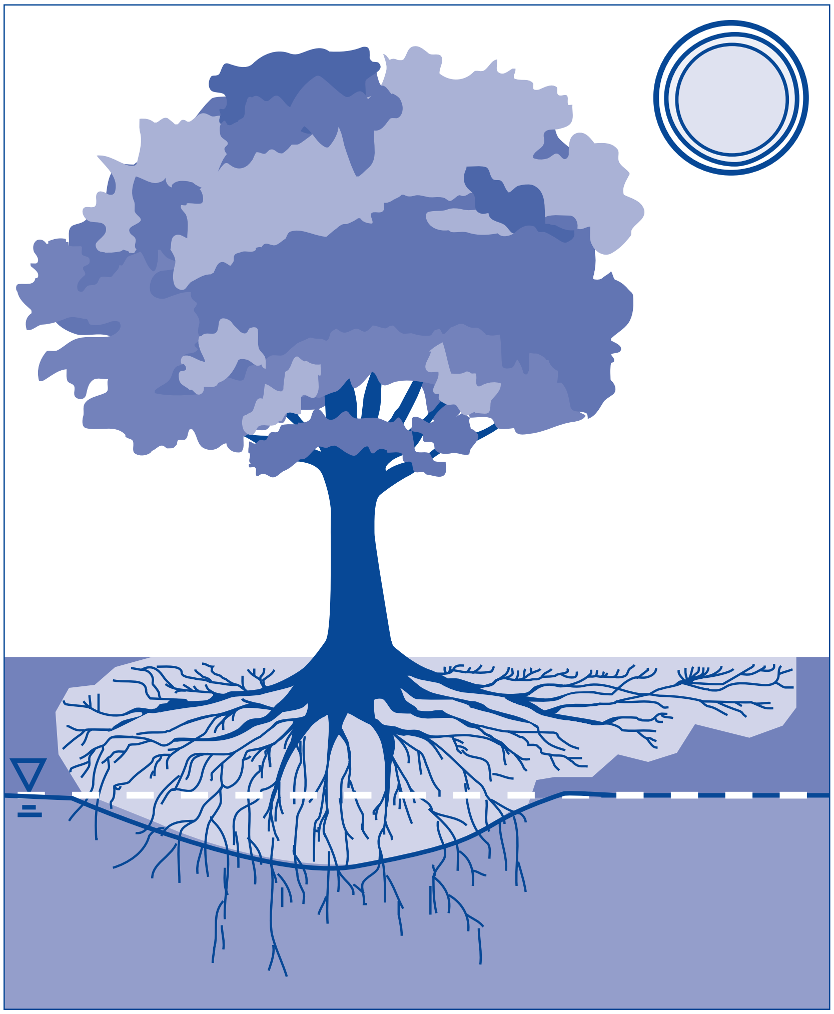
Technical and Regulatory Guidance Document

Phytotechnology



April 2001

Prepared by
Interstate Technology and Regulatory Cooperation Work Group
Phytotechnologies Work Team

ABOUT ITRC

Established in 1995, the Interstate Technology and Regulatory Cooperation (ITRC) Work Group is a state-led, national coalition of personnel from the regulatory and technology programs of more than 35 states and the District of Columbia; three federal agencies; and tribal, public, and industry stakeholders. The organization is devoted to reducing barriers and speeding interstate deployment of better, more cost-effective, innovative environmental technologies.

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The 1999 ITRC Phytotechnologies Team was made up of state regulators, industry representatives, a public stakeholder, and members of the USEPA interested in implementing the use of phytotechnologies.

EXECUTIVE SUMMARY

> *Terminology in this field of using plants to remediate, treat, stabilize, and control contaminated media is rather new. Throughout the development process of this document, we referred to the science as "phytoremediation." Recently realizing that we are actually discussing a variety of technologies and techniques in various applications to manage a contaminant, a contaminated plume, or the media containing contaminants, we now refer to "phytotechnologies" as the overarching terminology, while using "phytoremediation" more precisely to describe contaminant removal or destruction.*

Phytotechnologies are a set of technologies using plants to remediate or contain contaminants in soil, groundwater, surface water, or sediments. Some of these technologies have become attractive alternatives to conventional cleanup technologies due to relatively low costs and the inherently aesthetic nature of planted sites.

This attention on phytotechnologies led to the December 1999 publication of the ITRC document, *Phytoremediation Decision Tree*. The decision tree was designed to allow potential users to take basic information from a specific site and, through a flowchart layout, decide if phytotechnologies are feasible at that site.

The purpose of this document is to provide technical and regulatory guidance to help regulators understand, evaluate, and make informed decisions on phytotechnology proposals. This document includes a description of phytotechnologies, regulatory and policy issues, technical requirements for phytotechnologies, stakeholder concerns, case studies, and technical references.

The technical descriptions of phytotechnologies within this document concentrate on the functioning mechanisms. For example, the application of phytotechnology as a hydraulic control for groundwater is described as phytostabilization. This approach was selected to provide both scientific accuracy and a basic understanding of these mechanisms to the reader.

Phytotechnologies remain an emerging technology, and a section detailing current research efforts along with potential applications is also included. The case studies, which are included, were selected to cover the various phytotechnology mechanisms described in this document.

There are general regulatory issues regarding any application of remedial technologies—phytotechnologies are no exception. There are currently few, if any, specific regulations pertaining to the application of phytotechnologies. However, this document outlines the regulatory considerations and offers recommendations on issues that may be unique to phytotechnologies.

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1.0 DESCRIPTION OF PHYTOTECHNOLOGIES

Phytotechnologies use plants to remediate various media impacted with different types of contaminants. These technologies can be implemented either in situ or ex situ. Typical organic contaminants ("organics") that can be addressed using this technology include petroleum hydrocarbons, gas condensates, crude oil, chlorinated compounds, pesticides, and explosive compounds. Typical inorganic contaminants ("inorganics") include salts (salinity), heavy metals, metalloids, and radioactive materials. The affected media that phytotechnologies can be used to address include soils, sediments, groundwater, and surface waters. In addition, several emerging applications of phytotechnologies are being developed, such as the capabilities of vegetation to utilize atmospheric carbon emissions for greenhouse gas mitigation.

The specific phytotechnology mechanism used to address specific contaminants is dependent not only on the type of constituent and the media that is affected, but also on the remediation goals. Typical goals include containment, stabilization, sequestration, assimilation, reduction, detoxification, degradation, metabolization, and/or mineralization. To achieve these goals, the proper phytotechnology system must be designed, developed, and implemented using detailed knowledge of the site layout, soil characteristics, hydrology, climate conditions, analytical needs, operations and maintenance requirements, economics, public perception, and regulatory environment.

Many phytotechnologies apply fundamental information gained from agriculture, forestry, and horticulture to environmental problems. Therefore, the best place to start for someone relatively new or unfamiliar with the technology is a simple review of the plant physiological processes that are exploited in phytotechnologies for the cleanup and containment of hazardous waste sites.

1.1 Basic Plant Physiology

Plants typically grow by sending their roots into the soil and producing leaf and woody material into the terrestrial environment. To accomplish these basic growth habits, plants utilize carbon dioxide to photosynthesize carbon biomass, produce energy and release oxygen to the environment, take up and transpire water from the subsurface, absorb dissolved inorganics through the root system, and exude photosynthetic products into the root zone (Taiz and Zeiger, 1991). Each biological process contributes to the remediation of contaminants as described in the following subsections.

1.1.1 Inorganic Nutrition

The 13 essential inorganic plant nutrients (N, P, K, Ca, Mg, S, Fe, Cl, Zn, Mn, Cu, B, and Mo) are taken up by the root system as dissolved constituents in soil moisture. These elements are required by the plant for growth, development, or reproduction and are acquired either passively in the transpirational stream (see Section 1.1.3) or actively through transport proteins associated with the root membrane. Once inside the root system, the dissolved nutrients can be transported throughout the remainder of the plant through the vascular system of the plant known as the xylem.

In addition to these essential nutrients, other nonessential inorganics (such as various common contaminants: salt, Pb, Cd, As, etc.) can be taken up as well. Again, this uptake process can be either passive in the transpirational stream or active by substituting for the essential nutrient on the transport protein. Since these other inorganics are not essential to the plant and may represent potential toxins at high concentrations, the plant also contains various mechanisms to sequester or stabilize these extraneous inorganics and prevent translocation into the more sensitive, terrestrial portion of the plant. One primary mechanism is to sequester the nonessential inorganic into the vacuoles of the plant cells, which act, in part, as a storage receptacle for the plant. Another mechanism is to bind these inorganics in the soil or on the root surfaces, preventing them from entering into the plant system. Depending on the fate of the inorganic in the plant system, a suitable phytotechnology system can be developed for impacted sites. The primary mechanisms for the remediation of inorganics are based on the ability of the plants to accumulate or stabilize the inorganic constituents.

1.1.2 Photosynthetic Production of Plant Materials

The atmospheric carbon dioxide that enters plants cells through stomata (microscopic openings in the leaves) is incorporated into organic matter using reductants generated during photosynthesis. Photosynthates are translocated throughout the plant, even down into the root system, through another vascular system known as the phloem. These products can be incorporated into the biomass, metabolized to produce energy during cell respiration, or exuded into the root zone.

Typical compounds exuded by the plant roots include amino acids, enzymes, proteins, organic acids, carbohydrates, and other cellular materials. The exudation of carbon into the rhizosphere can account for as much as 20% of the total photosynthetic products produced by a plant (Campbell and Greaves, 1990). Soil organisms, including bacteria and fungi, tend to thrive in the immediate vicinity surrounding the roots because of this enriched carbon source in the subsurface. They have formed a symbiotic relationship with the plant roots where the soil organisms are supplied with various nutrients, including sources of carbon, oxygen, and other inorganic elements necessary for growth. In return for this enhanced soil environment, these organisms provide a protective barrier around the plant roots that can break down potential pathogens prior to encountering the plant root. Furthermore, the soil organisms can also enhance the uptake of essential plant nutrients and extend the effective root system for enhanced water uptake into the plants.

This region of soil, roots, and organisms is known as the rhizosphere and extends approximately 1–3 mm from the root surface (Shimp, et al., 1993; Schnook, 1998). The proliferation of soil organisms in the rhizosphere can be 3 or 4 orders of magnitude greater than the population of soil organisms in non-vegetated soils. The symbiotic relationship has a synergistic effect and is the primary mechanism accounting for the breakdown of organic contaminants in the environment through phytotechnologies.

1.1.3 Gas Exchange and Transpiration Processes

In the terrestrial portion of the plants, a complex gas exchange process known as transpiration occurs through the stomata of the leaves. Carbon dioxide enters while oxygen and water vapor exit. The water vapor is derived from the transpirational stream that begins when the root system takes up soil moisture and ends when the water evaporates into the atmosphere through the leaves. The process of water transport from roots to shoots to leaves is known as translocation. This whole process occurs primarily by the equilibrium driving force between liquid water in the leaves and the gaseous water (humidity) in the atmosphere. The process of water uptake from the subsurface for transpiration is the primary mechanism used in applications of hydraulic control and contaminant containment.

1.2 Mechanisms

In the field of phytotechnologies, several mechanisms can be used to address the different environmental conditions that may exist at a site. The specific mechanisms that are exploited depend on several factors, including the specific contaminant, current site conditions, the remedial objectives, and the regulatory issues. The basic physiological processes described in the previous section are the bases for the various phytotechnology mechanisms that can be used to clean up contaminated sites. Specifically, the ability of plant roots to sequester certain inorganic elements in the root zone is known in phytotechnologies as phytostabilization. Similarly, the exudation of photosynthetic products into the rhizosphere can lead to the phytostabilization of organic compounds as well. Alternatively, the exuded plant products can also lead to the enhanced biodegradation of organics by the soil organisms. In phytotechnologies, this process is known as rhizodegradation.

The ability of plants to take up and transpire large volumes of water from the subsurface also has been used in phytotechnologies to provide hydraulic control at contaminated sites. This hydraulic control can be used to prevent the horizontal migration or vertical leaching of contaminants. During the transpirational uptake of water, dissolved organic and inorganic contaminants in the subsurface can enter into the plant where they are subject to additional phytotechnology mechanisms. Specifically, once inside the plant, organic chemicals can be subject to various plant-produced enzymes that can break down the contaminants. This mechanism is known as phytodegradation. Similarly, the uptake and accumulation of inorganic elements into the plant tissues is known as phytoaccumulation. Finally, the uptake and subsequent transpiration of volatile contaminants through the leaves is known as phytovolatilization.

This document covers all areas of phytotechnologies, including inorganic and organic contaminants as well as the different media involved, including soil, sediments, surface water, and groundwater. These are summarized in Table 1-1. Furthermore, brief descriptions of the mechanisms used to treat these environmental conditions are provided in the following subsections. Finally, multiple phytotechnology mechanisms may be applicable, depending on the environmental conditions, and would generally occur in the order as they are presented, starting with the mechanisms occurring in the soil and ending with those occurring in the plants.

Table 1-1 Summary of Phytotechnology Mechanisms

Mechanism	Process Goal	Media	Typical Contaminants	Plant Types
Phytostabilization	Containment	Soils, sediments, sludges	As, Cd, Cr, Cu, Pb, Zn	Herbaceous species, grasses, trees, wetland species
Rhizodegradation	Remediation by destruction	Soils, sediments, sludges, groundwater	Organic compounds (TPH, PAHs, BTEX, pesticides, chlorinated solvents, PCBs)	Herbaceous species, grasses, trees, wetland species
Phytoaccumulation	Remediation by extraction and capture	Soils, sediments, sludges	Metals: Ag, Au, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Zn; Radionuclides: ^{90}Sr, ^{137}Cs, ^{239}Pu, $^{234,\,238}$U	Herbaceous species, grasses, trees, wetland species
Phytodegradation	Remediation by destruction	Soils, sediments, sludges, groundwater, surface water	Organics compounds, chlorinated solvents, phenols, pesticides, munitions	Algae, herbaceous species, trees, wetland species
Phytovolatilization	Remediation by extraction from media and release to air	Soils, sediments, sludges, groundwater	Chlorinated solvents, MTBE, some inorganics (Se, Hg, and As)	Herbaceous species, trees, wetland species
Evapotranspiration	Containment and erosion control	Groundwater, surface water, stormwater	Water soluble organics and inorganics	Herbaceous species, grasses, trees, wetland species

1.2.1 Phytostabilization (Inorganic and Organic)

The initial contact between the contaminant and the plant is in the root zone. It is in this region where the initial mechanism of phytostabilization occurs. This mechanism is the use of certain plant species to immobilize contaminants in the soil, sediments, and groundwater through the absorption and accumulation into the roots, the adsorption onto the roots, or the precipitation or immobilization within the root zone. These chemical contaminants then are rendered in a stable form. This is illustrated in Figure 1-1 for an inorganic contaminant (but this mechanism is also applicable for organic contaminants).

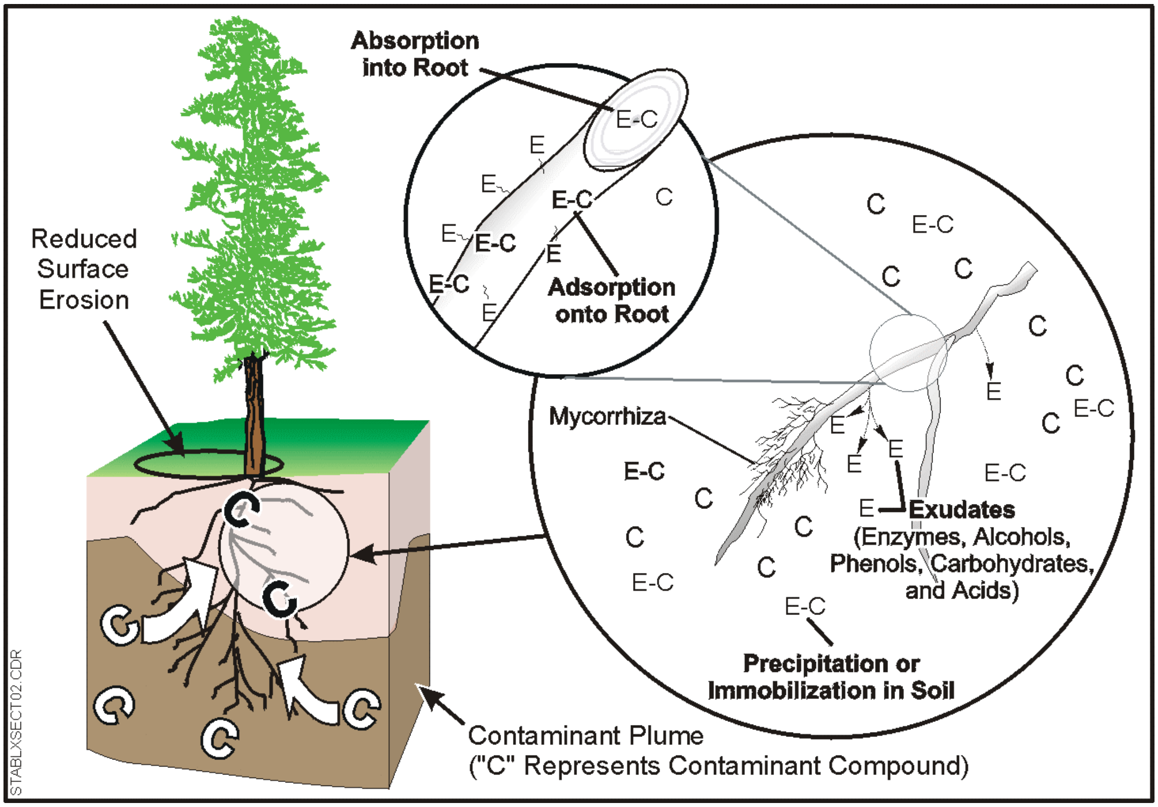


Figure 1-1 Phytostabilization of Inorganics (or Organics)

The three mechanisms within phytostabilization that determine the fate of the contaminants are described in more detail below. These processes reduce the mobility of the contaminant and prevent migration to the soil, groundwater, or air.

