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The Use of Vegetation in the Stabilization, Reclamation, and Remediation of Impacted INDOT Soils

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The Use of Vegetation in the Stabilization, Reclamation, and Remediation of Impacted INDOT Soils

Introduction

Soils can be severely impacted by transportation-related activities including highway construction, renovations, maintenance, and accidental spills. Reclamation or remediation of soils contaminated by salts, solvents, paints, petroleum, and metals may be necessary to comply with current environmental regulations and to avoid erosion of denuded areas. Vegetation as alternative for INDOT facilities in the remediation of contaminated soils and groundwater has not been fully explored.

Many uses have been found for vegetation in the recovery of disturbed and contaminated land. For example, the establishment of ground cover to prevent erosion has been used for many decades. Some fascinating and innovative uses for vegetation have been developed very recently, such as the extraction of arsenic from pesticide-contaminated soil using a fern.

Phytoremediation uses plants to degrade, extract, contain, or immobilize contaminants from soil and water. Phytoremediation is an innovative, cost-effective alternative to more conventional treatment methods used in the remediation of hazardous waste sites.

The major goal of this project was to write the manual ***PhytoRemediate®: Phytoremediation Decision Guide for Transportation Engineers*** and the attached compact disk ***PhytoRemediate®: Training Module for Transportation Engineers*** to assist transportation engineers and other professionals in the applicability of phytoremediation as an effective method of remediation engineering design. This guide is not a design manual, but identifies the decision-making processes necessary for successful remediation of contaminated sites using phytoremediation.

Findings

The major findings of this project are the writing of the manual ***PhytoRemediate®: Phytoremediation Decision Guide for Transportation Engineers*** and the attached compact disk ***PhytoRemediate®: Training Module for Transportation Engineers.***

The objectives of the manual and training module are to:

- Provide a decision guide for transportation engineers to evaluate the applicability of phytoremediation to contaminated sites. Phytoremediation projects have been proposed or applied to ecosystem restoration and soil, surface water, groundwater, and sediment remediation. This decision guide identifies and defines phytoremediation technologies, and provides examples of current research and case studies to aid in the evaluation of proposed phytoremediation applications.
- Develop a decision guide that is accessible for the Indiana Department of Transportation (INDOT) and the Indiana Department of Environmental Management (IDEM) teams and others to evaluate alternative remediation technologies.
- Present phytoremediation system characteristics that transportation engineers and other professionals need to assess the

potential applicability of phytoremediation to specific contaminated sites.

Present a summary of select case studies and their applicability to environmental problems identified by the Indiana Department of Transportation (INDOT), illustrating actual field applications of phytoremediation.

Implementation

The major findings of this project are the writing of the manual ***PhytoRemediate®: Phytoremediation Decision Guide for Transportation Engineers*** and the attached compact disk ***PhytoRemediate®: Training Module for Transportation Engineers.***

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PhytoRemediate®:

Phytoremediation Decision Guide for Transportation Engineers

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May 2004

PhytoRemediate®

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SCHOOL OF CIVIL ENGINEERING

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1.0 Introduction

Phytoremediation uses plants to degrade, extract, contain, or immobilize contaminants from soil and water. Phytoremediation is an innovative, cost-effective alternative to more conventional treatment methods used in the remediation of hazardous waste sites.

1.1 Purpose of Decision Guide and Intended Audience

The purpose of the *PhytoRemediate®: Phytoremediation Decision Guide for Transportation Engineers* is to assist transportation engineers and other professionals in the applicability of phytoremediation as an effective method of remediation engineering design. This guide is not a design manual, but identifies the decision-making processes necessary for successful remediation of contaminated sites using phytoremediation.

Figure 1. Many plants have been used for the phytoremediation of PAHs and PCBs.

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1.2 Objectives of Decision Guide

The objectives of *PhytoRemediate®: Phytoremediation Decision Guide for Transportation Engineers* are to:

- Provide a decision guide for transportation engineers to evaluate the applicability of phytoremediation to contaminated sites. Phytoremediation projects have been proposed or applied to ecosystem restoration and soil, surface water, groundwater, and sediment remediation. This decision guide identifies and defines phytoremediation technologies, and provides examples of current research and case studies to aid in the evaluation of proposed phytoremediation applications.
- Develop a decision guide that is accessible for the Indiana Department of Transportation (INDOT) and the Indiana Department of Environmental Management (IDEM) teams and others to evaluate alternative remediation technologies.
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- Present a summary of select case studies and their applicability to environmental problems identified by the Indiana Department of Transportation (INDOT), illustrating actual field applications of phytoremediation.

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2.0 Background of Phytoremediation

Phytoremediation consists of the technologies that use plants to clean up contaminated sites. The term phytoremediation (“*phyto*” = plant and “*remediation*” = correct evil) is relatively new. Phytoremediation originated in a number of research areas including constructed wetlands and agricultural applications.

Figure 2. Soil sampling for site characterization for phytoremediation site clean-up in Bedford, Indiana.

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2.1 What is Phytoremediation?

According to McCutcheon and Schnoor (2003), "phytoremediation involves the use of vascular plants, algae, and fungi either to remove and control wastes or to spur waste breakdown by microorganisms in the rhizosphere." An integral part of phytoremediation is the use of plants to promote microbial degradation or biotransformation of contaminants through the process of rhizodegradation. Phytoremediation is also low-cost, especially when compared to many of the traditional or conventional approaches for hazardous waste management. Vascular green plants have the ability to self-engineer or exert limited control over the plant rhizosphere, rhizosphere biogeochemistry, availability of water and plant nutrients, as well as the local microclimate. Mitsch and Jørgensen (2004) define self-engineering or self-design as "the application of self-organization in the design of ecosystems."

The hazardous wastes that can be treated using phytoremediation are actually quite diverse, including metals, metalloids, munitions, nonmetals, surfactants, radionuclides, salts, nutrients, xenobiotic organic chemicals (compounds that are foreign to living organisms), sewage, and air pollutants. Some of these xenobiotic organic chemicals include polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) pesticides, pentachlorophenol (PCP), and petroleum hydrocarbons. Phytoremediation also can be used for hydrologic control.

The mechanisms in phytoremediation can include the biotransformation of xenobiotic organic chemicals; degradation of inorganic compounds such as perchlorate and cyanide; and the use of evapotranspiration as a hydrologic control of hazardous wastes in soil, sediments, groundwater, and surface water. Phytoremediation uses green plants to accumulate metals, metalloids, and radionuclides and to stabilize metals and organic pollutants in the environment.

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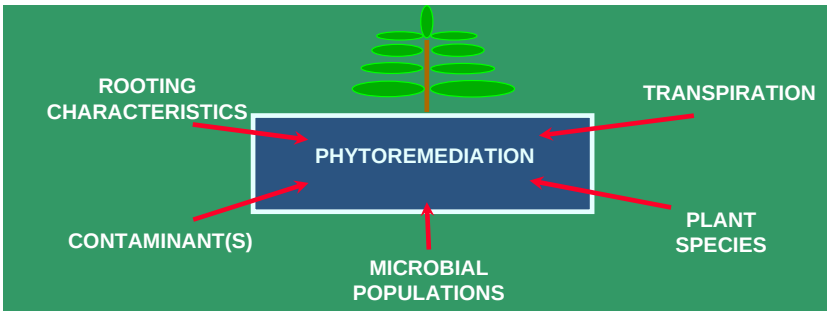

Figure 3. Phytoremediation Processes

2.2 Brief History of Phytoremediation

The history of phytoremediation is fairly recent (McCutcheon and Schnoor, 2003). Raskin et al. (1994) were reportedly the first to use the term phytoremediation in a 1991 proposal funded by the U.S. Environmental Protection Agency. Cunningham and Berti (1993) were the first to use the term phytoremediation in the open technical literature, although they noted that the use of green plants for wastewater treatment has occurred for over 300 years. Recently, there have been many applications of phytoremediation in natural and constructed treatment wetlands, and in air pollution control in ambient and indoor air. According to Cunningham and Lee (1995), in the 1970s, plant-based remediation of metals-contaminated soil and dredge material slurries was thoroughly investigated. Cunningham et al. (1996) asserted that matrix toxicity from contaminants may have limited these applications until research on hyperaccumulation was published by Brooks (1998). Alternative methods to manage phytotoxicity were established by several pioneers in phytoremediation (Chaney, 1983; Cunningham and Berti, 1993; U.S. DOE, 1994; Raskin et al., 1994; Baker et al., 1995; Dushenkov et al., 1995; Kumar et al., 1995; McCutcheon et al., 1995; Salt et al., 1995; and Schnoor et al., 1995b.).

