PHYTOTECHNOLOGIES FOR SITE CLEANUP

Fact Sheets on Ecological Revitalization

- This fact sheet is the fourth in a series of fact sheets related to ecological revitalization developed by the U.S. Environmental Protection Agency (EPA) Technology Innovation and Field Services Division (TIFSD). The information in this fact sheet is intended for EPA and state agency site managers, consultants, and others interested in the ecological revitalization of contaminated sites.
- The first three fact sheets can be found at *http://cluin.org/ecorevitalization* and include: (1) "Frequently Asked Questions about Ecological Revitalization of Superfund Sites," EPA 542-F-06-002; (2) "Revegetation of Landfills and Waste Containment Areas," EPA 542-F-06-001; and (3) "Ecological Revitalization and Attractive Nuisance Issues," EPA 542-F-06-003.
- Various information sources were used to prepare this fact sheet. These and additional information resources are listed at the end of the fact sheet.

Phytotechnologies use plants to extract, degrade, contain, or immobilize pollutants in soil, groundwater, surface water, and other contaminated media.

Introduction

Contaminated sites exist throughout the United States and elsewhere that require cleanup to protect human health and the environment. Phytotechnologies are a set of techniques that make use of plants to achieve environmental goals. These techniques use plants to extract, degrade, contain, or immobilize pollutants in soil, groundwater, surface water, and other contaminated media. Phytotechnologies remediate contaminants using several different mechanisms dependent on the application; Tables 1 and 2 summarize these mechanisms and applications.

Some phytotechnology applications could be primary methods of cleaning up or stabilizing contamination while others will supplement primary remedies. Phytotechnologies may potentially (1) clean up moderate to low levels of select elemental and organic contaminants over large areas, (2) maintain sites by treating residual contamination after completion of a cleanup, (3) act as a buffer against potential waste releases, (4) aid voluntary cleanup efforts, (5) facilitate nonpoint source pollution control, and (6) offer a more active form of monitored natural attenuation (McCutcheon and Schnoor 2003). Table 2 lists potential phytotechnology applications and associated mechanisms.

Phytotechnologies can treat a wide range of contaminants, including: organics, such as volatile organic compounds (VOC), polycyclic aromatic hydrocarbons (PAH), petroleum hydrocarbons, and munitions constituents; metals; and radionuclides—although not all mechanisms are applicable to all contaminants or all matrixes. This fact sheet (1) provides information that will help you evaluate whether phytotechnologies will work at your site, (2) summarizes the applications of phytotechnologies for various contaminants, and (3) includes links to additional sources of information.

WILL PHYTOTECHNOLOGIES WORK AT YOUR SITE?

As with all remediation strategies, phytotechnologies are site-specific, with applicability and performance that can vary widely based on parameters such as contamination and soil type, vegetation, and climate. It is best to evaluate a site early in the cleanup process to determine the possibility of using vegetation to achieve remediation, restoration, and/or containment goals. Because high concentrations of some contaminants may be toxic to plants and inhibit their growth, phytotechnologies are best applied at sites with low to moderate levels of contamination, used in conjunction with other treatment methods, or used as a final polishing step in site remediation. Finally, phytotechnologies can take significantly longer than other remedial technologies to achieve site goals because the plants must first establish well-developed roots and biomass to be effective. Nevertheless, phytotechnologies offer several significant advantages. Table 3 lists some advantages and disadvantages of applying phytotechnologies.

After reviewing site characteristics to determine if phytotechnologies would be effective at your site, it is important to select the appropriate phytotechnology mechanism and species. The mechanism and plants must be suitable to address contaminants of concern at the site and site characteristics such as soil type and climate. Ideally, the potential effectiveness of phytotechnology at a site is tested in a laboratory setting and through pilot field studies before full-scale application. Laboratory studies can determine if the target contaminant(s) can be removed under ideal conditions. If the lab study

TABLE 1
PHYTOTECHNOLOGY MECHANISMS

Mechanism	Description	Cleanup Goal
Phytodegradation	Ability of plants to take up and break down contaminants within plant tissues through internal enzymatic activity	Remediation by destruction
Phytoextraction	Ability of plants to take up contaminants into the plant and sequester the contaminant within the plant tissue	Remediation by removal of plants containing the contaminant
Phytohydraulics	Ability of plants to take up and transpire water	Containment by controlling hydrology
Phytosequestration	Ability of plants to sequester certain contaminants into the rhizosphere through release of phytochemicals, and sequester contaminants on/into the plant roots and stems through transport proteins and cellular processes	Containment
Phytovolatilization	Ability of plants to take up, translocate, and subsequently volatilize contaminants in the transpiration stream	Remediation by removal through plants
Rhizodegradation	Ability of released phytochemicals to enhance microbial biodegradation of contaminants in the rhizosphere	Remediation by destruction

Source: Interstate Technical Regulatory Council (ITRC). 2009. Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised.