Phytostabilization in the Root Zone: Proteins and enzymes produced by the plant can be exuded into the rhizosphere by the roots. These plant products target contaminants in the surrounding soil, leading to the precipitation or immobilization of the contaminants in the root zone. This mechanism within phytostabilization may reduce the fraction of the contaminant in the soil that is bioavailable.

Phytostabilization on the Root Membranes: Proteins and enzymes directly associated with the root cell walls can bind and stabilize the contaminant on the exterior surfaces of the root membranes. This prevents the contaminant from entering into the plant itself.

> ***Phytostabilization in the Root Cells*****:** Proteins and enzymes also are present on the root cell walls that can facilitate the transport of contaminants across the root membranes. Upon uptake, these contaminants can be sequestered into the vacuole of the root cells, preventing further translocation to the shoots.

An indirect effect of phytostabilization that can help remediate a site is the reduction of contaminant transport through erosion. Specifically, this technique can be used to stabilize contaminated sites by establishing a vegetative cover over areas where natural vegetation may be lacking due to high contaminant concentrations. Contaminant-tolerant species may be used to restore vegetation at the sites, thereby decreasing the potential migration of contamination through wind erosion, soil erosion, surface water runoff, and leaching of soil contamination to groundwater.

1.2.2 Rhizodegradation (Organic)

Rhizodegradation, which is also called phytostimulation, rhizosphere biodegradation, or plant-assisted bioremediation/degradation, is the breakdown of contaminants in the soil through the bioactivity that exists in the rhizosphere. This bioactivity is derived from the proteins and enzymes that can be produced and exuded by plants or from soil organisms such as bacteria, yeast, and fungi. Organic contaminants, even those considered potentially hazardous to humans such as certain petroleum hydrocarbons or chlorinated solvents, can be directly metabolized by these proteins and enzymes, leading to the degradation, metabolism, or mineralization of the contaminants. Furthermore, many of these contaminants can be broken down into harmless products or converted into a source of food and energy for the plants or soil organisms (Donnelly and Fletcher, 1994).

Alternatively, the natural substances released by the plant roots (i.e., sugars, alcohols, carbohydrates, and acids) contain organic carbon that provides food for the soil organisms, thereby enhancing their biological activities. These plant photosynthates stimulate the soil organisms to fortuitously cometabolically biodegrade the organic contaminants. Plants also aid microbial biodegradation by loosening the soil and transporting oxygen and water into the rhizosphere. This indirect effect is also classified as rhizodegradation.

Rhizodegradation is a symbiotic relationship that has evolved between the plants and the soil microbes. The plants provide nutrients necessary for the microbes to thrive while the microbes provide a healthier soil environment where the plant roots can proliferate. This relationship is shown in Figure 1-2 where the contaminated soils and groundwater are cleansed in the enhanced rhizosphere environment. This mechanism represents the primary mechanism through which organic contaminants can be remediated.

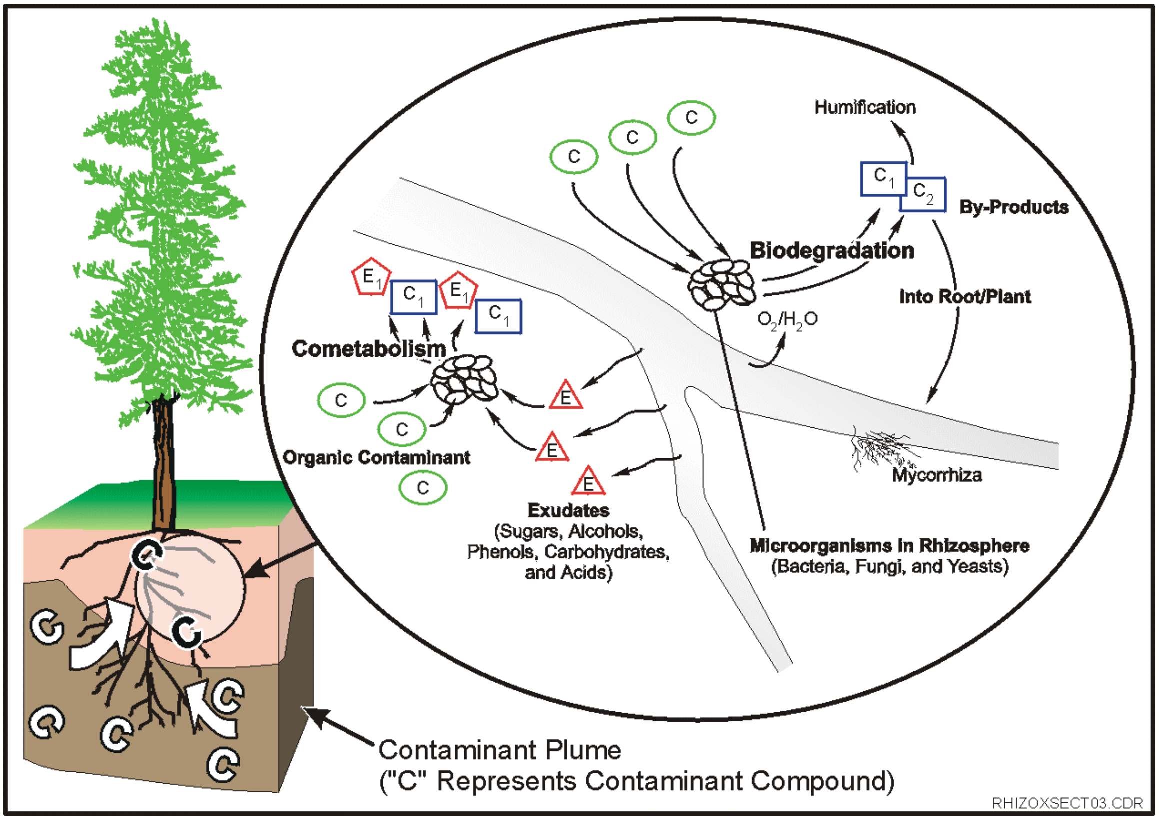


Figure 1-2 Rhizodegradation of Organics

1.2.3 Phytoaccumulation (Inorganic)

Phytoaccumulation, also called phytoextraction, refers to the use of metal- or salt-accumulating plants that translocate and concentrate these soil contaminants into the roots and aboveground shoots or leaves. Certain plants called hyperaccumulators absorb unusually large amounts of metals in comparison to other plants and the ambient metal concentration. In order for a plant to be classified as a hyperaccumulator, it must be able to accumulate at least 1,000 mg/kg (dry weight) of a specific metal or metalloid (for some metals or metalloids the concentration must be 10,000 mg/kg) (Baker et al., 1998). Similarly, halophytes are plants that can tolerate and, in many cases, accumulate large quantities of salt (typically, sodium chloride but also Ca and Mg chlorides). Hyperaccumulators and halophytes are selected and planted at a site based on the type of metals or salts present, the concentrations of these constituents, and other site conditions.

As a general rule, readily bioavailable inorganics for plant uptake include cadmium, nickel, zinc, arsenic, selenium, and copper. Moderately bioavailable metals are cobalt, manganese, and iron; whereas lead, chromium, and uranium are not very bioavailable. Lead can be made much more bioavailable by the addition of chelating agents, such as ethylene diamine tetra-acetic acid (EDTA) to soils (Schnoor, 1998). Similarly, the availability of uranium and radio-cesium 137 can be enhanced using citric acid and ammonium nitrate, respectively (Dodge and Francis, 1997; Riesen and Bruner, 1996).

In order for the inorganic contaminant to be remediated using plants, the constituent must come in contact with the plant roots. This contact is accomplished when the inorganic is dissolved in the transpirational stream that is then carried into the root zone and into the plant. This process is depicted below in Figure 1-3.

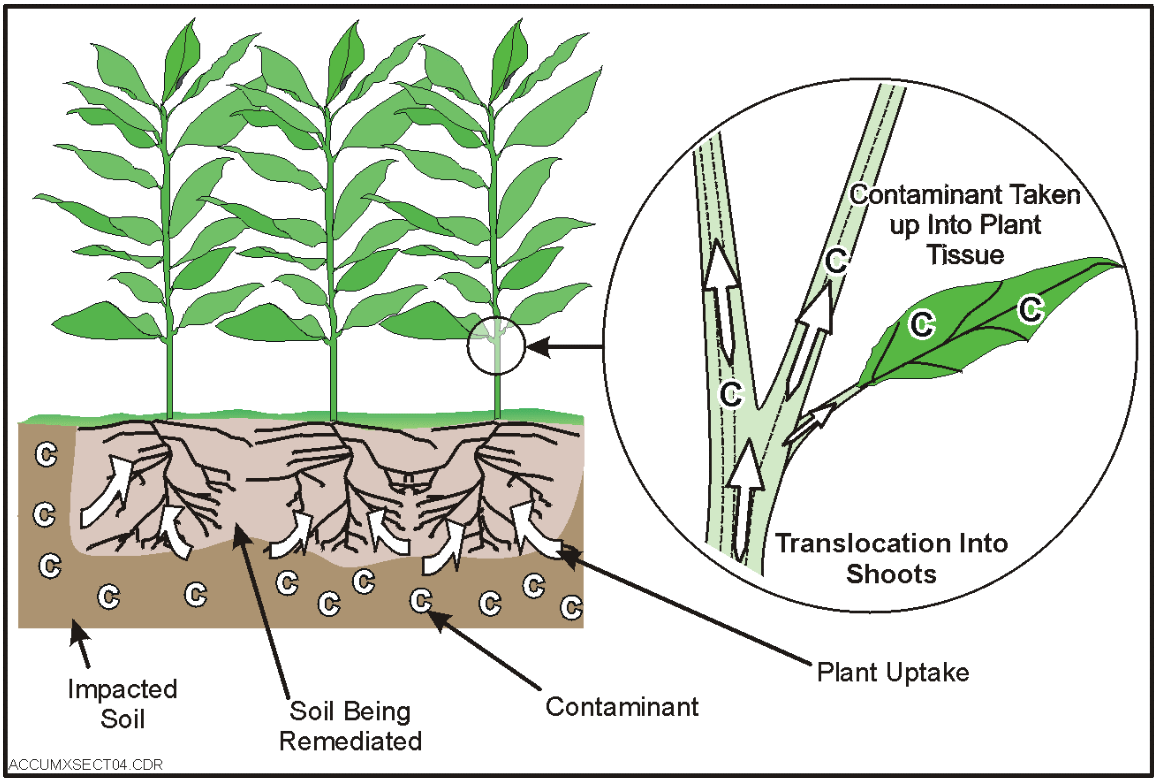


Figure 1-3 Phytoaccumulation of Inorganics

1.2.4. Phytodegradation (Organic)

Phytodegradation, also called phytotransformation, refers to the uptake of organic contaminants from soil, sediments, and water with the subsequent transformation by the plants. Depending on factors such as concentration and composition as well as the plant species and site conditions, an organic contaminant may be able to pass, to some extent, through the protective barrier of the rhizosphere. If this occurs, the organic may then be subject to bioremedial processes occurring within the plant itself. In order for a plant to directly degrade, mineralize, or volatilize a compound (see phytovolatilization below), it must be able to take that compound up through its roots. Plants transform organic contaminants through various internal, metabolic processes that help catalyze degradation. The contaminants are degraded in the plant with the breakdown products subsequently stored in the vacuole or incorporated into the plant tissues. This process is depicted in Figure 1-4.

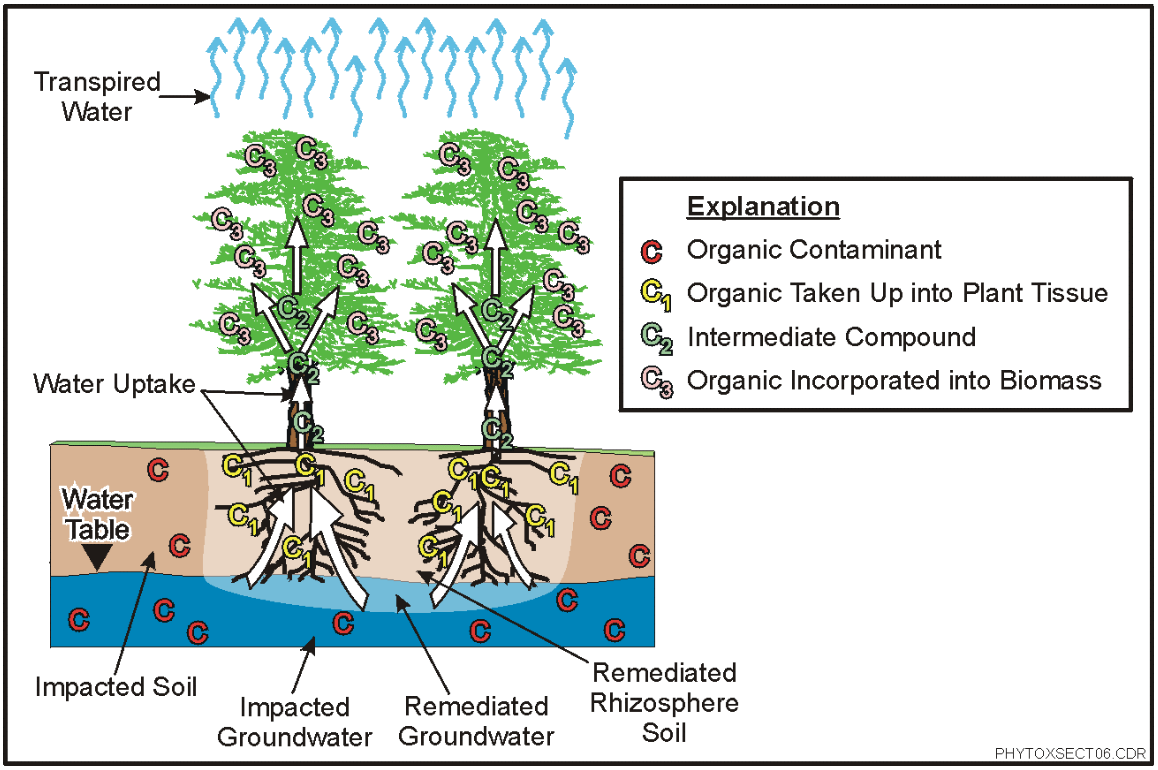


Figure 1-4 Phytodegradation of Organics

Direct uptake of organics by plants has been shown to be an efficient removal mechanism for sites contaminated with moderately hydrophobic organic chemicals. One of the chemical characteristics that influence the uptake of organics into a plant is the octanol-water partition coefficient, log K_{ow}. Chemicals that have been shown to be able to enter into the plant have been roughly characterized as having log K_{ow} values between 1 and 3.5 (Schnoor, 1998). Other factors that affect the ability of certain chemicals to be accessible by plant roots include hydrophobicity, polarity, sorption properties, and solubility. In order for the organic contaminant to be remediated using plants, the constituent must come into contact with the plant roots and must be dissolved in the soil water. Hydrophobic chemicals (log $K_{ow} > 3.5$) are generally not sufficiently soluble in water or are bound so strongly to the surface of the roots that they cannot be easily translocated into the plant. On the other hand, chemicals that are highly polar and very water soluble (log $K_{ow} < 1.0$) are not sufficiently sorbed by the roots nor are they actively transported through plant membranes due to their high polarity (Briggs et al., 1982). Most benzene, toluene, ethylbenzene, and xylene (BTEX) chemicals, chlorinated solvents, and short-chain aliphatic chemicals fall within the log K_{ow} range that allow them to be susceptible to phytodegradation.

The relative ability of a plant to take up a chemical from the soil or groundwater and translocate it to its shoots is described by the root concentration factor (RCF) and transpiration stream concentration factor (TSCF) for the chemical. Respectively, the RCF and TSCF are measures of the root concentration and xylem sap concentration of a contaminant relative to the concentration in the external solution. Higher RCF and TSCF values are an indication of enhanced contaminant uptake by plants. Both factors vary directly with the log Kow of the chemical; contaminants in solution with the highest TSCF contained a log K_{ow} of 1 to 3.5 (Briggs, et al., 1982; Schnoor, 1998). Equations describing the potential uptake of aqueous-phase contaminants are provided in Appendix A.

The uptake efficiency depends on the soil properties, physical-chemical properties of the contaminant in the soil, chemical speciation, and the plant itself. Once an organic chemical is taken up, the plant may store the chemical and/or its byproducts into the plant biomass via lignification (covalent bonding of the chemical or its byproducts into the lignin of the plant), or it can metabolize or mineralize the chemical completely to carbon dioxide and water (Schnoor, 1998). Specific plant-produced enzymes that are responsible for the breakdown of organic contaminants in plant tissues include dehalogenases, which remove halogen subgroups from compounds such as chlorinated solvents; oxygenases, which catalyze the oxidation of organic contaminants such as aliphatic hydrocarbons; and nitroreductase, which reduces the nitrogen-containing groups on explosive compounds such as trinitrotoluene (TNT) (Newman, 1995; Schnoor, et al., 1995).