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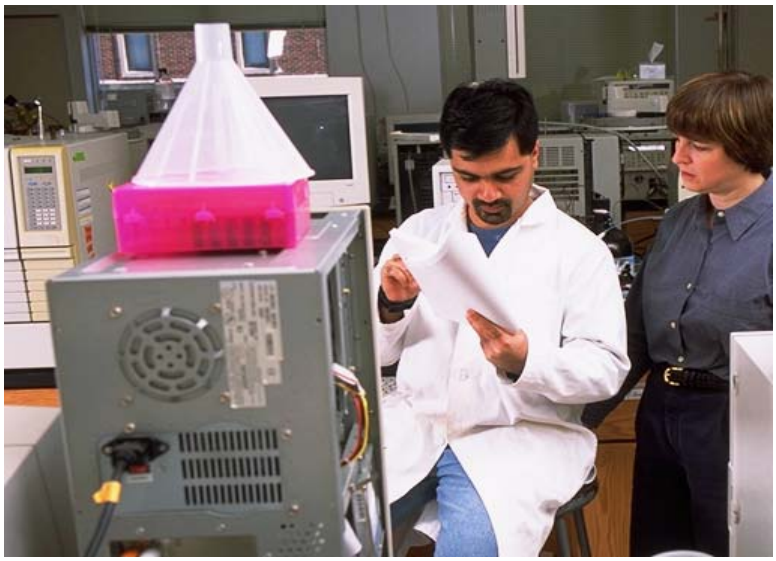

Figure 4. Phytoremediation pioneer Kathy Banks and student in the laboratory.

2.3 Basic Types of Phytoremediation: Processes and Mechanisms

There are several basic types of phytoremediation. The following phytoremediation technologies utilize several different processes and mechanisms. These are discussed as follows (McCutcheon and Schnoor, 2003):

- *Phytoextraction* is the use of plants to uptake contaminants and assimilate them into biomass. Chemicals are taken up from soil with water, by cation pumps, absorption, and translocation aboveground. Shoots and roots are harvested and then disposed in a landfill or smelted following volume reduction by incineration or composting. Hyperaccumulation of metals such as nickel is an example of phytoextraction.
- *Phytostabilization* is the use of plants to prevent the migration of contaminants through control of the hydraulic gradient or by reinforcing the soil structure. Phytostabilization is 1) revegetation to prevent soil erosion and sorbed pollutant transport, 2) use of plants to control pH, soil gases, and sorption to form stable

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mineral deposits, and 3) humification, lignification, and covalent or irreversible binding of some organic compounds through the action of plant roots.

- *Rhizosphere Bioremediation/Rhizodegradation* is the use of plant roots to sorb contaminants. Chemicals exuded or secreted from plant roots (root exudates) may also enhance rhizofiltration. It uses the following processes: plant root exudation, root necrosis, and processes supply organic carbon and nutrients to promote soil bacterial growth; stimulate enzyme induction and cometabolic degradation by mycorrhizal fungi and rhizo-microbial consortium; provide diverse rhizosphere habitat; and attenuate chemical transport and concentrations. Live roots also pump oxygen to anaerobes or leave aeration channels.
- *Phytodegradation/Phytotransformation* is the biochemical process that involves the uptake and metabolism of contaminants by plants. Aquatic and terrestrial plants take up, store, and biodegrade or biotransform xenobiotics to harmless by-products, products used to create new plant biomass, or by-products that are degraded by microorganisms and other processes to less harmful compounds. Growth and senescence enzymes are a part of plant metabolism, assimilation, or detoxification. Reductive and oxidation enzymes may be operative in different parts of the plant.
- *Phytovolatilization* is the process whereby volatile metals, metalloids, and organic compounds are taken up into the plant, re-speciated, and transpired. This process involves the uptake and metabolism of contaminants and the subsequent release by the plants into the atmosphere. Some xenobiotics are more easily degraded in the atmosphere.
- *Rhizofiltration* is the process whereby compounds are taken up, sorbed, or precipitated by roots.
- *Hydrologic Control/Plume Control/Phytocontainment* is the process whereby plants transpire large quantities of water which may contain shallow groundwater

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plumes or contaminated soil leaching by reversing horizontal aquifer hydrologic gradient or vertical soil moisture pressure gradient.

- *Riparian Corridors/Buffer Strips* use plants as a filter or barrier. They are used as vegetative cover or phytostabilization in the region around rivers, streams, lakes, and wetlands. These areas function as a buffer between these aquatic areas and the adjacent uplands.
- *Vegetative Cover* can be used for soil erosion control and soil stabilization.

An overview of phytoremediation is shown in Figure 3 and Table 1. Figure 3 summarizes the basic mechanisms in phytoremediation, whereas Table 1 summarizes these mechanisms with process goals, contaminant media, pollutants/contaminants, the plants used with established successes, and the status of the phytoremediation techniques.

2.3.1 Phytodegradation

Plants may enhance the biodegradation in the rhizosphere or the zone of influence around the plant roots. Another possible mechanism for contaminant biodegradation is metabolism within the plant. Some plants may be able to take in toxic compounds and detoxify them (USEPA, 2000).

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Table 1. Phytoremediation Overview

Mechanism	Process Goal	Media	Contaminants	Plants	Status
Phytoextraction	Contaminant extraction and capture	Soil, sediment, sludges	Metals: Ag, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Zn; Radionuclides: ^{90}Sr, ^{137}Cs, ^{239}Pu, $^{238,234}U$	Indian mustard, pennycress, alyssum, sunflowers, hybrid poplars	Laboratory, pilot, and field applications
Rhizofiltration	Contaminant extraction and capture	Groundwater, surface water	Metals, radionuclides	Sunflowers, Indian mustard, water hyacinth	Laboratory and pilot application
Phytostabilization	Contaminant containment	Soil, sediment, sludges	As, Cd, Cr, Cu, Hs???, Pb, Zn	Indian mustard, hybrid poplars, grasses	Field application
Rhizodegradation	Contaminant destruction	Soil, sediment, sludges, groundwater,	Organic compounds (TPH, PAHs, pesticides chlorinated solvents, PCBs)	Red mulberry, grasses, hybrid poplar, cattail, rice	Field application
Phytodegradation	Contaminant destruction	Soil, sediment, sludges, groundwater surface water	Organic compounds: chlorinated solvents, phenols, herbicides, munitions	Algae, stonewort, hybrid poplar, black willow, bald cypress	Field demonstration
Phytovolatilization	Contaminant extraction from media and release to air	Groundwater, soil, sediment, sludges	Chlorinated solvents, some inorganics (Se, Hg, and As)	Poplars, alfalfa black locust, Indian mustard	Laboratory and field application
Hydrologic control (plume control)	Contaminant degradation or containment	Groundwater surface water,	Water-soluble organics and inorganics	Hybrid poplar, cottonwood, willow	Field demonstration
Vegetative cover (evapotranspiration cover)	Contaminant containment, erosion control	Soil, sludge, sediments	Organic and inorganic compounds	Poplars, grasses	Field application
Riparian corridors (non-point source control)	Contaminant destruction	Surface water, groundwater	Water-soluble organics and inorganics	Poplars	Field application

Source: USEPA, 2000.

