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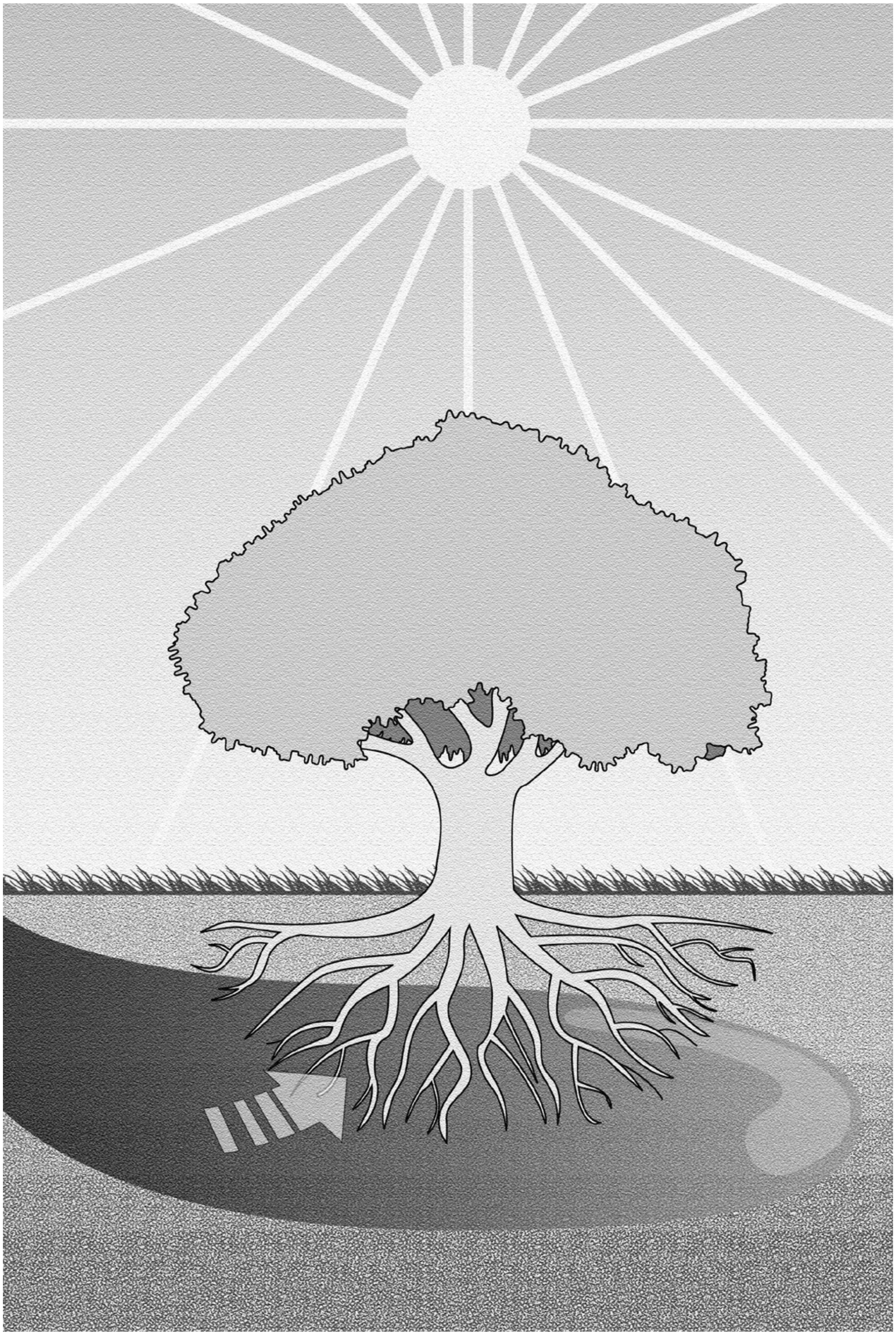
Brownfields Technology Primer: Selecting and Using Phytoremediation for Site Cleanup



Brownfields Technology Primer: Selecting and Using Phytoremediation for Site Cleanup

U.S. Environmental Protection Agency
Office of Solid Waste and Emergency Response
Technology Innovation Office
Washington, DC 20460

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Notice

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1.0 INTRODUCTION

1.1 Purpose

The Brownfields Technology Support Center (BTSC) (see box) has developed this document to provide an educational tool for site owners, project managers, and regulators to help evaluate the applicability of the phytoremediation process at brownfields sites. Cleanup technologies that reduce costs, decrease time frames, or positively affect other decision considerations (for example, community acceptance) can have a significant effect on the redevelopment potential of brownfields sites. Increased attention to brownfields sites and the manner in which they are redeveloped places greater importance on the selection of cleanup technologies.

Phytoremediation represents a group of innovative technologies that use plants and natural processes to remediate or stabilize hazardous wastes in soil, sediments, surface water, or groundwater. Because it is based on natural processes, phytoremediation may be easily adaptable to many redevelopment plans for brownfields sites. Phytoremediation is being evaluated at a variety of sites and on myriad contaminants to determine the conditions under which phytoremediation systems are effective in reducing contamination. The primer presents some of the advantages and technical limitations of phytoremediation that the evaluations indicate. The primer illustrates the potential of phytoremediation to serve as:

- An interim approach for stabilizing sites while other cleanup strategies are being evaluated
- An approach that augments the overall effectiveness of other cleanup technologies
- A stand-alone approach for providing cost-effective, long-term cleanup solutions

The primer also illustrates the potential limitations of phytoremediation and how such factors as levels of contaminants and properties of the soil, as well as concerns about potential risk of exposure may affect the use of phytoremediation at brownfields sites. Because phytoremediation is more than simply planting vegetation, brownfields decision makers must: (1) select the correct plants, (2) work effectively with regulators and the local community, (3) understand maintenance and monitoring requirements, and (4) compare the costs of phytoremediation with the costs of other technology options.

Until phytoremediation is a more proven and established technology, advocates for its use may find it necessary to demonstrate its potential applicability and efficacy on a site-specific basis. To do so may require an up-

Brownfields Technology Support Center

EPA recently established the Brownfields Technology Support Center to ensure that brownfields decision makers are aware of the full range of technologies available for conducting site assessments and cleanup, and can make informed decisions about their sites. The center can help decision makers evaluate strategies to streamline the site assessment and cleanup process, identify and review information about complex technology options, evaluate contractor capabilities and recommendations, explain complex technologies to communities, and plan technology demonstrations. The center is coordinated through EPA's TIO and works through the laboratories of EPA's Office of Research and Development. Localities can submit requests for assistance directly through their EPA Regional Brownfields Coordinators; online at <*http://brownfieldstsc.org*>; or by calling 1-877-838-7220 (toll free). For more information about the program, the point of contact is Dan Powell of EPA TIO at 703-603-7196 or <*powell.dan@epa.gov*>.

front commitment of time and resources to demonstrate that the performance of phytoremediation is comparable to the performance of traditionally accepted technology options. Such an investment ultimately could save site owners significant amounts of money when they clean up their properties for redevelopment.

1.2 Background

The U.S. Environmental Protection Agency (EPA) has defined brownfields sites as "abandoned, idled or under-used industrial and commercial facilities where expansion or redevelopment is complicated by real or perceived environmental contamination." Numerous technology options are available to assist those involved in the cleanup of brownfields sites. EPA's Technology Innovation Office (TIO) encourages the use of innovative, cost-effective technologies to characterize and clean up contaminated sites. An innovative technology is a technology that has been field-tested and applied to a hazardous waste problem at a site, but that lacks a long history of full-scale use. Although readily available information about its cost and how well it works may be insufficient to encourage use under a wide variety of operating conditions, an innovative technology has the potential to significantly reduce the cost and time required to redevelop brownfields sites.

Historically, fear of contamination and its associated liability has hampered redevelopment of brownfields sites. Phytoremediation offers a unique advantage over other remediation technologies. It provides ecosystem restoration and "green areas" that may be desired by the local community.

The process of redeveloping brownfields sites provides an excellent framework for using innovative technologies because: (1) state and federal regulators tend to be flexible in approving cleanup plans for brownfields sites, particularly those sites for which voluntary cleanup plans have been submitted; (2) most of the current brownfields sites are not encumbered by a history of litigation or enforcement actions for which traditional technologies already may have been specified; and (3) redevelopment plans have been prepared for many brownfields sites and are used to establish site-specific cleanup targets and the time frames for cleanup – that information provides an excellent basis for tailoring innovative approaches to the investigation and cleanup of individual sites.

1.3 Approach

This primer will assist brownfields decision makers in considering phytoremediation as an innovative treatment technology option for cleanup at brownfields sites. The document discusses the factors important in the selection of phytoremediation, such as regional climate and local growing conditions, location and type of contaminants to be treated, and site-specific redevelopment objectives. The primer illustrates how those factors can be potential advantages (or limitations) in the selection of phytoremediation at a brownfields site; presents examples that illustrate the field applications of phytoremediation at brownfields sites; and identifies additional resources to assist brownfields decision makers in evaluating phytoremediation as an option for their sites.

In addition, this document provides the following information in appendices:

- A list of ***acronyms***
- A ***glossary that explains technical terms*** related to phytoremediation
- A ***description of the processes of phytoremediation;***
- ***Decision tree diagrams*** developed by the Phytoremediation Work Group of the Interstate Technology and Regulatory Cooperation Work Group. The decision tree diagrams provides guidelines for determining the applicability of phytoremediation at a brownfields site after site characterization has been completed.

This primer is not an authoritative or original source of research on phytoremediation. Instead, it is intended to briefly describe the phytoremediation process and its potential applicability in a brownfields setting in a tone appropriate for audiences who have only a limited technical background.

It is important to note that this primer cannot be used as the sole basis for determining this technology's applicability to a specific site. That decision is based on many factors and must be made on a case-by-case basis. Technology expertise must be applied and treatability studies conducted to support a final remedy decision. For a more technical and thorough treatment of the topic and of issues described in this primer, consult EPA's *Introduction to Phytoremediation* (EPA/600/R-99/107, February 2000). Ordering information is provided in the Supporting Resources section of this primer.

2.0 WHAT IS PHYTOREMEDIATION?

Phytoremediation is the direct use of living green plants for in situ (in-place or on-site) risk reduction for contaminated soil, sludges, sediments, and groundwater, through removal, degradation, or containment of the contaminant (synonyms: green remediation and botano-remediation). Figure 1 illustrates the mechanisms involved in the phytoremediation process.