1.2.5 Phytovolatilization (Inorganic and Organic)

The last mechanism in the soil-plant-atmosphere chain of phytotechnology mechanisms that can lead to the remediation of various inorganic and organic contaminants is phytovolatilization. This mechanism begins with the uptake of a dissolved contaminant from the soil environment. The chemical speciation of the contaminant may be altered in the rhizosphere prior to uptake or in the plant after uptake. Once inside the plant, the contaminant, or a modified form of the contaminant, is translocated up into the leaves where it is released to the atmosphere through the process of transpiration. This is shown below in Figure 1-5 for an organic contaminant (but this mechanism is also applicable for certain inorganic contaminants). One mechanism that is similar to phytovolatilization is a mechanism where chemicals are exuded through the stomata in a liquid form. This occurs in a few plant species in tropical and near tropical environments, such as salt cedars. It allows some plants to use salt water, exuding the excess salts.

Once volatilized, many organic chemicals that are recalcitrant in the subsurface environment react rapidly in the atmosphere with hydroxyl radicals, an oxidant formed during the photochemical cycle. Some of these contaminants can pass through the plants to the leaves and volatilize into the atmosphere at comparatively low concentrations. One highly studied system is the use of poplars for the uptake and phytovolatilization of trichloroethylene (TCE) (or breakdown products of TCE) (Chappell, 1998). Similarly, tobacco plants have been modified to be able to take up the highly toxic methyl-mercury, alter the chemical speciation, and phytovolatilize relatively safe levels of the less toxic elemental mercury into the atmosphere (Heaton, et al., 1998).

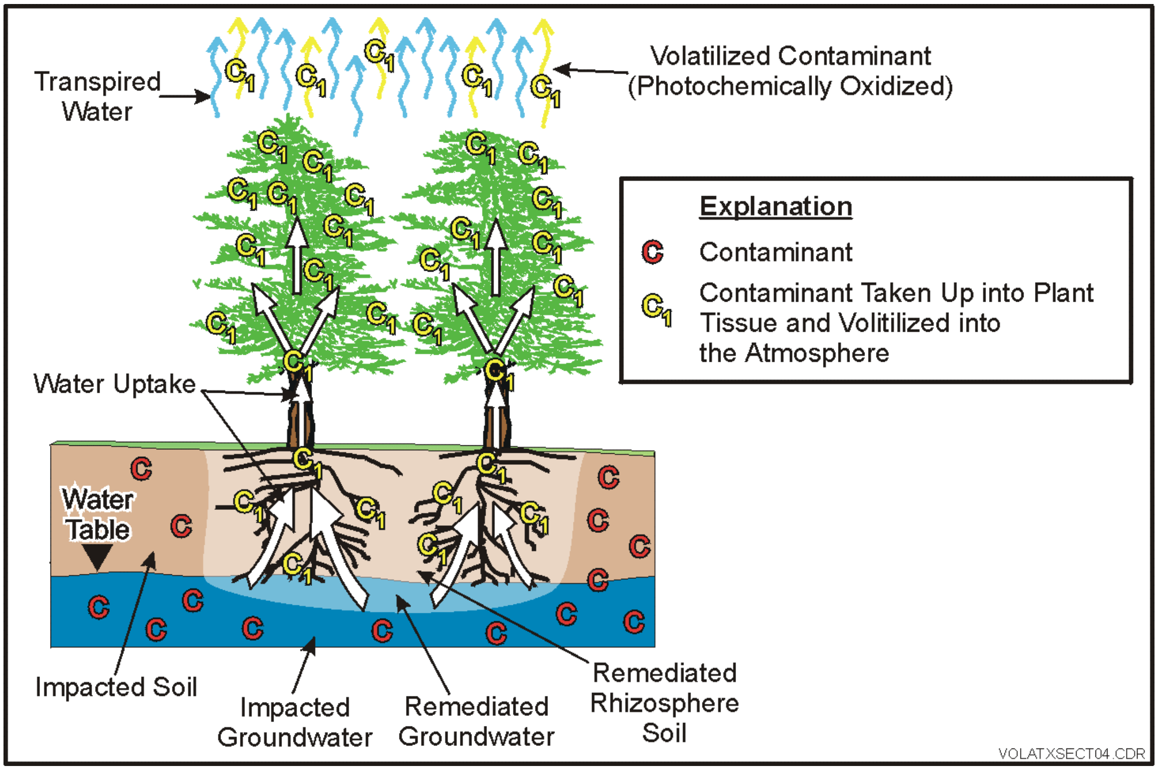


Figure 1-5 Phytovolatilization of Organics (or Inorganics)

1.2.6 Evapotranspiration

In addition to the ability of plants to stabilize or take up inorganics as well as promote the enhanced biodegradation of organics, plants also significantly affect the local hydrology. Specifically, plants have the ability to intercept a significant portion of rain on their leaf surfaces. This intercepted water is evaporated directly back into the atmosphere, preventing the water from reaching the ground surface (Viessman, et al., 1989). This effectively reduces the amount of infiltration and can be utilized to limit groundwater recharge. The differences in rain interception capacities are due to morphological factors of the leaves, such as structure (vertical vs. horizontal), cuticle (hairy vs. waxy), and density (number of leaves). A key factor in determining the amount of leaf coverage provided by specific plants is the leaf area index (LAI). The LAI is the ratio of leaf area to ground area and can have values greater than one. Typical rain interception capacities are provided in Table 1-2.

If the rain is not intercepted by the plant leaves and manages to reach the ground, it is then subject to the transpirational uptake by the plant root systems. Specifically, plants can take up and transpire significant volumes of water from the subsurface while the water is within the root zone (Licht, 1993). If the water is able to percolate below the root zone, then this water is available to recharge the groundwater. Typical plant transpiration rates are provided in Table 1-3 and include grasses and herbaceous species on a per area basis as well as trees on a per tree basis. The combined evaporation and transpiration of water is known as evapotranspiration (ET).

The uptake and transpiration of groundwater from the subsurface can be used to provide a certain degree of hydraulic control. Hydraulic control, which is also known as phytohydraulics, is the use of plants and trees to rapidly take up large volumes of water in order to contain or control the migration of subsurface water (Rock, 2000). This is particularly true for groundwater that has been tapped into by deep-rooted species such as prairie plants and trees. One classification of trees that has been widely studied in phytotechnologies is phreatophytes, which are deep-rooted, high-transpiring, water-loving trees that send their roots into regions of high moisture and that can survive in conditions of temporary saturation (Gatliff, 1994). Typical phreatophytes include cottonwoods, poplars, and willows. A more in-depth discussion of the ability of vegetation to capture groundwater is provided in Appendix D.

Table 1-2 Typical Plant Rain Interception Capacities

Plant Name	Plant Type	Magnitude and Duration of Rain	Interception Capacity
Natural Pasture	Mixed Grasses	389 mm in 5 months	14–19%
Alfalfa	Agricultural Crop	Unspecified	36%
Tall Panic Grass	Prairie Species	12.7 mm in 30 minutes	57%
Little Blue Stem	Prairie Species	12.7 mm in 30 minutes	50–60%
Birch	Tree Species	350 mm in 5 months	10%
Ash	Tree Species	38 mm rain (no time given)	24%
Spruce-Fir	Tree Species	272 mm in 5 months	30%

Table 1-3 Typical Plant Transpiration Rates

Plant Name	Plant Type	Transpiration Rate
Perennial Rye	Typical Lawn Grass	6.9 mm/day
Alfalfa	Agricultural Crop	10.5 mm/day
Common Reed	Wetland Species	11.2 mm/day
Great Bulrush	Wetland Species	21.9 mm/day
Sedge	Wetland/Prairie Species	48.2 mm/day
Prairie Cordgrass	Prairie Species	12.1 mm/day
Cottonwood	2 Year Old Tree	2.0–3.75 gpd per tree
Hybrid Poplar	5 Year Old Tree	20–40 gpd per tree
Cottonwood	Full, Mature Tree	50–350 gpd per tree
Weeping Willow	Full, Mature Tree	200–800 gpd per tree

1.3 Applications

For the effective application of phytotechnologies, the mechanisms described in the previous section need to be exploited in specific design applications. The specific application to be used at a contaminated site depends on the affected media, the constituents of concern, and the remedial goals. In many cases, hydraulic control or containment is one of the remedial objectives for a site to ensure that contaminants do not migrate off-site or impact other receptors. To accomplish hydraulic control, vegetative groundcovers, tree hydraulic barriers, and wetland plant systems can be used to control surface water and groundwater movements as well as physically stabilize the soil environment (i.e., reduce erosion, dust emissions, etc.). In addition to containment, another general objective for the remediation of a site is stabilization, accumulation, reduction, degradation, metabolism, or mineralization of specific contaminants in order to reduce the associated risks to human health and the environment. Therefore, the application of phytotechnologies is simply the logical and scientifically sound combination of the various phytotechnology mechanisms described in the previous section.

Once these mechanisms have been combined in a meaningful manner, growing, and in some cases, harvesting, plants from a contaminated site can be an aesthetically pleasing, solar energy-driven, and passive remediation method. However, this technology, like all remediation technologies, is appropriate only under certain conditions. Phytotechnologies are well-suited for sites where the following conditions are applicable:

- Sufficient area exists for growing vegetation.
- Treatment can be applied over long periods of time.
- Concentrations of contaminants are nontoxic to the plants.
- Other methods of remediation are not cost-effective or practicable.
- Existing systems may be supplemented to achieve remedial goals more rapidly.
- A transition from a primary treatment to a longer-term strategy may be desired.
- Vegetation can be used as a final cap for closing or restoring the site.

Table 1-4 Summary of Phytotechnology Applications

Application	**Process Goal**	**Media**	**Mechanisms**	**Typical Contaminants**	**Plant Types**
Vegetative Covers	Infiltration control	Surface water, rain water	Evapotranspiration	Covers for landfills	Herbaceous species, grasses, trees
Vegetative Covers	Remediation	Soils, sediments, sludges	Phytostabilization, rhizodegradation, phytoaccumulation, phytodegradation, phytovolatilization	Organic compounds (TPH, PAHs, PCBs), metals (Ag, As, Au, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Zn), radionuclides (^{90}Sr, ^{137}Cs, ^{239}Pu, $^{234, 238}$U)	Herbaceous species, grasses
Hydraulic Barriers	Hydraulic control	Groundwater	Evapotranspiration	Dissolved organic and inorganic compounds (metals, salts)	Trees, some prairie grasses
Vegetative Stands	Remediation	Subsurface soils, sediments, sludges and groundwater	Phytostabilization, rhizodegradation, phytoaccumulation, phytodegradation, phytovolatilization	Organic compounds, chlorinated solvents, and inorganic compounds	Trees, some prairie grasses
Treatment Wetlands	Remediation	Surface/waste water	Phytostabilization, rhizodegradation, phytoaccumulation, phytodegradation, phytovolatilization, evapotranspiration	Cr, N, P, Se, phenols, TPH, BTEX, chlorinated solvents, municipal waste	Wetland species
Riparian Buffers	Runoff control	Surface water, groundwater	Phytostabilization, rhizodegradation, phytodegradation, phytovolatilization	N, P, excess fertilizers, pesticides	Herbaceous species, grasses, trees, wetland species
Hydroponic Systems (Rhizofiltration)	Remediation	Pumped or surficial water streams	Phytostabilization, phytoaccumulation, evapotranspiration	Metals, radionuclides	Herbaceous species, wetland species

1.3.1 Vegetative Covers for Infiltration Control

The ability of plants to intercept rain and prevent infiltration from occurring or take up and remove significant volumes of water after it has entered the subsurface can be used to provide hydraulic control for remediation systems. Specifically, vegetative covers can be designed using specially formulated seed mixes or mixed communities of plants/trees that maximize rain interception and transpiration capacities. These canopies can be established over the affected areas to reduce infiltration from precipitation events and limit percolation into the deep subsurface (Veissman et al., 1989). This is shown for a typical rain event in Figure 1-6 where the initial rainfall is collected on the surfaces of the plant leaves (see the left illustration, Figure 1-6) based on the rain interception capacity (see Table 1-2). Once the capacity of the species to intercept rain has been exceeded, the additional rain that occurs falls to the ground surface where it can form runoff or begin percolating down into the soil (see the middle illustration, Figure 1-6). After the rain has ended, the water intercepted on the plant leaves and within the root zone is subject to evapotranspiration (see the right illustration on Figure 1-6) and can be removed prior to forming deep infiltration (or groundwater recharge). Vegetative covers can be designed to maximize the rain interception and transpiration capabilities to control groundwater recharge into a contaminant plume. Typical rain interception capacities as well as transpiration rates were provided earlier in Tables 1-2 and 1-3, respectively (see Section 1.2.6).

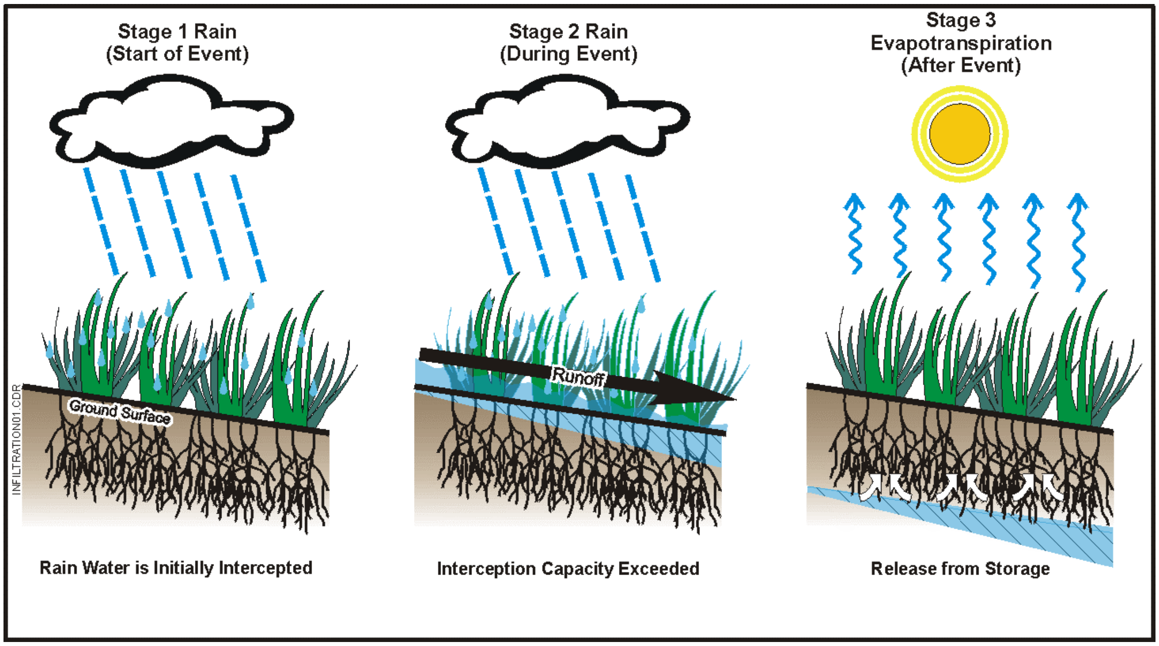


Figure 1-6 Infiltration Control from a Vegetative Cover

Two types of vegetative covers that are used as alternatives to conventional landfill covers are the evapotranspiration cover and phytoremediation cover. Evapotranspiration covers (also known as water-balance covers) are composed of soil and plants to maximize evaporation and transpiration processes of the plants and the available storage capacity of the soil to minimize water infiltration. The evapotranspiration cover is a form of hydraulic control by plants.

Phytoremediation covers are used as landfill covers and consist of soil and plants to minimize infiltration of water and to aid in the degradation of underlying waste. These covers assist in the degradation of the contaminant as well as prevent the formation and movement of the leachate. The phytotechnology mechanisms include hydraulic control, rhizodegradation, phytodegradation, phytovolatilization, and, perhaps, phytoextraction (Rock, 2000).

In general, vegetative covers are not appropriate for sites that produce landfill gas in chronic, large, or uncontrolled amounts. Landfill gases such as methane can be toxic to plants and must be controlled through other means. Vegetative covers have not been shown to prevent the diffusion of gases from landfills.

1.3.2 Vegetative Covers for Surface Soil Remediation

In addition to the ability of plants to intercept rain and prevent infiltration, densely rooted groundcover plants and grasses can be used to promote the enhanced biodegradation of organics in shallow surface soils. The primary mechanism involved in this application is rhizodegradation. The use of this type of phytotechnology has been applied at various scales from bench to full-scale for the remediation of petroleum hydrocarbons. In general, these types of covers are primarily geared toward more recalcitrant compounds that are typically less mobile, such as polycyclic aromatic hydrocarbons (PAHs). Reviews of these works can be found in the literature (Flathman and Lanza, 1998).