TABLE 2
PHYTOTECHNOLOGY APPLICATIONS

Application	Media	Mechanisms
Constructed Treatment Wetland/ Aquatic Plant Lagoon	Sediment Surface Water	Phytodegradation Phytoextraction Phytovolatilization Rhizodegradation
Field Crops/ Grass, Forb, Herb, or Fern Gardens	Soil Sediment	Phytodegradation Phytoextraction Phytovolatilization Rhizodegradation
Landfill Cover	Soil Sediment Surface Water	Phytoextraction Phytohydraulics Phytosequestration
Riparian Buffer	Soil Sediment Surface Water Groundwater	Phytodegradation Phytoextraction Phytohydraulics Phytosequestration Phytovolatilization Rhizodegradation
Tree Hydraulic Barrier	Groundwater	Phytoextraction Phytohydraulics Phytosequestration
Tree/Shrub Plantation	Soil Sediment Groundwater	Phytodegradation Phytoextraction Phytovolatilization Rhizodegradation

Sources: ITRC. 2009. Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised. McCutcheon, S.C. and J. L. Schnoor. 2003. Phytoremediation: Transformation and Control of Contaminants. John Wiley & Sons, Inc., Hoboken, New Jersey. ISBN: 0-471-39435-1. 987 pp.

TABLE 3
ADVANTAGES AND DISADVANTAGES FOR PHYTOTECHNOLOGIES

Advantages
Substantial cost savings are possible.
Greater public acceptance may result from use of an environmentally-friendly "green" and low-tech remedial technology.
Operation and maintenance costs are typically lower than those required for traditional remedies (such as soil vapor extraction), because the remedy is generally resilient and self-repairing.
Vegetation can help to reduce or prevent erosion and fugitive dust emissions.
Plants can also improve air quality and sequester greenhouse gases.
Plants can improve site aesthetics (visual appearance and noise).
Site soil structure and fertility are not negatively impacted (and likely are improved).
Remedy may be applicable at remote locations.
Can be used adjacent to and without damage to mature trees and shrubs, and hardscape like decks and slate walkways.
Phytotechnologies may be used in combination with other restoration or mitigation goals, such as a vegetated cap or creating ecological diversity.
Potential to create new habitat or supplement existing habitat.
Final stages of a phytotechnology project can provide a land reuse/restoration asset upon completion.
Disadvantages
Phytotechnologies may not be appropriate for sites with contamination at significant depths due to the generally shallow distribution of plant roots.
A longer time period than more traditional, intrusive cleanup technologies may be required to achieve remedial goals.
A large land area may be required for effective treatment in certain situations.
High initial contaminant concentrations at a site may be phytotoxic and inhibit or prevent plant growth.
Amendments and cultivation practices might exert unintended effects on contaminant mobility.
Cultivation of vegetation can be more difficult under the adverse conditions of contaminated soil or groundwater; plant growth and associated remediation may not occur during winter season.
A risk analysis may be necessary before disposal of any contaminated plant material.
Potential to create new fate and transport pathways that may never have existed at the site prior to applying a particular phytotechnology (i.e., due to habitat creation).
Sampling and analysis of plant and core tissues may be required to verify contaminant transfer issues occurring within the plant.

Sources: ITRC. 2009. Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised. EPA. 2001a. Phytoremediation of Contaminated Soil and Ground Water at Hazardous Waste Sites, EPA 540-S-01-500. February.

is successful, the pilot study will demonstrate if the site conditions are compatible with the selected plants. These studies use site soil and/or groundwater samples containing a range of concentrations of the target contaminants to determine remedial effectiveness. As for many remedial approaches, sites undergoing treatment with phytotechnologies will be monitored to assess performance. Decision trees and other information to support evaluation of phytotechnology at a specific site are provided in Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised (ITRC 2009).

Photograph 1: *Collection of gas and water vapor from a poplar tree at the Oregon Poplar Superfund Site in Clackamas, Oregon. Native and hybrid poplar trees were planted on the site in 1998 to remediate groundwater contaminated with volatile organic compounds. Source: EPA. http://www.epa.gov/superfund/accomp/news/phyto.htm*

APPLICATIONS OF PHYTOTECHNOLOGIES

The effectiveness and economic viability of a phytotechnology depend on climate, elevation, precipitation, soil type and quality, the type, age, distribution, and concentration of contamination, media, and the viability of the plants and planting system used for each site. Results of research, laboratory studies, and field tests at similar sites can serve as a guide to determining whether phytotechnologies are appropriate for a site. Successful precedence can help you identify appropriate plant species for implementation at your site. If relevant existing local data are not available or applicable, then site specific studies may be needed. If local data are used, ensure that site conditions are similar to the surrounding, undisturbed areas.

This section discusses contaminants that have been successfully remediated or contained using phytotechnologies and contaminants for which applications have not proven effective. As phytotechnology is relatively new, methods, plant selection, and applications are constantly evolving and improving. The phytotechnology matrix in Table 4 lists mechanisms, applications, and levels of testing for contaminants that phytotechnologies have effectively removed or controlled.

Organic Compounds

Many organic compounds can be contained or remediated through phytodegradation, rhizodegradation, phytosequestration, and phytovolatilization. In addition, phytohydraulics can be used to contain or remediate groundwater contaminated with organic compounds. Information on how phytotechnologies apply to organic compounds is included below.

Chlorinated Solvents and Volatile Organic Compounds (VOC)

Poplar trees, whose roots can grow up to 15 feet, have proven successful at many sites for groundwater control and contaminant removal through rhizodegradation, phytodegradation, and phytovolatilization of chlorinated solvents

Photograph 2: *Trees planted by Argonne National Laboratory in Murdock, Nebraska in 2005. Phytoextraction is one of the technologies used to remediate groundwater contaminated with carbon tetrachloride. Source: Argonne National Laboratory.*

through leaves and bark, as well as sorption of contaminants to plant tissues (Compton et al. 2003). Phytovolatilization can potentially release some contaminants into the atmosphere. However, high levels of chlorinated solvents have not been found in the air around the vegetation (EPA 2001b).