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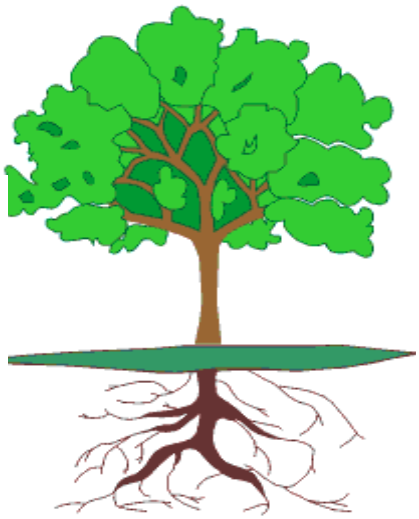
Phytodegradation is the breakdown of contaminants taken up by the plant through metabolic processes within the plant, or the breakdown of contamiants external to the plant through the effect of compounds (such as enzymes) produced by the plant.

Physical Effects involve the transpiration of volatiles and hydraulic control of dissolved plume.

Enhanced rhizosphere biodegradation



Accumulation in roots translocated to shoots and leaves.

Figure 5. Phytoremediation Mechanisms
(modified from USEPA, 2001 and the tree graphic from http://www.cist.org/ay/gm/ga1501.htm)

2.3.2 Phytoextraction

Phytoextraction, or phyto-mining, is the process of the accumulation or hyperaccumulation of contaminants in the shoots and leaves of the plants, and then harvesting the plant and removing the contaminant from the site. Unlike the destructive

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degradation mechanisms, phytoextraction yields of plant biomass with contaminants, typically metals, which must be disposed or recycled.

Rhizofiltration is similar to phytoextraction because it also is a concentration technology. Rhizofiltration differs from phytoextraction because the mechanism is root accumulation and harvest of a contaminant using hydroponic or other aquaculture techniques.

Phytovolatilization, transpiration of volatile contaminants through plants into the atmosphere, is another possible mechanism for removing a contaminant from the soil or groundwater of a site (USEPA, 2000).

2.3.3 Containment and Immobilization of Contaminants

Bioavailability is defined by Mitsch and Jørgensen (2004) as the amount of contaminant present that can be taken up readily by organisms. Bioavailability is a critical factor in the application of bioremediation and hence phytoremediation. Containment using plants either enhances sorption of the contaminants to the soil, rendering them nonbioavailable, or immobilizing them relative to physical transport. Environmental and health risk reduction can be accomplished by transforming the contaminant into a form that is not hazardous, or by rendering the contaminant nonbioavailable.

Hydrologic control is another type of containment of contaminants. Groundwater contaminant plume control can be achieved by using plants to increase the evapotranspiration from a site. Some plants use tremendous quantities of water in evapotranspiration, and can extend roots to great depths to draw from the unsaturated zone (vadose zone) and ultimately from the saturated zone (phreatic zone).

Vegetative cover, also evapotranspiration or water-balance cover, systems are another application utilizing the natural mechanisms of plants to minimize infiltrating

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water. If there is potential for gas generation, a vegetative cover may not be an appropriate option (USEPA, 2000).

2.3.4 Phytoremediation Applications

A summary of phytoremediation applications is shown in Table 2. These applications are described by the mechanism of phytoremediation, the pollutant or contaminant, the contaminant media, the plant(s) used, the status of the project, and the reference citation.

Table 3 is a summary of phytoremediation technologies applicable to different contaminant types. The technology media, whether used for contaminated soil or water, are phytoextraction, rhizofiltration, phytostabilization, rhizodegradation, phytodegradation, and phytovolatilization. The technology media are chlorinated solvents, metals, metalloids, munitions, nonmetals, nutrients, PAHs, PCBs, PCP, pesticides, petroleum hydrocarbons, radionuclides, and surfactants. This summary of phytoremediation technologies will enable INDOT to make informed decisions and proper engineering design when dealing with specific environmental problems as well as the effectiveness of these phytoremediation technologies.

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Table 2. Phytoremediation Applications

Mechanism	Contaminant	Media	Plant	Status	Reference
Degradation	Atrazine and nitrates	Surface Water	Poplar	Applied	Schnoor, 1995a
Degradation	Landfill leachate	Groundwater	Poplar	Applied	Licht, 1990
Degradation	TCE	Groundwater	Poplar and cottonwood	Field demonstration	Rock, 1997
Degradation	TNT	Wetlands	Various plants	Field demonstration	Bader, 1996 Carreira, 1996 McCutcheon, 1995
Degradation	TPH	Soil	Grasses and crops	Field demonstration	Banks et al., 1997 Drake, 1997
Extraction-Concentration in shoot	Lead	Soil	Indian mustard	Field demonstration	Blaylock et al., 1997
Extraction-Concentration in root	Uranium	Surface water	Sunflower	Field demonstration	Dushenkov et al., 1997
Extraction, Volatilization	Selenium	Soil and Surface Water	Various plants	Applied	Bañuelos, 1996 Terry, 1996

Source: USEPA, 2000.

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Table 3. Phytoremediation Technologies Applicable to Different Contaminant Types [1,2]

Technology Media	Phytoextraction		Rhizofiltration	Phytostabilization	Rhizodegradation	Phytodegradation		Phytovolatilization	
	Soil	Water	Soil	Soil	Soil	Soil	Water	Soil	Water
Chlorinated solvents	F	F			F	F	F	F	F
Metals[3]	F	F	F	F				G(Hg)	
Metalloids	G	F(Se)		T				G	F (Se)
Munitions					G	G	F		
Nonmetals	G	G			F				
Nutrients	F	F	F[5]		G	F	F		
PAHs					F				
PCBs	G	G			F	G	G		
PCP				G	F				
Pesticides	F	F			F	F	F	T	
Petroleum hydrocarbons	T				F	F	F	T	
Radionuclides[4]	G	F	F	G					
Surfactants					T				

[1]The applicability of a particular method of phytoremediation to each contaminant type has been judged by the current state or stage of the application.
This is indicated in the table by the following designations:

T - The application is at the theoretical stage.
G - The application has been researched in the greenhouse or laboratory.
F - The application has been researched using field plots or has been applied in full-scale field systems.

[2]All contaminants can be controlled using vegetative covers. The vegetative cover, riparian corridors, buffer strips, and hydrologic control are not included in the table because they can be considered combinations of the other phytoremediation technologies.
[3]Reeves and Brooks 1983; Baker et al., 1995, Salt et al. 1995; Nanda Kumar et al. 1995; Cornish et al. 1995.
[4]Salt et al. 1995; Nanda Kumar et al. 1995; Cornish et al. 1995.
[5]In constructed wetlands.

Source: USEPA, 2000.

Table 4 summarizes phytoremediation technologies and the methods of contaminant control. Emphasis is placed on whether the contaminant is destroyed through biotransformation, extracted or taken up into the plant, or contained using vegetative cover or riparian corridors.

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Table 4. Summary of Phytoremediation Technologies and Method of Contaminant Control

Method	Destruction	Extraction/Uptake	Containment
Phytoextraction (concentration)		*	
Rhizofiltration		*	
Phytostabilization		*	
Rhizodegradation	*		
Phytodegradation	*		
Phytovolatilization		*	
Plume control			
Vegetative cover	*[a]		*[b]
Riparian corridors	*	*	*

a Phytoremediation cover.
b Evapotranspiration cover .

Source: USEPA, 2000.