Similarly, halophytes and hyperaccumulators can be planted into areas to remediate shallow soils of salts and heavy metals (or trace elements), respectively. Typically, the primary mechanism involved with this application for inorganic contaminants is either phytostabilization or phytoaccumulation. The specific mechanism that is exploited is dependent on the specific inorganic being addressed, the chemical speciation, and bioavailability. Typical metals (trace elements) that have been treated with this phytotechnology application include Pb, Cd, Zn, Ni, Se, As, and Cu. Also, Na, Mg, and Ca chloride salts can be treated using this application as well (Banuelos, et al., 1998; Cipollini and Pickering, 1986; Hinchman, et al. 1997; Keiffer, 1996; Keiffer and Ungar, 1996; Kumer, et al. 1995; Martin, et al, 1996; Salt, et al., 1995; Spier, et al, 1992).

The typical range of effectiveness for both the inorganic and organic applications is 1–2 feet bgs; however, depths down to 5 feet bgs have been reported as within the range of influence under some situations (Olsen and Fletcher, 1999). The time required to achieve cleanup using this phytotechnology application may take several seasons.

1.3.3 Groundwater Hydraulic Barriers

In addition to using plants as vegetative covers, deep-rooted species, particularly trees, can be used to create hydraulic barriers to minimize or prevent groundwater and plume migration. The application of hydraulic barriers requires the consideration of several factors, including the following:

- The amount of land available to establish a hydraulic barrier is generally large.
- The length of time required for trees to become an effective pump-and-treat system.

- Effects of climatic and seasonal conditions on the rate of water uptake.
- Effects of fluctuating water levels and the tolerance of trees to saturated conditions.
- Groundwater removal is limited by the depth of root penetration.
- The transpiration rates of vegetation are not well documented or consistently measurable.

For plume control, these deep-rooted, high-transpiring plants or trees must be actively tapping into the groundwater to take up and transpire the groundwater. Furthermore, a relatively large number of trees are generally required to achieve sufficient control and should be concentrated at the down-gradient edge of the plume (Matso, 1995). The amount of groundwater that can be taken up by a stand of trees is dependent on many factors, including the age of the trees, the depth of groundwater, the soil conditions, and the climate region where the site is located. Typical water uptake and transpiration rates were shown previously in Table 1-3 (see Section 1.2.6).

The basic premise behind this application of phytotechnologies is that the deep-rooted plants or trees access the groundwater and cause a local depression in the water table through uptake and transpiration. This depression is sufficient to prevent the migration of groundwater beyond the boundary of the tree stand. This is shown conceptually in Figure 1-7. Because of the depths involved, the time required to become an effective hydraulic barrier may take several years. Furthermore, sufficient area must be available to support an adequate number of trees necessary to achieve the degree of hydraulic control desired. The design of such systems will require some form of groundwater modeling that shows the effects of trees on the water levels and flow rates.

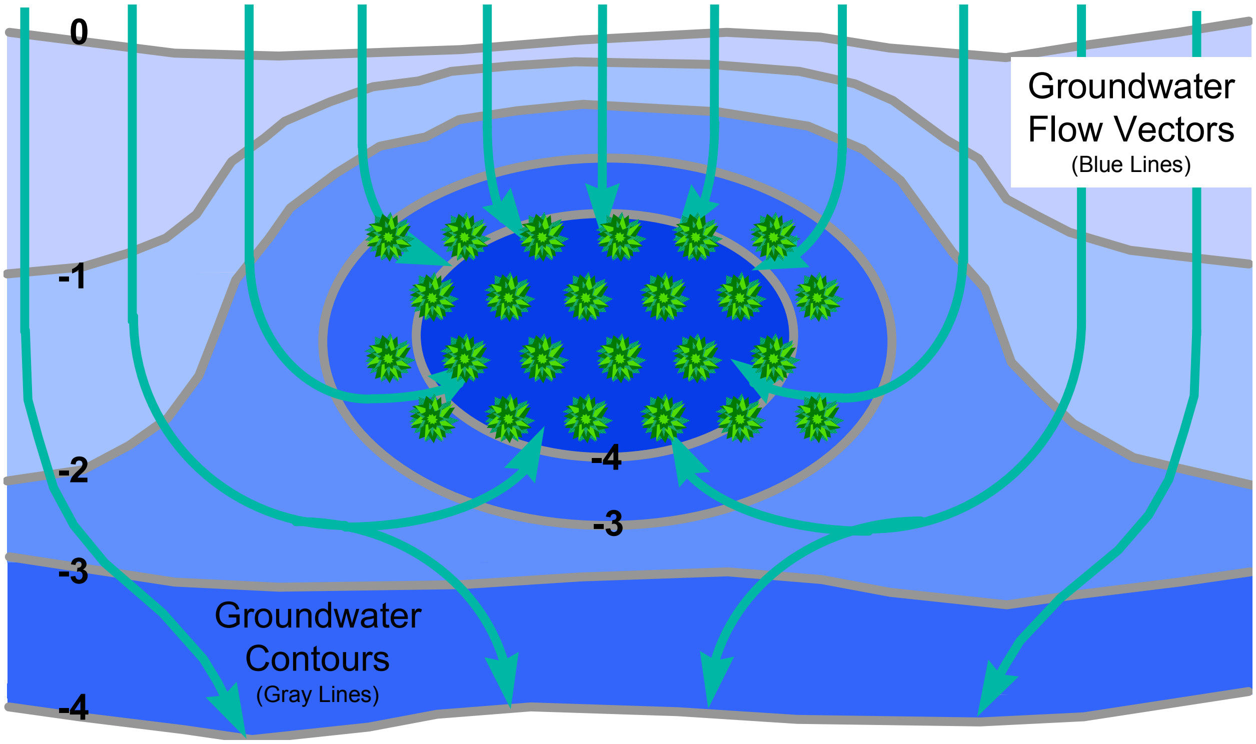
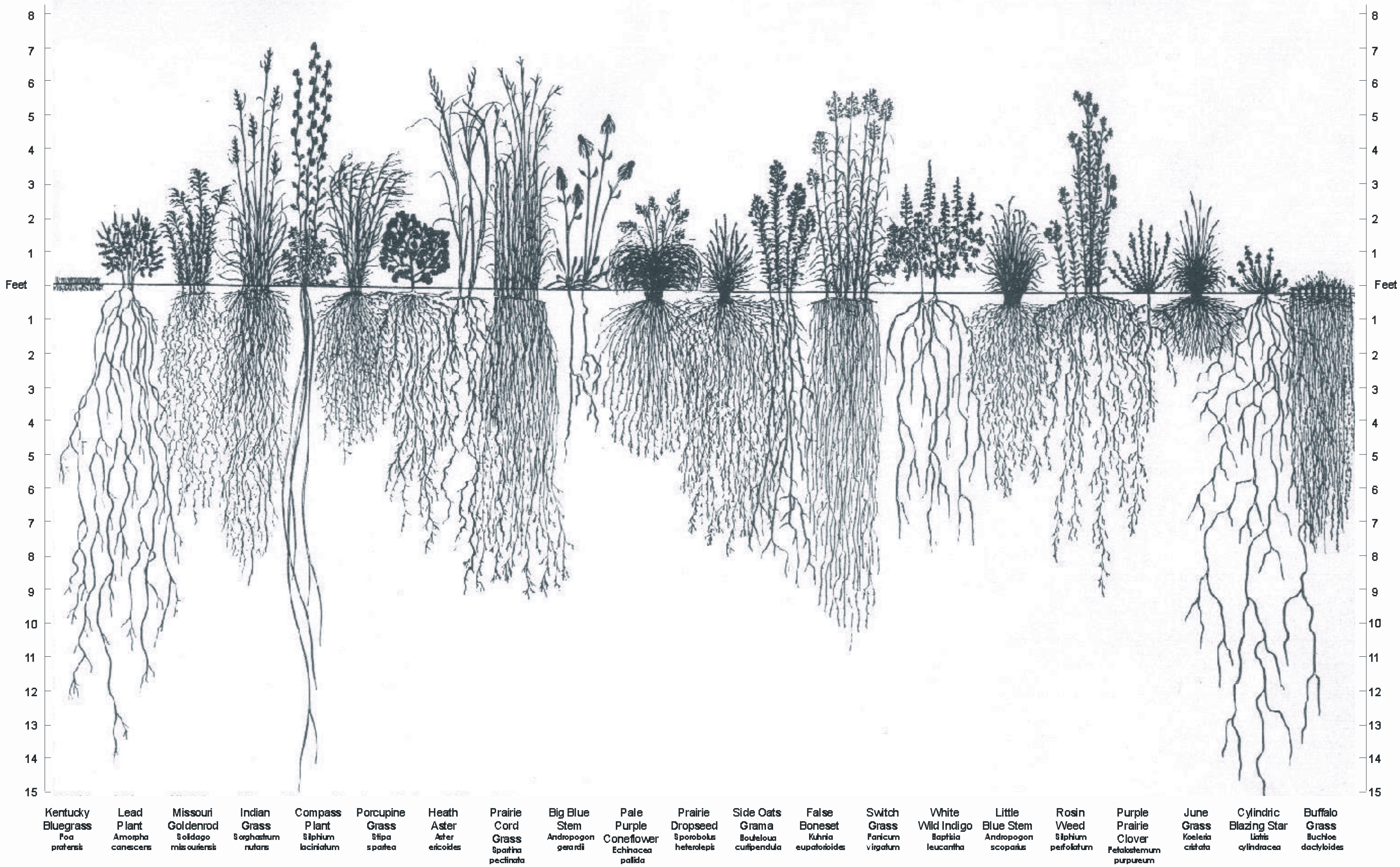


Figure 1-7 Tree Hydraulic Barrier for Preventing Plume Migration

1.3.4 Tree Stands for Subsurface Soil and Groundwater Remediation

In addition to the ability of deeper rooted plants and trees to take up and transpire groundwater, these species can be used to remediate deeper soils as well as contaminated plumes that are located near the top of the water table. Equations for calculating the rate of uptake of a contaminant into a plant are provided in Appendix A. As the contaminated soils and groundwater are exposed to the root systems of the plants and trees, the mechanisms for remediating inorganics (phytostabilization, phytoaccumulation, and phytovolatilization) and organics (phytostabilization, rhizodegradation, phytodegradation, and phytovolatilization) come into play. Each of these mechanisms was shown conceptually in Figures 1-1 to 1-5, respectively (see Sections 1.2.1 to 1.2.5). Again, the species used to provide the soil and groundwater remediation must tolerate the contaminant concentrations expected to be encountered.

Although this type of phytotechnology application has generally focused on the use of trees to provide hydraulic containment, additional work is occurring on the use of other species such as prairie grasses. Many prairie species have root systems that can reach 10 to 15 ft below surface level as illustrated in Figure 1-8 below (USEPA, 1998). Furthermore, many of these species have high water-uptake and transpiration rates as shown in Table 1-3.



Root Systems of Prairie Plants - From the U.S. EPA Handbook on Natural Landscapes

Conservation Design Forum, Inc.

Heidi Natura 1995 ©

Figure 1-8 Typical Rooting Depths of Natural Prairie Species

Depending on the chemical in the soil or groundwater, the specific species being used, soil conditions, and other factors, the specific mechanism that will be the primary method for achieving remedial goals may vary. Furthermore, several of these mechanisms may operate in series or in conjunction with each other. There is also some current scientific debate concerning which mechanisms are the predominant modes of action. A primary example of this is the use of deep-rooted trees to contain and remediate TCE. One school of thought is that the TCE is unaffected as it passes through the rhizosphere but is taken up from the groundwater in its parent form and released into the atmosphere through phytovolatilization (Newman, et al., 1997). A second school of thought is that there is some degradation or transformation of the TCE that occurs while the contaminant is translocating through the trees (Anderson and Walton, 1991). Furthermore, these byproducts are then released into the atmosphere through transpiration. Therefore, there is a combination of phytodegradation in combination with phytovolatilization. A final school of thought for the remediation of TCE from groundwater is that the parent compound is actually degraded in the rhizosphere with the subsequent uptake of the byproducts into the trees to be eventually released during transpiration (Orchard, et al., 1999). Therefore, the mechanisms involved in this phytotechnology application include rhizodegradation followed by phytovolatilization. Obviously, more research is needed to resolve this debate; however, groups have shown that this application of phytotechnologies (regardless of which mechanisms are involved) is effective at treating TCE in groundwater (Chappell, 1998).

1.3.5 Treatment Wetlands for Surface/Waste Water Remediation

Wetland systems are those in which the water is near enough to the soil surface to maintain saturated conditions year-round and capable of supporting the related wetland vegetation (Christensen-Kirsh, 1996). There are laws governing the use of natural wetlands that may not apply to constructed wetlands. Two common types of constructed wetland systems include subsurface flow and free water surface flow.

Subsurface flow systems use the flow of contaminated water through a permeable medium, such as sand or gravel, to keep water below the surface and minimize odor. Free water surface flow systems simulate a type of natural wetland in which the contaminated water flows over the soil at shallow depths. Both systems require impermeable barriers or liners to prevent the infiltration of the contaminated surface water into the groundwater.

Wetland systems are complex systems that can be used to treat water such as stormwater runoff as well as municipal or industrial wastewater. A conceptual representation of the various mechanisms involved in a wetland treatment system is shown in Figure 1-9. Treatment wetlands are used for clarification where the inorganic and organic contaminants are subject to the phytotechnology mechanisms described earlier in the plant matter or in the sediments. Furthermore, wetland plants provide subsurface oxygenation that promotes the rhizodegradation of organic contaminants. In addition, various contaminants can be phytoaccumulated or phytodegraded in the wetland plants, eliminating them from the effluent. Finally, some organics and perhaps some volatile inorganics can be released through phytovolatilization as well. Each of these phytotechnology mechanisms have been used in wetlands to remediate heavy metals, trace elements, agricultural runoff (phosphate, nitrate, ammonia), total petroleum hydrocarbons, oil and grease, diesel range organics, phenols, pesticides, and biological pathogens (Kadlec and Knight, 1996).

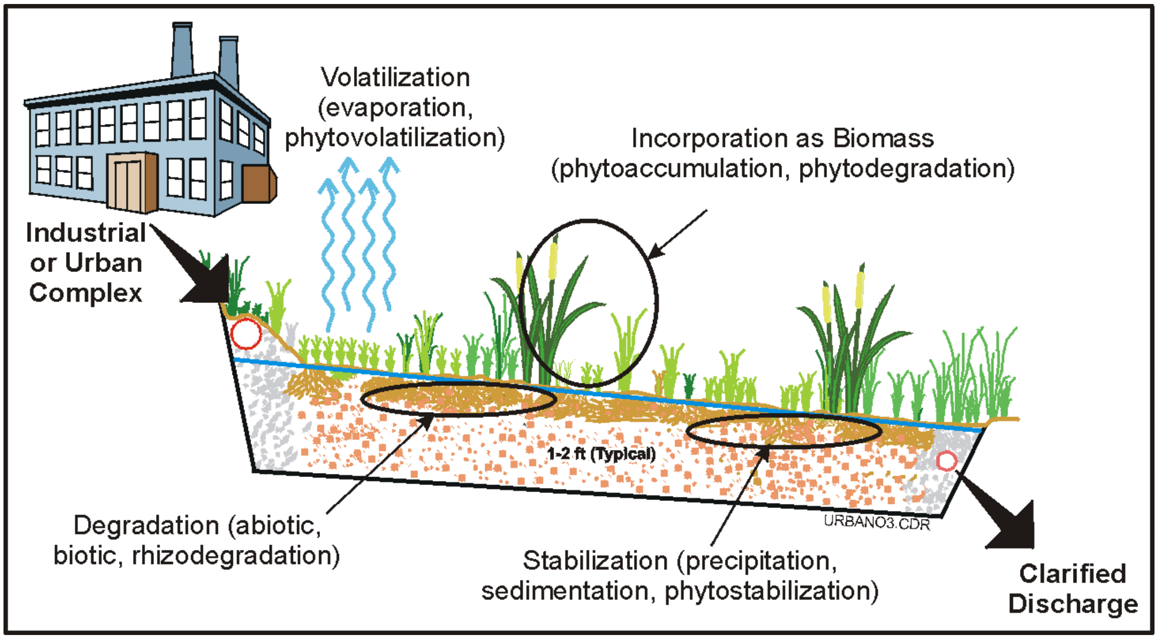


Figure 1-9 Treatment Wetland

The wetland can contain both terrestrial and aquatic plants (Christensen-Kirsh, 1996) and should be designed with sufficient area to support both. Constructed wetlands may require a habitat management plan depending upon the design of the wetland and the type of wildlife it can attract. One advantage of wetlands is that the accumulation and subsequent biodegradation (or composting) of detritus material in the sediments provide an internal source of heat that can contribute to the continuous operation of the wetland as a treatment system throughout the year. However, periodic harvest of the plants as well as the dredging of the wetland sediments may be required from time to time to prevent the continuous buildup of detritus, which can eventually alter the flow system.

1.3.6 Riparian Buffers for Runoff Control

Riparian buffers are vegetated areas that protect adjacent water resources from non-point source pollution, provide bank stabilization, and habitats for aquatic and other wildlife. The formal definition of riparian buffers is diverse and depends on the individual or group defining the term. Natural riparian buffers are composed of grasses, trees, or both types of vegetation. If riparian buffers are maintained or reestablished, they can exist under most land uses: natural, agricultural, forested, suburban, and urban. A cross-sectional view of a typical riparian buffer is shown in Figure 1-10.

As agriculture and urbanization have encroached upon streams, rivers, lakes, and beachfronts, the impacts to water bodies is evident. The problems include sediments from agriculture runoff; sediments resulting from lands cleared to build homes and offices; non-point source runoff from urbanization; and agricultural and urban chemicals, including nutrients, pesticides, and animal waste.

