Phytoremediation Bibliography

Alexander, M. (1999). Biodegradation and bioremediation. San Diego, Academic press.

Anderson, T. A. and J. R. Coats (1994). Bioremediation through rhizosphere technology. Washington, DC, American Chemical Society.

Aniol, A. and J. P. Gustafson (1990). Genetics of tolerance in agronomic plants. Heavy metal tolerance in plants: Evolutionary aspects. A. J. Shaw. Boca Raton, CRC Press: 255-268.

Baker, A. J. M. and R. R. Brooks (1989). "Terrestrial higher plants which hyperaccumulate metal elements - a review of their distribution, ecology and phytochemistry." Biorecovery 1: 81-126.

Baker, A. J. M., S. P. McGrath, et al. (1994). Metal hyperaccumulator plants: A review of the ecology and physiology of a biological resource for phytoremediation of metal-polluted soils. Phytoremediation of contaminated soil and water. N. Terry and G. Bañuelos. Boca Raton, FL, CRC Press: 85-107.

Baker, A. J. M. and P. L. Walker (1990). Ecophysiology of metal uptake by tolerant plants. Heavy metal tolerance in plants: Evolutionary aspects. A. J. Shaw. Boca Raton, FL, CRC Press: 155-177.

Bollag, J. M., T. Mertz, et al. (1994). Role of microorganisms in soil bioremediation. Bioremediation through rhizosphere technology. T. A. Anderson and J. R. Coats. Washington, D.C., American Chemical Society: 2-10.

Borovik, A. S. (1990). Characterizations of metal ions in biological systems. Heavy metal tolerance in plants: Evolutionary aspects. A. J. Shaw. Boca Raton, CRC Press: 3-4.

Bradshaw, A. D., T. Mcneilly, et al. (1990). The essential qualities. Heavy metal tolerance in plants: Evolutionary aspects. A. J. Shaw. Boca Raton, CRC Press: 323-334.

Chaney, R. L., Y. M. Li, et al. (1999). Improving metal hyperaccumulator wild plants to develop commercial phytoextraction systems: approaches and progress. Phytoremediation of contaminated soil and water. N. Terry and G. Bañuelos. Boca Raton, FL, CRC Press: 129-158.

Chaudhry, Q., M. Blom-Zandstra, et al. (2005). "Utilising the synergy between plants and rhizosphere microorganisms to enhance breakdown of organic pollutants in the environment." Environmental Science and Pollution Research 12(1): 34-48.

Background. Phytoremediation is a promising technology for the cleanup of polluted environments. The technology has so far been used mainly to remove toxic heavy metals from contaminated soil, but there is a growing interest in broadening its applications to remove/degrade organic pollutants in the environment. Both plants and soil microorganisms have certain limitations with respect to their individual abilities to remove/break-down organic compounds. A synergistic action by both rhizosphere microorganisms that leads to increased availability of hydrophobic compounds, and plants that leads to their removal and/or degradation, may overcome many of the limitations, and thus provide a useful basis for enhancing remediation of contaminated environments. Main Features. The review of literature presented in this article provides an insight to the nature of plant-microbial interactions in the rhizosphere, with a focus on those processes that are relevant to the breakdown and/or removal of

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organic pollutants. Due consideration has been given to identify opportunities for utilising the plant-microbial synergy in the rhizosphere to enhance remediation of contaminated environments. Results and Discussion. The literature review has highlighted the existence of a synergistic interaction between plants and microbial communities in the rhizosphere. This interaction benefits both microorganisms through provision of nutrients by root exudates, and plants through enhanced nutrient uptake and reduced toxicity of soil contaminants. The ability of the plant-microbial interaction to tackle some of the most recalcitrant organic chemicals is of particular interest with regard to enhancing and extending the scope of remediation technologies. Conclusions. Plant-microbial interactions in the rhizosphere offer very useful means for remediating environments contaminated with recalcitrant organic compounds. Outlook. A better knowledge of plant-microbial interactions will provide a basis for improving the efficacy of biological remediation. Further research is, however, needed to investigate different feedback mechanisms that select and regulate microbial activity in the rhizosphere.

Ciucani, G., H. Mosbaek, et al. (2004). "Uptake of tributyltin into willow trees." *Environmental Science and Pollution Research* 11(4): 267-272.

Background. Organotins have been used world-wide as antifoulants in ship paints. Repeatedly, severe effects on aquatic species have resulted. The use of organotins for this purpose was ruled out, and dumping of contaminated harbor sludge into the sea was prohibited. Land-based dumping is seen as an alternative. Objective. This study investigates sorption, uptake and translocation of tributyltin (TBT) to willow trees in order to evaluate phytoremediation as treatment option. The study considers the influence of pH on the plant uptake of organotins. Experimental set-up. Chemicals investigated were the weak base tributyltin chloride (TBTC1) and the neutral tributyltin hydride (TBTH). Organotins were extracted from solution and plant material with toluene, and analyzed as tin by AAS with graphite oven. The pH in solution varied from pH 4 to pH 7. The sorption to living and dead roots, stems and leaves was measured in shaking experiments. The uptake into intact trees was measured at nominal levels of 1 and 10 mg TBT/l for TBTH and TBTC1 at low and high pH. Results. The sorption to roots and leaves dropped for dead tissue, but did not vary much with pH. The sorption to stems increased for dead stems and with pH. The solubility of TBTC1 in water was below 10 mg/l and lowest at pH 4. Concentrations of TBTC1 and TBTH in solutions with trees dropped rapidly to low values. Highest TBT contents in trees were found in roots and lower stems. The concentrations followed the concentrations in solution. The pH had only a small effect on the plant uptake of TBTC1, and no effect on the uptake of TBTH. No effective translocation to higher stems or leaves was found. Discussion. An ion trap mechanism that accumulates the weak base TBTC1 in the xylem sap of plants and leads to upward translocation could not be detected. Neither TBTC1 at low or high pH, nor the neutral lipophilic chemical TBTH, were translocated effectively to leaves. The TBT<sup>+</sup> cation sorbed strongly to plant tissue. The exact mechanism for the strong sorption of the cation is unknown, but similar effects have been observed for algae, liposomes and isolated biomembranes. Conclusions. Both the uptake of the neutral TBTH and the uptake of the neutral molecule form of TBTC1 into willows was as is to be expected from theory. The cation TBT<sup>+</sup> showed an unexpected behavior which has been observed before. No ion trap occurs, and the phytoextraction of TBT is not feasible. Outlook. Planting trees, or other appropriate vegetation, could have a beneficial remediation effect by aeration of the TBT-contaminated soil or sludge. In a follow-up paper, the toxicity of TBT to willow trees will be described.

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Di Baccio, D., R. Tognetti, et al. (2003). "Responses of *Populus deltoides* x *Populus nigra* (*Populus* x *euramericana*) clone I-214 to high zinc concentrations." *New Phytologist* 159(2): 443-452.

We hypothesized that poplar can be useful for the extraction of zinc (Zn) from contaminated soils and water. However, the physiological response and the base of tolerance of poplar plants to this heavy metal are little known. Plants of *Populus deltoides* x *P. nigra* (*P. x euramericana*) I-214 clone were grown in glasshouse and treated with three different Zn concentrations (1, 100 and 1000  $\mu\text{m}$ ). Growth analysis, Zn concentration in leaves, stem and roots, and photosynthetic parameters were measured at different times of exposure during the annual growth cycle. Significant reductions in foliage and total dry mass, and impairment of gas exchange properties occurred at applications of 100  $\mu\text{m}$  and 1000  $\mu\text{m}$  Zn. Modifications of leaf area, chlorophyll b concentration, diameter at the stem base, and Zn concentrations of old leaves, stem and roots were also shown after Zn treatment. We concluded that poplar plants have the potential to be used for plantations in Zn-contaminated soils, in the range of tested Zn concentrations.

Donnelly, P. K. and J. S. Fletcher (1994). Potential use of mycorrhizal fungi as bioremediation agents. *Bioremediation through rhizosphere technology*. T. A. Anderson and J. R. Coats. Washington, D.C., American Chemical Society: 91-99.