2.4 Technical Considerations for Phytoremediation

According to USEPA (2000), several key issues should be considered when evaluating whether phytoremediation is a potential solution or design mechanism to clean up contaminated sites. Some of the key issues are as follows:

1. Determine whether phytoremediation will effectively remove target contaminants. Laboratory studies on properly selected plants and the site contaminants may be necessary to support the use of phytoremediation at a particular site. These pilot studies will show if the plants to be used at the site are capable of remediation before the implementation of field-scale phytoremediation.

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2. Consider the effectiveness of the remediation technique over the time required for plant establishment.
3. Consider if phytoremediation is likely to clean-up the site in an acceptable time frame. (what is the difference between 2 and 3)??
4. Identify adequate backup or contingency plan if phytoremediation is attempted and does not succeed. The monitoring of the efficacy of any innovative treatment such as phytoremediation may be more extensive or expensive than would be required when using traditional technologies. The monitoring should address both the decrease in concentration of the contaminants in the media of concern (contaminant reduction) as well as examine the fate and transport mechanisms of the contaminants. The monitoring plan must be suited to the site.

2.5 Economic Considerations for Phytoremediation

Because phytoremediation is a relatively new and emerging technology, reliable cost information is not readily available. As a result, the ability to develop cost comparisons needs to be assessed on a site-specific basis. Two considerations that influence the economics of phytoremediation are: 1) the potential for the application and 2) the cost comparison to conventional treatments. Care must be taken to compare whole system costs, which may include the design costs, operating cost, and monitoring needs that are summarized in Table 5 (USEPA, 2000).

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Table 5. Economic Considerations for Phytoremediation

---------- Design costs: ----------		Operating costs:	Monitoring:
Site characterization	Chelating agents	Maintenance	Soil nutrient
Work plan and report preparation	pH control	Irrigation water	Soil pH
Treatability and pilot testing	Drainage	Fertilizer	Soil water
Installation costs	Infrastructure	pH control	Plant nutrient status
Site preparation	Irrigation system	Chelating agent	Plant contaminant status (roots, shoots, stems, leaves)
Facilities removal	Fencing	Drainage water disposal	Tree sap flow monitoring
Debris removal	Planting	Pesticides	Air monitoring
Utility line removal/relocation	Seeds, plants	Fencing/pest control	Weather monitoring
Soil preparation	Labor	Replanting	
Physical modification: tilling	Protection		

Source: USEPA, 2000

The following discussion describes cost estimates for phytoremediation (USEPA, 2000 and Glass, 2000). Cost comparisons are also shown in Tables 6 and 7.

2.5.1 Phytoextraction Costs

Phytoextraction uses plants that are known to accumulate contaminants in the shoots and leaves of these plants, and subsequently harvesting the plant and removing the contaminant from the site. Example phytoextraction costs are as follows:

1. The estimated 30-year costs (1998 dollars) for the remediation of a 12-acre site contaminated with lead were $12,000,000 for excavation and disposal;

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$6,300,000 for soil washing; $600,000 for the construction of a soil cap; and $200,000 for phytoextraction (Cunningham et al., 1996).

2. Cost estimates made for remediation of a hypothetical case of a 20-in.-thick layer of sediments contaminated with Cd, Zn, and ^{137}Cs from a 1.2-acre chemical waste disposal pond indicated that phytoextraction would cost about one-third the amount of soil washing (Cornish et al., 1995).
3. Costs were estimated to be $60,000 to $100,000 using phytoextraction for the remediation of a one acre site that consisted of a 20-inch thick sandy loam compared to a minimum of $400,000 for just the excavation and storage of this soil (Salt et al., 1995).

2.5.2 Rhizofiltration Costs

Rhizofiltration is a concentration technology where the mechanism is root accumulation and harvest of the contaminant in the roots. The cost of removing radionuclides from water with sunflowers has been estimated to be $2 to $6 per thousand gallons of water (Dushenkov et al. 1997).

2.5.3 Phytostabilization Costs

Phytostabilization uses plants to prevent the migration of contaminants by controlling the hydrologic gradient or by reinforcing the soil structure. A cropping system used as a phytostabilization technique has been estimated at $200 to $10,000 per hectare, equivalent to $0.02 to $1.00 per cubic meter of soil, assuming a 1-meter root depth (Cunningham et al. 1995b).

2.5.4 Hydrologic Control Costs

Hydrologic control or the use of plants to move water from the contaminated sediments by evapotranspiration is quite effective. Estimated costs for remediation of an

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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 using trees for groundwater control (Gatliff, 1994).

2.5.5 Vegetative Cover Costs

Vegetative cover for soil erosion and sediment control, and soil stabilization is also an effective phytoremediation technique. Cost estimates indicate savings for an evapotranspiration cover compared to a traditional cover design to be 20 to 50%, depending on availability of suitable soil for the plant growth medium used for vegetative cover (RTDF, 1998).

2.5.6 Rhizodegradation

Rhizodegradation is also an effective phytoremediation technique. Cost estimates indicate a projected savings of 80% using rhizodegradation when compared to conventional treatment. Total petroleum hydrocarbons (TPH) can be removed using this *in situ* phytoremediation application (USEPA, 2000).

2.5.7 Phytoremediation cost comparisons and estimates

A summary of cost comparisons is shown in Tables 6 and 7. These cost comparisons are identified by specific case studies or problems, the basic phytoremediation applications used, and costs as compared to conventional treatments. The projected savings are also summarized.

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Table 6. Cost Comparisons

Problem	Phytoremediation Application	Cost ($ thousand)	Conventional Treatment	Cost ($ thousand)	Projected Savings
Lead in soil, 1 acre[a]	Extraction, harvest disposal	$150-250	Excavate and landfill	$500	50-65%
Solvents in groundwater, 2.5 acres[b]	Degradation and hydrologic control	$200 installation and initial maintenance	Pump and treat	$700 annual running cost	50% cost saving by third year
TPH in soil, 1 acre[c]	*In situ* degradation	$50-100	Excavate and landfill incinerate	$500	80%

Source: USEPA, 2000.
[a] Phytotech estimate for Magic Marker site (Blaylock et al. 1997).
[b] PRP estimate for Solvent Recovery Systems of New England site (USEPA, 2000).
[c] PERF estimate (Drake, 1997).

2.6 Environmental Problems Identified by the Indiana Department of Transportation (INDOT)

The Indiana Department of Transportation (INDOT) may encounter environmental problems as a result of accidental spills and disposal of hazardous materials, construction and maintenance of roads, and the salting of roads. Potential contaminants include solvents and petroleum, heavy metals in soils from paint disposal, excessive soil salinity that restricts plant growth and makes the soil susceptible to erosion, and road construction resulting in disturbance to natural wetlands and destruction of roadside vegetation leading to soil erosion.

According to the information obtained from the Environmental Services Section of INDOT, the main environmental problems leading to remediation and reclamation are presented below followed by a brief discussion.

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Table 7. Phytoremediation Cost Estimates

Contaminant Media	Estimated Costs	Source
Soil	$1-10/cubic meter	Cunningham et al., 1996, (DuPont)
Soil	$10/cubic yard	Glass, 2000 (Geraghty & Miller)
Soil	$15-20/ton	Drake, 1997 (Exxon)
Soil	$25-50/ton	Blaylock et al. 1997 (Phytotech)
Soil	$29-48/cubic meter	Salt et al., 1995
Soil	$80/cubic yard	Glass, 2000(R. Levine, DOE)
Soil	$96/cubic yard	Glass, 2000(Jerger et al. IT Corporation)
Soil	$100-150/cubic meter	Glass, 2000(R. Chaney, USDA)
Water (per 1,000 gallons treated)	$0.64	Glass, 2000(V. Medina, EPA)
Water (per 1,000 gallons treated)	$2.00-6.00	Blaylock et al. 1997 (Phytotech)
Vegetative Cover (e.g. Landfill Cap, Wastewater	$10-20,000/acre	Glass, 2000 (Christensen-Kirsh 1996, citing CH2M Hill data)
Vegetative Cover (e.g. Landfill Cap, Wastewater)	$14-30,000/acre	Glass, 2000 (EPA RTDF Action Team)

Source: Glass, 2000

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Underground Storage Tanks (USTs): USTs with leaking petroleum products resulting in soil contamination are one of the foremost environmental problems encountered by INDOT. These USTs are located on the properties acquired by INDOT for road construction and facility development. On an average, INDOT undertakes several such projects a year and most address several USTs with environmental impact. At present, the remedial approach followed by INDOT is to remove the tank, and the contaminated soil, and transport both to a landfill for disposal. This is the least expensive option for INDOT. However, INDOT does encounter some petroleum contamination of soil on associated properties due to the violation of right-of-way. Such problems are due to intrusion of INDOT property soils by contaminant plumes as a result of other responsible parties. Under these circumstances, INDOT does use bioremediation technology for clean-up.