Hydrology is the most important factor that determines the effectiveness of riparian buffers. Removal of contaminants from surface runoff requires that the flow of water be sufficiently slow to allow sediments to settle out. To be effective, runoff water must spread evenly across the buffer. If channels develop due to erosion, the effectiveness of the buffer is greatly reduced. Contaminants in the groundwater can seep into these surface water bodies unless they are removed. The roots of the trees, shrubs, and grasses in the riparian buffer provide an energy source for bacteria that can promote the stabilization, accumulation, reduction, degradation, metabolism, or mineralization of the contaminants. Therefore, each of the mechanisms of phytostabilization, rhizodegradation, phytoaccumulation, phytodegradation, and phytovolatilization can come into play in riparian buffers.

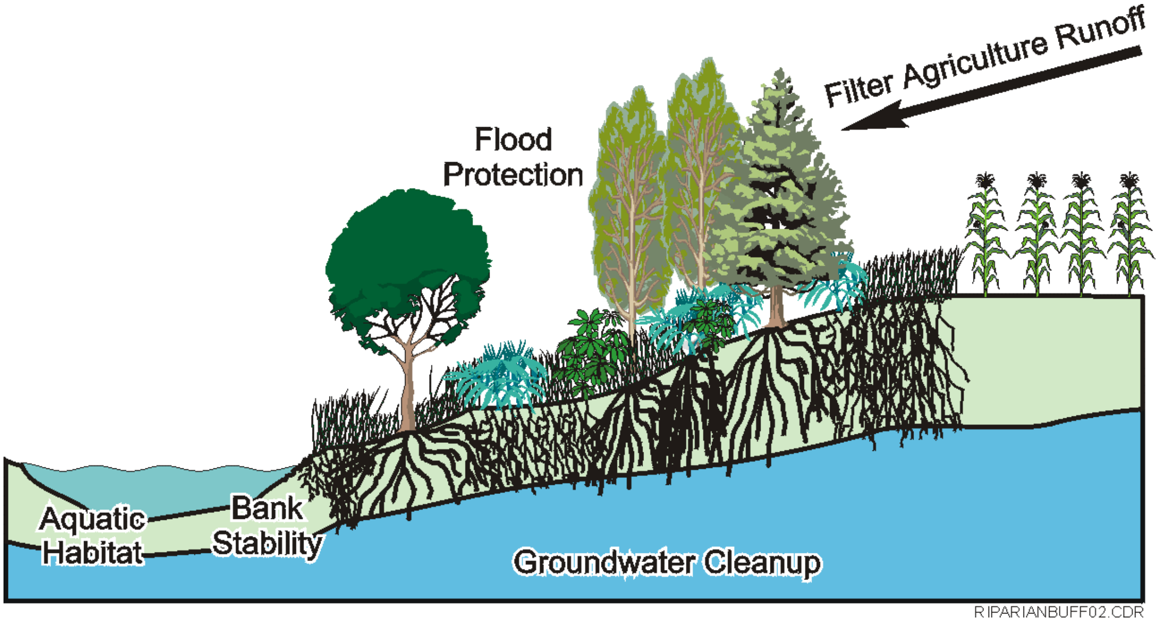


Figure 1-10 Riparian Buffers

In order to control hydrology, the width of the buffer can be controlled. Buffers that are too narrow may not be sustainable, provide adequate pollution control, or provide adequate stream bank protection. Buffers wider than necessary, limit the adjacent land use and impact landowners.

A good example of an effective application of riparian buffers is the remediation of cropland runoff, such as nitrate-nitrogen fertilizer. During standard agricultural practices, fertilizer is often applied to croplands prior to or immediately after the emergence of newly planted crops. Since these crops are not fully developed, there is a significant amount of the fertilizer that is not immediately utilized and can form runoff or percolate down into the groundwater. These sources of contamination can then mobilize and eventually impact surrounding water bodies. Riparian buffers constructed around the water bodies can be used to convert the nitrate-nitrogen into nitrogen gas that is released to the atmosphere prior to impacting the water body. This transformation occurs through the process of denitrification, which is a function that occurs in all higher plants.

1.3.7 Hydroponic Systems for Treating Water Streams (Rhizofiltration)

Sections 1.3.1–1.3.6 describe in-situ applications of phytotechnologies. However, phytotechnologies can also be applied as an ex-situ technology, such as in a pump-and-treat system where the treatment consists of supplying contaminated water as the influent into an area where plants are cultivated. Alternatively, the contaminated water stream can be passed through artificial, planted systems known as hydroponic systems. Typically hydroponic systems utilize an artificial soil medium, such as sand mixed with perlite or vermiculite. Specific plant species are planted into this artificial soil, and the stream of water that is to be treated is then passed through the system. Alternatively, the plants can be raised with their roots directly in the flowing water stream but supported with some sort of wire mesh or other physical mechanism. Typically, however, the plants to be used for cleanup are raised separately in greenhouses using a nutrient solution. Once the plants have developed large root systems, the contaminated water is diverted from the waste site and brought to the plants. Alternatively, the plants are cultivated and transported to the contaminated site. As the roots or plants become saturated with contaminants, the plants are generally harvested and replaced with a new set of plants. One advantage of these systems is that they can be in operation throughout the year because the plants are raised in greenhouses. A schematic diagram of a hydroponic system is shown in Figure 1-11.

This application of phytotechnologies, also called rhizofiltration, has only been applied to inorganically impacted waters (Salt, et al., 1995; Vasudev, et al., 1996; Dushenkov, et al., 1997a; Dushenkov, et al., 1997b). Depending on the concentration of the contaminant, the flow rate of the contaminated water, and the area available for constructing these systems, the treatment of the water stream may be able to be conducted entirely above ground using plants developed from germination to harvest. Large-scale, low-flow systems have been constructed that utilize this design.

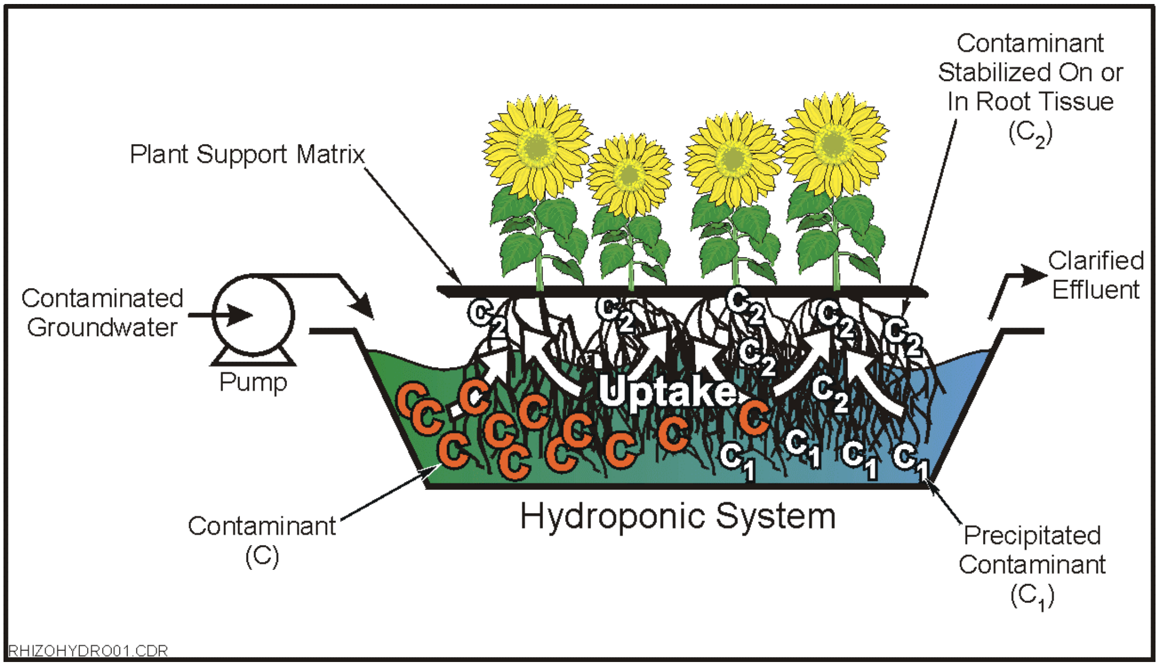


Figure 1-11 Rhizofiltration of Inorganics

2.0 REGULATORY AND POLICY ISSUES WITH PHYTOTECHNOLOGIES

Phytotechnologies are specific applications that can cover a broad range of environmental situations. When implementing phytotechnologies at a contaminated site, it will be important to educate regulators, stakeholders, and the public on how phytotechnologies work. The following issues are likely to be raised by regulators, stakeholders, and the public:

- What is the regulatory driver for cleanup (Voluntary Cleanup, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), Resource Conservation and Recovery Act (RCRA), underground storage tank (UST), etc.)?
- What is the contaminant of concern?
- What media is being cleaned (soil, sediment, surface water, or groundwater)?
- What are cleanup levels for the contaminant?
- Will cleanup levels be attained within a reasonable restoration time frame?
- Will the human health and ecological risks be adequately addressed?
- What will be the monitoring requirements for the site?
- What research has been conducted regarding the effectiveness of phytotechnologies?
- What will be the effect of genetically modified or non-native plants if they are to be used at the site?
- What is the fate and transport of the contaminant? Will it be transferred to another media?
- How will contaminated plant material be disposed?
- Will there be a contingency plan if the performance data indicate the system is not achieving the performance requirements within a specified time frame?
- Will a periodic review be conducted to reevaluate the effectiveness of phytotechnologies at the site?
- What criteria will be used to determine when the remediation is complete and the site is “closed”?

If phytotechnologies are selected as remedial alternatives, design information must address regulatory and policy issues. This chapter is intended to summarize some issues and concerns and provide recommendations to address them. Concerns regarding the use of phytotechnologies are discussed in Section 2.1.5.

2.1 Remedial Objectives

The key to successfully applying any technology is ensuring that the technology is applicable to the remediation objectives and site conditions. For phytotechnologies, the remedial objective can be containment, remediation, or both.

2.1.1 Control and Containment

Phytotechnology systems can be designed to provide control and containment although there is the potential to remediate as well. If containment is the primary objective, the main focus should be on utilizing rain interception and evapotranspiration or groundwater uptake and transpiration. An application for a phytotechnology project with the primary objective of containment should include modeling results regarding the effects of the plants on contaminant fate and transport. If a vegetative cover is proposed, hydrologic models to estimate infiltration or runoff should also be presented. For groundwater hydraulic control, this could include models that predict plume migration or stability. Several models for these applications are available in the literature.

Some proposals for applying phytotechnologies will focus primarily on containment but may also discuss the potential for contaminant remediation. This is to be expected. Again, the primary objective of containment should be stated and not be confused with the potential remediation aspects of phytotechnologies.

2.1.2 Contaminant Reduction/Removal

If a containment strategy is not acceptable, the proposed application of phytotechnologies should include a mechanism for stabilizing, sequestering, reducing, degrading, metabolizing, or mineralizing the contaminants. For inorganic contaminants, phytotechnology mechanisms that may be included in an application include phytostabilization, phytoaccumulation, and phytovolatilization. Similarly, for organic contaminants, applicable mechanisms include phytostabilization, rhizodegradation, phytodegradation, and phytovolatilization. These remediation mechanisms can be combined with containment using phytotechnologies unless other mechanisms for containment exist, such as a pump-and-treat system for groundwater.

The applications of phytotechnologies that combine containment with remediation include phytoremediation covers, groundcover systems for remediating surface soils, tree stands for remediating soil and groundwater, wetland treatment systems, riparian buffers, and aboveground hydroponic systems. In addition to modeling the effects of the vegetation on the surface or subsurface hydrology, a phytotechnology application should include sufficient background information describing the remediation aspects of the treatment system. This could include case studies, bench-scale or pilot-scale tests conducted specifically for the proposed application, or a literature review. Several case studies are provided in this document for each of the various phytotechnology applications (see Appendix D, Case Studies). An extensive bibliography is also provided (see Section 5, Bibliography and References). A list of additional references provided by the United States Environmental Protection Agency (USEPA) in conjunction with the Remediation Technologies Development Forum (RTDF) can be found on the Internet at: http://www.rtdf.org/public/phyto/phytobib/biba-b.html. For groundwater capture and contaminant removal, a detailed discussion is given in Appendix A.

2.1.3 Regulatory Evaluation and Approval

Each application of phytotechnologies is site-specific. Regulations (40 Code of Federal Regulations [CFR] 300.430) specify that a treatment remedy must be "protective of human health and environment, maintain protection over time, and minimize untreated waste." The view of the regulator on the applicability of phytotechnologies must be the same as for any other technology. System designers must demonstrate how phytotechnologies will decrease risk to human health and the environment and meet all appropriate performance standards.

To obtain regulatory approval, sufficient data should be presented early in the process to avoid any regulatory barriers at the later stages of design. The Superfund evaluation and remedy selection process offers a road map for the evaluation of remediation technologies at hazardous waste sites. Evaluating phytotechnologies under Superfund rules will help concerned parties determine if the technology is applicable for the site under consideration (Rock, 2000).

Often the most difficult sites to remediate are abandoned facilities on the National Priorities List (NPL) or Superfund sites. Under Superfund laws, USEPA uses nine criteria to evaluate remedial alternatives. These criteria, as appropriate for phytotechnologies, are listed below:

- ***Overall protection of human health and the environment*** determines whether phytotechnologies eliminate, reduce, or control threats to public health and the environment through institutional controls, engineering controls, or treatment.
- ***Compliance with Applicable or Relevant and Appropriate Requirements (ARARs)*** evaluates whether the phytotechnology application meets federal, state, and local environmental statutes, regulations, and other requirements that pertain to the site.
- ***Long-term effectiveness and permanence*** considers the ability of phytotechnologies to protect human health and the environment over time and the reliability of such protection, including the degree of certainty that the alternative will prove successful.
- ***Reduction of contaminant toxicity, mobility, or volume through treatment*** evaluates the effectiveness of phytotechnologies in reducing the harmful effects of principal contaminants, reducing the contaminants' ability to move in the environment, and reducing the amount of contamination present.
- ***Short-term effectiveness*** considers the length of time needed to implement the phytotechnology application and the risks that the system poses to workers, residents, and the environment during implementation.
- ***Implementability*** considers the technical and administrative feasibility of implementing the phytotechnology application, such as the practicability and difficulty of construction and the availability of goods and services.
- ***Cost*** considers the estimated capital, operation and maintenance, and monitoring costs as well as present net worth costs. Present net worth is the total cost of the alternative over time in terms of today's dollars.
- ***State acceptance*** considers whether the state agrees with USEPA's analysis and recommendations of the studies and evaluations performed.
- ***Community acceptance*** will be addressed in the Record of Decision (ROD) Amendment. The ROD will include a responsiveness summary that presents public comments and USEPA's responses to those comments. Acceptance of phytotechnologies will be evaluated after the public comment period.

2.1.4 Permit and Ordinance Requirements

Phytotechnologies may require approvals and/or permits from one or more regulatory authority (federal, state, and/or local) depending on the mechanisms involved and the applications being proposed. If surface water is being remediated, a National Pollutant Discharge Elimination System (NPDES) permit may be required at the final point of discharge. Similarly, if a treatment system utilizes phytovolatilization as a mechanism of remediation, an air permit may be necessary. Finally, various city ordinances may need to be consulted before a phytotechnology system design can be approved. Specifically, certain cities and states restrict the use and cultivation of plant species that may be considered invasive or noxious. Lists of plants classified as invasive or noxious can be obtained from the local cooperative extension agent.

If a phytotechnology project requires contaminated groundwater to be pumped to the surface as irrigation for the plants, a RCRA permit may be necessary. Although USEPA has granted an exemption to allow "treated" groundwater to be re-injected, it is not clear whether pumping contaminated groundwater to the surface as irrigation to plants constitutes treatment, thereby, satisfying the requirement of RCRA 3020 (b). It is also not clear whether this requirement would apply to non-CERCLA or non-RCRA sites such as state remedial and voluntary cleanup sites. Even if a RCRA permit is not necessary, many states will require a permit or approval by the appropriate regulatory authority. For this reason, it is crucial that communication be established with the appropriate regulatory authority while in the planning phases of a project.

In addition, if a project requires excavation or removal of contaminated soil from one area to another, it will be considered land disposal (pursuant to 40 CFR 268) and a RCRA permit will be required. However, RCRA 3000(k) does not consider movement of contaminated media within a defined Area of Contamination (AOC) as land disposal. Pursuant to 40 CFR 264 Subpart S, this exemption was extended to Corrective Action Management Unit (CAMU). It is not clear if soil moved from one area to another within the disposal site during a phytotechnology project will be exempt from this requirement. It is also not clear if this requirement applies to non-RCRA sites.

Similarly, federal and state regulations have long dictated not only the application of a landfill cover as a remedial alternative, but also its actual technical design. RCRA is the controlling federal law for both municipal solid waste (MSW) and hazardous waste (HW) landfills. RCRA regulations require that the final cover have permeability no greater than $1\text{x}10^{-5}$ cm/sec. This permeability requirement applies for both MSW and HW landfills (RCRA Subtitle D and C, respectively). States have the ability to make this permeability requirement stricter. It is this engineering standard that makes approval of evapotranspirative (ET) covers difficult.