Glass, D. J. (1999). International activities in phytoremediation: industry and market overview. *Phytoremediation and innovative strategies for specialized remedial applications*. A. Leeson and B. C. Allenman. Columbus, OH, Battelle Press: 95-100.

Gordon, J. C. (2001). "Poplars: Trees of the people, trees of the future." *Forestry Chronicle* 77(2): 217-219.

Poplars and willows have been and are important in human history and affairs but they have not garnered the attention and respect their many positive attributes deserve. They can be even more important in the future as human population pressures increase the need for wood, watershed and riparian rehabilitation and protection, environmental monitoring and improvement, carbon sequestration, phytoremediation and basic biological understanding. Whether, and to what degree, poplars and willows achieve their potential will depend on coordinated action that includes systematic collection of biological materials, establishment of an environmental monitoring network based on poplars and willows, creation of a "poplars, willows and water" task force to assess watershed and riparian rehabilitation tasks, enhanced genome research and an advanced, ecosystem-based regulatory framework for poplar and willow systems based on altered genomes. These must be presented in an ecosystem framework with their risks and benefits clearly described.

Hammer, D., A. Kayser, et al. (2003). "Phytoextraction of Cd and Zn with *Salix viminalis* in field trials." *Soil Use and Management* 19(3): 187-192.

Use of high biomass crops such as the willow *Salix viminalis* to extract metals for soil remediation has been proposed as an alternative to the low biomass-producing hyperaccumulating plants. High yields compensate for the moderate heavy-metal concentrations in the shoots of such species. We report the first long-term trials using *Salix viminalis* to extract heavy metals from two contaminated soils, one calcareous (5 years) and one acidic (2 years). Total metals extracted by the plants were 170 g Cd ha<sup>(-1)</sup> and 13.4 kg Zn ha<sup>(-1)</sup> from the calcareous soil after 5 years, and 47 g Cd ha<sup>(-1)</sup> and 14.5 kg Zn ha<sup>(-1)</sup> from the acidic soil after 2 years; in the first year outputs were negligible. After 2 years, *Salix* had performed better on the acidic soil because of larger biomass production and higher metal concentrations in shoots.

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Addition of elemental sulphur to the soil did not yield any additional benefit in the long term, but application of an Fe chelate improved the biomass production. Cd and Zn concentrations were significantly higher in leaves than stems, highlighting the necessity to collect leaves as well as shoots. On both soils, concentration in shoots decreased with time, indicating a decrease in extraction efficiency.

Harmsen, J., J. van der Waarde, et al. (1999). Growing biomass to stimulate bioremediation: technical and economic perspective. *Phytoremediation and innovative strategies for specialized remedial applications*. A. Leeson and B. C. Allenman. Columbus, OH, Battelle Press: 39-44.

Hong, M. S., W. F. Farmayan, et al. (2001). "Phytoremediation of MTBE from a groundwater plume." *Environmental Science & Technology* 35(6): 1231-1239.

The feasibility of phytoremediation to both remediate and hydraulically contain a methyl tert-butyl ether (MTBE) contaminated groundwater plume was investigated in a three-phase study that included the following elements: (i) a laboratory bioreactor study that examined the fate and transport of C-14-radiolabeled MTBE in hybrid poplar trees, (ii) a novel approach for a mathematical modeling study that investigated the influence of deep-rooted trees on unsaturated and saturated groundwater flow, and (iii) a field study at a Houston site with MTBE-contaminated groundwater where hybrid poplar trees were planted. In the laboratory study, the predominant fate pathway was uptake and evapotranspiration of [C-14]-MTBE from leaves and stems of poplar cuttings rooted in hydroponic solution. The modeling study demonstrates that phytohydraulic containment of MTBE in groundwater by deep-rooted trees can be achieved. The field study demonstrated significant groundwater uptake of groundwater by deep-rooted trees via direct measurement in the first three seasons. The use of vegetation may provide a cost-effective in situ alternative for containment and remediation of MTBE-contaminated groundwater plumes.

Jones, S. A., R. W. Lee, et al. (1999). Phytoremediation of trichloroethylene (TCE) using cottonwood trees. *Phytoremediation and innovative strategies for specialized remedial applications*. A. Leeson and B. C. Allenman. Columbus, OH, Battelle Press: 101-108.

Kamath, R., J. A. Rentz, et al. (2004). Phytoremediation of hydrocarbon-contaminated soils: principles and applications. *Petroleum Biotechnology: Developments and Perspectives*. 151: 447-478.

Kelley, S. L., E. W. Aitchison, et al. (1999). Bioaugmentation of poplar roots with *Amycolatasp.* CB1190 to enhance phytoremediation of 1,4,-dioxane. *Phytoremediation and innovative strategies for specialized remedial applications*. A. Leeson and B. C. Allenman. Columbus, OH, Battelle Press: 139-144.

Kruckeberg, A. R. and A. L. Kruckeberg (1990). Endemic metallophytes: their taxonomic, genetic, and evolutionary attributes. Heavy metal tolerance in plants: Evolutionary aspects. A. J. Shaw. Boca Raton, CRC Press: 301-312.

Larsen, M., S. Trapp, et al. (2004). "Removal of cyanide by woody plants." *Chemosphere* 54(3): 325-333.

Hydrogen cyanide is a high volume production chemical that causes severe environmental problems. The toxicity of potassium cyanide (KCN) to basket willow trees (*Salix viminalis*) was tested. In aqueous solution, 2 mg CN l(-1) as KCN depressed the transpiration after 72 h about 50%. Trees exposed to 0.4 mg CN l(-1) in aqueous solution showed initially a depression of transpiration,

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but recovered. Doses of 8 and 20 mg CN l<sup>(-1)</sup> in aqueous solution were quickly mortal to the trees. At the end of the test, almost all cyanide had disappeared from the solutions. Levels of cyanide in plants were related to the toxicity, with no elevated levels of cyanide in plants exposed to 0.4 mg CN l<sup>(-1)</sup>. Willows grown in sand survived 423.5 h irrigation with 20 mg CN l<sup>(-1)</sup>. Willows grown in sand irrigated with 50 mg CN l<sup>(-1)</sup> died within a few days. The roots of the surviving willows were able to consume about 10 mg CN kg fresh weight<sup>(-1)</sup> h<sup>(-1)</sup>. Vascular plants possess the enzymes beta-cyanoalanine synthase and beta-cyanoalanine hydrolase, which convert free cyanide to the amino acid asparagine. The in vivo capacity of woody plants (willow, poplar, elder, rose, birch) to remove cyanide was evaluated. Tests were performed with detached leaves and roots in KCN solutions of different concentrations. The highest removal capacity was obtained for basket willow hybrids (*Salix viminalis* x *schwerinii*). The Michaelis-Menten kinetics was determined. Realistic values of the half-saturation constant,  $K_m$ , were between 0.6 and 1.7 mgCN l<sup>(-1)</sup>; the maximum metabolic capacity,  $v_a$ , was around 9.3 mg CN kg fresh weight<sup>(-1)</sup> h<sup>(-1)</sup>. The removal of cyanide by plants might be useful in phytoremediation and treatment of wastewater from gold mining. (C) 2003 Elsevier Ltd. All rights reserved..

Laureysens, I., R. Blust, et al. (2004). "Clonal variation in heavy metal accumulation and biomass production in a poplar coppice culture: I. Seasonal variation in leaf, wood and bark concentrations." *Environmental Pollution* 131(3): 485-494.

The use of plants to decontaminate soils polluted by heavy metals has received considerable attention in recent years as a low-cost technique. Poplars (*Populus* spp.) can accumulate relatively high levels of certain metals, and have the added advantage of producing biomass that can be used for energy production. A short rotation coppice culture with 13 poplar clones was established on a former waste disposal site, which was moderately polluted with heavy metals. Total content of metals in leaves, wood and bark were determined in August and October/November. Significant clonal differences in accumulation were found for most metals, although clones with the highest concentration of all metals were not found. Cadmium, zinc and aluminum were most efficiently taken up. The lowest concentration was found in wood; the highest concentrations were generally found in senescing leaves, making removal and treatment of fallen leaves necessary. (C) 2004 Elsevier Ltd. All rights reserved.