Lead Contamination: Contamination of soils by lead due to the past use of lead-based paints on road bridges is one of the most serious problems faced by INDOT. There are several lead contaminated sites throughout Indiana.

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Figure 6. Excavator removing an underground storage tank

(source: http://www.in.gov/dot/programs/environment/images/TankYank.jpg)

Figure 7. Many INDOT bridges have been painted with lead-based paint.

(Source: http://www.in.gov/dot/div/envassess/bridges/br7c2.html)

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Hazardous materials spills: Hazardous materials spills are not very common for INDOT sites. These spills occur sporadically and the information about the spill is reported directly to Indiana Department of Environmental Management (IDEM). Subsequently, INDOT identifies the responsible parties and determines the required cleanup in coordination with IDEM. However, INDOT is faced with a dilemma when they are not able to identify or locate the responsible parties. In this case, INDOT incurs the cost of cleanup. The exact number of these incidents is unknown.

Deicing salts: Surface water run-off from highways and storage of deicing salts result in potential environmental problems for INDOT. Highway run-off water laden with deicing salts has a maximum impact on soils and receiving water bodies during spring. This impact is negligible in summer and in fall is non-existent. However, the main environmental concern from INDOT's point of view is the run-off resulting from the uncovered salt storage at a few sites in the state.

Soil Erosion and sediment control: INDOT construction activities for road building results in soil erosion. Soil erosion and sediment control measures are undertaken by INDOT by hiring contractors who reclaim impacted soils. One option is the use of vegetation to stabilize impacted soils. INDOT receives at least five or six non-compliance notices for soil erosion and sediment control problems per year. Identifying the sites requiring soil erosion and sediment control, and implementing plant stabilization is seen as the least expensive option.

Apart from the above mentioned problems, INDOT also faces other environmental issues such as the mitigation of impacted natural wetlands and the existence of roadside landfills. Natural wetlands are impacted because of construction activities of INDOT. Regulations require INDOT to mitigate any impacts on wetlands through restoration of the impacted area. INDOT also has encountered problems resulting from the roadside landfills that are present on the properties acquired for their

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(source: http://www.in.gov/dot/programs/environment/images/TankYank.jpg)

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facilities. Problems like landfill leachate are reported to be of concern, however, no information about the nature or the pollution load of leachate is available.

Figure 8. Soil erosion control implemented by INDOT
(source: http://www.in.gov/dot/programs/environment/images/checkdampane.jpg)

3.0 Phytoremediation Case Studies

The success of using phytoremediation is typically site-specific and, as a result, examination of various case studies can be very helpful to professionals. The case studies included briefly describes the basic on-site conditions. These conditions may include contaminant concentrations and the extent of the contamination; project implementation details such as the objectives and the basic engineering design; results to date; and contact information or references for written material relative to the specific project.

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3.1 Phytoremediation Case Study #1: J-Field, Aberdeen Proving Ground, Edgewood, Maryland

3.1.1 Problem Statement

The J-Field, Aberdeen Proving Ground project, a five-year phytoremediation project, is a contaminated site of one acre. This field demonstration is one of the most extensively studied phytoremediation projects in the United States. The contaminants are 1,1,2,2-tetrachloroethane (1,1,2,2-TeCA) and trichloroethene (TCE) in the soil and groundwater.

3.1.2 Phytoremediation Application

One hundred and eighty three hybrid poplar trees (*P. deltoides x trichocarpa*) were planted in 1997. The objective was to contain a volatile organic compound (VOC) plume and reduce contaminant mass through transformation and transpiration using phytoremediation and hydrologic control. An additional 150 hybrid poplars as well as 450 native trees (species such as tulip trees, silver maples, evergreen hollies, loblolly pines, oaks, and willows) were also planted. Conventional remediation technologies have been tested on-site, but the presence of unexploded ordnance, a low permeability aquifer, and the continuously-fed contaminant plume hindered the progress of phytoremediation. The low groundwater velocity on-site and presence of an adjacent freshwater marsh are factors that enhanced the effectiveness of phytoremediation for this particular project.

The MODFLOW and earthVision models were used to estimate site-specific inputs on hydrology, transpiration and biodegradation, and aquifer and plume characterization.

The models demonstrated that the poplar trees have the potential to remove up to 360 lbs per year of VOCs in 30 years. In addition, dense non-aqueous phase liquid (DNAPL) was recently discovered on-site.

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3.1.3 Results

The increase in transpiration rates of the planted hybrid poplar trees and adjacent native forest has caused a hydraulic cone of depression in the center of the plantation. This depression has caused a reversal of groundwater flow into the plantation in the summertime, rather than towards the adjacent marsh. Transpiration rates were estimated using sap flow analysis and local weather data. Results indicate that it will take about 10 to15 years to achieve maximum transpiration rates of 2000 gallons per day. The leaf area index method was also used as a means of predicting the time of canopy closure, which coincides with the peak transpiration rate. Approximately three to six more years are needed to attain almost complete canopy closure. The volatilization research revealed that leaves do not transpire the bulk of the contaminants and therefore the degree of volatilization of harmful gases from the trees was found to be minimal. Results are showing evidence of biotic and abiotic degradation and lowered concentrations of VOCs in the groundwater. It is believed that the poplars are also enhancing in situ biodegradation of the contaminants. The contaminant reduction due to phytoremediation is primarily due to phytodegradation, phytovolatilization, and rhizodegradation.

Contact: Steven Hirsh, U. S. Environmental Protection Agency.

3.2 Phytoremediation Case Study #2: Kauffman & Minteer, Jobstown, New Jersey

3.2.1 Problem Statement

This is a five acre Superfund site consisting of a garage/office building, a former truck washing area, a former collection pit area, a drainage ditch, and a former unlined lagoon. Discharge from the lagoon and washing area has contaminated the shallow groundwater

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on site, and threatened the Wenonah-Mount Laurel aquifer, a source of drinking water for the community.

3.2.2 Phytoremediation Application

Phytoremediation started in 1998 when 75 hybrid poplar (*P. maximowiczii x trichocarpa*) and native black willow (*Salix nigra*) were planted in the former lagoon and drainage ditch areas. The objectives of this phytoremediation study were: 1) to examine the capacity of the trees to mitigate shallow soil and groundwater contamination at the planting sites, and 2) to prevent migration of the contaminant plume by hydrologic control. A contaminant ion was primarily cis-1,2-DCE and TCE.

3.2.3 Results

It is too early to assess the success of phytoremediation at this site. In 2001, some of the wells actually had an increase in TCE, cis-1,2- DCE, and vinyl chloride concentrations since initial data were collected 1998 and September 1999. This may be due to soil excavation and backfilling at the drainage ditch and former truck wash area. Recent transpiration gas samples showed insignificant amounts of TCE, and significant amount of water uptake by the trees (hydrologic control).

Contact: George Prince, U. S. Environmental Protection Agency.