While there are provisions within RCRA to allow alternative covers, these covers must demonstrate permeability rates that are equivalent to the engineered covers. This permeability standard directly conflicts with the concept and design of ET covers. An ET cover assumes that the subsoil can act as a reservoir for water while awaiting the ET process.

If the concern with landfill covers is to minimize the amount of water that penetrates the cover, a performance-based standard limiting the amount of water that passes through the liner would serve the same purpose. For example, a performance-based standard of a certain amount of water per acre per year would provide protection to the landfill while at the same time allowing ET covers to be designed and installed.

ITRC and the Air Force Center for Environmental Excellence are currently working with USEPA to include this concept in the revised RCRA Guidelines currently being prepared.

2.1.5 Advantages, Limitations, and Stakeholder Concerns

Phytotechnologies offer many advantages over alternative approaches. In terms of economics, phytotechnologies are estimated to be at least 40% less costly than other in-situ remedial approaches. For ex-situ technologies, phytotechnologies are estimated to be 90% less costly compared to alternatives (Glass, 1998). Phytotechnologies can also be used to remove low levels of contamination to meet remedial goals for large areas. A more detailed discussion of the economic considerations for phytotechnologies is provided in Appendix C.

A remediation technology comparable in costs to phytotechnologies is natural attenuation. However, like all remedial technologies, natural attenuation and phytotechnologies are not applicable at all sites, although phytotechnologies can be used to enhance natural attenuation while maintaining plume stability. The ability to reduce, stabilize, sequester, degrade, metabolize, and mineralize contamination using phytotechnologies is faster than natural attenuation alone. Other advantages of phytotechnologies are listed below.

- Low maintenance, passive, in-situ, self-regulating, solar-driven system.
- Potentially applicable in remote locations without utility access.
- Decreased air and water emissions as well as secondary wastes.
- Control of soil erosion, surface water runoff, infiltration, and fugitive dust emissions.
- Applicable to simultaneously remediate sites with multiple or mixed contaminants.
- Habitat creation or restoration provides land reclamation upon completion.
- Favorable public perception, increased aesthetics, and reduced noise.
- Increasing regulatory approval and standardization.
- Carbon dioxide and greenhouse gas sequestration.

Like all remediation technologies, phytotechnologies have limitations and are not applicable to all sites. The primary limitations are the growth habit of the planted system, root penetration of the selected plant(s), and amount of land available for planting. For phytotechnologies to be effective, the contaminated media must be in contact with the plant roots. Therefore, the limiting factor is the capability for contaminant mass transfer to the treatment zone, or root zone. However, this is also true for other in-situ bioremediation technologies. Phytotechnologies can be relatively slow in comparison to more active remediation technologies and is dependent on local climatic conditions. Therefore, phytotechnologies should be balanced with a site-specific risk assessment to determine the appropriateness of application. Additional potential limitations are listed in Table 2-1 below and must be understood by site owners, technology vendors, regulators, stakeholders, and the public.

Table 2-1 Potential Limitations of Phytotechnologies

	MECHANISMS						APPLICATIONS						
POTENTIAL LIMITATION	**Phytostabilization**	**Rhizodegradation**	**Phytoaccumulation**	**Phytodegradation**	**Phytovolatilization**	**Evapotranspiration**	**Vegetative Covers (Infiltration Control)**	**Vegetative Covers (Soil Remediation)**	**Groundwater Hydraulic Barriers**	**Tree Stands (Remediation)**	**Treatment Wetlands**	**Riparian Buffers**	**Hydroponic Systems (Rhizofiltration)**
Restricted to available land							X	X	X	X	X	X	X
Growth habit (annual, biennial, or perennial)							X	X	X	X	X	X	
Slow plant growth rates							X	X	X	X	X	X	
Dependence on climate, growth season							X	X	X	X	X	X	
Susceptible to infestation, and diseases							X	X	X	X	X	X	X
May be difficult to establish / maintain vegetation							X	X	X	X	X	X	X
Slow / shallow root penetration	X	X	X	X	X	X		X	X	X			
Limited contaminant mass transfer into root zone	X	X	X	X	X			X		X			
Phytotoxicity of contaminants	X	X	X	X	X			X		X	X	X	X
Limited database and performance data available	X			X	X		X			X		X	X
Potential transfer to secondary media	X				X		X				X		
By-products may be more toxic		X		X				X		X	X	X	
Bioaccumulation of contaminants in vegetation			X					X		X	X	X	
Mechanisms not completely understood	X	X	X	X	X	X	X	X	X	X	X	X	X
Fate, transport, and efficacy not well documented	X	X	X	X	X	X	X	X	X	X	X	X	X
Unfamiliarity by public / regulatory communities	X	X	X	X	X	X	X	X	X	X	X	X	X

Regulators and stakeholders will require data demonstrating the proposed phytotechnology system will work as well as other options. Attempts to apply phytotechnologies beyond their limits will fail.

2.2 Design Issues and Recommendations

Site owners, technology vendors, regulators, stakeholders, and the public must review the advantages and limitations of using phytotechnologies to remediate contaminated sites. When developing and reviewing the designs of phytotechnology systems, these advantages and limitations need to be incorporated into the process.

2.2.1 Root Depth Limitations

Phytotechnologies have been used to remediate metals, pesticides, solvents, explosives, crude oil, PAHs, and landfill leachates. In all these applications, the plant root zone was in contact with the contaminated media.

The effective range for plants to affect contaminants is dependent on the rooting depth of the plant system. Typical lawn-type grasses generally produce roots down to 1 ft bgs. Prairie species are known for their deep roots and can yield systems that are 10 to 15 ft bgs (USEPA, 1998). Alfalfa, a deep tap-rooted species, has also been documented as being able to produce roots down to 33 ft bgs (Shimp, et al., 1993). For tree species, typical rooting depths range from 10 to 12 ft bgs (Ferro, 1998). However, root systems down to 33 ft bgs, and even deeper, have been reported as well (Shimp, et al., 1993; Nyer and Gatliff, 1996).

For proposed applications of phytotechnologies, it is recommended that the rooting depth for groundcover plants should typically be in the 1 to 2 foot range. For trees, rooting depths down to 12 ft may be achieved. However, under special circumstances where hydrogeological conditions are suitable, deeper rooting depths beyond these typical values may also be reached. Engineering methods may be proposed that have been successful at inducing the development of deeper root systems. These methods include sub-irrigation systems, soil mounding, and the use of impermeable barriers that restrict rainwater infiltration. Specialized planting methods have also been successful at encouraging deeper root growth.

2.2.2 Large Surface Area Required

In general, there may not be any difference in land area requirements between phytotechnologies and alternative technologies for impacted surface soils or sediments. However, surface soil treatment using phytotechnologies may require extensive use of agronomic practices and farming equipment, so the available space will need to be sufficient to support these activities. Phytotechnology systems designed to treat surface water or groundwater generally require more land area than alternative methods. For instance, a “conventional” pump-and-treat system may only require space for a small building to house a treatment system and a strip of land with monitoring wells along a designated boundary to monitor the site. By contrast, a phytotechnology system designed to pump the same volume may require several rows of trees and the associated area to support them. If the size of the land area is very limited, in-situ phytotechnologies may be difficult or not applicable.

To determine the necessary land requirements for a phytotechnology system, knowledge of the water uptake and transpiration rates throughout the life of the plant will be required. Typical evapotranspiration estimates (Table 1-3, Section 1.2.6) can be used with groundwater models to predict the estimated groundwater withdrawal necessary to achieve hydraulic control. The amount of vegetation required to achieve the same level of control can be calculated by comparing the estimated groundwater withdrawal rate with the water uptake and transpiration rates. For example, a groundwater model that predicts a withdrawal rate of 5 gpm to maintain hydraulic control can be achieved using 360 five-year-old poplars pumping at an annual rate of 20 gallons per day (gpd) per tree. However, the area required to support the 360 trees at 10 foot spacing between trees would be approximately 0.65 acres (over 28,000 ft^2).

For wetland systems, the area required to conduct remediation is determined by the expected discharge of the contaminated water into the system and the amount of time necessary for the contaminants to "settle out" or stabilize in the sediments. These two parameters will allow the volumetric capacity of the wetland to be calculated. Depending on whether the system is a surface or subsurface design, the area required to contain the necessary volume can be calculated and compared to the available space at the site. For example, if a specific contaminant flows in at 100,000 gpd and settles out (stabilizes in the sediments) in 5 days, the volumetric capacity of the wetland should be at least 500,000 gallons. If the system is a surface flow system with an average water depth of 2 ft, the surface area required for the wetland is 0.77 acres (over 33,000 ft^2).

For phytotechnology systems designed to treat surface water or groundwater, it is recommended that similar calculations be presented in the application for system approval. A higher level of detail than these examples may be required and is available in the literature (Kadlec and Knight, 1996).

2.2.3 Seasonal Nature of Phytotechnologies

In one example in the previous section, an annual water uptake rate of 20 gpd per tree for five-year-old poplars was used. This rate takes into account the winter dormancy by dividing the total volume of water taken up in a season (i.e., ~1/2 year) by the number of days in a year (i.e., 365 days). When reviewing literature listing plant transpiration rates, the basis for listed values should also be noted. Transpiration estimates can either be reported as annual rates based on an average, as described above, or as single events. Single event rates can be highly dependent on temperature and humidity (i.e., hot, dry day vs. a cool, wet day). Typically, for trees, values are reported in volume per day per tree (i.e., gallons per day per tree, or gpd per tree). Similarly, the basis should also be reported for groundcover-type plants that are typically reported in volume per unit area per unit time (i.e., gallons per acre-day, or gpd per acre).

In addition to temperature and humidity, phytotechnologies are limited by the length of the growing season. A growing season is defined as the average first to average last frost dates for a region. This climatological information is available at local agricultural extension services. Plants are dormant during winter periods, unless they are in a temperate climate where freezing temperatures are infrequently experienced (i.e., the southern U.S. regions). Because of this restriction, sites with longer growing seasons may be more suitable for phytotechnologies than sites with shorter growing seasons. Furthermore, the seasonal nature of the technology also needs to be considered when estimating the amount of time required to accomplish cleanup objectives.

System designers must take into account the seasonal nature of phytotechnologies and must ensure that the system will meet the remediation goals even during dormant periods. Sufficient data must be provided to regulators and stakeholders that describe how the contaminant will be contained or treated during the dormant period.

When plants are used as hydraulic barriers and/or to remediate contaminant plumes, a "conventional" pump-and-treat system may be required as a supplement when trees are dormant. Alternatively, the phytotechnology system can be designed to compensate for plume migration during the dormant season. If the rate of contaminant migration during the dormant season is well documented and sufficient area is available, trees can be planted where the leading edge of the plume is suspected to be after the winter. This system design would be adequate as long as the leading edge of the plume is not suspected to travel beyond the final rows of trees by the end of the dormant season.

For vegetative covers designed to prevent infiltration, there can be a reduced amount of infiltration during the winter since the precipitation may be snow rather than rain. However, during the spring thaw, a large influx of infiltration may result and should be considered in the design. Specifically, there should be a net reduction of infiltration during the primary growing season (i.e., summer) that compensates for the heavy infiltration after the thaw. For vegetative covers designed to remediate surface soils, the annual dormant cycle provides a large influx of available carbon into the subsurface for soil microbes to feed upon and continue remediation during winter. This carbon comes from the turnover of roots that occurs annually when plants go dormant (Olsen and Fletcher, 1999).

The treatment efficiency of constructed wetlands will be reduced during winter, but remediation will continue as long as a complete freeze does not occur. Internal heat generated by decaying plant material can prevent freezing.

The seasonal nature of phytotechnologies should be addressed in the design of the system. Furthermore, the cooperative extension agent should be consulted to confirm the growing season for specific plant species. Finally, monitoring should be conducted throughout the year, including the dormant months.

2.2.4 Limited Number of Contaminants Evaluated and Performance Data

Phytotechnologies have been a successful treatment for soil and groundwater contaminated with heavy metals (i.e., Pb and As), metalloids, a limited number of radioactive elements, some halogenated compounds, various pesticides, and some petroleum compounds. Researchers continue to expand the list of contaminants acceptable for phytotechnologies, but the number is limited. Furthermore, phytotechnologies do not and will not work on all contaminants. When presented with an application for phytotechnologies, regulators and stakeholders should require data that demonstrate that phytotechnologies are appropriate for the contaminant of concern. Data from research laboratories, greenhouse studies, and pilot studies should be used as supporting information.

A major regulatory hurdle for the application of phytotechnologies is the lack of performance data. Phytotechnologies have been studied extensively through research projects and small-scale demonstrations, but there are few full-scale applications of the technology. Furthermore, specific regulatory standards for phytotechnologies do not exist. Currently, installations can be approved on a site-specific basis, but regulators may not be comfortable permitting full-scale projects based on the data from the pilot-scale projects currently in existence. Further research and development of the phytotechnology mechanisms and applications described in this document should lead to wider acceptance and use of phytotechnologies.

Site owners and system designers will need to provide as much data as possible on similar applications of phytotechnologies under similar site conditions when proposals for projects are submitted. Regulators and stakeholders should review the data to reach a consensus on whether phytotechnologies are applicable at the site. Many factors such as the contaminant of concern, contaminated media, size of the site, time to complete cleanup, and type of phytotechnology being proposed will be factors in determining the type and amount of performance data needed.

In general, performance data requirements will likely be the same as for any other technology. Specifically, soil and groundwater samples that exhibit a reduction in concentration or mass over time will provide strong evidence that phytotechnologies are effective. Similarly, water table elevation data, contaminant plume maps, and monitoring data will provide evidence of the success or failure of the phytotechnology system. Monitoring requirements are likely to contain elements specific to phytotechnologies that would not be necessary for conventional technologies. These could include plant growth assessments, plant tissue sampling for contaminants of concern, and measurements of transpiration and root penetration.

2.2.5 Economic Considerations

The cost-effectiveness of a phytotechnology system is more of a concern to the site owner and system designer. Regulators and stakeholders will be more concerned that the proposed remediation system will work and provide protection to human health and the environment. The cost-effectiveness of phytotechnologies is a significant concern at brownfields sites, orphan sites, or in states that utilize a reimbursement program. In many cases, it is recommended that cost information be included in the phytotechnology proposal.

The cost estimates for applying phytotechnologies vary widely in the literature, and there is little information on the conditions used to determine costs. However, phytotechnologies have been estimated to be at least 40% less costly than other in-situ remedial approaches, such as soil washing, thermal treatment, electrokinetics, chemical stabilization, air sparging, soil vapor extraction, biostimulation, and solvent extraction. For ex-situ technologies, phytotechnologies have been estimated to be 90% less costly compared to alternatives such as dig and haul (landfilling); incineration; and pump-and-treat technologies, including carbon adsorption, air stripping, advanced oxidation, reverse osmosis, filtration, bioreaction, dissolved air flotation, etc. (Glass, 1998; Schnoor, 1998). More specific information on the economic comparison of phytotechnologies to other technologies is provided in Appendix C.

2.2.6 Mobilization Concerns

There is a potential danger of mobilizing contaminants from soil into the groundwater or from soil and groundwater into air. Mobilization from soil to groundwater could occur through several mechanisms that may include

- excessive irrigation,
- addition of chelating agents or surfactants,
- chemical transformation of the chemical of concern, or
- pH manipulation.

Certain phytotechnologies such as phytoextraction depend on the manipulation of the solubility of the material to make it bioavailable to the plant. Such manipulation must be applied carefully to avoid migration of contaminants. For example, adding chelating agents to solubilize lead could result in contamination of underlying soils and groundwater.

Contaminants may be moved from soil and groundwater to air through plant transpiration. Plants have been noted to transpire volatile contaminants such as PCE, TCE, and Hg (Compton et al., 1998; Newman et al., 1997; Meagher et al., 1995). Other contaminants may be volatilized given the proper plants and conditions.

2.3 Performance Issues and Recommendations

There are many factors that affect the performance of phytotechnologies, including the composition, concentration, solubility, toxicity, and other chemical properties of the contaminant. Furthermore, another important factor is the ability to bring the contaminated media in contact with the plant roots. For surface water remediation, constructing wetlands that bring the contaminated water into contact with the plants can extend the limits of the technology. Similarly, groundwater that is below the root zone of trees can be pumped to the surface and applied to the plants as irrigation water.

2.3.1 Safety Considerations

Phytotechnologies are passive, in-situ technologies that provide an additional level of safety by reducing soil erosion, surface water runoff, and infiltration. Since plants take up contaminants, there is also a decrease in the amount of contaminants available to be dissolved in groundwater.

Fewer field activities, particularly earthmoving activities, are associated with setup and construction of a typical phytotechnology system, producing a significantly reduced amount of fugitive dust and other air emissions when compared to more “conventional” technologies, such as “dig and haul”. Similarly, since phytotechnology projects rarely use large machinery, less noise is generated.

Although safety issues are generally not the primary drivers for selecting a site cleanup technology, safety issues should be considered when evaluating cleanup alternatives.

2.3.2 Time to Complete Cleanup

Phytotechnologies are limited by plant growth rate, rooting depth, and length of the growing season. Because of these limitations, a longer restoration time may be required to achieve cleanup goals than with more conventional methods, such as excavation and landfilling or incineration. Phytotechnologies may take several years to complete, whereas traditional methods may only take weeks or months. However, if the projected risks over time are shown to be minimal through a suitable risk analysis, phytotechnologies may be more cost-effective than other alternatives. On the other hand, phytotechnologies are probably not the remediation technique of choice for sites that pose acute or chronic risks to humans and other ecological receptors. Furthermore, risks may change seasonally, depending on the growth cycle of the vegetation.