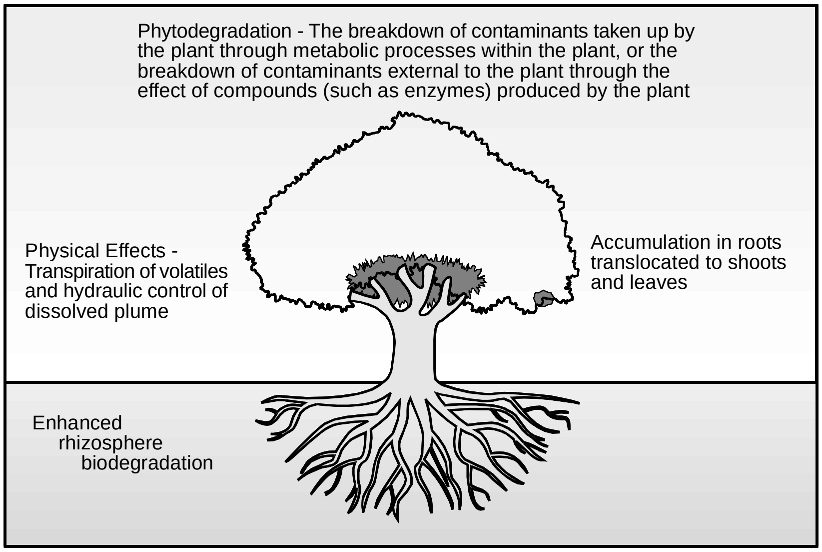


Figure 1: Examples of Mechanisms Involved in Phytoremediation

Phytoremediation warrants consideration for cleaning up brownfields sites at which there are relatively low concentrations of contaminants (that is, organics, nutrients, or metals) over a large cleanup area and at shallow depths. Another potential application for phytoremediation is at sites that currently are “mothballed” and may be redeveloped in the future. Phytoremediation can be a cost-effective alternative approach for reducing the leaching of contaminatnts through soil or groundwater, reducing the run-off of contaminated stormwater, beginning an initial level of cleanup, and improving the aesthetic condition of a site. Phytoremediation warrants consideration for use in conjunction with other technologies when the redevelopment and land use plans for the site include the use of vegetation.

Phytoremediation is distinct from Monitored Natural Attenuation (MNA), that is, a controlled and monitored site cleanup approach that relies on natural attenuation processes to achieve remediation objectives within time frames that are reasonable vis-à-vis more active methods. Though both processes involve some similar elements such as biodegradation, sorption, volatilization, stabilization, phytoremediation technologies represent active processes that are designed and implemented to control and eliminate contamination. MNA and phytoremediation also are similar in that both might be considered significant components of a treatment-train approach to hazardous waste cleanup at brownfield sites. For more information on EPA's directives regarding the the use of MNA refer to <*http://www.epa.gov/superfund/resources/gwdocs/monit.htm*>.

Successful Reduction of Lead Contamination

Phytoextraction was demonstrated at a site in Trenton New Jersey that had been used for the manufacture of lead acid batteries. Phytoextraction using Indian mustard (*Brassica juncea)* and ethylenediaminetetraacetic acid (EDTA) soil amendment reduced the average surface lead concentration by 13 percent in one growing season. The target soil concentration of 400 milligrams per kilogram (mg/kg) was achieved in approximately 72 percent of a 4,500 square-foot area. (Some of the reduction may be attributed to dilution as a result of tilling and spreading contaminants deeper into the soil column.) For more information, contact Larry D’Andrea of EPA at (202) 673-4314 or *D’Andrea.Larry @epa.gov.*

2.1 Types of Sites and Contaminants Treated by Phytoremediation

There is potential to use phytoremediation beneficially under a wide variety of site conditions. Types of sites at which phytoremediation has been applied or evaluated include: pipelines; industrial and municipal landfills; agricultural fields; wood treating sites; military bases; fuel storage tank farms; gas stations; army ammunition plants; sewage treatment plants; and mining sites.

Phytoremediation is being tested and evaluated for its effectiveness in containing and treating a wide array of contaminants found at brownfields sites. While much more testing is needed, current results indicate that plants have the potential to enhance remediation of the following types of contaminants:

- Petroleum hydrocarbons
- Benzene, toluene, ethylbenzene, and xylene (BTEX)
- Polycyclic aromatic hydrocarbons (PAH)
- Polychlorinated biphenyls (PCB)
- Trichloroethene (TCE) and other chlorinated solvents
- Ammunition wastes and explosives
- Heavy metals
- Pesticide waste
- Radionuclides
- Nutrient wastes (such as phosphates and nitrates)

One of the more optimal applications of phytoremediation is as a containment technology. Since many brownfields sites are characterized by wide-spread contamination at low concentrations that are close to target cleanup levels, phytoremediation is a good containment alternative if geology and rainfall amounts are favorable.

Table 1 lists types of sites at which phytoremediation has been employed with some level of success in cleaning up the sites. The table provides only a representative sample of sites and contaminants.

2.2 Plants Species Used for Phytoremediation

Plants species are selected for use according to their ability to treat the contaminants of concern and achieve the remedial objectives for redevelopment (for example, time frame and risk management), and for their adaptability to other site-specific factors such as adaptation to local climates, depth of the plant's root structure, and the ability of the species to flourish in the type of soil present. Often the preferred vegetation characteristics include: an ability to extract or degrade the contaminants of concern to nontoxic or less toxic products, fast growth rate, adaptability to local conditions, ease of planting and maintenance, and the uptake of large quantitities of water by evapotranspiration (see the glossary of terms in Appendix 1 for definitions of technical terms). The selection and use of plant species must be conducted with care to prevent the introduction of non-native species into areas where those species are not already present. Plant species that are benign under most circumstances may become a problem when introduced into a new area. For example, water hyacinth is considered a noxious aquatic weed that should be used only in isolated bodies of water from which there are no risks of unintentional transport (for example, by flood).

Maintenance requirements should be considered when selecting plant species for use at brownfields sites; those requirements may include the frequency with which the plant must be mowed; the need for fertilizer; and the need for replanting, pruning, harvesting, and monitoring programs.

Table 1
Selected Phytoremediation Projects

Contaminant(s)/ Purpose of Project	Media/ Mechanism	Plant Species	Location (Scale*)	Point of Contact
Chlorinated solvents/ Control groundwater migration at an urban brownfields site and remove TCE and derivatives from groundwater	Groundwater/ Phytoextraction, phytovolatilization, rhizodegradation	Hybrid poplar and willow	Findlay, OH (Full scale)	Steve Synder, Ohio Environmental Protection Agency (OEPA) (419) 352-8461 Ed Gatliff, Applied Natural Sciences, Inc. (ANS) (513) 942-6061
Chlorinated solvents/ Biologically (pump and treat) contaminated groundwater	Soil/ Rhizodegradation, phytovolatilization	Hybrid poplar, white willow, native species	Solvents Recovery Systems of New England, Southington, CT (Full scale)	Steve Rock, U.S. EPA (513) 569-7149 Ari Ferro, Phytokinetics (801) 750-0950
Chlorinated solvents/ Control groundwater migration and remove solvents from groundwater	Groundwater/ Phytovolatilization, rhizosphere biodegradation, phytodegradation	Eastern cottonwood	Carswell AFB, TX (Pilot)	Steve Hitt, U.S. EPA (214) 665-6736 Greg Harvey, USAF (937) 255-7716
Heavy metals/ Reduce lead concentration in soil	Phytoextraction	Indian mustard	Trenton, NJ Brownfields Site (Pilot)	Larry D'Andrea, U.S. EPA (212) 637-4314 Dr. Michael Blaylock, Edenspace (703) 961-8700
BTEX compounds/ Treat petroleum and organic contaminants; prevent contaminated groundwater from migrating	Soil and groundwater/ Hydraulic control, phytoextraction, phytovolatilization, rhizodegradation	Hybrid poplar	Ashland Chemical Co, Milwaukee, WI (Full scale)	Scott Ferguson, Wisconsin Department of Natural Resources (WDNR) (414) 263-8685 Dr. Louis Licht, Ecolotree (319) 358-9753
PAH's/Control groundwater and surface water migration, stabilize soil, and degrade contaminants	Soil and groundwater/ Hydraulic control, rhizodegradation	Grasses, hybrid poplar	Oneida, TN (Full scale)	Dr. John Novak, VA Tech (540) 231-6132 Dr. Louis Licht, Ecolotree (319) 358-9753
Explosives and fertilizers/ Contain and treat toxic solvents	Soil and groundwater/ Phytodegradation, phytovolatilization	Hybrid poplar	Aberdeen Proving Ground, MD (Pilot)	Harry Compton, U.S. EPA (732) 321-6751 Steve Hirsh, U.S. EPA (215) 814-3352
Wood preservatives/ Treat PAHs and DNAPLs	Soil and groundwater/ Rhizodegradation, hydraulic control	Herbaceous species and hybrid poplar	Laramie, WY (Full scale)	Marisa Latady, Wyoming Department of Environmental Quality, (307) 777-7752 Jennifer Uhland, CH$_2$M Hill (303) 771-0900

Source: Various research documents, internet web sites, and discussions with points of contact.
Notes:
* Full scale = Phytoremediation is part of the final remedy for site cleanup
Pilot scale = Phytoremediation is being evaluated as a potential treatment technology for the site.

Several types of plants and sample species frequently used for phytoremediation are listed below:

- Hybrid poplars, willow, and cottonwood trees
- Grasses (rye, Bermuda grass, sorghum, and fescue)
- Legumes (clover, alfalfa, and cowpeas)
- Aquatic and wetland plants (water hyacinth, reed, bullrush, and parrot feather)
- Hyperaccumulators for metals (such as alpine pennycress for zinc or alyssum for nickel)

Herbaceous species, such as mustard, alfalfa, and grasses, can be used in the remediation of contaminants in surface soil. Hybrid poplars, willows, cottonwood, and other woody species that have rapid growth rates, deep roots, and high transpiration rates (resulting in uptake of abundant quantities of water), can be in the remediation of contaminants in groundwater or can be used to provide hydraulic control.

Phytoremediation Selected for RCRA Corrective Action

An Ashland Chemical Company tank farm in Milwaukee, Wisconsin shows the potential for the use of phytoremediation at active industrial sites, as well as the adaptability of the technology for brownfields sites. Under the Resource Conservation and Recovery Act (RCRA), the facility was required to remediate contamination with petroleum products and organic solvents that resulted from years of fuel and solvent handling at the facility. Hybrid poplar trees have been arrayed to prevent contaminated groundwater from discharging into an adjacent river while remediating concentrations of contaminants in soil and groundwater. An extensive monitoring program, consisting of several monitoring wells transects and frequent groundwater and soil sampling, assesses the project's impact on groundwater migration, concentrations of contaminants, and growth conditions for the trees. Despite that rigorous program, the project was considerably less expensive than excavating and landfilling contaminated soil and pumping and treating contaminated groundwater. For more information, contact Scott Ferguson of the Wisconsin Department of Natural Resources at (414) 263-8685.

Constructed wetlands also are being used to remediate contaminated sites. There are two broad categories of wetland plants -- emergent and submerged species. Emergent plants, those rooted in shallow water with most of the plant exposed above the water's surface, transpire water and can be easier to harvest, if necessary. Submerged species, which lie entirely beneath the water's surface, do not transpire water but provide more biomass (increased vegetative growth and density) for the uptake and sorption of contaminants. (See the glossary). Plant species that have a relatively high biomass generally improve the overall effectiveness of phytoremediation. (See the Selection and Design of a Phytoremediation System section of this primer for a more detailed discussion of the role biomass plays in phytoremediation).

2.3 Phytoremediation Processes

Phytoremediation is the broad term for the use of plant systems to remediate contamination. Phytoremediation can be classified further on the basis of the physical and biological processes involved. Those processes include:

Hydraulic control: The use of plants to rapidly uptake large volumes of water to contain or control the migration of subsurface water (synonym: phytohydraulics).

Phytodegradation: The breakdown of contaminants taken up by the plant through metabolic processes within the plant, or the breakdown of contaminants external to the plant through the effect of compounds (such as enzymes) produced by the plant (synonym: phytotransformation).

Phytoextraction: The uptake of a contaminant by plant roots and the translocation of that contaminant into the aboveground portion of the plants; the contaminant generally is removed by harvesting the plants. This technology is applied most often to soil or water contaminated with metals.

Phytostabilization: The immobilization of a contaminant through absorption and accumulation by roots, adsorption onto roots, or precipitation within the root zone of plants.