Studies have shown that poplar trees can create a hydraulic barrier by extracting large amounts of shallow groundwater (RTDF 2005). For example, at the Aberdeen Proving Ground site, plantings of poplars reversed groundwater flow during the summer months (Van Den Bos 2002). However, water uptake, as well as contaminant uptake in soil, essentially stops during the winter when plants are dormant. Rhizodegradation continues but at a reduced rate. During project design, it is important to model seasonal variations in water uptake by the trees. If the model shows that the plume will travel beyond the trees by the end of the dormant season, then a backup system would be needed (ITRC 2009).

Munitions

Phytotechnologies show considerable promise for explosives remediation, especially for treatment of large volumes of lightly contaminated soil and groundwater through phytodegradation (McCutcheon and Schnoor 2003). The Department of Defense has conducted extensive research into using phytotechnologies for cleanup of ground and surface water contaminated with explosives, including trinitrotoluene (TNT), cyclotrimethylenetrinitramine (RDX), and similar compounds. Most research studies have been conducted using wetland plants and have shown promising results. For example, two engineered wetlands were constructed at the Iowa Army Ammunition Plant to phytoremediate explosives-contaminated surface water. The wetlands successfully remediated RDX in surface water from approximately 800 parts per billion to non-detect levels (Kiker et al. 2001).

In addition, research is being conducted on the development of transgenic plants (see Transgenics Section of this fact sheet) that are able to phytoremediate RDX-contaminated soils. The plants have an enzyme that uses bacteria to break down RDX and decrease toxicity of the contaminant (Rylott et al 2006).

Perchlorate is a common munitions constituent. A laboratory study by the University of Georgia showed that perchlorate-contaminated water could be remediated through phytodegradation and rhizodegradation under anaerobic conditions. Laboratory studies for perchlorate-contaminated soil (simulating field conditions) also showed removal of perchlorate (Willey 2007).

Persistent Organic Pollutants (POP)

POPs consist of a group of contaminants, mainly pesticides and polychlorinated biphenyls (PCB), with the following characteristics: toxicity, persistence, bioaccumulation, and long-range transport. Phytotechnologies are generally not considered to be feasible for stockpiles of PCB-contaminated soil but can be used as a polishing technology for residual contamination in soil. While a pilot study using three different types of plants (zucchini, sedge, and fescue) showed insight for future studies, none of the species in this study were likely to provide a cost-effective alternative to traditional treatment methods. Soil samples after one growing season revealed no detectable decrease in soil PCB concentrations, and the study reported that it could take several growing cycles before a decrease in soil PCB concentration might be observed (Whitfield Aslund et al. 2006).

POPs have been treated using phytostabilization and phytohydraulics. Laboratory research has shown the potential for rhizodegradation and phytoextraction of PCBs. Preliminary research has identified plant species that effectively accumulate highly weathered pesticide and PCB residues from the soil. Research from the Ukraine and Kazakhstan has shown that bean plants can accumulate and even decompose the pesticide dichlorodiphenyltrichloroethane (DDT) (EPA 2006).

Pesticides such as dichlorodiphenyldichloroethylene (DDE) have been detected in the roots of a variety of vegetables, but translocation of these contaminants from the roots to the shoots has been found only in zucchini and pumpkin (Willey 2007). For example, a pilot study was conducted that compares the ability of closely related species (zucchini and squash) to take up DDE from contaminated soil as well as from hydroponic solutions. Results from the study show that zucchini roots and stems extracted 12 times more DDE than squash tissue. In addition, in hydroponic solutions, squash was significantly more sensitive to DDE exposure than zucchini (Chhikara, S. and others 2010).

Petroleum Products

Petroleum products that have impacted soil, surface water, or groundwater have been successfully remediated, generally through rhizodegradation. Most commonly, studies on rhizodegradation of petroleum products used grasses; but other species, such as hybrid poplars, willows, and legumes, were also used. However, the presence of mixtures of contaminants at a site poses greater difficulty for designing and selecting a successful phytoremediation approach. Moreover, high molecular weight PAHs and aged petroleum products are less bioavailable and not successfully remediated by phytotechnologies (Van Epps 2006).

Laboratory and field studies have shown that lower weight PAHs can be remediated using various combinations of grasses through rhizodegradation and phytovolatilization. Native grasses, perennial ryegrass (*Lolium perenne*), introduced cool-season and warm-season grasses, and legumes have been used (EPA 2001a).

Metals and Other Inorganics

Metals and other inorganics cannot be degraded through phytotechnology mechanisms. Generally, phytotechnologies have had limited success in efforts to extract metals. An alternative is to stabilize the metals and ecologically restore the site using soil amendments. "The Use of Soil Amendments for Remediation, Revitalization and Reuse" (EPA 542-R-07-013) provides additional information on this topic (EPA 2007) and is available at: http://www.clu-in.org/download/remed/epa-542-R-07-013.pdf. "Chelators" can be added to soil to enhance the plant-availability of contaminants, but some types of amendments may also increase the bioavailability and mobility of these chemicals, and may cause leaching of the chelated pollutants into groundwater (Chaney et al. 2007).

Some metals and metal-complexes in soils can be remediated by phytoextraction and phytosequestration. Phytovolatilization can occur with some metals (specifically, mercury and selenium). Phytohydraulics can also be used to contain and treat groundwater contaminated with certain metals. High-biomass plants extract low levels of metals as essential nutrients, while hyperaccumulators can take up and concentrate a particular contaminant up to 100 or 1,000 times greater than the concentration in soil; this higher concentration of metals in the leaves may discourage animal consumption of the plants (Pollard and Baker 1997) or provide an advantage to plants in colonizing harsh soils. Phytotechnology applications for a variety of metals are discussed below.