In general, phytotechnologies are not recommended for time-critical cleanups but are suitable for sites where time is less of an issue. Regulators, stakeholders, and site owners must reach a consensus on the length of time considered reasonable for site cleanup to be completed. If the consensus of the parties fits the profile for phytotechnologies, then these technologies may be options for the site.

2.3.3 Monitoring Requirements

System designers should identify the specific phytotechnology mechanism being utilized in the system design. Furthermore, the proposed monitoring should include some methodology, either through bench-scale comparisons or actual field measurements, for assessing contaminant fate and transport. In general, the efficacy of phytotechnologies can be monitored using standard techniques for soil and water. However, additional monitoring of the plant tissues is often required to ensure that the plants are not posing any environmental risks, particularly to other ecological receptors (i.e., transfer to the food chain). The analysis of inorganic contaminants, specifically metals, in plant tissues is well established, relatively straightforward, and has generally low detection limits. Unfortunately, there are few widely accepted analytical methods that can adequately monitor plant tissues for organic contaminants. More research is needed to develop analytical methods with reasonable detection limits. Particular issues include

- Following the fate of the parent compound during phytostabilization.
- Determining the composition of transformation byproducts during rhizodegradation.
- Following the fate of byproducts that undergo further phytostabilization.
- Following the fate of the parent compound into the plant tissues.
- Determining the composition of transformation byproducts during phytodegradation.
- Following the fate of the parent compound during phytovolatilization.
- Following the fate of byproducts that undergo further phytovolatilization.
- Making quantitative mass balances in the soil-water-plant system.

It is recommended that at a minimum, a monitoring plan should rely on standard soil and water analytical techniques to generate the necessary data to show that the phytotechnology system is performing. These primary lines of evidence can then be supported with additional analytical techniques that address contaminant fate and transport in the plant tissues, root penetration, and transpiration rates. However, the analytical methods to monitor system performance should be approved in the planning stages of the project. If the application for system approval does not adequately address monitoring concerns expressed by regulators and stakeholders, the proposed system should not be approved.

2.3.4 Achieving Cleanup Goals

The cleanup levels established for sites are based upon the protection of human health and the environment, regardless of the remediation technology used. To determine whether phytotechnologies can achieve the cleanup goals within the specified restoration time frame, greenhouse tests or pilot studies should be requested by regulatory agencies. These tests should directly test the prospective plant species with the contaminants of concern.

Alternatively, if sufficient background information is already available in the literature, the system designer should provide a review of that literature. This review should include a list of the contaminants of concern, the plant species shown to remediate those contaminants, the contaminant concentrations examined, and the time frame to reach the specified endpoints. Finally, from that list of results, the system designer should recommend which specific plant species should be utilized in the design of the phytotechnology system.

2.3.5 Public Acceptance Process

Public acceptance is a very important issue when dealing with the remediation of contaminated sites. Due to the advantages posed by this technology and the general perception that “green” technologies are better for the environment, the public perception of phytotechnologies can be quite favorable. However, a perception could be that phytotechnologies are merely beautification and not cleanup. Whether these opinions are founded in fact is somewhat beside the point since the concerns of the public must be addressed by the regulators and stakeholders, which means that they must be addressed by the system designer and site owner. Before proceeding with a phytotechnology project, these concerns must be placated.

If phytotechnologies are anticipated to be an option to remediate a contaminated site, public involvement early in the process is crucial. It is especially important to consider how phytotechnologies fit into future land uses of the property to be remediated. Future land uses of property are largely determined by zoning. Local residents around the site are likely to demonstrate agreement with the local land use planning authority on the future use of the property. Addressing concerns may include an education program that provides information on how phytotechnologies work in general, what specific mechanisms are being utilized at the site, what applications of phytotechnologies can be designed, and the reasons why the proposed design will work. Just as in the process of gaining regulatory and stakeholder approval, the system designer must provide scientific information supporting the effectiveness of phytotechnologies. These efforts will increase public acceptance and understanding of phytotechnologies.

2.3.6 Disposal of Plant Wastes

Phytoaccumulation can offer significant cost advantages over alternative schemes of soil excavation and treatment or disposal for soils contaminated with inorganics, specifically metals. The economic feasibility of recovering the inorganic contaminants from the plant tissue and determining if the plant waste is a hazardous waste are important issues to consider when applying this technology. Incineration or composting can be a treatment option to concentrate the metals. The feasibility of subsequent recovery depends on the concentration of the metal and the cost of the procedure. Testing the plant tissue (leaves, roots, etc.) for listed chemicals of concern will determine if the plant tissue is a hazardous waste or has a recoverable component. Regulators will play a role in determining the testing method and requirements for the ultimate disposal of the plant waste.

Regulators and the public are likely to be involved in plant disposal issues, including whether plant material generated by the phytotechnology system presents a larger hazard than the undisturbed site. The system designer and site owner must develop a test plan to demonstrate that the plants grown at the site are not a hazardous waste. This will be particularly true for applications designed to treat inorganics using phytoaccumulation. Specifically, if the plants have been used to accumulate radionuclides, the resulting plant waste may be considered a low-level radioactive waste. Similarly, plants used to accumulate heavy metals may contain hazardous levels and thus be considered a hazardous waste after harvesting. Testing the harvested portions of the plants for contaminant concentrations should be used to characterize the material for disposal.

If plant waste disposal is necessary (as hazardous or some other type of regulated waste), a waste disposal plan will be required. This plan should cover all aspects of minimizing waste and collecting the harvested plant materials as well as the proper disposal of hazardous waste. If these issues cannot be resolved, it is recommended that an alternative phytotechnology strategy (i.e., phytostabilization) or a different technology be considered altogether.

2.4 Fate and Transport Issues and Recommendations

Since phytotechnologies can be considered as remediation systems that utilizes natural systems to stabilize, sequester, accumulate, degrade, metabolize, or mineralize contaminants, ecosystems that develop as a result of a phytotechnology project are subject to fate and transport issues. These fate and transport issues will be a concern of regulators, stakeholders, and the public and must be addressed before a phytotechnology system can be implemented. These issues include whether the contaminant is toxic to the plants, whether the plants grown at the site pose additional risks for further ecological exposure or food-chain accumulations, and whether the contaminant is transferred into the air or transformed into a more toxic form. At the heart of these issues is whether the contaminants or contaminant byproducts are bioavailable or converted into mobile forms that can impact groundwater.

2.4.1 Bioavailability of Contaminants

Bioavailability is the proportion of a chemical present in a form accessible to organisms. For example, organic mercury is highly bioavailable and is a significant environmental concern. Conversely, reduction of the mercury to the ionic or elemental forms will render the metal less bioavailable and, therefore, less harmful. Similarly, barium is more absorbed by animals when present as barium chloride than when present as barium sulfate (the later form more prevalent in soils). However, there is generally not enough information to assess the bioavailability of many contaminants. Furthermore, it can be difficult to quantify the bioavailability of a contaminant since conditions at the site such as pH, soil moisture, organic matter content, and the presence (or absence) of other compounds in the soil can affect bioavailability. In addition, the stability of the bioavailable form can also vary depending on site conditions. Some chemicals can change form readily, while other chemical forms are extremely stable. The recalcitrance of chemicals at a site also influences bioavailability.

Bioavailability is a controversial area in both regulation and remediation. The routine assumption of 100% bioavailability of contaminants, including 100% bioavailability to plants, often overestimates the impacts of the contaminant. Solubility of the constituent plays a major role in the bioavailability of contaminants to plants. Research has shown that many organic contaminants do not accumulate in significant amounts in plant tissue since they are minimally water soluble. However, some organics can be taken up, particularly those that are phytovolatilized. Furthermore, many inorganics are present in insoluble forms and require the addition of chemical amendments (chelates) in order for them to become more bioavailable.

For phytoaccumulation of inorganics, the use of amendments greatly enhances the ability of plants to uptake contaminants, so that the plant material can be harvested later for recovery or disposal. However, this approach should be examined carefully where there is a potential for wind drift or off-site transport of contaminated soil by surface runoff, or leaching of contaminants to groundwater.

Increasing bioavailability through chemical amendments can also increase the potential for exposure. USEPA estimated in 1993 that 2–10% of the total mass ingested by animals might be soil (USEPA, 1993). This percent corresponds to 1 to 40 grams per kilogram body weight per day. Therefore, enhancing the bioavailability of chemicals in the soil can potentially impact wildlife that resides at or near the site even if they do not consume the vegetation. If the animals do consume vegetation, there is concern that phytotechnologies can increase bioavailability by increasing the accumulation of contaminants in the edible portions of the plant, including the fruits, seeds, and leaves. This potential is greater than if the accumulation occurred only in the stems and roots.

Site owners and system designers must address bioavailability on a site-specific basis since it is dependent on the composition of the contaminant, the type of phytotechnology application and the conditions at the site. This could include educating concerned parties regarding bioavailability and issues specific to the site.

2.4.2 Toxicity of Contaminants to Plants

High concentrations of contaminants may inhibit plant growth and eliminate phytotechnologies as remedial options for site cleanup. The site owner and system designer must present evidence that phytotechnologies will work at contaminant levels present at the site. Plant species already growing at the site should be compared to plants documented to be effective in literature. If existing species cannot be found in the literature, greenhouse toxicity tests should be performed. If the tests show existing plants not to be tolerant of contaminant levels, a species found in the literature should be considered.

2.4.3 Ecological Exposures, Food-Chain Accumulations, and Eco-Risk Assessments

One concern is that phytotechnologies may not provide adequate protection for ecological receptors and could lead to the accumulation of contaminants in the food chain. Specifically, there may be concern that contamination below the ground surface will be transferred into the terrestrial portions of the plants, causing new exposure pathways. This is particularly true for phytoaccumulation, phytodegradation, and phytovolatilization. However, during phytodegradation or phytovolatilization, a small percentage of organic chemicals can remain in the cell structure of the plant (Chappell, 1998). Fencing the site to prevent animals from coming in contact with the plants and a maintenance plan to address plant litter can greatly reduce risk of exposure. These issues may also be prevalent for applications utilizing phytostabilization or rhizodegradation when considering soil-borne receptors (i.e., insects, worms, burrowing animals, etc.).

If a contaminant is shown to be bioavailable, an ecological risk assessment will likely be required. The level of detail required for an ecological risk assessment is site-specific and will vary with the application. For example, a risk assessment for phytostabilization should address the roots and receptors that may ingest or contact them. If a contaminant enters into the terrestrial portion of the plant (leaves, stems, branches, etc.) during phytoaccumulation, then pathways through those plant structures will need to be assessed as well. An ecological risk assessment should include a discussion on contaminant bioavailability (see Section 2.4.1).

USEPA has developed guidance to assist in the preparation of ecological risk assessments (USEPA, 1999). This protocol allows the concentration of a contaminant to be estimated in plants using the plant bioconcentration factor (BCF). BCFs are specific for each contaminant. The contaminant dose can be calculated for a wildlife species based on the concentration of the contaminant in the plants and any predator-prey relationships that exist for that specific wildlife. The calculated dose can be compared to benchmark values shown to affect that species. These calculations allow individuals proposing phytotechnology projects to determine the potential risk from incidental plant ingestion by wildlife prior to implementing the project. It should also be noted that the contaminant dose at the site may change with time since lower concentrations in the contaminated media could result in lower concentrations in the plants. However, this may vary with the plant species used in the project.

The BCF value references provided in this document are based on typical agronomic plants and may not accurately estimate the risk from plants used in phytotechnologies. Since the application of phytotechnologies may require harvesting and sampling plant tissues for contaminants prior to disposal, the information obtained may contribute to the field of conducting ecological risk assessments since it compares actual field data to calculated values. Currently, the information used to estimate contaminant concentrations in plants using BCF values are based on very limited studies.

2.4.4 Transfer of Contaminants to the Air

An additional route of exposure is by the transfer of contaminants to the air. For example, some plants can take up highly toxic methyl mercury and transform it to the less toxic elemental mercury and volatilize it to the atmosphere (Meagher and Rugh, 1996). However, the fate of elemental mercury in the atmosphere may be a regulatory concern. This application of phytovolatilization may be viewed as transferring a contaminant from the subsurface to the air, even though the toxicity of the chemical has been reduced. Similarly, the transpiration of certain organic chemicals has raised health concerns even though most of these organics rapidly photodegrade. Vapor contaminant concentrations of transpired gases are extremely low.

If phytovolatilization is proposed for a site, site owners and system designers will need to address contaminant transfer. Data must be provided demonstrating that the transfer of contaminants to the air poses a greater or lesser risk for exposure than other remedial options. In some cases, it may be acceptable to allow a phase transfer from the subsurface to the air to occur provided that this mechanism results in a higher level of protection to human health and the environment.

2.4.5 Transformation of Contaminants

Bioavailability, plant toxicity, ecological exposures, food-chain accumulations, and the transfer of contaminants to air may result in the formation of degradation products. Specifically, organic contaminants subject to rhizodegradation or phytodegradation will produce multiple intermediate byproducts dependent on the biodegradation pathway. These byproducts have inherently different chemical properties than the parent compound and may behave differently in the environment. A classic example from bioremediation is the transformation of TCE into the more toxic vinyl chloride.

In general, researchers have not clearly identified degradation pathways of contaminants to carbon dioxide, water, methane, and other basic compounds that become incorporated into organic matter (McCutcheon, 1995). Therefore, the fate of organics and their degradation products will remain an issue until more research is completed. It is recommended that equal consideration be given to degradation products as to the original contaminant when implementing phytotechnologies.

3.0 TECHNICAL REQUIREMENTS FOR PHYTOTECHNOLOGIES

Technical requirements for phytotechnology systems are similar to any in-situ remediation system. In order to start developing the concept of applying phytotechnologies to a particular site, several technical requirements should be fulfilled. These include formulating a design team, developing a design checklist, conducting initial site visits, and gathering information pertinent to the site. Once these startup requirements have been met, the design team should put together a clear and concise proposal for implementing the phytotechnology system. This proposal should be reviewed and approved by regulators, stakeholders, and site owners prior to being implemented. The technical requirements for phytotechnologies should include elements similar to other technologies such as

- startup requirements,
- site characterization requirements,
- treatability studies,
- proposal development,
- setup construction,
- operation and maintenance,
- monitoring requirements,
- contingency plans, and

- reporting.

3.1 Startup Requirements

For an adequate phytotechnology system to be designed, developed, and implemented, a design team consisting of professionals from various fields of study should be formulated. This design team should be fairly familiar with the site through site visits, background information, and available baseline characterization data. Upon initially meeting to discuss the potential application of phytotechnologies at a particular site, the design team should establish a checklist outlining data requirements, site needs, timetables, and expectations. This checklist should take the design team from the conceptual stage of phytotechnologies in general to the highly detailed and specific needs and requirements for the site with an adequately designed phytotechnology system that can achieve the cleanup goals.

3.1.1 Design Team

The evaluation of a phytotechnology design for a contaminated site normally requires a multidisciplinary team. The evaluation team should consist of the following disciplines (or have personnel on the team capable of completing each of the tasks):

- ***Soil Scientist/Agronomist.*** Evaluate the ability of the soil conditions to support plants that will remediate the contaminant of concern or render it non-bioavailable. Develop a soil amendment plan to prepare and maintain the site throughout the duration of the phytotechnology application.
- ***Hydrologist.*** Complete groundwater or surface water modeling, including runoff control from irrigation systems. Conduct a site-wide water balance and model the fate and transport of the contaminant of concern.
- ***Plant Biologist/Botanist.*** Evaluate a range of plants capable of remediating the contaminant and determine if the soil or groundwater are sufficient to support the plants of choice. Conduct greenhouse screening tests using water and/or soil samples from the site to ensure that the plants will remediate the contaminant of concern. Determine planting requirements, including density, patterns, field preparation, and equipment needs. Develop plans for planting in the field.
- ***Risk Assessor/Toxicologist.*** Formulate exposure pathways and risk scenarios. Evaluate the ecological and human health risks of using phytotechnologies, and compare them to the risks associated with implementing one of the alternatives. Conduct greenhouse toxicity evaluations.
- ***Regulatory Specialist.*** Determine the regulatory requirements, final cleanup limits, sampling and analysis requirements, data quality, operation and maintenance requirements, and handling and disposal of any generated wastes. Review and report any regulations pertinent to the project (i.e., solid, water, and air emissions).
- ***Environmental Engineer.*** Coordinate all the information being gathered. Design field systems (i.e., irrigation, pumping, water control, rooting, security, automated sensors, etc.) to optimize the phytotechnology system. Evaluate the phytotechnology system to meet cleanup objectives, including containment zones, contaminant remediation

mechanisms, sampling and analysis plan, operation and maintenance plan, schedules, compliance, and cleanup time.

- ***Field Manager/Health and Safety Officer.*** Review and make practical adjustments to the plans for actual implementation in the field. Secure or construct all necessary equipment, supplies, and machinery. Ensure that health and safety requirements are in place and adhered to during field activities.
- ***Cost Engineer/Analyst.*** Review the projected cost of the system as well as compare to any alternatives. Ensure that all costs for the project are captured. Maintain budgets and expenditures throughout the project.