Laureysens, I., L. De Temmerman, et al. (2005). "Clonal variation in heavy metal accumulation and biomass production in a poplar coppice culture. II. Vertical distribution and phytoextraction potential." *Environmental Pollution* 133(3): 541-551.

Short rotation coppice cultures (SRC) are intensively managed high-density plantations of multi-shoot trees. In April 1996, an SRC field trial with 17 different poplar clones was established in Boom (Belgium) on a former waste disposal site. In December 1996 and January 2001, all shoots were cut back to a height of 5 cm to create a coppice culture. For six clones, wood and bark were sampled at the bottom, middle and top of a shoot in August and November 2002. No significant height effect of metal concentration was found, but for wood, metal concentrations generally increased toward the top of the shoot in August, and decreased toward the top of the shoot in November. Phytoextraction potential of a clone was primarily determined by metal concentration and by biomass production. Shoot size and number of shoots per stool were less important, as a high biomass production could be achieved by producing a few large shoots or many smaller shoots. Clone Fritzi Pauley accumulated 1.4 kg ha<sup>(-1)</sup> of Al over two years; Wolterson and Balsam Spire

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showed a relatively high accumulation of Cd and Zn, i.e. averaging, respectively 47 and 57 g ha<sup>-1</sup> for Cd and 2.4 and 2.0 kg ha<sup>-1</sup> for Zn over two years. (C) 2004 Elsevier Ltd. All rights reserved.

Leeson, A. and B. C. Alleman (1999). Phytoremediation and innovative strategies for specialized remedial applications. Columbus, OH, Battelle Press.

Lefebvre, C. and P. Vernet (1990). Microevolutionary processes on contaminated deposits. Heavy metal tolerance in plants: Evolutionary aspects. A. J. Shaw. Boca Raton, CRC Press: 285-299.

Licht, L. A. and J. G. Isebrands (2005). "Linking phytoremediated pollutant removal to biomass economic opportunities." Biomass & Bioenergy 28(2): 203-218.

Phytoremediation (phyto) strategies employ trees, shrubs, and/or grasses for treating contaminated air, soil, or water. These strategies include buffers, vegetation filters, in situ phytoremediation plantings and percolation controlling vegetative caps. The design parameter that separates phytoremediation from landscaping is purposefully placing and growing a root-zone reactor volume with predictable pollutant removal performance. This phyto-reactor integrates with other engineered systems to cover landfills, treat petrochemical spills in soils, intercept a soluble subsurface plume, and capture non-point surface sediment entrained in urban or field runoff. There are many potential economic opportunities for biomass associated with phytoremediation, including bioenergy and traditional industrial products such as solid wood products and reconstituted products (i.e., paper, chip board, laminated beams, and extruded trim). More intangibly, phyto creates environmental benefits such as soil erosion control, carbon sequestration, and wildlife habitat. Phyto also creates socio-economic benefits by diversify regional manufacturing into new products that employs local labor, thus building value-added industry. Alternative crops develop a greater diversity of products from the farmland, making the regional economy less exposed to global commodity crop price fluctuations. Thus, a strategic phyto treatment of non-point agricultural runoff would help diversify land use from annually tilled crops (corn, soybeans, wheat) into perennial, untilled tree crops. A landscape rebuilt using phyto would create diversity represented in business potential, healthier air and water, wildlife habitat and aesthetics. Moreover, phyto provides local and current pollutant treatment. Such timely treatment of pollutants that would otherwise move to our downstream or downwind neighbors is key to the environmental justice concept. We present four case study summaries to illustrate installed commercial applications of phytoremediation. (C) 2004 Published by Elsevier Ltd.

Liphadzi, M. S., M. B. Kirkham, et al. (2003). "EDTA-assisted heavy-metal uptake by poplar and sunflower grown at a long-term sewage-sludge farm." Plant and Soil 257(1): 171-182.

Little information is available concerning the efficacy of chelates applied to biosolids (sewage-sludge)- treated soil for heavy-metal removal. The purpose of the experiment was to determine the availability to sunflower (*Helianthus annuus* L.) and hybrid poplar (*Populus deltoides* Marsh. x *P. nigra* L.) seedlings, of non-essential (Cd, Ni, Pb) and essential heavy metals (Cu, Fe, Mn, Zn) in field soil injected with biosolids since 1976 and treated with ethylenediamine-tetraacetic acid (EDTA) in 2001. Sunflower was grown at two densities, 20 000 and 60 000 plants/ha, and poplar at 10 000 plants/ha. The tetrasodium salt of EDTA was applied at rates of 0, 0.5, 1, and 2 g EDTA salt per kg surface (25-cm depth) soil. The EDTA did not affect uptake by poplar of the three nonessential (Cd, Ni, Pb) and four essential (Cu, Fe, Mn, Zn) heavy metals. For sunflower, the 1.0 g/kg rate of chelate addition resulted in

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maximal removal of the three non-essential heavy metals ( Cd, Ni, Pb). Uptake of the essential heavy metals by sunflower was little affected by the EDTA. At the 20 000 plants/ha density, leaves of sunflower grown with 1.0 g EDTA Na-4.2H(2)O per kg soil accumulated more Cd, Ni, and Pb than leaves of sunflower grown without the EDTA salt. At this density, concentrations of Cd in leaves of sunflower without EDTA and with 1.0 g/kg EDTA salt were 2.2 and 6.5 mug/g, respectively; for Ni, they were 6.7 and 19.2 mug/g, respectively; and for Pb, they were 15.6 and 46.9 mug/g, respectively. At the 60 000 plants/ha density, stems of sunflower grown with 1.0 g EDTA Na-4.2H(2)O per kg soil accumulated more Cd, Ni, and Pb than stems of sunflower grown without the EDTA salt. At this density, concentrations of Cd in stems of sunflower without EDTA and with 1.0 g/kg EDTA salt were 0.6 and 4.6 mug/g, respectively; for Ni, they were 1.7 and 17.6 mug/g, respectively; and for Pb, they were 5.2 and 42.8 mug/g, respectively. Removal of the non-essential heavy metals by sunflower was greater at the higher plant density ( 60 000 plants/ha) compared to the lower one ( 20 000 plants/ha).

Ma, X. M., A. R. Richter, et al. (2004). "Phytoremediation of MTBE with hybrid poplar trees." *International Journal of Phytoremediation* 6(2): 157-167.

This research investigates the fate and transport of methyl tert-butyl ether (MTBE) in phytoremediation, particularly the uptake and volatilization of MTBE in lab-scale hydroponic systems. The research reveals that MTBE was taken up by hybrid poplar cuttings and volatilized to the atmosphere. Volatilization of MTBE occurred through both stems and leaves. The concentration of MTBE in the transpiration stream declined exponentially with height, indicating that the uptake and volatilization along the stems are an important removal mechanism of MTBE in phytoremediation. Volatilization, via diffusion from the stems, has not been directly measured previously. No volatile MTBE metabolites were detected; however, mass balance closure and metabolite detection were not primary objectives of this study. The greatest amount of MTBE in plant biomass was associated with the woody stems from the previous year's growth, owing in part to the large biomass of stems. MTBE in the plant tissues appears to reach a steady state concentration and there does not appear to be an accumulation process that could lead to highly elevated concentrations relative to the groundwater source.

Macnair, M. R. (1990). *The genetics of metal tolerance in natural populations. Heavy metal tolerance in plants: Evolutionary aspects.* A. J. Shaw. Boca Raton, CRC Press: 235-254.

Mezzari, M. P., B. Van Aken, et al. (2004). "Mathematical modeling of RDX and HMX metabolism in poplar (*Populus deltoides* x *Populus nigra*, DN34) tissue culture." *International Journal of Phytoremediation* 6(4): 323-345.