Phytovolatilization: The uptake and transpiration of a contaminant by a plant, with release of the contaminant or a modified form of the contaminant to the atmosphere from the plant.

Rhizodegradation: The breakdown of a contaminant in soil through microbial activity that is enhanced by the presence of the root zone (synonyms: plant-assisted degradation, plant-assisted bioremediation, plant-aided in situ biodegradation, and enhanced rhizosphere biodegradation).

Rhizofiltration: The adsorption or precipitation onto plant roots or the absorption into the roots of contaminants that are in solution in the root zone.

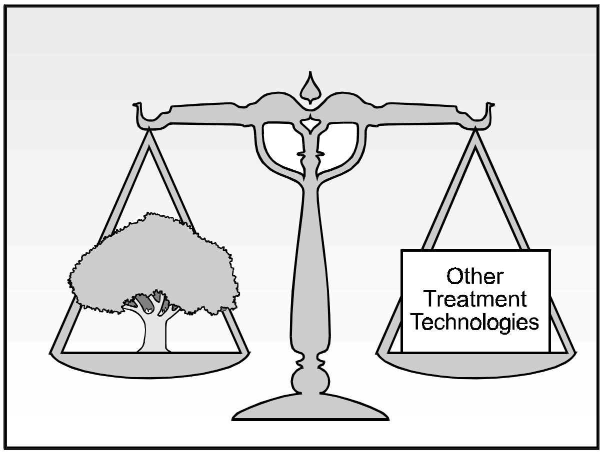
Appendix 2 to this document provides a brief explanation of the mechanisms of phytoremediation. For more technical information about the various processes of phytoremediation, refer to EPA's *Introduction to Phytoremediation* (EPA/600/R-99/107, February 2000). Table 2 shows the types of contaminants and media that can be treated by commonly used plants. The table also includes the type(s) of phytoremediation process that occur in each situation identified.

Table 2
Types of Plants, Contaminants, and Media

Type of Contaminant	Medium	Type of Plant													
		Alfalfa	Alyssum	Bald cypress	Black locust	Cottonwood	Grasses	Hybrid poplars	Indian mustard	Pennycress	Red Mulberry	Stonewort	Sunflower	Water hyacinth	Willow
Organic	Soil			▲ PD RD			▲ RD	▲ PD RD			▲ RD	▲ PD			▲ PD RD
	Sediment			▲ PD RD			▲ RD	▲ PD RD			▲ RD	▲ PD			▲ PD RD
	Groundwater			▲ PD		▲ HC		▲ HC PD				▲ PD			▲ HC PD
Inorganic	Soil	▲ PV	▲ PE		▲ PV		▲ PS	▲ PE PS PV	▲ PE PS PV	▲ PE			▲ PE		
	Sediment	▲ PV	▲ PE		▲ PV		▲ PS	▲ PE PS PV	▲ PE PS PV	▲ PE			▲ PE		
	Groundwater					▲ HC		▲ HC	▲ RF				▲ RF	▲ RF	▲ HC

▲	Plant is effective for the type of contamination and medium shown.
HC	Hydraulic control
PD	Phytodegradation
PE	Phytoextraction
PS	Phytostabilization
PV	Phytovolatilization
RD	Rhizodegradation
RF	Rhizofiltration

3.0 APPLICATION OF PHYTOREMEDIATION FOR THE CLEANUP OF SOIL, SEDIMENT, SURFACE WATER, AND GROUNDWATER



Phytoremediation has been attempted on a full- or demonstration-scale basis at more than 200 sites nationwide. Although phytoremediation is a naturally-occurring process, discovery of its effectiveness and advances in its application as an innovative treatment technology at waste sites, including brownfields sites, have been recent. The technology first was tested actively at waste sites in the early 1990s, and use of the approach has been increasing. As the number of successful demonstration projects grows and new information about the application of phytoremediation becomes available, the use of phytoremediation as a treatment technology is increasing because the technology has been proven an efficient and effective approach at brownfields sites.

3.1 Advantages to the Selection of Phytoremediation at Brownfields Sites

When deciding on the applicability of phytoremediation at a brownfields site, decision makers should compare the potential effectiveness and efficiency of phytoremediation technology with other treatment technologies that might be appropriate for the site. The comparison should address any specific needs of and conditions at the site. Several characteristics that are common to brownfields sites should be considered during the decision-making process. Those characteristics include the need to enhance the redevelopment potential and economic value of the affected properties; the desire to avoid indirect impacts on the community (such as hauling large quantities of excavated soil through neighborhoods); sensitive public relations issues; and the fact that, sometimes, the problem at a brownfields site is a "perceived" one, rather than actual contamination. Some advantages phytoremediation offers in a brownfields redevelopment setting are listed below.

- **Potentially treats a wide variety of contaminants.** *Relevance*: Brownfields sites often are made up of a collection of former manufacturing facilities or manufacturing processes that have left behind a legacy of contaminants. Research has shown that plant species used in remediation can potentially treat a wide variety of contaminants or families of contaminants (for example, treating both organics and metals).

- **Provides in situ treatment.** *Relevance*: Stakeholders' concern about potential health risk at brownfields sites can play a significant role in the selection of a treatment remedy. If a site is located in a populated area, as is often the case, or near sensitive receptors, such as school children or residents, phytoremediation offers a solution through which soil remains in place during treatment and is usable after treatment. Phytoremediation does not require excavation of soil, and its application may require only minimum materials handling. Further, phytoremediation can have a positive effect on the aesthetic character of a site.

- **Offers a permanent solution.** *Relevance*: In some cases, phytoremediation can destroy most or all the pollutants, leaving little or no residual contamination. Permanent mitigation of potential risks can broaden the appeal of a site to a potential developer. In addition, future redevelopment may be encouraged if the developer is not required to place such institutional controls as deed restrictions because there are no residual contaminants of concern.

- **Serves as an interim solution.** *Relevance*: In addition to offering a permanent solution, in some cases phytoremediation can act as a stop-gap measure to contain the spread of contaminants and begin the treatment process. Although phytoremediation may not be the selected final technology, the benefits of a well designed and capably managed phytoremediation system may be preferable to the risks that might be posed should a brownfields site be left completely untreated during preparation of the final redevelopment plan and selection of a final remedy.

- **Installation and operating and maintenance costs can be low.** *Relevance*: Phytoremediation systems are installed and maintained by traditional agricultural or landscaping equipment, materials, and practices. Those techniques typically are less expensive in up-front and long-term costs than technology-intensive alternatives that may require the use of sophisticated equipment.

- **Can be integrated into the natural environment and landscaping plans.** *Relevance*: Phytoremediation can be designed to be unobtrusive and aesthetically pleasing in a variety of site layout conditions. Wetlands, forests, or grasslands are examples of natural areas that can be used in phytoremediation design to enhance or restore the physical appearance of a brownfields site. Other treatment technologies that may employ heavy construction equipment, large pumps or wells, or other equipment (for example, an incinerator) may have less visual appeal and may be objectionable to certain stakeholder groups.

Using Poplars to "Pump and Treat" Groundwater

A system consisting of a dense stand of hybrid poplar, white willow, and six native tree species was installed at the Solvents Recovery Systems of New England (SRSNE) Superfund Site in Southington, Connecticut. The overall objective of the project was to biologically "pump and treat" contaminated groundwater, reducing the amount and toxicity of contaminated groundwater that reaches the traditional mechanical extraction wells and ultraviolet-oxidation system. Initial greenhouse studies found that the concentration of total volatile organic compounds (VOC) at the site did not limit the growth of the trees. Sap flow measurements reported as field results indicate that the stand of trees is accomplishing both its goals, pumping contaminated groundwater and removing some pollutants in the process. For more information, contact Steve Rock of EPA at (513) 569-7149 or *rock.steven@epa.gov*.

- **Can be an effective element of a unified treatment-train remediation approach.** *Relevance*: From a cost savings and treatment effectiveness point of view, it is often advisable to combine, spatially and/or over time, different treatment technologies into a unified cleanup strategy. Treatment trains are implemented in cases where no single technology is capable of treating all of the contaminants in a particular medium or where one technology might be used to render a medium more easily treatable by a subsequent technology. Phytoremediation is a technology that can provide benefit when used in concert with more intensive and therefore more expensive technologies. It thus reduces overall project costs, while achieving cleanup goals.

3.2 Related Uses of Plants at Brownfields Sites

Aside from landscaping applications, plants with potential use for phytoremediation also have other potential applications for protecting the environment at brownfields sites. Installing vegetated areas, called riparian buffers, next to surface water resources can provide protection from non-point source pollution, while at the same time stabilize the banks of the water bodies and provide a habitat area for wildlife. Vegetation is often a crucial component in the abatement of soil erosion in riparian zones, as well as any area in which soil erosion could occur if the soil is not protected. Hybrid poplars and other trees are being tested as an alternative to grassy clay caps, which often are used at landfills to direct rainwater away and help minimize the volume of leachate from those landfills. The mechanism is a similar to that involved in using plants to control site hydrology. Species of trees, such as hybrid poplars, quickly take up large quantities of water and can be used to reduce plumes of groundwater.

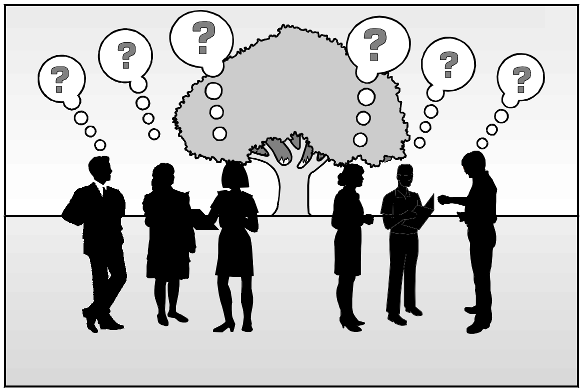
3.3 Discussions with Regulators

Many regulators have been receptive to the use of phytoremediation at brownfields sites because of the increasing number of positive results demonstrated. However, as in the selection of any innovative treatment technology, it is important to consider site-specific conditions and develop a level of certainty that phytoremediation is applicable for the site. Stakeholders that wish to use phytoremediation should be prepared to demonstrate that the performance of the system would compare favorably with that of other traditional and innovative technology options and that phytoremediation is the preferred option for the site. In addition, regulatory requirements may vary by state or region; federal, state, and local regulatory agencies should be consulted to determine those requirements. Consulting with the regulatory agencies will provide access to members of those agencies' staff who may have expertise in and experience with phytoremediation at similar sites. Demonstrating the technical results and success stories of implementation of phytoremediation at similar sites can help tip the scales toward regulatory acceptance. Up-front efforts to evaluate the advantages of using phytoremediation will pay off in increased overall support of the process of remedy selection and expedited approval of the redevelopment plans by regulatory agencies.

3.4 Community Involvement

Acceptance of a redevelopment plan that involves the use of any cleanup technology can be a sensitive community issue. It is important to promote acceptance of the redevelopment plan and the cleanup alternatives by involving the community early in the decision-making process through community meetings, newsletters, or other outreach activities. An advantage of phytoremediation is that it is an easily understood approach. Phytoremediation is more intuitive than many other treatment technologies and therefore may gain greater acceptance in the community. For an individual site, the community should be aware of how use of the technology may affect redevelopment plans and the adjacent neighborhood. For example, there may be aesthetic or visual improvements that result from the planting of trees or the creation of a wetland; there may be site-security issues or long-term maintenance issues which may affect site access; or there may be risk factors that must be conveyed to the community and may require the preparation of a risk-management plan.