Arsenic

Arsenic contaminated soil and groundwater have been successfully remediated through phytoextraction. Some ferns, such as *Pteris vittata*, have been shown to hyperaccumulate arsenic effectively (Ma et al. 2001). These ferns grow in areas with mild climates and have roots that extend about 12 inches into the soil, depending on soil texture and arsenic concentration in the soil (Liao et al. 2004). Therefore, appropriate sites for this application are limited to those in mild climates with relatively shallow contamination. Phytoextraction of arsenic is applicable for small or large sites.

At appropriate sites, hyperaccumulating ferns, such as Pteris vittata and *Pityrogramma calomelanos*, can accumulate over 2 percent arsenic in their biomass (Gonzaga et al. 2006); Edenfern™ can accumulate arsenic in its fronds at levels up to 100 times the underlying soil concentration (Edenspace 2010). While *Pteris vittata* is considered a hyperaccumulator for arsenic, the plant converts arsenate to arsenite (a highly toxic form of arsenic), so caution is required if using these plants (Peer 2005). At a contaminated site, fronds can be harvested for recycling or landfill disposal. Where recycling is feasible, arsenic in the fronds can be recovered at rates greater than 70 percent through fluid extraction; recovered arsenic can be reused in industrial applications.

Cadmium

Phytoextraction of cadmium contaminated soil has been shown to be very slow because of the low biomass and slow growth rate of cadmium-specific hyperaccumulators. However, research studies show that the process can be enhanced by using two-phase planting of the hyperaccumulator Cress (*Rorippa globosa*). In two-phase cultivation, the plants are transplanted into contaminated soils twice in one year by harvesting the plants when they are flowering. Research results are promising, but literature reviewed for this fact sheet does not document field applications (Wei and Zhou 2006).

TABLE 4
PHYTOTECHNOLOGY MATRIX

Contaminant	Phytotechnology Mechanism						Applications									Scale					Additional Comments	Reference
	Phytosequestration	Rhizodegradation	Phytohydraulics	Phytoextraction	Phytodegradation	Phytovolatilization	Constructed Treatment Wetland/Aquatic Plant Lagoon	Field Crops/Gardens	Landfill Cover	Riparian Buffer	Tree Hydraulic Barrier	Tree/Shrub Plantation	Hydroponic Solutions	Sorption to plant tissues	Hyper-accumulation	Greenhouse	Laboratory	Field	Pilot	Full-scale		
Organic Compounds																						
BTEX		✓	✓		✓	✓	✓	✓			✓							✓	✓	✓	Poplars, willows, grasses, and legumes have been used to remediate soil and groundwater.	Phytotechnology Profile for Fort Drum Gasoline Alley*
Chlorinated Solvents		✓	✓		✓	✓	✓						✓	✓				✓	✓	✓	Poplar trees take up chlorinated solvents from contaminated groundwater.	Compton 2003 EPA 2001b
PCBs	✓	✓	✓	✓													✓		✓		Not feasible for stockpiles of PCB-contaminated soil but can be used as a polishing technology.	Whitfield Aslund et al. 2006
Munitions		✓			✓		✓	✓				✓	✓			✓	✓	✓	✓		Wetland plants take up TNT, RDX, and similar compounds.	Kiker et al. 2001 Willey 2007
PAHs		✓						✓				✓						✓				Van Epps 2006
Pesticides	✓		✓				✓	✓		✓							✓		✓		Bean plants have been shown to accumulate and decompose DDT. Zucchini roots and stems can extract DDE and are less sensitive to DDE exposure than squash tissue. Hybrid poplars have been used in riparian buffer strips.	EPA 2006 Chhikara, S. and others 2010 EPA 2000
Petroleum Products		✓			✓	✓	✓	✓				✓					✓	✓		✓	Aged petroleum products are not usually bioavailable and not successfully treated via phytotechnologies. Low molecular weight PAHs have been remediated using native grasses, perennial ryegrass (Lolium perenne), introduced cool-season and warm-season grasses, and legumes.	Van Epps 2006 EPA 2001a
Inorganics																						
General																					Bioconcentration is a concern for metals.	
Arsenic			✓	✓				✓	✓						✓			✓	✓	✓	Appropriate for sites with contaminants in the top 12-24 inches of soil. Poplars used to control landfill leachate in closed portions of a landfill.	Ma et al. 2001 Gonzaga et al. 2006 Edenspace 2010 EPA 2000
Cadmium	✓			✓			✓	✓				✓			✓	✓	✓	✓	✓		Uptake of cadmium into plants is slow.	Wei and Zhou 2006
Chromium	✓			✓			✓	✓								✓	✓	✓			Willow and Birch trees take up chromium but it stays in the roots. Tumbleweed and Russian thistle accumulate chromium.	Pulford et al. 2001 Krishnani et al. 2004 Gardea-Torresdey et al. 2005
Copper				✓			✓	✓					✓		✓	✓	✓	✓			Soil amendments can increase copper uptake in Indian mustard, but field tests are needed to determine feasibility.	Kuzovkina et al. 2004 Wu et al. 2004
Nickel				✓			✓	✓							✓	✓	✓				Plants in the mustard family accumulate nickel.	Chaney et al. 2007
Selenium	✓			✓		✓	✓					✓							✓		Duckweed and Water hyacinth have been used to treat selenium using wetlands, and Indian mustard and Canola phytovolatilize selenium.	EPA 2001a EPA 2000
Radionuclides	✓	✓		✓			✓	✓					✓		✓	✓	✓	✓			Sunflower plants remove uranium, cesium, and strontium from hydroponic solutions. Soil amendments can increase radionuclide uptake in Johnson grass.	EPA 2004