Three mathematical models were developed based on a fate study as an approach to define transformation pathways of hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX) and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX) within plant cells. [U-C-14]RDX and [U-C-14]HMX were added in Murashige and Skoog (A\S) liquid media containing *Populus deltoides* x *P nigra* (DN34) tissue cultures. Radioactivity of samples was analyzed using HPLC, a bio-oxidizer and liquid scintillation counter. Based on information collected, transformation pathways of nitramine compounds were fitted with the raw data obtained and using a modified "green liver" model. Ordinary differential equations were developed and simulations were performed with MicroMath Scientist version 2.0 (Micro-Math Inc., St. Louis: MO, USA). The three models, with different sequential transformation processes, were tested in order to support the raw data (model I) and the assumptions of the modified "green liver" model (models II and III). The results showed a high correlation between the collected data

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and the simulated concentrations for all models. Thus, the simplest model developed (model I) is the best model description of these particular results. The results obtained suggest that the principle of parsimony should be applied. The "green liver"-based models also demonstrated a reliable approach for the investigation of degradation pathways of nitramines within plant cells.

Mirck, J., J. G. Isebrands, et al. (2005). "Development of short-rotation willow coppice systems for environmental purposes in Sweden." *Biomass & Bioenergy* 28(2): 219-228.

During the last three decades, driving forces behind the development of short-rotation willow coppice (SRWC) in Sweden have been changing from a primary focus on biomass production towards emphasis on environmental applications. In most cases, current commercial SRWC practice is geared towards a combination of biomass production for energy purposes and environmental goals. The latter goals range from decreasing the impact of specific contaminants in the environment to organic waste handling in a recycling system in urban and/or agricultural areas. Where biomass production and pollutant management overlap, the science of phytoremediation has its practical application. Through phytoremediation, waste products that previously have been a burden for the society can be used as valuable resources to increase short-rotation willow biomass production. In this paper we will present the terminology and definitions of different types of phytoremediation. We also give an overview of five different cases of phytoremediation activities with a potential for large-scale implementation. Some of the types of activities are already commercially used in Sweden: others seem promising but still need further development. (C) 2004 Elsevier Ltd. All rights reserved.

Moffat, A. J., A. T. Armstrong, et al. (2001). "The optimization of sewage sludge and effluent disposal on energy crops of short rotation hybrid poplar." *Biomass & Bioenergy* 20(3): 161-169.

An experiment was set up to test the effect of sewage sludge application and waste water irrigation on the biomass production of two poplar varieties, *Populus trichocarpa* x *P. deltoides* "Beaupre", and *Populus trichocarpa* "Trichobel". Three sludge applications were examined factorially with two irrigation regimes (with and without), over the two final years of a three-year rotation. The effects of treatment on soil and soil water were monitored, and the amount of heavy metals removed in the biomass was quantified. Irrigation had a significant effect on biomass of both poplar varieties, with *Beaupre*: yielding more than *Trichobel*. Sludge application was not effective in increasing biomass yield, but the experiment was valuable in identifying that modest amounts of sludge (approximately 100 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>) were acceptable environmentally and did not compromise biomass production. Cadmium uptake was detected in the poplar biomass, but the amounts were small and insufficient for poplar to be used in phytoremediation of metal-contaminated land. Crown Copyright (C) 2001 Published by Elsevier Science Ltd. All rights reserved.

Nzengung, V. A., C. Wang, et al. (1999). Phytoremediation of perchlorate contaminated water: laboratory studies. Phytoremediation and innovative strategies for specialized remedial applications. A. Leeson and B. C. Allenman. Columbus, OH, Battelle Press: 39-244.

Orchard, B. J., W. J. Doucette, et al. (1999). Laboratory studies on plant uptake of TCE. Phytoremediation and innovative strategies for specialized remedial applications. A. Leeson and B. C. Allenman. Columbus, OH, Battelle Press: 127-132.

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Peterjohn, W. and D. Correll (1984). "Nutrient dynamics in an agricultural watershed: Observations on the role of a riparian forest." *Ecology* 65: 1466-1475.

Pulford, I. D., D. Riddell-Black, et al. (2002). "Heavy metal uptake by willow clones from sewage sludge-treated soil: The potential for phytoremediation." *International Journal of Phytoremediation* 4(1): 59-72.

Willow (*Salix* spp.) has shown potential for use in the phytoremediation of soil contaminated with heavy metals. In particular, it can be grown in short rotation coppice systems to produce biomass that can be used for energy production. Twenty different species or varieties of willow, grown over 2 years (1995 to 1997) on a soil that was highly contaminated with heavy metals due to long-term sewage sludge disposal, showed considerable variation in survival, biomass production and metal uptake. The willows could be divided into two groups after the first harvest. One group had relatively low Ni and Cu in the bark and high Cd and Zn in the wood, with a good survival rate and biomass production. This group partitioned Cu, Cd, and Zn into the wood tissue from the bark, whereas Ni was excluded. The second group had relatively high Ni and Cu in the bark and low Cd and Zn in the wood and performed poorly in terms of survival and biomass production. Of the 20 types of willow used, 11 showed potential for use in phytoremediation, combining good survival and biomass production with high metal uptake. Of the others, 2 failed to survive until the second harvest: and the other 7 had very poor survival rates.

Pulford, I. D. and C. Watson (2003). "Phytoremediation of heavy metal-contaminated land by trees - a review." *Environment International* 29(4): 529-540.

This paper reviews the potential for using trees for the phytoremediation of heavy metal-contaminated land. It considers the following aspects: metal tolerance in trees, heavy metal uptake by trees grown on contaminated substrates, heavy metal compartmentalization within trees, phytoremediation using trees and the phytoremediation potential of willow (*Salix* spp.). (C) 2002 Elsevier Science Ltd. All rights reserved.

Rentz, J. A., B. Chapman, et al. (2003). "Stimulation of hybrid poplar growth in petroleum-contaminated soils through oxygen addition and soil nutrient amendments." *International Journal of Phytoremediation* 5(1): 57-72.

Hybrid poplar trees (*Populus deltoides* x *nigra* DN34) were grown in a greenhouse using hydrocarbon-contaminated soil from a phytoremediation demonstration site in Heath, Ohio. Two independent experiments investigated the effect of nutrient addition on poplar growth and the importance of oxygen addition to root development and plant growth. Biomass measurements, poplar height, and leaf color were used as indicators of plant health in the selection of a 10/5/5 NPK fertilizer applied at 1121 kg/ha (112 kg-N, 24.4 kg-P, 46.5 kg-K per ha) to enhance hybrid poplar growth at the Heath site. Five passive methods of oxygen delivery were examined, including aeration tubes, gravel addition, and an Oxygen Release Compound(R) (ORC) When ORC was placed in coffee filters above hydrocarbon-contaminated soil, a statistically significant increase of 145% was observed in poplar biomass growth, relative to unamended controls. The ORC in filters also stimulated significant increases in root density. A 15.2-cm interval of soil directly below ORC addition exhibited an increase from 2.6 +/- 1.0 mg/cm<sup>3</sup> to 4.8 +/- 1.0 mg/cm<sup>3</sup>, showing stimulation of root growth in hydrocarbon-stained soil. The positive response of hybrid poplars to oxygen amendments suggests that overcoming oxygen limitation to plants should be considered in phytoremediation projects when soil contamination exerts a high biochemical oxygen demand, such as in former refinery sites.

## Phytoremediation Bibliography

Robinson, B., S. Green, et al. (2003). "Phytoremediation: using plants as biopumps to improve degraded environments." *Australian Journal of Soil Research* 41(3): 599-611.

Plants pump large amounts of water, solutes, and organic matter as part of their normal physiological processes. This pumping action can be exploited to improve degraded environments by stabilising, removing, or breaking-down contaminants in the substrates. In addition, soil amendments such as fertilisers and microbes may also be added to enhance the efficacy of the operation. Basic plant physiology sets limits on the capacity of phytoremediation. However, combining this technology with the production of saleable products may render the extra time needed for clean-up relatively unimportant. Phytoremediation is still poorly developed, particularly the phytoextraction of heavy metals. Continual innovation will greatly expand the scope and efficacy of phytoremediation. The greatest potential use for this technology may be in developing countries that have the highest levels of environmental degradation, and scant funds for remediation. Phytoremediation could provide a low-cost and sustainable way to improve local economies. Here a case study is reported on the phytoremediation of a 3.6 ha sawdust pile that was leaching unacceptable amounts of boron (B) into local waterways. High water-use poplars were used to control leaching and potentially remove B from the site via phytoextraction. Selected trees that are coppiced before leaf-fall could be mulched and used to provide 'organic' B on nearby orchards that are deficient in this element.