4.0 PRACTICAL CONSIDERATIONS AND LIMITATIONS



As is true of any cleanup alternative, phytoremediation offers a number of advantages, as described in the preceding section. However, it also has technical limitations related to the types and levels of contaminants present, soil properties, acceptable exposure risks, and other site-specific considerations. Discussed in this section are a number of factors that decision makers may find necessary to consider when evaluating phytoremediation as a cleanup option for their site. A more comprehensive discussion of potential limitations to the implementation of phytoremediation can be found in the documents listed in the Supporting Resources section of this primer.

The total length of time required to clean up a site through phytoremediation may be too long to be acceptable for some redevelopment objectives. Phytoremediation is limited by the natural growth rate of plants and the length of the growing season. Several growing seasons may be required before phytoremediation systems become effective, while traditional methods may require a few weeks to a few months. Therefore, low removal rates may prohibit the use of phytoremediation in cases in which the time period available for cleanup is limited and is a key criterion in selecting a technology.

The growth rate of a plant species will have a direct effect on the potential for use at a particular site. For example, fast-growing grasses will begin treating soil contamination more quickly than a tree, which must establish deeper roots to treat target contaminants. As plants, particularly trees used in phytoremediation, mature their root structures deepen and their capacity to treat deeper levels of contamination improves. Phytoremediation can provide a number of benefits during the course of vegetation maturation. Plantings during initial stages can provide a cover that minimizes water infiltration. As the tree roots mature, phytodegradation, rhizodegradation, and/or phytovolatilization processes can take place to treat contaminants at increasing depths below the surface. In fully mature stages, phytoremediation cover can develop a hydraulic control, hydrostatic barrier function. Figure 2 illustrates the progressive development stages for phytoremediation to

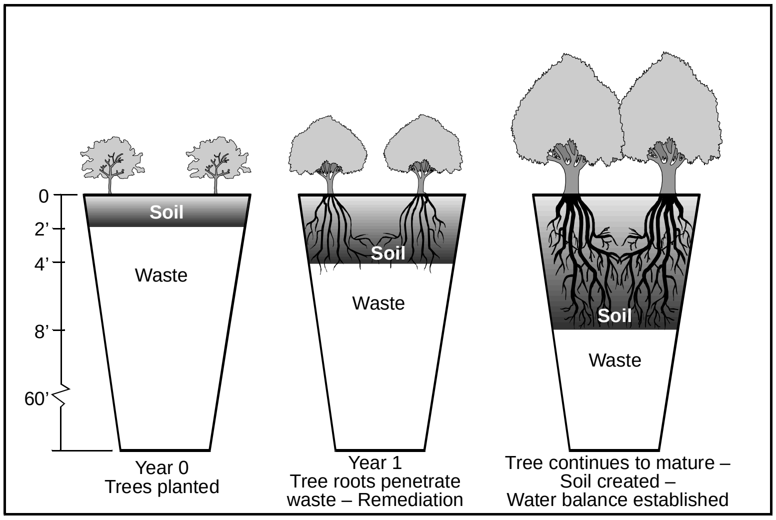


Figure 2. Phytoremediation Developmental Stages

Source: EPA. 2000. *Introduction to Phytoremediation* (EPA/600/R-99/107). National Risk Management Research Laboratory. February.

support capping to reduce infiltration, degradation, and then hydraulic control. While this developmental process can be beneficial, consideration also must be given to whether phytoremediation is a safe and protective remedy during the time it takes for the plants to establish themselves to a point at which they are treating the contaminants effectively.

It must be determined whether phytoremediation can be effective for the site-specific conditions and contaminants. For example, phytoremediation works better in shallow soils and groundwater, unless deep-rooted plants are suitable for the site. In addition, phytoremediation works best on certain types of contaminants or mixed waste and may be less effective when used on other combinations of waste. For example, phytoremediation may not be the most effective treatment option if levels of contamination are so high that concentrations of contaminants are toxic to plants (phytotoxic).

In some cases, phytoremediation might not provide adequate protection, from an eco-receptor perspective. For example, contamination that is below ground can be transferred into the leaves and stems of plants that are a food source. Further, in some cases, contaminants are not destroyed in the phytoremediation process; instead, they are transferred from the soil onto the plants and then are transpired in to the air. Phytoremediation could also increase the rates of bioaccummulation of contaminants than might otherwise occur.

Potential costs associated with monitoring and maintaining the phytoremediation process at the site also must be factored into the selection process. Maintenance costs often are lower with phytoremediation than with conventional treatment technologies. On the other hand, monitoring costs could be higher, especially if the cleanup rates are slower and monitoring of the site continues longer than monitoring for conventional treatment technologies. An activity that will increase the cost of long-term maintenance is the harvesting and proper disposal of plant materials that contain contaminants. The state of phytoremediation technology is emerging, and more information from treatability studies and long-term applications are needed to support its consideration as a viable technology. Until that information is available, the diversity of opinions about the conditions and contaminants for which phytoremediation may be a well-suited cleanup technology will continue. Consulting with technical experts to determine the applicability of phytoremediation on a site-by-site basis is advised. Further, in many cases, it will be important to identify a contingency plan for cleaning up the site in the event that phytoremediation will not meet cleanup objectives in an effective and timely manner.

5.0 SELECTION AND DESIGN OF A PHYTOREMEDIATION SYSTEM

The design of a phytoremediation system varies according to the contaminants, the conditions at the site, the level of cleanup required, and the plants used. As previously noted, contaminants and site conditions are perhaps the most important factors in the design and success of a phytoremediation system. Other factors that influence the selection and design of a phytoremediation system are discussed below.

5.1 Technical Factors

Because phytoremediation is an agronomic process, it is highly dependent on climate and site-specific characteristics. Soil properties determine the ability of a plant species not only to become established in the soil, but also to maximize biomass and, therefore, removal of contaminants. Soil parameters typically analyzed to determine whether phytoremediation is applicable include texture; pH; moisture content; organic matter content; lime content; cation exchange capacity; and content of nutrients, such as calcium, magnesium, potassium, phosphate, and sulfate.

As with most treatment technologies, innovative or not, a treatability study should be conducted before a final remediation technology can be selected for use at a site to demonstrate that the technology will work at that specific site. Information to assess the effectiveness of phytoremediation also may be available in existing literature. For example, research may reveal phytotoxicity levels or regional agronomic practices for the simple application of phytoremediation, given adequate site characterization and monitoring.

Where treatability studies are necessary, site characterization and bench-scale tests may be used to determine system performance in the field and evaluate whether the design will meet the desired level of cleanup in the specified time period. For phytoremediation, it may be necessary to conduct treatability studies under laboratory conditions (for example, in an artificial hydroponic system) to simulate site conditions and obtain an initial result that proves the effectiveness of the design. Acceleration of the process can be expedited by typical approaches, including artificial light, water, and temperature conditions. The advantage of such laboratory studies is that the process can be accelerated to provide early results and reduce implementation time.

Local climatic conditions, particularly the length of the growing season, govern the type and number of crops that can be planted each year and therefore the annual rate of removal of contaminants. Climatic conditions, such as rainfall and temperatures, also influence irrigation strategies and the selection of plant species. Plant species that grow well in the Pacific Northwest may not survive in the arid Southwest.

Hydrologic models allow the calculation of the flow of water and how that flow might be affected by the application of phytoremediation. Irrigation flows can have an impact on groundwater conditions and ultimately on the movement of the contaminants to be treated. Although irrigation of plants may be necessary to ensure a robust start for a phytoremediation system, even in drought conditions, careful modeling may be necessary to predict with any certainty the effects of phytoremediation at a site.

Agronomic techniques include the addition of nutrients necessary for vigorous growth in vegetation. To maximize the efficiency of the phytoremediation treatment system, the soil type first must be determined. Analysis will help determine the need for amendments, such as nitrogen, potassium, phosphorous, manure, sewage sludge compost, straw, or mulch, which are added as required to improve the performance of the plant. For example, maintenance of the phytoremediation system may require the addition of chemicals to stabilize metals in the soil or the addition of chelates to ensure that plants take up the contaminants. A close working relationship with regulators is especially important in such a situation to quickly determine any rules, regulations, or prohibitions related to the addition of amendments to the subsurface. Any changes made in the soil through the application of soil amendments, however, should be evaluated and monitored for their effects on the site conditions.

Remediating Wood Preservatives and Residual DNAPLs
Phytoremediation is being tested as an approach to addressing both wood preservatives and dense non-aqueous phase liquids (DNAPL) at a RCRA site in Laramie, Wyoming. The active Union Pacific Railroad (UPRR) facility became contaminated with polycyclic aromatic hydrocarbons (PAH) during almost 100 years of treating railroad ties with creosote. UPRR installed a bentonite-filled trench to contain contaminated groundwater but had no means of addressing residual PAHs in soil and groundwater because of the perceived technical infeasibility of cleaning up to the relatively low maximum contaminant levels (MCL). The Wyoming Department of Environmental Quality (WDEQ) approved a phytoremediation demonstration that will serve as a research project for the WDEQ as well as the facility and therefore includes rigorous requirements for monitoring. More than 10,000 plants are being installed at a 50-acre site, including test plots in highly contaminated “hot spots” at which the technique’s ability to address high levels of contamination will be assessed. Particular attention has been paid to selecting native species that will be tolerant of Laramie’s harsh climate, and seed and plant stock for the plantings have been harvested from the Laramie area. The public has been included in planning for the project, as well, and the phytoremediation plot has been integrated into Laramie’s greenspace plan and bicycle trail system. A bike trail to the site was completed in early 2001, and a 1.5-mile bike loop through the phytoremediation plot is being planned. For more information, contact Marisa Latady of WDEQ at (377) 777-7752.

Biomass is the amount of living or organic matter produced by plants. Increased biomass results in higher levels of treatment and containment because more materials available to the plant (including contaminants) are used to support growth. Phytoremediation designs commonly involve higher planting densities than standard agronomic rates for various species to overcome decreased germination because of contaminated soils and to maximize overall production of biomass for the area. Consulting with an experienced agronomist is essential to designing a healthy and productive phytoremediation system.

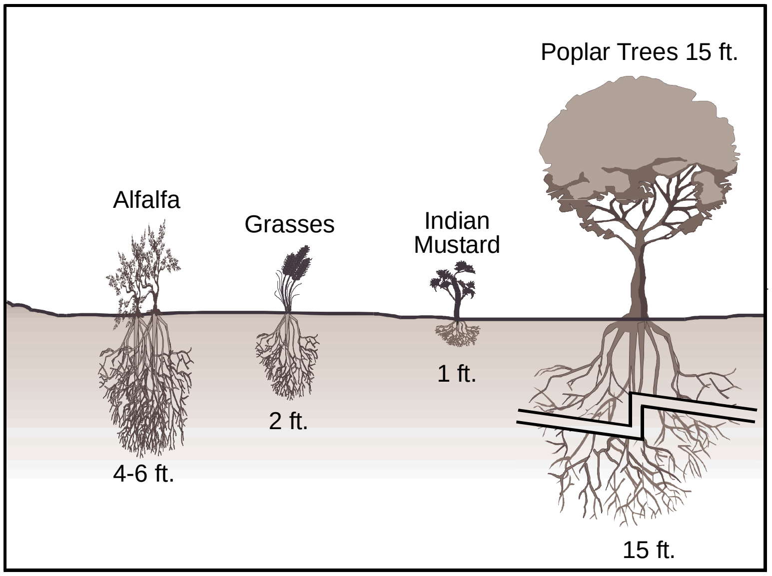


Figure 3: Root Depth

Source: EPA. 2000. *Introduction to Phytoremediation* (EPA/600/R-99/107). National Risk Management Research Laboratory. February.