Notes:
BTEX Benzene, toluene, ethylbenzene, and xylenes
PAH Polycyclic aromatic hydrocarbon
PCB Polychlorinated biphenyl
RDX Cyclotrimethylenetrinitramine
TNT Trinitrotoluene

* Phytotechnology Profiles can be found at *http://www.clu-in.org/products/phyto*

Chromium

While a chromium-specific hyperaccumulator has not been identified, recent studies indicate that certain plant species can be applied to address chromium contamination in soil, surface water, or groundwater by removal through phytoextraction and phytostabilization. For example, willow (*Salix spp.*) and birch (*Betula spp.*) trees are able to take up chromium and could be used to treat chromium-contaminated groundwater; however, chromium stays mainly within the roots (Pulford et al. 2001). In addition, chromium in estuaries (specifically, high saline coastal waters) can be absorbed by agricultural waste material, or bagasse (fiber remaining after juice is removed from sugarcane) (Krishnani et al. 2004). Finally, tumbleweed or Russian thistle (*Salsola kali*) has been shown to accumulate chromium, specifically chromium(VI); this indicates that this plant might be considered for phytoextraction of chromium in soil (Gardea-Torresdey et al. 2005).

Copper

No known hyperaccumulator has been identified for phytoextraction of copper. Initial studies using a greenhouse hydroponic system (i.e., plants grown in a media nutrient solution) have shown that black willow (*Salix nigra*) accumulates more copper than other willow species, but field studies are necessary to determine the feasibility of this species for phytoextraction of copper (Kuzovkina et al. 2004). In addition, soil amendments, such as phosphate, can increase copper uptake as shown in initial studies using Indian mustard (*Brassica juncea*) plants, and could be further researched for phytotechnology applications (Wu et al. 2004).

Lead

The use of soil amendments and planted systems to stabilize lead in soil is quite effective (EPA 2007). However, because lead is only sparingly bioavailable in soil, phytoextraction is ineffective. Significant research has gone into the use of soil chelators to enhance bioavailability of lead, but these amendments can cause the indiscriminate increase of lead mobility, and leaching of the chelated lead into surface and groundwater while not being very effective for increasing lead uptake by plants (Chaney et al. 2007).

Nickel

Mine sites with nickel impacted soils have been successfully remediated by phytoextraction using the hyperaccumulators *Alyssum sp.*, which include plants in the mustard family. In addition, Alyssum hybrids have been developed to allow phytomining (that is, extracting nickel from the plants by drying and combusting the plants) (Chaney et al. 2007).

Selenium

Selenium impacted soil, sediment, and surface water have been successfully remediated through phytoextraction, phytosequestration, and phytovolatilization, depending on the plants used. For example, the aquatic plants duckweed (*Lemnaoideae*) and water hyacinth (*Eichhornia spp.*) can effectively remediate selenium using constructed treatment wetlands (EPA 2001a). In addition, Indian mustard (*Brassica juncea*) and canola (*Brassica napus*) have been used in phytovolatilization of selenium; in this application, selenate is converted to a less-toxic dimethyl selenite gas and released to the atmosphere (EPA 2000).

Zinc

Pilot studies to date have shown that phytoextraction is likely not effective for removing zinc from soil. Many plant species are not able to accumulate significant amounts of zinc. Those that do effectively remove zinc are slow growing, or do not have much biomass. Moreover, although a few plant species can accumulate zinc (for example, *Thlaspi caerulenscens*), the presence of other contaminants commonly found with zinc, such as copper, can limit the growth of these plants and their uptake of zinc (Lombi et al. 2001).

Radionuclides

Phytoextraction has been considered for remediation of soil and water contaminated with radionuclides. Some studies show that the potential of phytoextraction could be greater for addressing technetium (Tc) than other radionuclides. While Tc appears to be less bioavailable in terrestrial ecosystems, aquatic plants have a strong potential to accumulate and retain Tc. Regarding other radionuclides, sunflower plants effectively remove uranium, cesium, and strontium from hydroponic solutions. In addition, plants such as redroot pigweed take up cesium and strontium from contaminated soil (EPA 2004).

Soil amendments can increase plant uptake of radionuclides. One study showed that Johnson grass (*Sorhgum halpense*) planted in soil amended with poultry litter accumulated greater amounts of cesium and strontium than did other plant species in soil amended with poultry litter or other soil amendments.

Transgenics

No full-scale applications of transgenic, or genetically altered, plants for site remediation are known. A few laboratory and pilot studies have shown promising results in using transgenic plants for phytoextraction of contaminants (for cases where effective natural plants have not been identified). Transgenic research on a variety of applications is occurring for constructed treatment wetlands, field crops, and tree plantations for several contaminants. Much of the current transgenic research is focused on understanding the genomics behind the ability of some plants and bacteria to modify or remove pollutants (Doty 2008). This section includes some examples of transgenic research being conducted.