Robinson, B. H., T. M. Mills, et al. (2000). "Natural and induced cadmium-accumulation in poplar and willow: Implications for phytoremediation." *Plant and Soil* 227: 301-306.

Rockwood, D. L., C. V. Naidu, et al. (2004). "Short-rotation woody crops and phytoremediation: Opportunities for agroforestry?" *Agroforestry Systems* 61(1): 51-63.

Worldwide, fuelwood demands, soil and groundwater contamination, and agriculture's impact on nature are growing concerns. Fast growing trees in short rotation woody crop (SRWC) systems may increasingly meet societal needs ranging from renewable energy to environmental mitigation and remediation. Phytoremediation, the use of plants for environmental cleanup, systems utilizing SRWCs have potential to remediate contaminated soil and groundwater. Non-hyperaccumulating, i.e., relatively low contaminant concentrating, species such as eucalypts (*Eucalypts* spp.), poplars (*Populus* spp.), and willows (*Salix* spp.) may phytoremediate while providing revenue from fuelwood and other timber products. Effective phytoremediation of contaminated sites by SRWCs depends on tree-contaminant interactions and on tree growth as influenced by silvicultural, genetic, and environmental factors. Locally adapted trees are essential for phytoremediation success. Among the different agroforestry practices, riparian buffers have the greatest opportunity for realizing the SRWC and phytoremediation potentials of fast growing trees. Agroforestry that combines SRWC and phytoremediation could be an emerging holistic approach for sustainable energy, agricultural development, and environmental mitigation globally.

Rubin, E. and A. Ramaswami (2001). "The potential for phytoremediation of MTBE." *Water Research* 35(5): 1348-1353.

This paper examines the potential for phytoremediation of MTBE, a gasoline additive that has become a prevalent and persistent groundwater pollutant, due to its' non-sorbing and non-reactive nature in water. A novel experimental design is developed to measure plant uptake and transpiration of

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MTBE from hydroponic systems, separating these processes from passive volatilization of the chemical. Plant uptake experiments indicate 30% reduction in MTBE mass in water over a 1-week period by small poplar saplings, at both high (1600 ppb) and low (300 ppb) MTBE concentrations. Active plant uptake of MTBE was approximately double that achieved by passive volatilization through a balsam poplar control. MTBE was detected in biomass at the 100-ppb level, confirming passage of MTBE through the plant. A mass balance indicated that MTBE was largely untransformed during transport through the small poplar saplings to air. The high degree of MTBE removal achieved by small plants over a short period of time indicates great potential for successful phytoremediation of subsurface MTBE plumes using poplar trees. The fraction of MTBE removed from the hydroponic systems correlated well with volume of water transpired by the plants; the correlation enabled computation of the MTBE transpiration stream concentration factor of approximately 1, an important parameter for the design of engineered MTBE phytoremediation systems. (C) 2001 Published by Elsevier Science Ltd.

Seaward, M. R. D. and D. H. S. Richardson (1990). Atmospheric sources of metal pollution and effects on vegetation. Heavy metal tolerance in plants: Evolutionary aspects. A. J. Shaw. Boca Raton, CRC Press: 75-93.

Sebastiani, L., F. Scebba, et al. (2004). "Heavy metal accumulation and growth responses in poplar clones Eridano (*Populus deltoides* x *maximowiczii*) and I-214 (*P. x euramericana*) exposed to industrial waste." *Environmental and Experimental Botany* 52(1): 79-88.

In this study, the effects of non-hazardous levels of heavy metal (Zn, Cu, Cr and Cd)-enriched organic waste on biomass partitioning and heavy metal accumulation in plant organs in July and October were determined for two poplar clones (*Populus deltoides* x *maximowiczii*-clone Eridano and *P. x euramericana*-clone I-214) commonly used in Italian poplar plantations. Soil amended with the industrial organic waste did not exert any toxic effects on plants. Leaf, stem, root and woody cutting biomasses of treated plants were significantly greater than in the controls in both clones, except for stem biomass at the beginning of October. Leaf area of Eridano and I-214 treated plants was significantly higher than that of control plants, both in July and October, while specific leaf area (SLA) did not show any significant changes due to treatment. Shoot (SMR) and root mass ratios (RMR) were not significantly affected by the treatment in July, while in October plants grown in treated soil showed significant differences in stem and root biomass allocation with respect to controls. Among the four heavy metals (Zn, Cu, Cr and Cd) contained in the industrial organic waste, only Zn, Cu and Cr concentrations in plants differed consistently between clones or soil treatments, while Cd levels were always below the detection limits. Both phytoextraction and phytostabilisation strategies were observed in the two clones studied. The results suggested that only non-hazardous industrial biosolid levels might be environmentally sustainable for poplar plantations. (C) 2004 Elsevier B.V. All rights reserved.

Shann, J. R. and J. J. Boyle (1994). Influence of plant species on in situ rhizosphere degradation. *Bioremediation through rhizosphere technology*. T. A. Anderson and J. R. Coats. Washington, D.C., American Chemical Society: 70-81.

Shannon, M. C., G. S. Banuelos, et al. (1999). "Tolerance of Hybrid Poplar (*Populus*) Trees Irrigated with Varied Levels of Salt, Selenium, and Boron." *International Journal of Phytoremediation* 1(3): 273-288.

Agricultural drainage waters and industrial effluents often consist of waste waters laden with salts, boron (B), selenium (Se), molybdenum (Mo), and other contaminants. However, increasing shortages of high-quality water in arid

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and semiarid regions and increasing demands to maintain the water quality in rivers, lakes, streams, and groundwater have made water reuse an imperative. Trees have been viewed as potential candidates for wastewater reuse because of their capacities for high evapotranspiration, high growth rates, and abilities to accumulate salts and specific ions in a marketable product that is not biologically hazardous. Clones of eight hybrid poplar (*Populus* spp.) crosses were tested for salt tolerance and ion uptake characteristics in a sand culture study in Riverside, CA. After hardwood cuttings were planted and established under nonsaline conditions, young saplings were treated with artificial waste waters containing different levels of salts, Se, and B. High salt concentrations reduced growth and led to leaf damage and shedding; however, Se and B had no detrimental effect on growth. Salinity affected Se and B accumulation patterns in leaves. A significant degree of genetic variation in salt tolerance was noted among the clones. The salinity at which dry weight was reduced ranged from about 3.3 to about 7.6 dS m super(-1) depending on clone, and the relative decrease in dry weight yield with increasing salinity varied among clones and ranged from about 10 to 15% per dS m super(-1). This would indicate that poplars, whereas certainly more salt tolerant than avocado trees, are significantly less salt tolerant than eucalyptus. Leaf Cl concentrations increased in relation to the Cl concentrations in the irrigation waters, but also were subject to clonal variation. Salt tolerance in poplar was generally related to Cl in the leaves and stems but was also influenced by growth and vigor characteristics, as well as the allometric relationships between leaves and stems that influenced the sinks in which ions could accumulate before reaching toxic levels.

Shaw, A. J. (1990). Heavy metal tolerance in plants: Evolutionary aspects. Boca Raton, FL, CRC Press.

Singh, O. V. and R. K. Jain (2003). "Phytoremediation of toxic aromatic pollutants from soil." *Applied Microbiology and Biotechnology* 63(2): 128-135.

The enormous growth of industrialization, and the use of numerous aromatic compounds in dyestuffs, explosives, pesticides and pharmaceuticals has resulted in serious environmental pollution and has attracted considerable attention continuously over the last two decades. Many aromatic hydrocarbons, nitroaromatic compounds, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, diauxins and their derivatives are highly toxic, mutagenic and/or carcinogenic to natural microflora as well as to higher systems including humans. The increasing costs and limited efficiency of traditional physicochemical treatments of soil have spurred the development of new remediation technologies. Phytoremediation is emerging as an efficient treatment technology that uses plants to bioremediate pollutants from soil environments. Various modern tools and analytical devices have provided insight into the selection and optimization of remediation processes by various plant species. Sites heavily polluted with organic contaminants require hyperaccumulators, which could be developed by genetic engineering approaches. However, efficient hyperaccumulation by naturally occurring plants is also feasible and can be made practical by improving their nutritional and environmental requirements. Thus, phytoremediation of organics appears a very promising technology for the removal of contaminants from polluted soil. In this review, certain aspects of plant metabolism associated with phytoremediation of organic contaminants and their relevant phytoremediation efforts are discussed.