Because various plant species have different root structures, careful consideration must be given to selecting the most appropriate species to address contaminants at individual sites. Figure 3 illustrates typical root depths of four plants commonly used in phytoremediation and demonstrates the depth to which each of the species may be most effective. The figure illustrates the potential limitation of phytoremediation to shallow soils.

5.2 Strategies for Contaminant Control

Phytoremediation can support a variety of cleanup strategies. One such strategy is to plant the contaminated area with a specific species known to extract the targeted contaminant, subsequently harvest the resulting biomass, and then reduce the harvested material by composting or burning. The resulting pile then becomes a concentration of the extracted chemical that can be treated as hazardous waste or, if the contaminant is a metal, recycled. Another strategy, which focuses on containment, is to surround an underground plume of contaminants with a selected species of plants to prevent further movement of the plume through the establishment of a hydrostatic barrier of tree roots, that is, the groundwater is taken up by the tree roots and therefore does not migrate beyond the roots. Hybrid poplars have achieved successes in such approaches.

A common interim approach for brownfields sites has been capping or paving over a site to minimize infiltration of water. Several experiments have been conducted to create “phytocaps” as improvements of asphalt coverings. A phytocap is a combination of trees and other vegetation capable of absorbing and transpiring most of the infiltration water, thereby reducing the risk that contaminants will spread. A phytocap must be planted densely so that the rate at which the evaporative processes of the plants take place matches the rate of infiltration of water. The approach thereby eliminates the need to construct an impermeable surface.

Treatment or capture of contaminated groundwater under a site may require a certain minimum surface area and configuration of trees, depending on groundwater flow rates and considerations related to the contaminant. Surface water buffers and corridors, groundwater interceptor strips, and vegetative covers are examples of applications of phytoremediation that can be integrated into redevelopment landscaping plans on both large and small sites.

5.3 Innovative Technology Treatment Trains

Phytoremediation can be an effective component of treatment train approaches that combine innovative technologies with traditional remediation technologies. The purpose of combining technologies can be to reduce the volume of material that requires further treatment, to prevent emission of volatile contaminants during excavation and mixing, or to treat several contaminants in a single medium.

An example might be to use phytoremediation as part of a treatment train involving soil vapor extraction and/or air sparging. If the volatized compounds are passed through a properly designed plant rhizoshere zone before being extracted or discharged to the atmosphere, there can be enhanced degradation of hazardous compounds.

Hybrid poplars or other deep-rooted species with high groundwater uptake rates could serve in a treatment wall capacity when installed in a way that intercepts migrating contaminated groundwater plumes. The groundwater that flows through the plant treatment wall would in many cases become adequately treated such that MNA could be implemented as the final stage of the train. In shallow aquifer situations phytoremediation could replace more costly and intensive technologies such as pumping and treating.

Anaerobic, reducing conditions are required for effective degradation of chlorinated solvents and other organic compounds. A process whereby chemicals secreted from tree roots lead to anaerobic degradation of chlorinated solvents currently is receiving research attention. This research has examined the process in naturally occurring trees, therefore in the context of MNA. For additional information see the *International Journal of Phytoremediation, Vol. 2 (3)*, 2000.

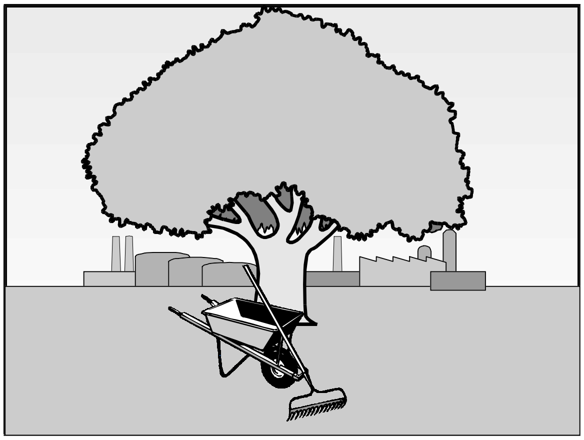
5.4 Design Team

It is important that the development and evaluation of a particular phytoremediation design and long-term performance strategy at a brownfields site be performed by an experienced multidisciplinary team. The design team can help the decision makers weigh the advantages and limitations of phytoremediation and select and design a system that best addresses the factors discussed in this section. The team might include experts in the following disciplines or fields:

Design Team Disciplines

- ☑ Soil Science or Agronomy
- ☑ Hydrology
- ☑ Plant Biology
- ☑ Environmental Engineering
- ☑ Regulatory Analysis
- ☑ Cost Engineering and Evaluation
- ☑ Risk Assessment and Toxicology
- ☑ Landscape Architecture

6.0 OPERATION AND MAINTENANCE



A phytoremediation treatment system must be monitored and evaluated periodically to measure the effectiveness of operations and progress toward attainment of the remedial objectives for brownfields redevelopment. Monitoring can help determine the most effective course for continued operation and maintenance. This section describes responsibilities for operation and maintenance at a phytoremediation site.

6.1 Operation and Maintenance

Maintenance is required to obtain a healthy stand (or growth of plants). Weed control and irrigation probably are the two most important practices. Because of the proliferation of specific weeds, predators, and diseases that can cause significant reductions in yields, it may be necessary to rotate crops to maintain increased biomass production. Weeds also can be controlled by employing mechanical (cultivation) or chemical (herbicides) methods. Irrigation water should compensate for normal losses to evaporation and transpiration. The method of irrigation also must be considered carefully. Drip irrigation tends to minimize evaporation of water, improve efficiency, and reduce costs. The long-term maintenance needs of wetland systems typically are minimal and may consist of monitoring the distribution and level of water, removing vegetation and contaminants, and other predominantly land-management activities, such as control of access and maintenance of berms.

6.2 Disposal

In phytoextraction systems, plant material must be harvested and disposed of. Plants that accumulate contaminants may pose a risk of spreading contamination into the food chain if they are consumed by insects or other animals. Consideration should be given to addressing the need to avoid consumption of contaminated plants by wildlife or livestock before plants are harvested. At brownfields sites, the end uses under a redevelopment plan can be a determining factor in the potential risk to human and environmental receptors that accumulated contaminants may pose. The brownfields site redevelopment plan therefore can affect the need for disposal.

It is important to monitor the system and test whether the plants contain any hazardous substances. If there are no hazardous substances present, the material could be composted or worked into the soil on site. If that is not possible, off-site disposal will be required. The harvest of contaminated biomass and possible disposal of the material as hazardous waste would be subject to applicable regulations, such as those established under the Resource Conservation and Recovery Act (RCRA). One option is disposal of contaminated material in a regulated landfill. Disposal under RCRA can add costs to a phytoremediation project. However, the removal and disposal of plant material used in phytoremediation generally involves the transporting and handling of materials that are of far less volume and that probably are less hazardous than materials generated by operations that involve soil excavation or other innovative or traditional remediation technologies. Therefore, phytoremediation can be a strategy for decreasing the costs of handling, processing, and possibly landfilling the materials.

6.3 Performance Evaluation and Monitoring

To evaluate the short-term performance and effectiveness of phytoremediation, the concentrations of contaminants and degradation products should be measured. Monitoring should be conducted for soil, groundwater, plant root and mass, and evapotranspiration vapor. Rigorous performance evaluation will help demonstrate the system’s ability to meet cleanup goals and objectives. Because phytoremediation is an emerging technology, standard performance criteria for phytoremediation systems have not yet been established, and performance must be determined on a site-by-site basis.

Long-term monitoring typically is necessary for phytoremediation systems that require long time horizons to demonstrate their continued effectiveness. Monitoring may be continued after short-term cleanup goals have been met to determine the impact of the phytoremediation system on the ecosystem.

A monitoring plan should be developed to guide both short- and long-term monitoring. The plan should discuss the following elements: constituents or other parameters to be monitored; the frequency and duration of monitoring; monitoring and sampling methods; analytical methods; monitoring locations; and quality assurance and quality control (QA/QC) requirements.

7.0 COST OF PHYTOREMEDIATION

Phytoremediation is an emerging technology; standard cost information still is being developed on the basis of experiences in implementing phytoremediation projects. This section provides information that compares costs associated with the use of phytoremediation to costs associated with the use of conventional treatment technologies based on actual cost estimates for three sites, as well as other sample costs based on laboratory and pilot scale work and field information.

Many of those costs associated with phytoremediation are not unique to phytoremediation, but are common to remediation technologies. The major cost components for the implementation of phytoremediation include the costs of:

- Site characterization
- Treatability studies
- Full-scale design (costs will vary according to the contaminants, the site characteristics, and the variety and amount of vegetation needed)
- Construction costs (includes direct capital costs for site preparation, plant material, and irrigation and monitoring equipment and indirect costs, such as those for permitting during construction, contingency design, and startup)
- Operation and maintenance and monitoring costs (includes the cost of labor, materials, chemicals, utilities, laboratory analysis, disposal, and monitoring)

As discussed in other sections of this primer, startup and maintenance costs often are less with phytoremediation than with conventional treatment technologies because: (1) phytoremediation is a natural process using solar energy; (2) phytoremediation is in situ and requires no digging or hauling of contaminated soil; and (3) little or no mechanical equipment is required to operate the phytoremediation process. On the other hand, monitoring costs could be higher than with conventional treatment technologies because monitoring typically is required for a longer period of time at sites where phytoremediation is used.

In comparing the potential costs to use phytoremediation with the potential cost to use conventional treatment technologies at a site, care must be taken to compare the costs of the entire system for the entire life cycle. Under phytoextraction, the cost of processing and ultimate disposal of biomass generated is likely to account for a major percentage of overall costs.

7.1 Cost Savings Based on Actual Cost Estimates

Table 3 provides site-specific estimates that have been reported of the cost savings realized by using phytoremediation rather than conventional treatment technologies

7.2 Sample Phytoremediation Costs

The estimated 30-year costs (1998 dollars) for remediating a 12-acre lead site were $12,000,000 for excavation and disposal, $6,300,000 for soil washing, $600,000 for a soil cap, and $200,000 for phytoextraction (Cunningham 1996 in *Introduction to Phytoremediation* (EPA/600/R-99/107)). The costs of cleanup of various heavy metals at the Twin Cities Army Ammunition Plant, Minneapolis-St. Paul, MN Project were reported in the Federal Remediation Technologies Roundtable (see Supporting Resources) to be $153 per cubic yard of soil over the life of the project.

The costs of removing radionuclides from water with sunflowers has been estimated to be $2 to $6 per thousand gallons of water (Dushenkov et al. 1997 in *Introduction to Phytoremediation* (EPA/600/R-99/107)). The costs of cleanup of explosives at the Milan Army Ammunition Plant, Milan, TN were reported in the Federal Remediation Technologies Roundtable (see Supporting Resources) to be $1.78 per thousand gallons of water over the life of the project.

Estimated costs for hydraulic control of an unspecified contaminant in a 20-foot-deep aquifer at a 1-acre site were $660,000 for conventional pump-and-treat and $250,000 for phytoremediation (Gatliff 1994 in *Introduction to Phytoremediation* (EPA/600/R-99/107)).