Permits from U.S. Department of Agriculture and or state agencies may be needed prior to testing or using transgenic plants. For additional information on USDA permits for studies and other applications involving transgenic plants, see: *http://www.aphis.usda.gov/permits/brs_epermits.shtml.*

Phytotechnology Success Stories on Superfund Sites

- **Aberdeen Proving Grounds, J-Fields, Maryland:** Hybrid poplar trees were used to remove TCE and tetrachloroethylene (PCE) contamination from the groundwater. http://www.epa.gov/reg3hscd/super/sites/MD2210020036/index.htm
- **Combustion, Inc., Louisiana:** Poplars, native willows, and eucalyptus were used to remediate PCB contamination in groundwater. http://www.epa.gov/region6/6sf/pdffiles/0600472.pdf
- **Tibbetts Road, New Hampshire:** A wooded phytoremediation area was planted to treat soil and groundwater contaminated with chlorinated and non-chlorinated solvents. http://www.wildlifehc.org/ewebeditpro/items/O57F3072.pdf
- **Aberdeen Pesticide Dumps, North Carolina:** Trees were planted to remediate groundwater contaminated with VOCs, pesticides, semi-volatile organic compounds (SVOC), and metals. http://www.epa.gov/region04/waste/npl/nplnc/aberdnnc.htm
- **Fort Wainwright, Alaska:** Willows were planted to remediate soil and groundwater contaminated with pesticides. http://www.clu-in.org/products/phyto/search/phyto_details.cfm?ProjectID=44
- **Bay Road, California:** Eucalyptus and tamarisk were planted for hydraulic control of groundwater contaminated with arsenic within a slurry wall. http://www.clu-in.org/products/phyto/search/phyto_details.cfm?ProjectID=64
- **McCormick and Baxter Superfund site, Oregon:** Hybrid poplars and perennial rye grasses were used to remediate shallow soil contaminated with PAHs and pentachlorophenol (PCP). http://www.deq.state.or.us/lq/cu/nwr/McCormickBaxter/
- **Hanford 100-N Area, Washington:** Phytoremediation was selected as a polishing step for groundwater contaminated with strontium 90. http://www.hanford.gov/docs/gpp/science/em21/phyto%20work%20plan.pdf
- **Naples Truck Stop, Utah:** Poplars were used to remediate groundwater contaminated with petroleum products. http://www.clu-in.org/products/phyto/search/phyto_details.cfm?ProjectID=190
- **Palmerton Zinc Pile Superfund Site, Pennsylvania:** Grasses were used for hydraulic control and stabilization of soil, sediment, and groundwater contaminated with metals. http://www.epa.gov/reg3hscd/super/sites/PAD002395887/index.htm
- **Fort Drum Gasoline Alley, New York:** Willows were used to remediate surface water contaminated with benzene, toluene, ethylbenzene, and xylenes (BTEX). http://www.clu-in.org/products/phyto/search/phyto_details.cfm?ProjectID=229
- **East Multnomah County Groundwater Contamination, Cascade Corporation Site (OU 2), Oregon:** Poplars were used to remediate groundwater contaminated with TCE. http://www.deq.state.or.us/lq/ECSI/ecsidetail.asp?seqnbr=635
- **Edward Sears Poplar Site, New Jersey:** Hybrid Poplars were used to remediate groundwater contaminated with volatile organic compounds. http://costperformance.org/profile.cfm?ID=62&CaseID=62
- **Kauffman and Minteer Site, New Jersey:** Native black willows and hybrid poplars were planted in this pilot study to remediate soil and groundwater contaminated with chlorinated solvents. http://cluin.org/download/techfocus/phyto/RemediationJ-13-3-21.pdf (p. 31)
- **Oregon Poplar Site, Oregon:** Native and hybrid poplar trees were planted on the site in 1998 to remediate groundwater contaminated with volatile organic compounds. http://www.epa.gov/superfund/accomp/news/phyto.htm

The transgenic plants *Arabidopsis thaliana L.* and tobacco (*Nicotiana tobacum*) can transform methyl-mercury into elemental mercury before releasing it into the atmosphere. From a regulatory perspective, however, such mercury releases are not acceptable; therefore, these genetically altered plants are not recommended for phytovolatilization of mercury. A research team at the University of Georgia successfully developed a transgenic yellow poplar (*Liriodendron tulipifera*) that is fast growing, pest resistant, and effective at absorbing mercury. This transgenic poplar transformed ionic mercury to a much less toxic and less volatile metallic mercury (Meagher 1999; Dhankher and Meagher 2003). Additional research is focusing on (1) increasing plant tolerance to mercury and arsenic, (2) transforming the toxic elements to promote transport from roots to shoots, (3) transforming these toxic elements to promote storage in the aboveground plant parts, (4) enhancing the plants' ability to trap toxicants aboveground, and (5) enhancing transporters for uptake and storage (Meagher 2007).

In 2007, researchers at the University of Washington published promising results regarding the development of a transgenic poplar for phytoremediation of trichloroethylene (TCE), vinyl chloride, carbon tetrachloride, benzene, and chloroform in water and air (Doty and others 2007).

Field studies completed using transgenic Indian mustard plants to phytoremediate soil contaminated with selenium and boron show promise. The transgenic plants accumulated much more selenium in their leaves and tolerated the contaminated soil better than natural Indian mustard plants (growing much more successfully in contaminated soil) (Banuelos 2005).

Additional examples of phytotechnology research, including the use of transgenic plants and endophytes, or bacteria that reside within plant tissue, can be found in Doty's "Enhancing phytoremediation through the use of transgenics and endophytes" (2008).