Stanton, B., J. Eaton, et al. (2002). "Hybrid poplar in the Pacific Northwest - The effects of market-driven management." *Journal of Forestry* 100(4): 28-33.

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Hybrid poplar is a new addition to the Northwest's agricultural economy, with over 50,000 acres currently in production. Originally conceived as feedstock for the energy industry, poplar has been grown primarily as raw material for the paper business. However with falling prices for wood chips, efforts are now under way to manage poplar for the solid wood market. Poplar's utility also extends to its use in the treatment of municipal and industrial wastewater, nutrient removal from agricultural runoff, and phytoremediation of industrial landfills. Future applications are likely to exploit its carbon sequestration ability in the developing markets for tradable pollution credits.

Sun, W. H. H., J. B. Lo, et al. (2004). "Phytoremediation of petroleum hydrocarbons in tropical coastal soils - I. Selection of promising woody plants." *Environmental Science and Pollution Research* 11(4): 260-266.

Goal, Scope and Background. This glasshouse study is aimed at evaluating tropical plants for phytoremediation of petroleum hydrocarbon-contaminated saline sandy subsurface soils. Tropical plants were selected for their ability to tolerate high salinity and remove No. 2 diesel fuel in coastal topsoil prior to further investigation of the phytoremediation feasibility in deep contaminated soils. The residual petroleum-hydrocarbon contaminant at the John Rogers Tank Farm site, a former petroleum storage facility, at Hickam Air Force Base, Honolulu, Hawaii, is located in a coastal area. It lies below a layer of silt in the subsurface, in loamy sand characterized by moderate salinity and high pH. Little is known regarding the ability of tropical plants to remediate petroleum hydrocarbon-contaminated subsurface soil in Hawaiian and other Pacific Island ecosystems although suitable plants have been identified and utilized for bioremediation in surface soil or marine sediments. Methods. The experiments were conducted in long narrow pots under glasshouse conditions in two phases. A preliminary experiment was done with nine tropical plants: kiawe (*Prosopis pallida*), milo (*Thespesia populnea*), common ironwood (*Casuarina equisetifolia*), kou (*Cordia subcordata*), tropical coral tree (*Erythrina variegata*), false sandalwood (*Myoporum sandwicense*), beach naupaka (*Scaevola sericea*), oleander (*Nerium oleander*), and buffelgrass (*Cenchrus ciliaris*). These plants were screened for resistance to high salinity treatment (2% NaCl) and two diesel fuel levels (5 and 10 g No. 2 diesel fuel/kg soil) in separate treatments. Plants that showed good tolerance of both factors were further evaluated in a second phase for their efficacy in the phytoremediation of diesel-fuel petroleum hydrocarbons under moderate salinity treatment (1% NaCl). Results. Tropical coral tree and buffelgrass were susceptible to either 2% NaCl or diesel fuel at 10 g/kg soil, but tolerant of diesel fuel at 5 g/kg soil. Kiawe, mile, kou, common ironwood, N. oleander, beach naupaka and false sandalwood were tolerant of high salinity (2% NaCl) or high diesel fuel level (10 g/kg soil). These seven plants were also tolerant of the combined adverse effects of a moderate salinity (1% NaCl) and 10 g diesel fuel/kg soil. Three trees, kiawe, milo and kou significantly accelerated the degradation of petroleum hydrocarbons in the soil spiked with 10 g diesel fuel/kg soil under a moderate salinity treatment (1% NaCl). Conclusion. Thus the tropical woody plants, kiawe, milo and kou showed potential for use in phytoremediation of petroleum hydrocarbons in coastal tropical soils. Recommendations and Outlook. Two fast growing trees, milo and kou, appeared promising for further phytoremediation evaluation in experiments that simulate the soil profile at the field site.

Sung, K. J., M. Y. Corapcioglu, et al. (2001). "Plant contamination by organic pollutants in phytoremediation." *Journal of Environmental Quality* 30(6): 2081-2090.

Phytoremediation is a remediation technique that involves plant uptake, transformation, accumulation, and/or volatilization of soil-and aqueous-phase

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contaminants or by the stimulation of microbial co-metabolic activity in the rhizosphere of the plant. Even when the principal mechanism is by stimulation of bacteria, any resultant plant contamination cannot be overlooked. For the purpose of modeling, a two-compartment plant model has been developed. The model divides the plant into the shoot compartment (which can be harvested) and the root compartment (into which contaminants can accumulate). Numerical experiments were conducted to investigate model behavior and to determine important parameters affecting plant contamination. Johnsongrass [*Sorghum halepense*(L.) Pers.] was used to evaluate the model behavior. The contaminants TNT (2,4,6,-trinitrotoluene) and chrysene were selected on the basis of their contrasting aqueous-phase solubilities. The results indicate that plant contamination and soil remediation by plants depend on soil properties such as soil organic carbon content, the physicochemical properties of the contaminants such as the octanol-water partition coefficient, and plant properties. The most important factor affecting plant contamination is bioavailability. As bioavailability increased, the concentrations in root and shoot compartments were predicted to increase. Microbial activities and plant contamination are closely related, which suggests that plants and microorganisms can have complementary roles in phytoremediation.

Terry, N. and G. Banuelos (1999). Phytoremediation of contaminated soil and water. Boca Raton, FL, CRC Press.

Thomas, P. R. and J. K. Buck (1999). Agronomic management for phytoremediation. Phytoremediation and innovative strategies for specialized remedial applications. A. Leeson and B. C. Allenman. Columbus, OH, Battelle Press: 115-120.

Thomas, P. R. and J. J. Jrueger (1999). Salt tolerance of woody phreatophytes for phytoremediation applications. Phytoremediation and innovative strategies for specialized remedial applications. A. Leeson and B. C. Allenman. Columbus, OH, Battelle Press: 21-26.

Thomas, S. A., P. Becker, et al. (1999). Mycoremediation: a method for test- to pilot-scale application. Phytoremediation and innovative strategies for specialized remedial applications. A. Leeson and B. C. Allenman. Columbus, OH, Battelle Press: 63-68.

Tognetti, R., L. Sebastiani, et al. (2004). "Gas exchange and foliage characteristics of two poplar clones grown in soil amended with industrial waste." *Tree Physiology* 24(1):75-82.

Plants can remove or immobilize various environmental contaminants; however, little is known about the physiological mechanisms underlying responses to soil amendment with biosolids contaminated with heavy metals. We investigated the responses of cuttings of hybrid poplar clones Eridano and I-214 grown for a season in soil amended with nutrient-rich organic material from tanneries, which contains potentially toxic amounts of heavy elements. Plant growth traits, gas exchange parameters, stomatal density and leaf layer thickness of frozen-hydrated leaves and foliar concentrations of heavy metals and nitrogen were determined. Overall, soil amendment increased net assimilation rate and growth, but the cuttings accumulated only small quantities of heavy metal soil contaminants.

Trapp, S., G. Ciucani, et al. (2004). "Toxicity of tributyltin to willow trees." *Environmental Science and Pollution Research* 11(5): 327-330.

Background. Tributyltin is an organotin compound, used as an antifouling agent in ship paint, with heavy impact on the marine environment. Contaminated

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dredged harbor sludge is now dumped on land. The toxicity of tributyltin (TBT) to trees has not yet been quantified. Eventually, a vegetation cover on the dumped sludge could be established for the purpose of non-food cash crop production and phytoremediation. Methods. The phytotoxicity of tributyltin chloride (TBTC1) and tributyltin hydride (TBTH) was measured at pH 4 and at pH 7 using the willow tree transpiration test. Different pH levels of the nutrient solutions were achieved by adding ammonium salt (low pH) or nitrate (high pH) as nitrogen source. Results and Discussion. At low PH (pH 4), all trees showed symptoms of poor health. Transpiration decreased at concentrations above or equal to 0.1 mg TBTC1/l and 1 mg TBTH/L. The TBT toxicity was more pronounced at pH 7. The trees survived even the highest dose of 10 mg/l TBTC1 or TBTH, although their growth and transpiration was strongly reduced. Conclusion. In contrast to other organisms, TBTC1 and TBTH were less toxic to higher plants. Recommendations and Outlook. The toxicity of TBT is no hindrance for establishing vegetation on TBT-contaminated sludge. Phytoremediation and cash crop production could be possible with suitable plants.