Cost estimates indicate savings for an evapotranspiration cover compared to a traditional cover design to be 20-50%, depending on availability of suitable soil (RTDF 1998 in *Introduction to Phytoremediation* (EPA/600/R-99/107)).

Studies indicate that phytoremediation is competitive with other treatment alternatives, as costs are approximately 50 to 80 percent of the costs associated with physical, chemical, or thermal techniques at applicable sites.

Table 3
Estimated Cost Savings Through the Use of Phytoremediation Rather Than Conventional Treatment

Contaminant and Matrix	Phytoremediation		Conventional Treatment		Projected Savings
	Application	Estimated Cost	Application	Estimated Cost	
Lead in soil (1 acre)[a]	Extraction, harvest, and disposal	$150,000 -$250,000	Excavate and landfill	$500,000	50-65 percent
Solvents in groundwater (2.5 acres)[b]	Degradation and hydraulic control	$200,000 for installation and initial maintenance	Pump and treat	$700,000 annual operating cost	50 percent cost saving by third year
Total petroleum hydrocarbons in soil (1 acre)[c]	In-situ degradation	$50,000 - $100,000	Excavate and landfill or incinerate	$500,000	80 percent

Source: Introduction to Phytoremediation. EPA/600/R-99/107. February 2000.

[a] Phytotech estimate for Magic Marker site

[b] Potentially responsible party estimate for SRS site

[c] PERF estimate

8.0 SUPPORTING RESOURCES

This section identifies Internet sites and documents that will help the user obtain additional information about phytoremediation. In addition, Table 4 presents a list of references used to prepare this document and a guide to the subject matter included in each reference.

- **EPA. Office of Research and Development (ORD) Internet web site (*http://www.epa.gov/ord*).** ORD is the principal scientific and research arm of EPA. ORD conducts research and fosters the use of science and technology in fulfilling EPA's mission. ORD is organized as three national laboratories and two national centers located in a dozen facilities around the country and in Washington, D.C. Several EPA laboratories have work underway to determine the fate of contaminants in phytoremediation applications. Much of this work is based at the EPA National Risk Management Research Laboratory (NRML). (Refer to the description below.) ORD along with the Office of Solid Waste and Emergency Response (OWSER) supports the Remediation Technologies Development Forum (RTDF) that also is described in more detail below. In addition within ORD, the EPA National Exposure Research Laboratory (NERL) *http://www.epa.gov/NERL/*, is exploring topics such as the degradation of TNT by wetland plants and plant enzyme-contaminant interactions. The EPA-supported Hazardous Substance Research Center at Kansas State University engages in research on plant and contaminant interactions. EPA Region 10 continues to explore and encourage innovative applications and interactions between phytoremediation and ecosystem restoration.

- **EPA. National Risk Management Research Laboratory (NRMRL). *Introduction to Phytoremediation* (EPA/600/R-99/107). February 2000. (Web site availability *http://cluin.org/techfocus*).** The National Risk Management Research Laboratory, (NRMRL), part of EPA's Office of Research and Development, conduct research into ways to prevent and reduce risks from pollution that threaten human health and the environment. The laboratory has a broad program of investigating methods and their cost-effectiveness for prevention and control of pollution including those relevant to remediation of contaminated sites, sediments and groundwater. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. Its Superfund Innovative Technology Evaluation (SITE) Program encourages the development and implementation of innovative treatment technologies for hazardous waste site remediation. The phytoremediation document has been developed to provide a tool for site regulators, owners, neighbors, and managers to evaluate the applicability of phytoremediation to a site. Information on the SITE program or individual projects can be found at *http://www.epa.gov/ORD/SITE*.

- **Federal Remediation Technologies Roundtable (FRTR) Case Studies *http://www.frtr.gov/cost***
  The Federal Remediation Technologies Roundtable (FRTR) case studies contain detailed information about specific remedial technology applications. FRTR case studies are developed by the U.S. Department of Defense (DoD), the U.S. Army Corps of Engineers (USACE), the

U.S. Navy, the U.S. Air Force (USAF), the U.S. Department of Energy (DOE), the U.S. Department of the Interior (DOI), and the U.S. Environmental Protection Agency (EPA). As of September 1998, FRTR published and made available on its Internet site 140 cost and performance case studies. The case studies focus on full-scale and large field demonstration projects and include background information about the site, a description of the technology, cost and performance data for the technology application, and a discussion of lessons learned. Both innovative and conventional treatment technologies for contaminated soil, groundwater, and solid media are included. A search function on the web site allows a user to search the case studies using key words for media, contaminant, and primary and supplemental technologies.

- **Interstate Technology and Regulatory Cooperation Work Group (ITRC). *Phytoremediation Decision Tree*. November 1999 (Web site availability *http://www.itrcweb.org*).** ITRC is a state-led national coalition dedicated to achieving better environmental protection through the use of innovative technologies. ITRC helps regulatory agencies and technology developers, vendors, and users reduce the technical and regulatory barriers to the deployment of new environmental technologies. ITRC products and services are building the collective confidence of the environmental community about using new technologies. Phytoremediation is one such technology. ITRC has provided a tool that can be used to determine whether phytoremediation can be effective at a given site. It allows the user to use basic information about a specific site to decide, through the use of a flow chart layout, whether phytoremediation is feasible at that site.

- **EPA. *Phytoremediation Resource Guide.* June 1999 . (EPA 542-B-99-003) (Web site availability *http://cluin.org/techfocus*).** The document identifies a cross-section of information intended to aid users in remedial decision-making, including abstracts of field demonstrations, research documents, and information about ordering publications.

- **EPA. *A Citizen's Guide to Phytoremediation.* April 2001. (EPA 542-F-01-002) (Web site availability *http://cluin.org/techfocus*).** The document is a technology fact sheet developed to help communicate to citizen stakeholders issues related to the use of phytoremediation.

- **The Remediation Technologies Development Forum (RTDF). Internet web site (*http://www.rtdf.org*)** - EPA established the RTDF in 1992 by determining what government and industry can do together to develop and improve the environmental technologies needed to address their mutual cleanup problems in the safest, most cost-effective manner possible. The RTDF fosters public- and private-sector partnerships to undertake research, development, demonstration, and evaluation efforts focused on finding innovative solutions to high-priority problems. The RTDF has grown to include partners from industry, several federal and state government agencies, and academia who voluntarily share knowledge, experience, equipment, facilities, and even proprietary technology to achieve common cleanup goals. The Phytoremediation of Organics Action Team and the In-Place Inactivation and Natural Ecological Restoration Technologies (IINERT) Soil- Metals Action Team are two of eight Action Teams that foster collaboration between the public and private sectors in developing innovative phytoremediation solutions to hazardous waste problems. The Action Teams include representatives from industry, government, and academia who share an interest in further developing and validating the of use of plants and trees to remediate organic hazardous wastes in soil and water.

- **Public Technologies, Inc. Brownfieldstech Internet web site (*http://www.brownfieldstech.org*)** - The site is a source of information about characterization and remediation of brownfields sites. The web site is sponsored by EPA's TIO. It is hosted and maintained by Public Technology, Inc. (PTI), the technology development arm of the National League of Cities, the National Association of Counties, and the International City/County Management Association. The site focuses on the demonstration, dissemination, and promotion of innovative characterization and remediation technologies for brownfields. Its goal is to help local governments increase efficiencies and reduce costs associated with brownfields redevelopment. See “Hot Technologies” page for links to reports on projects utilizing phytoremediation.

- **EPA. The Hazardous Waste Clean-Up Information (Clu-In) System Internet web site (*http://cluin.org/techfocus*)** - EPA’s Clu-In provides information about innovative treatment technologies to the hazardous waste remediation community. It describes programs, organizations, publications, and other tools for federal and state personnel, consulting engineers, technology developers and vendors, remediation contractors, researchers, community groups, and individual citizens. The site is managed by EPA’s TIO and is intended as a forum for all waste remediation stakeholders.

Table 4
References by Topic

Reference	What is Phytoremediation	Examples of Phytoremediation	Advantages and Considerations in Selecting Phytoremediation	Significance of Site Characterization
Rock, Steven. 1997. “Phytoremediation.” *The Standard Handbook of Hazardous Waste Treatment and Disposal*, Second Edition. Harry Freeman, ed. McGraw Hill.	●	●		
CERCLA Education Center. 2000. Innovative Treatment Technology Course, Module on Phytoremediation.	●		●	
Phytoremediation Work Team, Interstate Technology and Regulatory Cooperation Work Group. 1999. *Decision Tree Document*. November.	●	●	●	
EPA. 1998. *A Citizen’s Guide to Phytoremediation*, Technology Fact Sheet (EPA 542-F-98-011). August.	●			
Brownfieldstech.org Internet web site (particularly for case studies). 2000.	●	●		
Rock, Steven and Philip Sayre. 1998. “Phytoremediation of Hazardous Wastes: Potential Regulatory Acceptability.” Vol. 8, No. 4.	●		●	
Black, Harvey. 1999. “Phytoremediation: A Growing Field with Some Concerns.” *The Scientist*. Volume 13, Number 5. March.	●			
Interstate Technology and Regulatory Cooperation Work Group. 1999. *Phytoremediation Technical and Regulatory Guidance*.	●		●	●
CH2MHill. 1999. *Guidance for Successful Phytoremediation*. Prepared for CWRT. March.	●	●	●	
Lasat, Mitch. 2000. “Notes of a Plant Scientist.”	●			
EPA. 2000. *Introduction to Phytoremediation* (EPA/600/R-99/107). February.	●	●	●	●
EPA. 1999. *Phytoremediation Resource Guide* (EPA 542-B-99-003). June.	●			
EPA. 1998. *Electrokinetic and Phytoremediation In Situ Treatment of Metal-Contaminated Soil: State-of-the-Practice*.	●	●		●

Note: The table provides a list of references that were used to develop this primer.

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APPENDIX 1

LIST OF ACRONYMS AND GLOSSARY OF KEY TERMS

bgs	Below ground surface
BTEX	Benzene, toluene, ethylbenzene, and xylene
BTSC	Brownfields Technology Support Center
cm	Centimeter
EPA	U.S. Environmental Protection Agency
ITRC	Interstate Technology Regulatory Cooperation Work Group
NRMRL	National Risk Management Research Laboratories
PAH	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyl
PCP	Pentachlorophenol
QA/QC	Quality assurance and quality control
RCRA	Resource Conservation and Recovery Act
TCA	Trichloroethane
TCE	Trichloroethylene
TIO	Technology Innovation Office
TNT	Trinitrotoluene
UPRR	Union Pacific Railroad
VOC	Volatile organic compound

Abiotic
Not biotic or living.

Absorption
The process of one substance actually penetrating into the structure of another substance. The process is different from adsorption, in which one substance adheres to the surface of another substance.

Adsorption
The physical process that occurs when liquids, gases, or suspended matter adheres to the surfaces of, or in the pores of, an adsorbent material. The process is physical and occurs without a chemical reaction.

Agronomic
The application of soil and plant sciences to soil management and crop production; scientific agriculture.

Bench-Scale
Testing phase conducted to demonstrate effectiveness of an emerging treatment technology; usually a small-scale version is tested under laboratory conditions.

Bioaccumulation
The absorption and concentration of contaminants, such as heavy metals, in plants and animals. Bioconcentration is a synonym for bioaccumulation.

Biomass
All the living matter present in a given area; organic structures produced by living organisms. The generic term for any living matter that can be converted into usable energy through biological or chemical processes. Can be expressed numerically as a mass-density or as calories per unit area.