Resources Used for this Fact Sheet

Banuelos, Gary and others. 2005. "Field Trial of Transgenic Indian Mustard Plants Shows Enhanced Phytoremediation of Selenium-Contaminated Sediment." Environmental Science and Technology. Vol. 39, No. 6, pp. 1771-1777. http://chemphys.armstrong.edu/nivens/Chem3300/phyto3.pdf

Chaney, Rufus L., Minnie Malik, Yin M. Li, Sally L. Brown, Eric P. Brewer, J. Scott Angle, and Alan J. M. Baker. 1997. "Phytoremediation of soil metals." Environmental Biotechnology. Vol. 8, pp. 279-284.

Chaney, Rufus L., J. Scott Angle, C. Leigh Broadhurst, Carinne A. Peters, Ryan V. Tappero, and Donald L. Sparks. 2007. "Improved Understanding of Hyperaccumulation Yields Commercial Phytoextraction and Phytomining Technologies." Journal of Environmental Quality. Vol. 36, pp. 1429-1443.

Chhikara, Sudesh, Bibin Paulose, Jason C. White, and Om Parkash Dhankher. 2010. Understanding the Physiological and Molecular Mechanism of Persistent Organic Pollutant Uptake and Detoxification in Cucurbit Species (Zucchini and Squash). Environ. Sci. Technol. Accepted April 21, 2010.

Compton, Harry R., George R. Prince, Scott C. Fredericks, and Christopher D. Gussman. 2003. "Phytoremediation of Dissolved Phase Organic Compounds: Optimal Site Considerations Relative to Field Case Studies." Remediation. Summer Edition.

Dhankher, Om Parkash and Richard B. Meagher. 2003. Strategies for the Engineered Phytoremediation of Mercury and Arsenic Pollution.

Doty, Sharon L. and others. 2007. "Enhanced Phytoremediation of Volatile Environmental Pollutants with Transgenic Trees." Proceedings of the National Academy of Sciences of the United States of America. Vol. 104, No. 43, pp. 16816 – 16821. http://www.pnas.org/content/104/43/16816.full

Doty, S.L. 2008. "Enhancing phytoremediation through the use of transgenics and endophytes." New Phytologist. Vol. 179, pp. 318-333.

Edenspace. 2010. Phytoremediation of Arsenic-Contaminated Soils. Edenspace Systems Corporation; SBIR Success Stories. http://www.edenspace.com/products/envirosolutions.html?expandable=1

Gardea-Torresdey JL, G. de la Rosa, J.R. Peralta-Videa, M. Montes, G. Cruz-Jimenez, and I. Cano- Aguilera. 2005. "Differential uptake and transport of trivalent and hexavalent chromium by tumbleweed (Salsola kali)." Arch Environ Contam Toxicol. PMID:15696348.

Gonzaga, Maria Isidoria Silva, Jorge Antonio Gonzaga Santos, and Lena Qiying Ma. 2006. "Arsenic Phytoextraction and Hyperaccumulation by Fern Species." Scientia Agricola. (Piracicaba, Braz.). Vol. 63, No. 1. Piracicaba Jan./Feb. http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0103-90162006000100015

Interstate Technical Regulatory Council (ITRC). 2009. Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised.

Kiker, Jackson H., Steve Larson, Donald D. Moses, and Randy Sellers. 2001. "Use of Engineered Wetlands to Phytoremediate Explosives Contaminated Surface Water at the Iowa Army Ammunition Plant, Middletown, Iowa." Proceedings of the 2001International Containment and Remediation Technology Conference and Exhibition. http://www.containment.fsu.edu/cd/content/pdf/416.pdf

Krishnani, K., V. Parimala, and X.G. Meng. 2004. "Detoxification of chromium(VI) in coastal water using lignocellulosic agricultural waste." Water SA. Vol. 30, pp. 541-545.

Kuzovkina, Y.A., M. Knee, and M.F. Quigley. 2004. "Cadmium and copper uptake and translocation in five willow (Salix L.) species." Int J Phytoremediation. Vol. 6, pp. 269-287.

Liao, X.-Y., T.-B. Chen, M. Lei, Z.-C. Huang, X.-Y. Xiao, and Z.-Z. An. 2004. "Root distributions and elemental accumulations of Chinese brake (Pteris vittata) from As-contaminated soils." Plant and Soil. Vol. 261, No. 1-2, pp. 109-116.

Lombi, E., F. J. Zhao, S. J. Dunham, and S. P. McGrath. 2001. "Phytoremediation of Heavy Metal-Contaminated Soils : Natural Hyperaccumulation versus Chemically Enhanced Phytoextraction." J. Environ. Qual. Vol. 30, pp. 1919-1926.

Ma, L. Q., K.M. Komar, C. Tu, W.H. Zhang, Y. Cai, and E.D. Kennelley. (2001). "A fern that hyperaccumulates arsenic: a hardy, versatile, fast-growing plant helps to remove arsenic from contaminated soils." Nature. Vol. 409, p. 579.

McCutcheon, S.C. and J. L. Schnoor. 2003. Phytoremediation: Transformation and Control of Contaminants. John Wiley & Sons, Inc., Hoboken, New Jersey. ISBN: 0-471-39435-1. 987 pp.