3.3 Phytoremediation Case Study #3: Vernal Naples Truck Stop, Vernal, Utah

3.3.1 Problem Statement

The Vernal Naples Truck Stop site is an example of using phytoremediation as a polishing step to clean up remaining contaminants after a faster, more conventional

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technology has sufficiently reduced contaminant levels by vacuum-enhanced pumping/biotreatment, thermal oxidation, and granular activated carbon filtration.

3.3.2 Phytoremediation Application

In 1998, phytoremediation began with the planting of approximately 300 poplar trees cross-gradient of the gasoline and MTBE plume.

3.3.3 Results

In 2000, 25 percent of the trees died and 35 percent were highly stressed due to insecticide spraying or a lack of irrigation. These trees were replaced with 50 more poplar trees in 2001. Gasoline concentrations have decreased since 1998.

In 2000, the MTBE plume moved down-gradient and off-site at a faster rate than the gasoline plume. Groundwater elevation contours do not indicate hydrologic effects from the planted trees.

Contact: Hays Griswold, U. S. Environmental Protection Agency.

3.4 Phytoremediation Case Study #4: Tibbetts Road, Barrington, New Hampshire

3.4.1 Problem Statement

The Tibbetts Road Superfund site is a two-acre site that was once used for the storage of drums containing thinners, solvents, antifreeze, kerosene, motor oil, polychlorinated biphenyls (PCBs), grease, and brake fluid. EPA has been working on the site since 1984, removing drums, excavating contaminated soil, and pumping and treating the contaminated groundwater.

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3.4.2 Phytoremediation Application

Approximately 1,400 hybrid poplars (one-year-old rooted *P. deltoides x nigra*) were planted in 1998 as a final polishing step after several years of active treatment at the site using vacuum extraction. Phytoremediation was chosen for the site primarily as a means of providing hydrologic control of the contaminant plume.

3.4.3 Results

In 2001, there was a decrease in the concentrations of VOCs in groundwater at the site. The water levels in the overburden aquifer decreased and no cone of depression has been observed. The effectiveness of phytoremediation on the groundwater hydrology is uncertain at this time.

Contact: Neil Handler, U. S. Environmental Protection Agency.

3.5 Phytoremediation Case Study #5: Former Chevron Light Petroleum Products Terminal, Ogden, Utah

3.5.1 Problem Statement

From the 1950s until 1989, Chevron stored and transferred petroleum products on this five-acre facility. The groundwater is contaminated with BTEX and other petroleum hydrocarbons.

3.5.2 Phytoremediation Application

In 1996, 40 poplar trees (*P. deltoides x nigra*) were planted in rows and were installed perpendicular to the direction of groundwater flow.

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3.5.3 Results

No zone of depression was observed under the trees. However, in 2000, a decrease in both BTEX and petroleum hydrocarbon concentrations had been observed.

Contact: Nickolee Zollinger, Phytokinetics, Inc.

3.6 Phytoremediation Case Study #6: Magic Marker Site

3.6.1 Problem Statement

Phytotech, Inc. (purchased by Edenspace Systems Corporation of Reston, Virginia in June, 1999) used soil amendments (i.e., ethylenediaminetetraacetic acid or EDTA) and hyperaccumulating plants to extract and accumulate lead and other metals from shallow soils. This phytoremediation was initiated in May 1997 at the former Magic Marker factory in Trenton, New Jersey. This urban brownfield is a 3 hectare (7 acre) site that used to be a lead-acid battery manufacturing company (Blaylock et al., 1997 and McCutcheon and Schnoor, 2003).

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3.6.2 Phytoremediation Application

The primary objectives of this project were to establish the effectiveness of the plants used as hyperaccumulators and to determine if these plants would reduce soil lead in surface soils (6 inches) on-site. Indian mustard (*Brassica juncea*) and sunflower (*Helianthus annus*) were the plants selected to extract lead from the contaminated soils.

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Figure 9. Phytoremediation greenhouse study.

3.6.3 Results

The Indian mustard and sunflower were able to accumulate lead in the aboveground plant tissue. All plants were able to exceed the project objective of a minimum lead uptake of 200 milligrams per kilogram of contaminated soil. There were differences between the amount of lead measured in plant shoots and the lead reduction measured in the soil from the treatment plot. The plant uptake alone did not account for the reductions encountered in the soil having the level of reduction was consistent with the mass of lead removed using plant uptake data.

3.7 Phytoremediation Case Study #7: Constructed Wetlands for the Remediation of Slag Leachates

3.7.1 Problem Statement

Blast-furnace slag, a by-product of steel production, is recycled and often used as fill material for roads and other transportation structures. In and around I-65 and I-80/94 in Northwestern Indiana, this material is generating unsightly leachate with an extremely

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unpleasant smell. The resulting reaction stems from under-weathered slag mixing with runoff to produce a greenish leachate, exhibiting high pH and hydrogen sulfide odor. This leachate has become a nuisance because of occurrence in public parks, and has forced the Indiana Department of Transportation to take remedial action.

Figure 10. Interstate 65 site in May 2002.

3.7.2 Phytoremediation Application

The overall objective of this project is to explore the use of constructed wetlands as a means to biologically and chemically eliminate the negative properties of the leachate. Field scale constructed wetlands have been constructed to treat the slag leachate at two locations. The design involves subsurface wetland cell placement to create anoxic conditions that would reduce total sulfur, high pH, and other pollutants, along with limiting open water exposure and nuisances.

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Figure 11. Interstate 65 site in late July 2003 showing the constructed wetlands.

3.7.3 Results

Laboratory and greenhouse studies are also testing the leachability of the slag material, constituents of the slag leachate, as well as possible media and plant combinations to use within the constructed wetland system.

Contact: James Hunter, Jason Hickey, M. Katherine Banks, and A. Paul Schwab, Purdue University.

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3.8 Flowchart/Decision-Tree

Emphasis was placed on the following components and/or questions in the development of the decision tree/flowchart used in *PhytoRemediate®: Phytoremediation Decision Guide for Transportation Engineers*:

1. What type of contamination is present (specifically integrate the environmental problems identified by INDOT)?
2. Is phytoremediation a *preliminary* consideration?
3. Will Indiana climate support the proposed plants (plants suited to site conditions?)
4. Is time of remediation or space requirements a constraint?
5. Is the contaminant physically within the range of the plant roots (rhizosphere)?
6. Will plants be used for hydrologic control ONLY (i.e., to prevent movement of the contaminants)?
7. Will water be applied to the phytoremediation system for irrigation?
8. Will Indiana regulations allow this type of phytoremediation treatment?
9. Is the contaminant phytotoxic?
10. Will the rhizosphere microbes and plant-exudates degrade the target contaminants in the rhizosphere?
11. Is the log K_{ow} of the contaminant or metabolic products between 1 and 3.5 (hydrophobicity)?
12. Will the plants degrade the contaminant after uptake?
13. Will the plants accumulate the contaminant?
14. Is the level of accumulation acceptable for this site?
15. Can controls be used to prevent the transfer of the contaminant or metabolic products to the ecosystem?

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16. Is the quantity and rate of transpiration acceptable for this site?
17. Does the plant material (if harvested) constitute a waste?
18. Can the contaminant or metabolites be immobilized to acceptable levels?