Biotic
Related to life or specific life conditions; living.

Brownfields
An abandoned, idled, or under-used industrial or commercial facility where expansion or redevelopment is complicated by real or perceived environmental contamination.

Cap
A barrier that covers contaminated media and that prevents rainwater from percolating into the ground and causing contaminants under the cap to leach into groundwater. Also may prevent surface exposure to covered contaminants.

Cation Exchange
A chemical process in which positively charged ions of like charge are exchanged equally between a solid and a solution (such as water).

Chelates
A compound in which a metallic ion is attached by covalent bonds to two or more nonmetallic atoms in the same molecule. Chelating agents are used to remove metals, particularly lead, from insoluble soil fractions and keep them in solution.

Concentration
The amount of a specified substance in a unit amount of another substance; the relative abundance of a solute in a solution.

Degradation
Decomposition of a compound by stages, exhibiting well-defined intermediate products.

Drip Irrigation
Irrigation whereby water is slowly applied to the soil surface through small emitters that have a low rate of discharge.

Emergent Plant
An herbacious plant standing erect and rooted in shallow water, with most of the plant growing above the water’s surface.

Evapotranspiration
The loss of water from the soil both by evaporation and by transpiration from the plants growing in the soil. Evaporation involves the change of state of water from liquid to gas form as water molecules escape from the surface of a body into the atmosphere. Transpiration is the process by which water is drawn from the soil by osmotic pressure of the root systems of vegetation and moved through the leaves to the surrounding atmosphere.

Extraction
Removal by chemical or mechanical action.

Full-Scale Technology
An established technology for which cost and performance information is readily available.

Groundwater
The supply of fresh water found beneath the Earth's surface, usually in aquifers, that supplies wells and springs.

Herbacious Plant
A plant with no persistent woody stem above ground.

Hydrostatic Barrier
In phytoremediation, the use of plants to control movement of water, generally from an area of higher levels of contamination to an area of lower levels of contamination.

Hyperaccumulators
Metallophytes that accumulate an exceptionally high level of a metal to a specified concentration or to a specified multiple of the concentration found in nonaccumulators. Alpine pennycress is an example (see metallophytes).

Immobilize
To make incapable of further movement.

In Situ
In place, without excavation. In situ soil technologies treat contamination without digging up or removing the contaminants.

Indian Mustard (*Brassica juncea*)
A potentially useful plant with relatively high biomass that is not a hyperaccumulator. The plant has been frequently used in toxic metal and radionuclide phytoextraction.

Infiltration
To pass into or through a substance (such as soil) by penetrating its pores or interstices; generally refers to water entering a physical area.

Innovative Treatment Technologies
A technology that has been field-tested and applied to a hazardous waste problem at a site, but lacks a long history of full-scale use. Information about its cost and how well it works may be insufficient to encourage use under a wide variety of operating conditions. Innovative treatment technologies are better analyzed on a site-by-site basis.

Inorganic Chemical or Compound
A chemical or compound that generally does not contain carbon atoms (carbonate and bicarbonate compounds are notable exceptions). Examples of inorganic compounds include various acids and metals.

Leaching
A process through which a liquid in contact with or moving through a solid mobilizes constituents from the solid through the actions of dissolution and physical transport.

Lignification
Formation into wood through the formation and deposit of lignin (a polymer functioning as a natural binder and support for the cellulose fiber of woody plants) in cell walls; the process of making something woody.

Mass Transfer
The conveyance of any material like liquids, gases, or solid materials from one location to another location; in phytoremediation, the term might refer to the conveyance of a contaminant from soil or groundwater to a plant.

Metallophytes
Plants that preferentially colonize in metal-rich soils.

Microorganisims
An organism too tiny to be seen by the unaided eye. Includes bacteria, algae, fungi, and viruses.

Natural Attenuation
An approach to cleanup that uses natural processes over time to contain contamination and reduce the concentrations and amounts of pollutants in contaminated soil and groundwater. The processes of natural attenuation include dilution, volatilization, biodegredation, and adsorption.

Nutrients
Elements or compounds essential for the growth and development of an organism. Nitrogen, phosphorous, and potassium are examples of essential plant nutrients.

Organic Chemical or Compound
A chemical or compound produced by animals or plants that contains mainly carbon, hydrogen, and oxygen.

Phreatophyte
A deep-rooted plant that obtains water from the water table.

Phytocap (or Vegetative Cap)
A long-term, self-sustaining planted area growing in and over materials that pose an environmental risk. The phytocap requires minimal maintenance and is designed to reduce the risk that the contaminant will leach.

Phytoremediation
A technology that uses living plants to remediate or stabilize contaminants in soil, sediment, surface water, or groundwater.

Phytotoxic
Harmful to plants.

Pilot-Scale Testing
Testing stage of a treatment technology, between bench- and full-scale, that is conducted in the field to provide data on performance, cost, and design objectives for the treatment technology.

Plume
A visible or measurable emission or discharge of a contaminant from a given point of origin into any medium.

Poplar (Eastern Cottonwood or *Populus deltoides*)
A tree widely studied for its potential for hydraulic control, phytodegredation, and phytovolatilization.

Rhizosphere
The zone of soil adjacent to plant roots that exhibits significantly higher microbial numbers, species, and activity than bulk soil.

Root Zone
Generally considered to be the area surrounding the underground part of a plant, the functions of which include absorption, aeration, and storage for the plant.

Sorption
The action of soaking up or attracting substances—a general term used to encompass the processes of absorption and adsorption.

Submergent Species
Plant species that lie entirely under water.

Transpiration
The plant-based process that involves the uptake, transport, and eventual vaporization of water through the plant's leaves.

Volatile Organic Compounds (VOC)
Organic chemicals capable of becoming vapor at relatively low temperatures.

Volatilization
The transfer of a chemical from the aqueous or liquid phase to the gas phase. Solubility, modular weight, the vapor pressure of the liquid and the nature of the gas-liquid affect the rate of volatilization.

APPENDIX 2

THE PROCESSES OF PHYTOREMEDIATION

Phytoremediation can be classified according to the biological processes involved. Those processes are described below.

Hydraulic Control, also known as phytohydraulics, is designed to control groundwater transport mechanisms through plant transpiration. The process uses plants that have a high transpiration rate to take up large quantities of water, thereby achieving hydraulic control of the site to contain contaminants and prevent their further migration. The transpiration rate depends on the type of plant, leaf area, nutrients, soil moisture, temperature, wind conditions, and relative humidity.

Phytodegradation, also known as phytotransformation, is the uptake of organic contaminants from soil and groundwater, followed by their degradation in plant tissue. The extent of degradation depends on the efficiency of contaminant uptake and the concentration of contaminants in soil and groundwater. Uptake efficiency depends on the contaminant's physical and chemical properties and the plant itself. After uptake, the plant either stores the contaminants or volatizes or metabolizes the contaminants completely to carbon dioxide and water. The process is an efficient removal mechanism at shallow depths for moderately hydrophobic organic contaminants like benzene, toluene, ethylbenzene, and xylene (BTEX); chlorinated solvents; and short-chain aliphatic hydrocarbons.

Phytoextraction uses plants to transport metals from the soil and concentrate them into roots and aboveground shoots that can be harvested. Many types of plants can be used to remove metals. Some grasses accumulate surprisingly high levels of metals in their shoots without exhibiting toxic effects. However, their low biomass production results in a relatively low extraction rate for metals. Genetic engineering or breeding of hyperaccumulating plants for high biomass production could make the extraction process highly effective. Using crop plants to extract metals from the soil seems practical because of their high biomass production and relatively fast growth rate. Crop plants also are easy to cultivate and exhibit genetic stability. However, using crop plants to accumulate metals is a potential threat to the food chain.

Phytostabilization uses plants to limit the mobility and bioavailability of metals in soil by sorption, precipitation, complexation, or the reduction of metal valences. The process helps to stabilize the soil matrix to minimize erosion and migration of sediment. To eliminate the possibility that residues in harvested shoots might become hazardous wastes, phytostabilizing plants should exhibit low levels of accumulation of metals in shoots. Phytostabilization immobilizes metal contaminants in the soil through a combination of processes, including reaction with soil amendments, adsorption or accumulation in the rhizosphere, and physical stabilization of the soil. In addition, the process minimizes the generation of airborne contaminants caused by wind erosion. Some researchers consider an interim measure to be applied until extraction becomes fully developed. Other researches are developing phytostabilization as a standard protocol of metal remediation technology, especially at sites at which removal of metals does not seem economically feasible.

Phytovolatilization uses plants to takeup volatile organic compounds (VOC) and the metabolic products of the plant and transpire them into the atmosphere. Because VOCs are released into the atmosphere through plant transpiration, air monitoring may be required. This form of phytoremediation may not be as desirable as in situ degradation, but it may be preferable to prolonged contamination of soil and groundwater contamination.

Rhizodegradation also known as phytostimulation, plant-assisted bioremediation, or enhanced rhizosphere bioremediation, is root-stimulated microbial degradation of organic contaminants. Rhizodegradation involves a root zone that provides a habitat for beneficial microbial growth and fungi associated with plant roots that help in metabolizing organic contaminants. Root turnover for trees like mulberry, osage orange, and apple release flavonoids and coumarin that stimulate the degradation of polychlorinated biphenyls (PCB).

Rhizofiltration is the removal or concentration of metal contaminants from an aquatic environment such as contaminated surface water and groundwater in the root zone. One variation of rhizofiltration removes metals by sorption, which involves biochemical processes. The roots absorb, concentrate, and precipitate metals from polluted effluent, which may include leachate from soil. Another variation of rhizofiltration is the construction of wetlands or reed beds for the treatment of contaminated water or leachate. The technology generally has been found to be cost-effective for the treatment of large volumes of wastewater that contain low concentrations of metals. Plant species used for rhizofiltration often are raised hydroponically in greenhouses and transplanted to a floating system in which the roots are in contact with contaminated water.