US Environmental Protection Agency (2000). Introduction to Phytoremediation. Cincinnati, OH, US EPA, National Risk Management Research Laboratory.

Vandecasteele, B., E. Meers, et al. (2005). "Growth and trace metal accumulation of two *Salix* clones on sediment-derived soils with increasing contamination levels." *Chemosphere* 58(8): 995-1002.

The growth and metal uptake of two willow clones (*Salix fragilis* 'Belgisch Rood' and *Salix viminalis* 'Aage') was evaluated in a greenhouse pot experiment with six sediment-derived soils with increasing field Cd levels (0.9-41.4 mg kg<sup>-1</sup>). Metal concentrations of eight elements were measured in roots, stems and leaves and correlated to total and soil water metal concentrations. Dry weight root biomass, number of leaves and shoot length were measured to identify eventual negative responses of the trees. No growth inhibition was observed for both clones for any of the treatments (max. 41.4 mg kg<sup>-1</sup> Cd, 1914 mg kg<sup>-1</sup> Cr, 2422 mg kg<sup>-1</sup> Zn, 655 mg kg<sup>-1</sup> Pb), allowing their use for phytoextraction on a broad range of contaminated sediments. However, dry weight root biomass and total shoot length were significantly lower for *S. viminalis* compared to *S. fragilis* for all treatments. Willow foliar Cd concentrations were strongly correlated with soil and soil water Cd concentrations. Both clones exhibited high accumulation levels of Cd and Zn in aboveground plant parts, making them suitable subjects for phytoextraction research. Cu, Cr, Pb, Fe, Mn and Ni were found mainly in the roots. Bioconcentration factors of Cd and Zn in the leaves were highest for the treatments with the lowest soil Cd and Zn concentration. (C) 2004 Elsevier Ltd. All rights reserved.

Verkleij, J. A. C. and H. Schat (1990). Mechanisms of metal tolerance in higher plants. Heavy metal tolerance in plants: Evolutionary aspects. A. J. Shaw. Boca Raton, CRC Press: 179-194.

Vervaeke, P., S. Luyssaert, et al. (2003). "Phytoremediation prospects of willow stands on contaminated sediment: a field trial." *Environmental Pollution* 126(2): 275-282.

Establishing fast growing willow stands on land disposed contaminated dredged sediment call result in the revaluation of this material and opens possibilities for phytoremediation. A field trial was designed to assess the impact of planting it willow stand (*Salix viminalis* L. 'Orm') oil the dissipation of organic contaminants (mineral oil and PAHs) in dredged sediment. In addition, the accumulation of heavy metals (Cd, Cu, Pb and Zn) in the biomass was determined. After 1.5 years, a significant decrease of 57% in the

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mineral oil concentration in the sediment planted with willow was observed. Degradation of mineral oil in sediment which was left fallow, was only 15%. The mineral oil degradation under willow was most pronounced (79%) in the root zone of the stand. In the sediment which was left fallow there was a significant reduction of the total PAH content by 32% compared with a 23% reduction in the planted sediment. The moderate and selective metal uptake, Measured in this study, limits the prospects for phytoextraction of metals from dredged sediment. (C) 2003 Elsevier Ltd. All rights reserved.

Vervaeke, P., F. M. G. Tack, et al. (2004). "Short- and longer-term effects of the willow root system on metal extractability in contaminated dredged sediment." *Journal of Environmental Quality* 33(3): 976-983.

Willow (*Salix* spp.) stands are often proposed as vegetation covers for the restoration and stabilization of contaminated and derelict land. Planting willows on dredged sediment disposal sites for biomass production can be an alternative to traditional capping techniques. However, with the introduction of willow stands on dredged sediment disposal sites, the possibility of increased contaminant availability in the root zone must be acknowledged as it can increase the risk of leaching. Two trials investigated the availability of Cd, Zn, Cu, and Pb in the root zones of willows grown on contaminated sediment. To assess the effects of willow root growth on metal extractability and mobility, bulk and rhizosphere sediment samples were extracted with deionized water, ammonium acetate at pH 7, and ammonium acetate-EDTA at pH 4.65. A rhizobox experiment was used to investigate the short-term effect of willow roots on metal availability in oxic and anoxic sediment. Longer-term effects were assessed in a field trial. The rhizobox trial showed that Cd, Zn, and Cu extractability in the rhizosphere increased while the opposite was observed for Pb. This was attributed to the increased willow-induced oxidation rate in the root zone as a result of aeration and evapotranspiration, which masked the direct chemical and biological influences of the willow roots. The field trial showed that Cu and Pb, but not Cd, were more available in the root zone after water and ammonium acetate (pH 7) extraction compared with the bulk sediment. Sediment in the root zone was better structured and aggregated and thus more permeable for downward water flows, causing leaching of a fraction of the metals and significantly lower total contents of Cd, Cu, and Pb. These findings indicate that a vegetation cover strategy to stabilize sediments can increase metal availability in the root zone and that potential metal losses to the environment should be considered.

Verwijst, T. (2001). "Willows: An underestimated resource for environment and society." *Forestry Chronicle* 77(2): 281-285.

In a global perspective and compared to poplar cultivation, willow cultivation has been the stepchild of the employment of the Salicaceae. While willows are grown and used for a large number of different purposes in both the northern and southern hemispheres, willow growing traditionally has been carried out on a small scale. However, the number of species in the genus *Salix* exceeds the number of *Populus* species by one order of magnitude, and the geographical distribution and physiognomic range of willow species is larger than of poplars. Only recently has a start been made to exploit the large biological variation within the genus *Salix* by means of breeding and selection and by means of new planting and management schemes. During only one century, the major obstacles to the availability of forest products have been shifting from technical and economic limitations to ecological and environmental constraints. Due to its high potential of environmental assets, a rapid development of all aspects of willow cultivation is envisaged during the next decades. Willow growing offers a range of products, services and new environmental applications well beyond the range of those encountered in poplar

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growing. As willow and poplar are closely related genera, several of the lessons learned during the large-scale breeding and cultivation of poplars are relevant to the field of willow growing. These include logistics, mitigation of risk for pest and disease transfer, and especially the need to ensure a wide genetic variability, containing material suitable for different site conditions. Large-scale implementation of sustainable short rotation forestry can be achieved by means of further exploitation of willow in its potential position in between forestry and agriculture, as a recipient of surplus organic nutrients from urbanised and intensively used agricultural areas and as a buffer between productive land and water courses.

Walton, B. T., E. A. Guthrie, et al. (1994). Toxicant degradation in the rhizosphere. Bioremediation through rhizosphere technology. T. A. Anderson and J. R. Coats. Washington, D.C., American Chemical Society: 11-26.

Walton, B. T., A. M. Hoylman, et al. (1994). Rhizosphere microbial communities as a plant defense against toxic substances in soils. Bioremediation through rhizosphere technology. T. A. Anderson and J. R. Coats. Washington, D.C., American Chemical Society: 82-92.

Wang, X., L. A. Newman, et al. (1999). Biodegradation of carbon tetrachloride by poplar trees: results from cell culture and field experiments. Phytoremediation and innovative strategies for specialized remedial applications. A. Leeson and B. C. Allenman. Columbus, OH, Battelle Press: 133-138.

Wang, X. P., M. P. Dossett, et al. (2004). "Fate of carbon tetrachloride during phytoremediation with poplar under controlled field conditions." Environmental Science & Technology 38(21): 5744-5749.