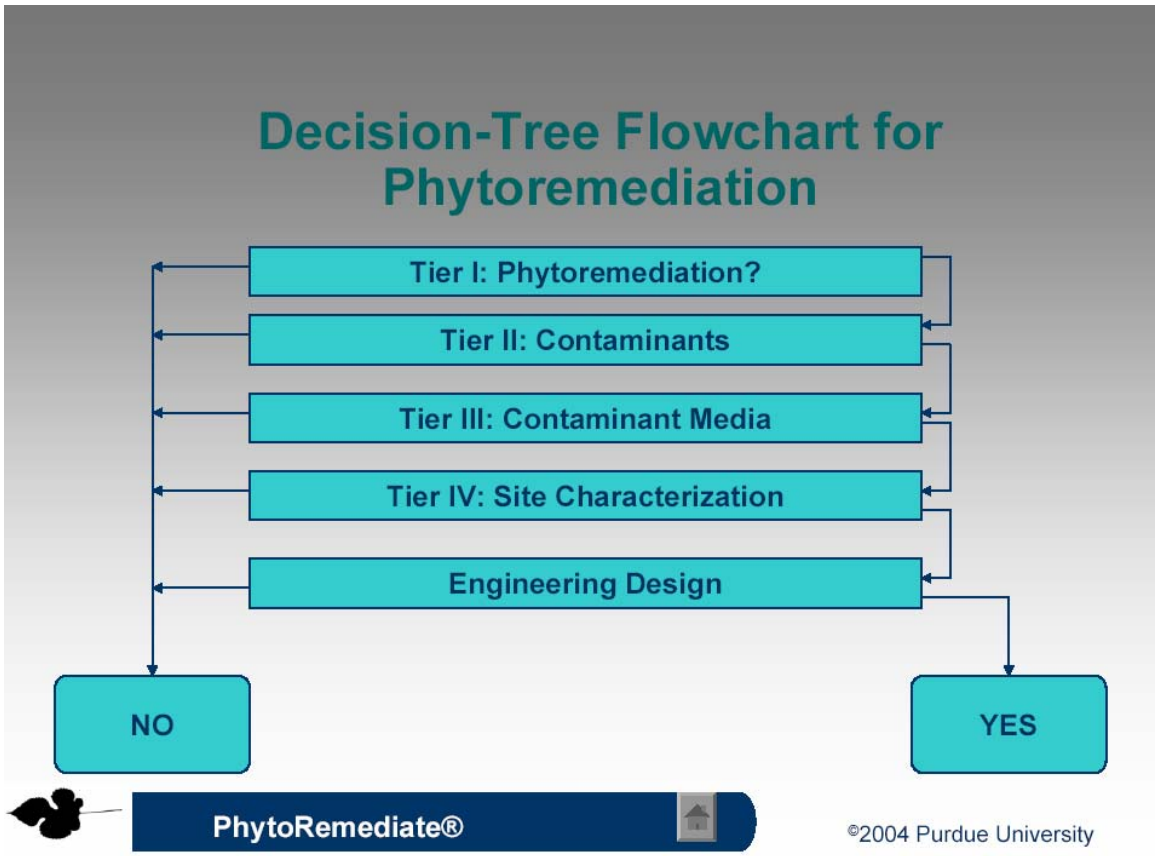

Figure 12. Decision-Tree Flowchart for Phytoremediation

3.8.1 Tier I: Phytoremediation?

The main consideration in Tier I of the decision-tree flowchart is whether or not phytoremediation is a preliminary consideration for the cleanup of a particular site. If phytoremediation is a preliminary consideration, one must proceed in the decision-tree flowchart to Tier II for the characterization of the contaminants. It is important to note that not all contaminated sites are suitable for phytoremediation.

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3.8.2 Tier II: Contaminants

Tier II of the decision-tree flowchart considers a complete characterization of all known contaminants to be considered for site remediation. One should refer especially to section 4d. on the *PhytoRemediate®: Preliminary Phytoremediation Design Checklist* when dealing with the known and characterized contaminants that are present on the site and then proceed to Tier III (Contaminant Media).

3.8.3 Tier III: Contaminant Media

The main consideration in Tier III of the decision-tree flowchart is to determine the contaminant media that are affected on the site. One should refer especially to the "Contaminant Media" sections on the *PhytoRemediate®: Preliminary Phytoremediation Design Checklist* when dealing with the known and characterized contaminants that are present on the site. The contaminant media may be air, surface water, groundwater, soil, sediment, sludge (biosolids), or even a combination of these media. This will very likely involve subsurface exploration to determine the nature and the extent of the contamination and then proceed to Tier IV (Site Characterization).

3.8.3.1 Contaminated Media Considerations

Phytoremediation can be used for in situ or ex situ applications. Phytoremediation is generally considered for in situ use by establishing vegetation in areas of contaminated soil or groundwater. However, soil can be excavated and placed into a treatment unit where phytoremediation can be applied. Groundwater or surface water can be pumped into a treatment unit established for phytoremediation or it can be sprayed onto vegetation.

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Figure 13. Contaminated soil core.

3.8.3.2 Phytoremediation of contaminant media: Soil, sediment, and sludge

The primary considerations for phytoremediation of soil are the depth and volume of contamination and soil characteristics that affect plant growth, such as texture and water content (degree of saturation). Phytoremediation is most appropriate for large areas of low to moderately contaminated soil that would be prohibitively expensive to remediate using conventional technologies. The contaminated soil should be within the root zone depth (rhizosphere) of the selected plant. Small volumes of contaminated soil concentrated in just a few areas are likely to be more efficiently remediated using other technologies.

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3.8.3.3 Phytoremediation of contaminant media: Groundwater

When groundwater contamination is encountered, phytoremediation can be used as a means of cleaning up a contaminant plume. The following phytoremediation technologies are used in the treatment of groundwater: phytodegradation, phytovolatilization, rhizofiltration, hydrologic control (plume control), vegetative cover, riparian corridors/buffer strips.

3.8.3.4 Phytoremediation of contaminant media: Surface water

When surface water contamination is encountered, one of the proven phytoremediation technologies used is constructed treatment wetlands. An example of this technology is found in the INDOT project described briefly in Case Study #7 found in Section 3.7.

3.8.4 Tier IV: Site Characterization

The main consideration in Tier IV is to properly and adequately characterize the contaminated site. The last section of the *PhytoRemediate®: Preliminary Phytoremediation Design Checklist* involves the site characterization. One must consider several environmental factors in order to properly and adequately characterize a contaminated site, such as climate, the length of the growing season, soils, hydrogeology, and topography to name a few. An excellent resource on site characterization is "Chemical and Physical Characterization of Soils" (Schwab, 1992). The site characterization phase may necessitate further sampling of the contaminated media. The preliminary consideration of applicable plants to use in the phytoremediation design will occur after site characterization is completed. In Tier IV, all of the information relative to contamination, contaminant media, and site characterization are integrated into the phytoremediation engineering design.

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Figure 14. Site characterization of contaminated soil.

3.8.5 Engineering Design

The following is a preliminary phytoremediation design checklist to be used by transportation engineers and other professionals to determine the applicability of phytoremediation as an effective method of remediation. It is imperative that INDOT establish the following: (1) whether phytoremediation is a preliminary option or consideration, (2) a characterization of the contaminants on the site, and (3) characterization and determination of the contaminant media, (4) site characterization, and (5) identification of the integral components of phytoremediation engineering design.

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3.8.6 Phytoremediation System Selection and Engineering Design Considerations

A decision-making process for evaluating whether or not phytoremediation is a viable option is provided by the following outline of the steps for applying phytoremediation:

- Define Problem
    - Conduct site characterization
    - Identify the problem: media/contaminant
    - Identify regulatory requirements
    - Identify remedial objectives
    - Establish criteria for defining the success of the phytoremediation system
- Evaluate site for use of phytoremediation
    - Perform phytoremediation-oriented site characterization
    - Identify phytoremediation technology that addresses contaminant media/contaminant/goals
    - Review known information about identified phytoremediation technology
    - Identify potential plant(s)
- Conduct preliminary studies and make decisions
    - Conduct screening studies
    - Perform optimization studies
    - Conduct field plot trials
    - Revise selection of phytoremediation technology, if necessary
    - Revise selection of plant(s), if necessary

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- Evaluate full-scale phytoremediation system
    - Design system
    - Construct system
    - Maintain and operate system
    - Evaluate and modify system
    - Evaluate performance
- Achieve objectives
    - Perform quantitative measurement
    - Meet criteria for success

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4.0 PhytoRemediate®: Preliminary Phytoremediation Design Checklist

Following the process of going through the decision-tree flowchart for phytoremediation: Tier I (Phytoremediation), Tier II (Contaminants), Tier III (Contaminant Media), Tier IV (Site Characterization), and the engineering designs, one should carefully evaluate this preliminary phytoremediation design checklist as an integral component of the engineering design.