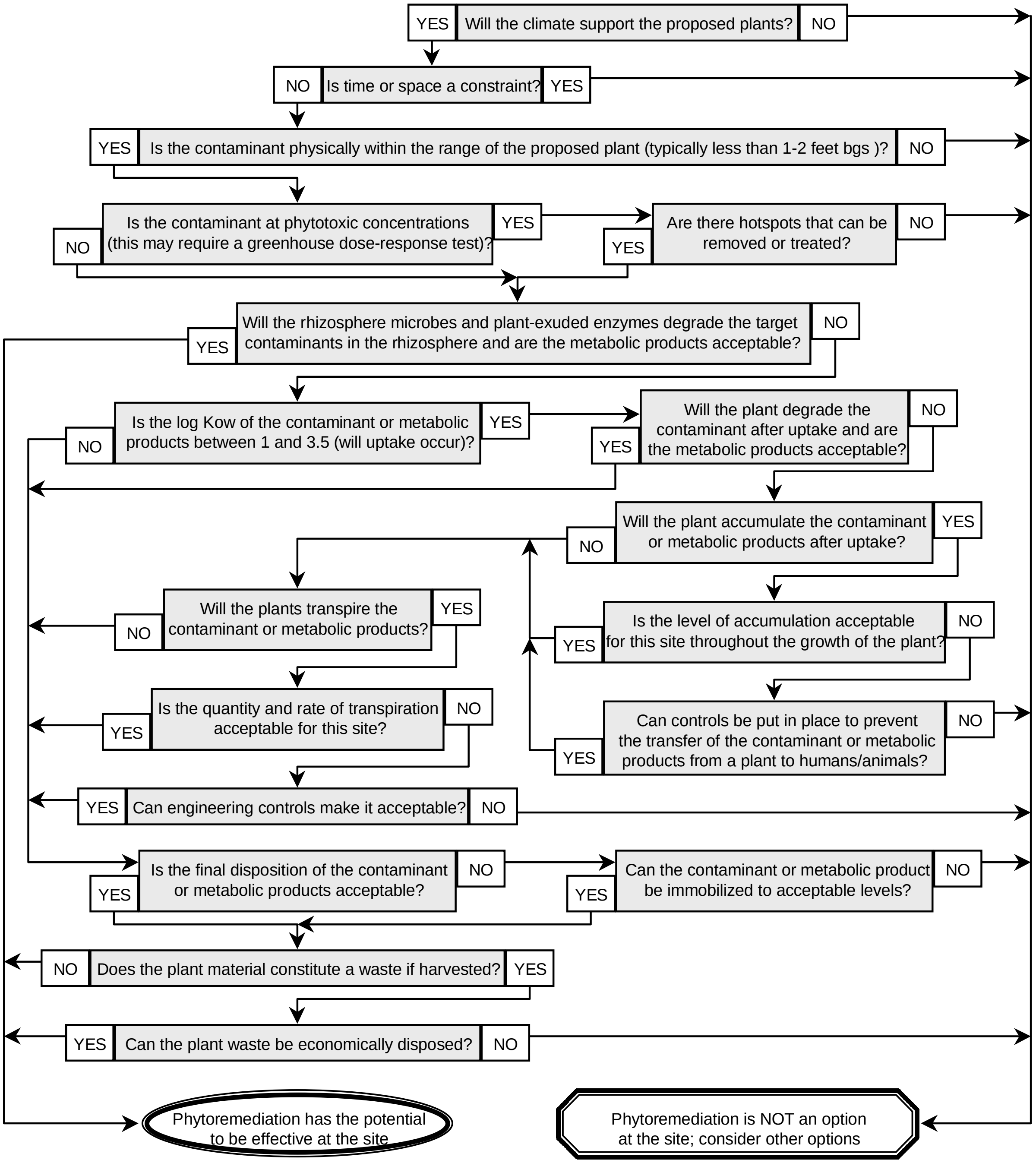
APPENDIX 3

PHYTOREMEDIATION DECISION TREE MODELS

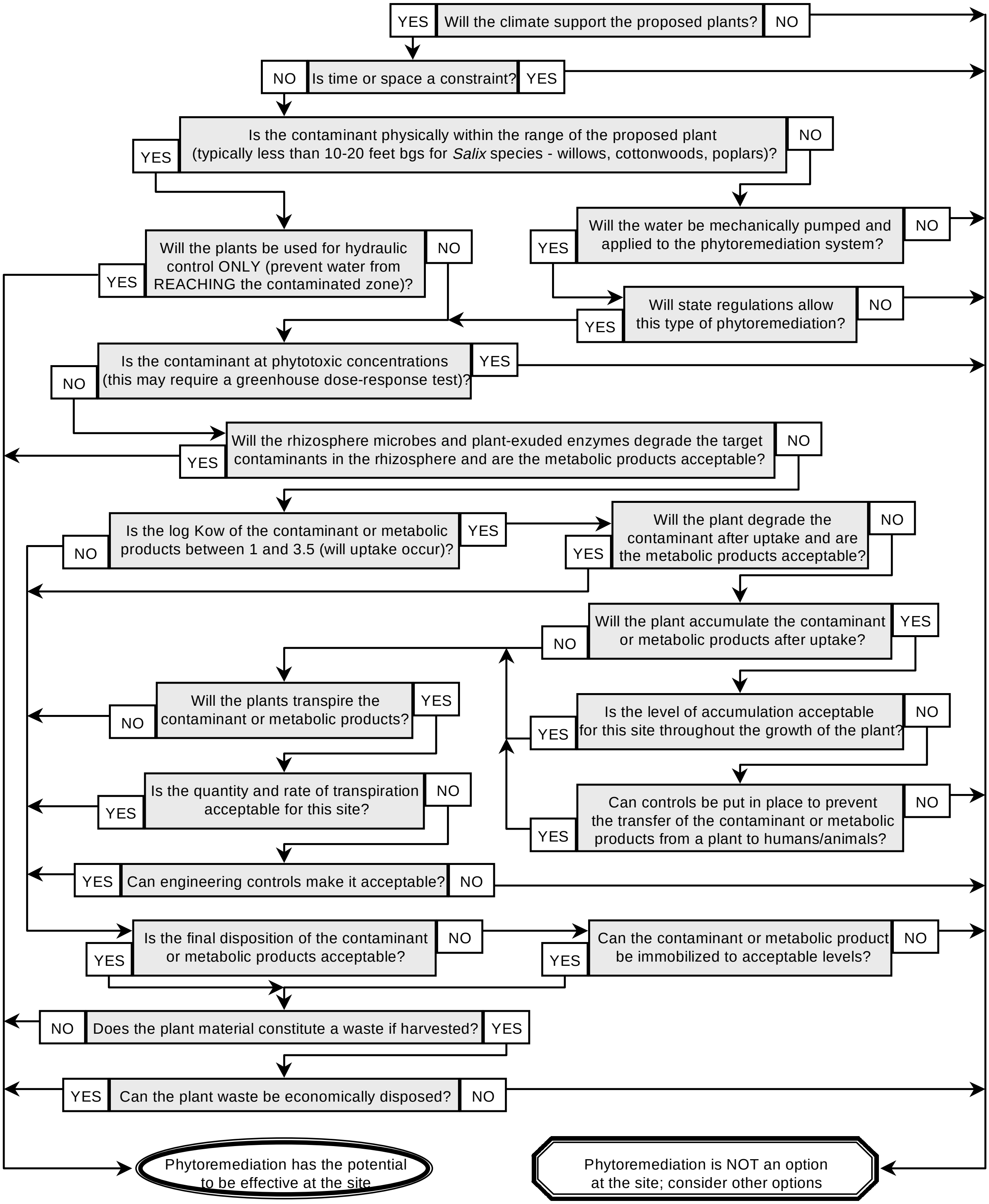
The three decision tree charts on the following pages were developed by the Phytoremediation Work Group of the Interstate Technology and Regulatory Cooperation Work Group (ITRC). The Phytoremediation Work Team effort, as part of the broader ITRC effort, is funded primarily by the U.S. Department of Energy. Additional funding and support is provided be the U.S. Department of Defense and the U.S. Environmental Protection Agency.

These charts provide guidelines for determining the applicability of phytoremediation at a brownfields site after site characterization for the treatment of soil, groundwater, or sediments has been completed.

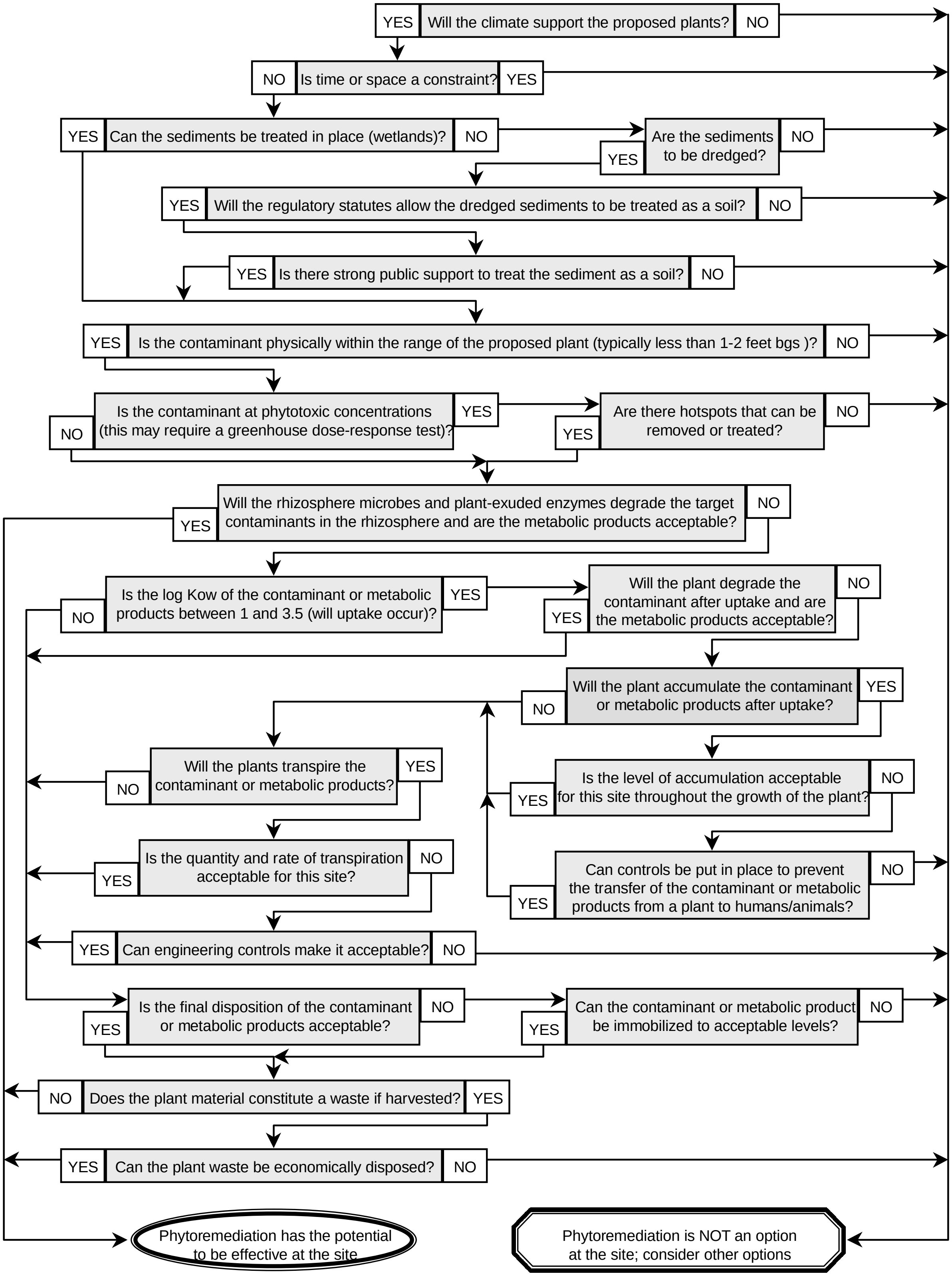
Decision Tree for Phytoremediation
Soil

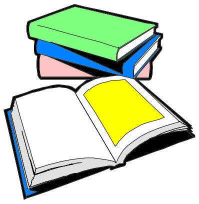


Decision Tree for Phytoremediation
Groundwater



Decision Tree for Phytoremediation
Sediments





For additional information, please see these other publications issued by the Brownfields Technology Support Center:

- ***Road Map to Understanding Innovative Technology Options for Brownfields Investigation and Cleanup, Second Edition***
  EPA 542-B-99-009

- ***Directory of Technology Support Services to Brownfields Localities***
  EPA 542-B-99-005

- ***Assessing Contractor Capabilities for Streamlined Site Investigations***
  EPA 542-R-00-001

- ***Brownfields Technology Primer: Requesting and Evaluating Proposals That Encourage Innovative Technologies for Investigation and Cleanup***
  EPA 542-R-01-005

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Brownfields Technology Primer:

Selecting and Using Phytoremediation for Site Cleanup

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