The fate of carbon tetrachloride (CT) during phytoremediation with poplar was assessed by examining the transpiration of CT from leaves, diffusion from soil, tree trunks, and surface roots, and accumulation of chloride ion in soil and plant tissues. Feedwater containing 12-15 mg/L CT was added to the field test beds planted with poplar, and over 99% of the CT was removed. No significant amount of CT was transpired or diffused into the air, and no significant amount of CT-chlorine accumulated in the tree tissues. Chloride ion accumulated in the soil accounted for all of the CT-chlorine removed. When soils from the root zones were compared to unvegetated soils, microbial mineralization of CT was not enhanced in soils from the root zones as compared to unvegetated soils. Thus, we conclude that uptake and dechlorination of CT by plant tissues is likely the primary mechanism for phytoremediation by poplar.

Watson, C., I. D. Pulford, et al. (2003). "Screening of willow species for resistance to heavy metals: Comparison of performance in a hydroponics system and field trials." International Journal of Phytoremediation 5(4): 351-365.

The aim of this study was to ascertain whether metal resistance in willow (*Salix*) clones grown in a hydroponics screening test correlated with data from the same clones grown independently in a field trial. If so, results from a short-term, glasshouse-based system could be extrapolated to the field, allowing rapid identification of willows suitable for planting in metal-contaminated substrates without necessitating long-term field trials. Principal Components Analysis was used to show groups of clones and to assess the relative importance of the parameters measured in both the hydroponics system and the field; including plant response factors such as increase in stem height, as well as metal concentrations in plant tissues. The clones tested fell into two distinct groups. *Salix viminalis* clones and the basket willow Black Maul (*S. triandra*) were less resistant to elevated concentrations of

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heavy metals than a group of hardier clones, including *S. burjatica* 'Germany,' *S.x dasyclados*, *S. candida* and *S. spaethii*. The more resistant clones produced more biomass in the glasshouse and field, and had higher metal concentrations in the wood. The less resistant clones had greater concentrations of Cu and Ni in the bark, and produced less biomass in the glasshouse and field. Significant relationships were found between the response of the same clones grown in the short-term glasshouse hydroponics system and in the field.

Weih, M. (2004). "Intensive short rotation forestry in boreal climates: present and future perspectives." *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* 34(7): 1369-1378.

Short rotation forestry (SRF) is regarded as a silvicultural practice employing high-density plantations of fast-growing tree species on fertile land with a rotation period of fewer than 10-12 years. I address the challenges and possibilities of SRF applications under the circumstances of a boreal climate, today as well as after anticipated climate change. The implications of a pronounced winter season for the performance of biomass crops are discussed. Poplars, aspens, and willows are superior in boreal SRF because of their fast growth rate in combination with good cold hardiness. These trees can enrich the coniferous forests of boreal regions and increase biodiversity in open agricultural landscapes of the boreal zone. Further, SRF plantations can serve as tools for the amelioration of environmental problems at local (e.g., phytoremediation) and global (e.g., increased greenhouse effect) scales. The biomass yields achieved in boreal SRF and the appropriate production systems appear do not appear to be principally different from warmer regions, but there are some differences with respect to the importance of fertilization, appropriate spacing, and rotation length. The major barriers for a rapid development of SRF appear not to be climatic, technical, or environmental constraints in many boreal regions.

Weih, M. and N. E. Nordh (2002). "Characterising willows for biomass and phytoremediation: growth, nitrogen and water use of 14 willow clones under different irrigation and fertilisation regimes." *Biomass & Bioenergy* 23(6): 397-413.

Fourteen clones of willow (*Salix* spp.) were characterised in terms of growth, nitrogen and water-use efficiency under different irrigation and fertilisation treatments. Cuttings of willow clones, some commercially introduced and others new material, were pot-grown outdoors in Central Sweden under four experimental treatments in a full-factorial design. The experiment covered the period from bud-break until leaf abscission and the experimental conditions included two irrigation and two fertilisation regimes. The growth of the clones was evaluated in terms of relative growth rate and total biomass production of whole plants and shoots. Nitrogen (N) economy was studied by means of N productivity, N accumulation and N losses by leaf abscission. Water economy was analysed with respect to intrinsic water-use efficiency (foliar carbon isotope ratio;  $\delta(13)C$ ) and the capacity of leaves to retain water (relative water content). Significant differences between clones were found in nearly all parameters measured and the clones varied in the responses to the experimental treatments (clone x factor interaction effects). Thus, clone ranking often changed depending on the experimental treatment. The results are discussed with respect to clone selection for different willow applications such as biomass production and phytoremediation, and willow growth performance under different water and nutrient availabilities. The growth-physiological characterisation of young willows in the short term (several months) is regarded as a suitable approach for pre-selection of promising clones prior to extensive field evaluation. (C) 2002 Elsevier Science Ltd. All rights reserved.

## Phytoremediation Bibliography

Wickland, D. E. (1990). Vegetation of heavy metal contaminated soils in North America. Heavy metal tolerance in plants: Evolutionary aspects. A. J. Shaw. Boca Raton, CRC Press: 39-50.

Widdowson, M. A., S. Shearer, et al. (2005). "Remediation of polycyclic aromatic hydrocarbon compounds in groundwater using poplar trees." *Environmental Science & Technology* 39(6): 1598-1605.

A seven-year study was conducted to assess the effectiveness of hybrid poplar trees to remediate polycyclic aromatic hydrocarbon (PAH) compounds in soil and groundwater at a creosote-contaminated site. A reduction in the areal extent of the PAH plume was observed in the upper half of the 2-m-thick saturated zone, and PAH concentration levels in the groundwater declined throughout the plume. PAH concentrations began to decline during the period between the third and fourth growing seasons, which coincided with the propagation of the tree roots to the water table region. Remediation was limited to naphthalene and several three-ring PAHs (acenaphthylene and acenaphthene). PAH concentrations in soil and aquifer sediment samples also declined over time; however, levels of four-ring PAHs persisted at the lower depths during the study period. The naphthalene to total PAH concentration ratio in the most contaminated groundwater decreased from > 0.90 at the beginning of the second growing season to approximately 0.70 at the end the study. Remediation in the lower region of the saturated zone was limited by the presence of a 0.3-m-thick layer of creosote present as a dense nonaqueous phase liquid (DNAPL). The nearly steady-state condition of the PAH concentrations observed during the last three years of the study suggests that the effectiveness of the phytoremediation system is limited by the rate of PAH dissolution from the DNAPL source.

Wu, L. (1990). Colonization and establishment of plants in contaminated sites. Heavy metal tolerance in plants: Evolutionary aspects. A. J. Shaw. Boca Raton, CRC Press: 269-284.

Ying, O. Y. (2002). "Phytoremediation: modeling plant uptake and contaminant transport in the soil-plant-atmosphere continuum." *Journal of Hydrology* 266(1-2): 66-82.

Phytoremediation is an emerging technology that uses plants and their associated rhizospheric microorganisms to remove, degrade, detoxify, or contain contaminants located in the soil, sediments, groundwater, surface water, and even the atmosphere. This study investigates phytoremediation of 1,4-dioxane from a contaminated sandy soil by a poplar cutting, which is associated with water flow in the soil as well as water movement and 1,4-dioxane translocation in the xylem and phloem systems. An existing one-dimensional mathematical model for coupled transport of water, heat, and solutes in the soil-plant-atmosphere continuum (CTSPAC) is modified for the purpose of this study. The model is calibrated with the laboratory experimental measurements prior to its applications. A simulation scenario is then performed to investigate phytoremediation of 1,4-dioxane by a poplar cutting in response to daily water flow and 1,4-dioxane transport for a simulation period of 7 days. Simulation shows that 1,4-dioxane concentration is high in leaves and low in roots with the stem in between. However, 1,4-dioxane mass in the stem (60%) is higher than that of leaves (28%) and roots (12%). This occurs because the stem volume used in this study is larger than those of leaves and roots. The simulation further reveals that about 30% of the soil 1,4-dioxane is removed within 7 days, resulting mainly from root uptake. A plot of the 1,4-dioxane concentrations in plant compartments as a function of time shows that the highest concentration in leaves is about 2600 mug/cm<sup>3</sup> and the lowest concentration in roots is about 350 mug/cm<sup>3</sup> at the end of the simulation. Results indicate that leaves

## Phytoremediation Bibliography

are an important compartment for 1,4-dioxane accumulation and transpiration. This study suggests that the modified CTSPAC model could be a useful tool for phytoremediation estimations. (C) 2002 Elsevier Science B.V. All rights reserved.