Meagher, Richard B. 1999. Phytoremediation of Ionic and Methyl Mercury Pollution. DOE-EMSP 6/14/1999. http://www.osti.gov/em52/1999projsum/54837.pdf

Meagher, R.B. (2007). Multigene strategies for engineering the phytoremediation of mercury and arsenic. In: Biotechnology and Sustainable Agriculture 2006 and Beyond: Proceeding of the 11th IAPTC&B Congress, Z. Xu, J. Li, Y. Xue, and W. Yang, eds (Beijing, China: Springer), 49-60. http://ersdprojects.science.doe.gov/workshop_pdfs/new_orleans_2003/first_session/Dhanker.pdf

Peer, Wendy Ann and others. 2005. Phytoremediation and Hypeaccumulator Plants.

Pollard, A. Joseph and Alan J. M. Baker. 1997. "Deterrence of herbivory by zinc hyperaccumulation in Thlaspi caerulescens (Brassicaceae)." New Phytologist. Vol. 135, Issue 4, pp. 655-658.

Poynton, CY, J.W. Huang, M.J. Blaylock, L.V. Kochian, and M.P. Elless. 2004. "Mechanisms of arsenic hyperaccumulation in Pteris species: root as influx and translocation." Planta. Vol. 219, No. 6, pp. 1080-1088.

Pulford, I. D., C. Watson, and S.D. McGregor. 2001. "Uptake of chromium by trees: prospects for phytoremediation." Environmental Geochemistry and Health. Vol 23, pp. 307–311.

U.S. Environmental Protection Agency (U.S. EPA). 2000. Introduction to Phytoremediation, EPA 600-R-99-107. February.

U.S. EPA. 2001a. Phytoremediation of Contaminated Soil and Ground Water at Hazardous Waste Sites, EPA 540-S-01-500. February. http://www.epa.gov/nrmrl/pubs/540s01500/epa_540_s01_500.pdf

U.S. EPA. 2001b. Evaluation of Phytoremediation for Management of Chlorinated Solvents in Soil and Groundwater, EPA 542-R-05-001. http://www.rtdf.org/public/phyto/chlor_solv_management.pdf

U.S. EPA. 2004. Radionuclide Biological Remediation Resource Guide, EPA 905-B-04-001. August. http://www.cluin.org/download/remed/905b04001.pdf

U.S. EPA. 2006. Reference Guide to Non-combustion Technologies for Remediation of Persistent Organic Pollutants in Stockpiles and Soil, EPA-542-R-05-006. December. http://www.clu-in.org/download/remed/542r05006/final_pops_report_web.pdf

U.S. EPA. 2007. The Use of Soil Amendments for Remediation, Revitalization and Reuse, EPA 542-R-07-013. December.

U.S. EPA. 2005. Evaluation of Phytoremediation for Management of Chlorinated Solvents in Soil and Groundwater, EPA 542-R-05-001. Prepared by the Remediation Technologies Development Forum (RTDF), Phytoremediation of Organics Action Team, Chlorinated Solvents Workgroup. January.

Van Den Bos, Amelie. 2002. Phytoremediation of Volatile Organic Compounds in Groundwater: Case Studies in Plume Control. Prepared for EPA Office of Solid Waste and Emergency Response, Technology Innovation Office. Washington DC. August. http://www.clu-in.info/download/studentpapers/vandenbos.pdf

Van Epps, Amanda. 2006. Phytoremediation of Petroleum Hydrocarbons. Prepared for EPA Office of Solid Waste and Emergency Response, Office of Superfund Remediation and Technology Innovation. Washington, DC. August. http://clu-in.org/download/studentpapers/A_Van_Epps-Final.pdf

Wei, S.H. and Q.Z. Zhou. 2006. "Phytoremediation of Cadmium-contaminated Soils by Rorippa globosa using Two-Phase Planting." Environ Sci Pollut Res Int. Vol. 13, number 3 (May), pp. 151-155. http://www.ncbi.nlm.nih.gov/pubmed/16758704

Wenzel, W.W., D.C. Adrians, D. Salt, and R. Smith. 1998. "Phytoremediation: A Plant-Microbe-Based Remediation System. Bioremediation of Contaminated Soils." Agronomy Monograph, No. 37, pp. 457-508.

Willey, Neil. 2007. Phytoremediation: Methods and Reviews. Humana Press.

Wu, L. H., H. Li, Y. M. Luo, and P. Christie. 2004. "Nutrients can enhance phytoremediation of copper-polluted soil by Indian mustard." Environmental Geochemistry and Health. Vol. 26, pp. 331-335.

Additional EPA Resources

- Clu-in Technical Focus on Phytoremediation: *http://www.cluin.org/techfocus/default.focus/sec/Phytotechnologies/cat/Overview*
- Phytotechnology Project Profiles: *http://www.cluin.org/products/phyto*

Additional Information Resources

- Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised.
- Interstate Technology and Regulatory Council (ITRC) Phytotechnologies Team. 2009.
- PHYTO-3, 187 pp. *http://www.itrcweb.org/Documents/PHYTO-3.pdf*
- International Journal of Phytoremediation: *http://www.tandf.co.uk/journals/titles/15226514.asp*
- International Society of Phytotechnologies: *http://www.phytosociety.org*
- U.S. Department of Agriculture Plants Database: *http://plants.usda.gov*
- Phytoremediation Electronic Newsgroup Network: *http://www.dsa.unipr.it/phytonet*

WHO CAN I CONTACT FOR MORE INFORMATION?

If you have any questions or comments on this fact sheet, please contact:

Steven Rock, EPA
rock.steven@epa.gov

Linda Fiedler, EPA
fiedler.linda@epa.gov

Office of Superfund Remediation
and Technology Innovation
(5203P)

EPA 542-F-10-009
September 2010
www.epa.gov