☐ Site Name: _____

☐ Is phytoremediation a consideration? (Tier I):_____

☐ Description of contamination (Tier II): _____

☐ Applicable Regulations: _____

☐ Contaminant Media (Tier III):

1) Air Contamination: Yes ☐ No ☐
2) Surface Water Contamination: Yes ☐ No ☐
3) Subsurface Water Contamination: Yes ☐ No ☐
   a) Depth of groundwater:
      i) ☐ <3 feet
      ii) ☐ 3-8 feet
      iii) ☐ >8 feet
4) Soil Contamination: Yes ☐ No ☐
   a) ☐ soil pH:
      i) ☐ >8
      ii) ☐ 6-8
      iii) ☐ <6

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b) ☐ Soil textural class (USDA):

i) ☐ fine?

ii) ☐ medium?

iii) ☐ coarse?

c) ☐ Soil order from *Soil Taxonomy* (USDA):

1. _____

2. ☐ Contaminants

i. ☐ Arsenic >40 mg kg^{-1}

ii. ☐ Boron >3 mg kg^{-1}

iii. ☐ Cadmium >15 mg kg^{-1}

iv. ☐ Chromium (total) >1000 mg kg^{-1}

v. ☐ Copper >200 mg kg^{-1}

vi. ☐ Mercury >20 mg kg^{-1}

vii. ☐ Nickel >100 mg kg^{-1}

viii. ☐ Zinc >500 mg kg^{-1}

ix. ☐ Cyanides (total) >250 mg kg^{-1}

x. ☐ Phenols >20 mg kg^{-1}

xi. ☐ Sulfates >2000 mg kg^{-1}

xii. ☐ Tars (as PAHs) >1000 mg kg^{-1}

xiii. ☐ Petroleum products >100 mg kg^{-1}

d) ☐ Depth of soil contamination:

i) ☐ <6 inches

ii) ☐ 6-12 inches

iii) ☐ 12-20 inches

iv) ☐ >20 inches

5) ☐ Sediment Contamination : Yes ☐ No ☐

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6) ☐ Sludge/Biosolids Contamination : Yes ☐ No ☐

☐ Site Characterization (Tier IV):

1. On-site/site-specific data available? : Yes ☐ No ☐
2. Laboratory data available? : Yes ☐ No ☐
3. Climate suitable for plants? : Yes ☐ No ☐
4. Length of growing season? : Yes ☐ No ☐ Specify:_____
5. USDA plant hardiness zone? : Yes ☐ No ☐ Specify:_____
6. Minimum temperature at site: _____
7. ☐ Average annual precipitation at site:

   _____
8. ☐ Drought probability:
   a. ☐ Low?
   b. ☐ Medium?
   c. ☐ High?
9. ☐ Plants to be considered for phytoremediation:_____

   _____
10. ☐ Hydrologic control necessary? : Yes ☐ No ☐
11. ☐ Type of phytoremediation to be used:
    a. ☐ Phytotransformation
    b. ☐ Phytoextraction
    c. ☐ Phytostabilization
    d. ☐ Rhizofiltration/Rhizosphere bioremediation
    e. ☐ Phytovolatilization
    f. ☐ Hydrologic control
    g. ☐ Riparian corridors and buffer strips
    h. ☐ Vegetative cover

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5.0 Plant selection process for phytoremediation

The plant selection process (USEPA, 2000) is an essential component of the phytoremediation engineering design. It is imperative to identify the specific phytoremediation technology and remedial goals to clean-up a contaminated site.

A site evaluation consists of the following:

- Location (also relative to plant/vegetation/ecosystem zones)
- Temperatures: averages, range
- USDA plant hardiness zone (range of average annual minimum temperature)
- Precipitation: amount, timing
- Length of growing season
- Amount of sun/shade
- Soil texture, salinity, pH, fertility, water content, structure (hardpans, etc.)
- Contaminant type, concentration, form
- Site-specific conditions or considerations
- Identify plants growing in contaminated portion of site.
    - Do these provide information as to what plants to select?
    - Will these plants compete with the selected plant?
    - If the native plants do compete with the selected plant, are they easily removed?
- Identify local plants and crops.
    - Do these plants provide information as to what plants to select?
    - Will a selected plant interfere with local plants?

One must identify important criteria for plant selection to be used in the phytoremediation strategy. The following generalized criteria should be considered:

- Disease resistance

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- Heat tolerance
- Cold tolerance
- Insect tolerance
- Drought resistance
- Salt tolerance
- Chemical tolerance
- Stress tolerance
- Legume/nonlegume
- Annual/biennial/perennial
- Cultural requirements: Due to the added stress of a contaminated soil environment, the cultivation and maintenance factors may have to be carefully monitored.
    - Seed pretreatment before germination (such as for some prairie grasses)
    - Planting method (seeds, sod, sprigs, whips, plugs, transplants), timing, density, depth (of seeds, root ball, or whips)
    - Mulching, irrigation, soil pH control, fertilization, protection from pests and disease
    - Fallen leaves, debris
    - Harvesting requirements
    - Labor and cost requirements should not be excessive
- Invasive, undesirable, or toxic characteristics
- Plant/seed source
- Establishment rate
    - Reproduction method/rate
    - Growth rate/biomass production

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6.0 Internet Resources on Phytoremediation

- Technology Focus—Phytoremediation (USEPA):
  http://clu-in.org/publications/db/tp.cgi?technology=5
- USEPA Innovative Technologies(USEPA):
  http://www.epa.gov/tio/remed.htm
- Phytoremediation Online Decision Tree Document:
  http://www.itrcweb.org/user/webphyto/envdept/phyto/wwwphyto/
- Phytoremediation (Missouri Botanical Garden):
  http://www.mobot.org/jwcross/phytoremediation/
- Bioremediation and Phytoremediation Glossary:
  http://members.tripod.com/~bioremediation/
- International Journal of Phytoremediation:
  http://www.aehs.com/journals/phytoremediation/
- Ground-Water Remediation Technologies Analysis Center (GWRTAC) Phytoremediation Reports:
  http://www.gwrtac.org/html/topics/phytorem.htm
- The Phytoremediation of Organics Action Team, established in 1997, is one of the six active Action Teams under the Remediation Technologies Development Forum (RTDF):
  http://www.rtdf.org/public/phyto/default.htm
- Toolkit for Greener Practices: Decision Tree:
  http://www.pca.state.mn.us/programs/p2-s/toolkit/decisiontree.html
- Hazardous Substances Research Center, Kansas State University (HSRC)
  www.engg.ksu.edu/HSRC/phytorem/home.html
- Phytonet, University of Parma, Italy (PHYTONET)
  www.dsa.unipr.it/phytonet/

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7.0 Conclusions and Summary

The use of the *PhytoRemediate®:A Phytoremediation Decision Guide for Transportation Engineers* will provide information for preliminary consideration during the decision-making process about the use of phytoremediation. Phytoremediation should be considered as a remediation option for the environmental problems listed below:

- Underground Storage Tanks (USTs) on properties acquired by INDOT for road construction and other developmental projects.
- Contamination of soils due to the use of lead-based paints on bridges.
- Hazardous materials and waste accidental spills.
- Impact of highway run-off water with deicing salts.
- Construction activities resulting in soil erosion.

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