3.1.2 Design Checklist

Phytotechnologies are in-situ remediation systems where a checklist can be used to plan, review, and evaluate the effectiveness of the technology. A checklist will provide site owners, system designers, technology vendors, regulators, stakeholders, and the public with a single set of data requirements, site needs, timetables, and expectations for the site. The checklist should include the following elements:

- Composition, roles, and responsibilities of the phytotechnology design team
- Project expectations of site owner, regulators, stakeholders, and the public
- Baseline site characterization
- Review of the site characterization data
- Agronomic assessment of the site
- Site visits
- Determination of the remedial objectives for the site
- Understanding of how phytotechnologies will achieve the remedial goals
- Identification and understanding of stakeholder/public concerns with phytotechnologies
- Feasibility studies for plant selection using laboratory tests and greenhouse studies
- Proposed design of a phytotechnology system
- Work plan for implementing the final design of the phytotechnology system
- Required data to evaluate the defined objectives and remediation goals
- Operations and maintenance plan for the phytotechnology project
- Monitoring plan for the project
- Estimated time to complete cleanup
- Plan to deal with secondary waste (contaminated plants) that may be generated by phytotechnologies
- Contingency plan if phytotechnologies do not achieve the remedial goals
- Closure criteria for the site

3.1.3 Site Visits

Early on in the process of developing a phytotechnology system, the design team should become familiar with site conditions by conducting site visits. These visits will help the team to design a phytotechnology system that meets site-specific needs and requirements. On the other hand, the design team must also ensure that site conditions are applicable to the remediation plan and that sufficient resources exist to support the design.

Initially, the design team should determine what areas are available to be planted, what potential obstructions may exist (above, below, and on the surface), and what existing vegetated areas there are at the site. Furthermore, photographic records of the relevant areas provide documentation for future reference as the designs and plans are developed. Finally, during this initial site visit, plans for conducting the initial site characterization or baseline measurements should be discussed. This could include marking sampling locations and inventorying the existing monitoring systems.

Additional site visits should be conducted to assess more specific information pertinent to each team member's area of responsibilities. For the soil scientist/agronomist, these activities would include sampling and analyzing the soils for agronomic parameters, soil conditions, and constituents of concern, as well as determining the soil amendment and irrigation requirements. Similarly, the hydrologist should determine if the surface of the site requires modification to prevent flooding or erosion. The plant biologist/botanist should survey the existing vegetation to determine if the proposed species are applicable to the site physical and climatic conditions. Finally, the field manager/health and safety officer should visit the site prior to the implementation of the phytotechnology system to ensure that all safety issues are addressed beforehand and that potential dangers to workers are clearly marked. Each of these site visits will ensure that the best remediation system is designed that will be protective of human health and the environment.

3.2 Site Characterization Requirement

The primary objective of the site characterization is to delineate the vertical and horizontal extent of the contamination and evaluate the site conditions. A complete site characterization is critical for the design and installation of a phytotechnology system. To begin developing a site-specific phytotechnology design, the design team needs to collect sufficient qualitative and quantitative information on site conditions and subsurface characteristics pertinent to the hazardous waste management and cleanup objectives. A complete site characterization is critical for the design and installation of a phytotechnology system. It should provide answers to questions such as the following:

- What kind of contamination exists at the site?
- Where and how is the contamination migrating?
- What hazards exist to public health or the environment?
- Will the selected remediation technique (phytotechnology) likely work?

Assessment of available data includes an analysis of the data validity, sufficiency, and sensitivity. Furthermore, the site characterization data should be critically reviewed for its specific applicability to a phytotechnology project.

Site characterization data should provide, at a minimum, information describing the site description, contaminant assessment, soil conditions, hydrogeological conditions, aerial conditions, and risk assessments. Each of these is detailed below.

Site Description: A site description should include detailed maps of the location, including property boundaries, surrounding features, residential or public areas, water bodies, roadways or other access-ways, and descriptive or historical names for all relevant features. Furthermore, a site description should include maps illustrating the scale of the infrastructure, surface features, structures, buried services, and other obstacles that will need to be removed and/or accounted for in the phytotechnology design. This includes buildings, structures, foundations, concrete pads, paved surfaces, tanks, pipes, drains, underground utility lines, monitoring/compliance wells, overhead power lines, and natural barriers. Other descriptive information that may be useful includes historical uses of the site, surrounding industrial or commercial sites, previous site investigations conducted, previous remediation efforts conducted, and the overseeing regulatory agencies.

Contaminant Assessment: The location and extent of the contaminant concentration must be accurately determined. The site characterization should provide detailed data about the contaminants of concern. As previously mentioned, phytotechnologies have limited applications. Phytotechnologies will not remove all contaminants and do not work if the contaminant concentration is too high. The site characterization of the contaminant should include all media that apply including soil, sediment, surface water, groundwater, and air emissions from the site. Regulators will work with site owners to determine the methods and frequency of sampling to identify the contaminants of concern.

Information about the contaminant distribution in the media of concern (i.e., soil, groundwater, surface water, etc.) is needed to properly design a phytotechnology system. For example, hot spots of contaminated soil may have to be removed prior to application of phytotechnologies. Likewise, the source of a groundwater plume may have to be remediated using another treatment system prior to addressing the dissolved plume with phytotechnologies. Furthermore, the distribution of a plume that is contaminating groundwater will dictate the location of the trees used in a hydraulic barrier application. Similarly, the location and flow of surface runoff will drive the location of riparian buffer strips. The presentation of this data for proper evaluation can be achieved through a combination of contour maps (horizontal), boring logs (vertical), transect maps (vertical), compositional analyses, and concentration data (horizontal and vertical) for all constituents of concern. This information would be used in conjunction with the soil conditions and hydrogeological data.

Soil Conditions: An evaluation of soil conditions (geological, geochemical, and microbiological) will determine whether the site is amenable to phytotechnologies and dictate the amount of work required to prepare the site for phytotechnologies. This analysis will include some basic geological characteristics, including the soil classification (sand, silt, clay), salinity, electrical conductivity (EC), cation exchange capacity (CEC), organic matter content, water holding capacity, and inorganic nutrient levels. These agronomic parameters can limit plant selection or dictate modifications in order to properly implement a phytotechnology system. The level of effort required to prepare the soil for planting will affect the time and cost of the overall project.

Geochemical information should also be evaluated for potential to affect the function and performance of the phytotechnology system and would include oxygen, carbon dioxide, and methane gas concentrations plus redox potential, pH, and soil moisture. This information is pertinent when evaluating the degradability of the contaminant under natural attenuation, active or passive biodegradation, or phytotechnology applications. If the soil/water that is immediately available to the plants has a high concentration of total dissolved solids (TDS) or if there are high levels of naturally occurring salts in the soils, then conditions may not favor phytotechnologies. In general, geological and geochemical information can be collected from site surveys, existing literature, remedial investigations, and feasibility studies. Site-specific data from activities such as drilling and sampling are keys to obtaining this essential information for designing the phytotechnology system.

Furthermore, additional information on the interaction between the native microbial populations, contaminants, and the plants and/or trees should be assessed. The above information is generally not available through standard site assessment reports or investigation and need to be assessed during treatability studies. Specifically, the role of microbes and plant interactions is currently being researched. In any case, additional collection of microbiological data may be required using techniques that have been developed. These complex interactions have the potential for beneficial or detrimental effects on the remediation. Native microbial consortia are often responsible for natural remediation processes (natural attenuation, bioremediation, and phytotechnologies) and can represent the primary concentration reduction mechanism.

Hydrogeological Conditions: Detailed information on the surface and subsurface hydrology must be available prior to the design and installation of the phytotechnology system. The required information includes groundwater levels, temperatures, flow velocity, porosity, hydraulic conductivity, site heterogeneity, depth of aquitard, and the continuity and thickness of the aquitard. The groundwater chemistry should be evaluated for potential to affect the function and performance of the phytotechnology system. The pH and salinity of the groundwater limit plant selection or require modification to properly implement a phytotechnology system.

Additional site-specific hydrogeological data such as the physical setting, stratigraphy, aquifer and aquitard heterogeneity, structure, and sedimentology should be obtained during site characterization. This information will help characterize subsurface conditions, as well as provide indications of preferential flow paths, perched zones, and water transmissive and resistive zones. Furthermore, all major controlling influences on groundwater recharge and flow should be defined (e.g., bedrock, production wells, tidal and seasonal influences, surface features, infiltration, etc.). It is important to understand seasonal changes in the flow direction and flux due to vertical and lateral recharge. In addition, aquifer tests should be performed to obtain hydrological data such as hydraulic conductivity, intrinsic permeability, etc.

Phytotechnologies for groundwater are limited to shallow (limited to root zone) unconfined aquifers. The water table must be within reach of the plant roots. The design of the groundwater treatment system must bring plant roots into contact with the contaminated zone of the aquifer. If contaminated groundwater is deeper than the root zone, then the groundwater could be remediated by pumping it to the surface and inducing it to flow toward the root zone of the plant.

Although plants can tolerate some fluctuation of the water table, the most desirable condition to establish a root zone is a stable water table.

Aerial Conditions: All the information related to the seasonal changes in climate, including temperature, humidity, precipitation (rain and snow), wind (speed and prevailing direction), and the probabilities of floods or droughts (25-, 50-, 100-year events, etc.) should be available from local weather stations (nearby cities, airports, major operating facilities). These site characteristics affect the design (plant selection and planting density) and maintenance (irrigation, mowing, debris, etc.) of the phytotechnology system. Furthermore, these factors are paramount to successfully designing systems to affect local hydrology (i.e., vegetative covers for infiltration reduction and hydraulic barriers for groundwater control). Flood and drought tolerances are criteria that can be used during plant selection.

In addition, climatic and seasonal changes can also affect phytotechnologies. For example, during winter, there is very little remediation by plants due to dormancy. Furthermore, during the planting seasons (mainly spring), air monitoring of the phytotechnology field activities may be required. Tilling the soil and preparing the site for planting will increase the likelihood of blowing dust particles. Odors from volatile organic compound (VOCs) may become noticeable during tilling operations. Similarly, at the end of the growing season, dust and plant particulate generated during harvesting may also need to be monitored.

Risk Assessment: A risk assessment of the site will include identifying the ecological and human health receptors at the site, developing potential pathways of exposure, evaluating the possibility of contaminant migration toward those receptors, and determining the potential toxicity of the contaminants at the site. The risk assessment will consider possible scenarios of inhalation, ingestion, and direct exposure of the contaminants by the receptors as well as toxicity values (available in the literature). Factors that should be incorporated into the risk assessment include the bioavailability, plant toxicity, ecological exposures, food-chain accumulations, and the transformation of the chemical composition or physical state (see Section 2.4).

Furthermore, the phytotechnology mechanism being utilized for cleanup (phytoaccumulation, phytovolatilization, rhizodegradation, etc.) affects the risk assessment. Each of these mechanisms provides different potential routes of exposures either through the plant, in the soil, or as gaseous emissions. The length of time to complete remediation will also affect the outcome of the risk assessment. Situations with immediate or acute risks are not suitable for phytotechnologies. Finally, risk mitigation measures such as security fencing or other institutional controls should be evaluated and incorporated into the risk assessment.

3.2.1 Initial Site Characterization/Background Information

An initial site characterization should be conducted to gather adequate information for determining if phytotechnologies are suitable options for remediating the site.

Sampling should be initiated at the source or suspected source(s). If the source is unknown, sampling will follow after conducting field monitoring such as a soil gas survey. Field screening is also used to locate targets for exploratory drilling or in determining the orientation of the water table. Field screening instruments often provide fast, inexpensive information. Field screening methods can often give sufficiently accurate data on a fairly simple disposal site to avoid further sampling. Common field sampling methods such as direct push technologies are used with on-site geophysical and analytical screening methods to delineate the contaminant plume. Geophysical field screening utilizes methods such as seismic refraction and other electromagnetic instruments to obtain geologic and hydrogeological conditions at a site. In addition, geophysical methods are used to locate buried objects and delineate residual and floating products. On-site analytical screening methods utilize on-site analytical instruments such as detector tubes, immunoassay, portable gas chromatograph, photoionization detectors, and x-ray fluorescence and ultraviolet meters to analyze the contamination at a site.

Sampling should be extended from the source to down gradient from the source until the plume is fully characterized. In choosing a site-specific approach to coring, one should keep in mind the need to have sufficient spatial distribution to be able to interpolate contaminant concentrations between boreholes. This is needed to estimate the mass of constituents present in the soil in the vadose zone, in mobile product, and entrapped below the water table. Soil cores should be analyzed from the surface to a depth below the water table where non-detection or contaminant levels below regulatory standards are obtained. Particular attention should be paid to the depth interval that spans a zone several feet above to several feet below the water table (within the zone of water table fluctuation as might be revealed in nearby water well records or from soil mottling). It is useful to conduct sampling at least every foot in this depth interval during initial site characterization.

The initial site characterization should provide data on the contaminants of concern, the media that is impacted, site conditions, local climate, remediation objectives, and cleanup standards. In addition, background information on the site could be gathered during the site assessment. Analyses of parameters during initial site characterization should include the parameters identified in Table 3-1.

Table 3-1 Analyses during Initial Site Characterization

Site Parameter	Monitoring
Geological property of soil and groundwater	Hydraulic conductivity, intrinsic permeability, and soil type
Vadose zone soil moisture content	Moisture in the soil
Contamination plume	Vertical (depth) and horizontal (lateral) extent of contamination
Groundwater flow	Groundwater elevation
Redox potential	400 mV > Eh > 800 mV optimal aerobic; 100 mV > Eh > 400 mV acceptable aerobic; Eh < 100 mV need stimulation; Eh < 0 reducing conditions
Existing vegetation assessment	Plant assessment studies
Agronomic conditions	Soil/groundwater minerals, pH
Climatic conditions	Temperature, humidity, rainfall, drought, growing season
Preexisting microbe population	Plate counts
Nutrient concentration	Carbon, nitrogen, and phosphorous

3.3 Treatability Studies

Phytotechnology treatability studies are recommended and may be required for all projects unless adequate site-specific information is available indicating a probable successful outcome. These studies may take the form of laboratory-scale germination tests, greenhouse-scale fate and transport studies and/or mass balances, or pilot- (or field-) scale tests to examine site-specific survivability and treatment efficacy under existing site conditions. Treatability tests will be in real time since plant growth cannot be accelerated and should be carried out for at least one growth cycle, including dormancy. Often, it may be suitable to include treatability tests in the field as the first year of the remedial application and/or while other alternatives are being considered, assuming that adequate action will be taken beforehand to address any immediate risks to human health and the environment. Typically, additional sampling and monitoring will be required during this initial pilot phase compared to subsequent years. Furthermore, the expected outcomes and potential pitfalls should be discussed and presented along with the contingencies for failed outcomes. However, once the treatability tests have been completed with successful outcomes, the vegetation already planted can be used as the final remedial system or incorporated into the final design.

For many phytotechnology projects, treatability studies will be necessary to test the survivability of candidate species under site-specific conditions and contaminants. These studies are performed to validate the proposed treatment scenario, optimize the design data, yield information on the fate of the contaminants in the plant system, and assure concerned parties that the phytotechnology system will achieve the desired results under existing site conditions. These studies can range from bench-, laboratory-, or greenhouse-scale experiments involving hydroponics, potted plants, or small test plots to on-site, pilot-scale trials involving larger-sized test plots.

Regulators usually require that treatability studies be conducted prior to implementing phytotechnologies if any one of the following conditions exist:

- Site characteristics or climatic conditions are not entirely favorable for the application of phytotechnologies.
- The contaminant of concern, plant species, or the combination of the two does not appear in the current phytotechnology databases.
- Data regarding the fate and transport (i.e., bioavailability, toxicity, food-chain accumulations, ecological exposures, transfer to other media, and/or transformation byproducts) are unknown or questionable.

These studies should be designed so that reasonable evaluation can be made on the ability of the plants to conduct the desired phytotechnology application and meet remedial objectives. Feasibility studies employ site-specific data previously obtained during the initial characterization. These experiments should duplicate field conditions (climate, sunlight, and soil moisture) as much as possible, because these factors significantly affect the rate of remediation and plant growth. When conducting tests away from the actual site, it is important to grow the plants in the contaminated media collected from the site. If the site has several soil types, samples of each type should be collected and assessed. If there are uncontaminated areas within the site, then soils from these areas should also be collected for use as experimental controls. Furthermore, these unimpacted soils can be used to assess the maximum concentrations that can be tolerated by the plants before health and growth rate are adversely impacted by artificially contaminating this soil with a representative, properly weathered or aged sample of the contaminants. If the contaminated media is surface water or groundwater, the candidate species can be planted in the soil from the site and irrigated with this water. In addition to determining whether these plant species are capable of meeting the remedial objectives in general, specific treatability studies can focus on a number of important issues relevant to the phytotechnology application. Some of the applicable treatability studies that should be considered prior to the application of a phytotechnology project and developed in a proposal are listed below.

Plant Screening Studies: The simplest treatability study is a plant screening experiment, which determines species that are tolerant to the contaminated media. This can include testing several concentrations of the contaminant and evaluating the plant health and growth. A contaminant may be considered toxic if the plant, relative to controls, is stunted, chlorotic (yellowed), brittle or wilted, or nutrient-deficient. This topic is discussed further in Section 3.3.1.

Fate and Transport Studies: The next level of treatability studies is to determine whether uptake and translocation of the contaminant or transformation byproducts occurs. This will include sampling and analyzing the plant tissues for the parent and daughter compounds. Harvests conducted at several times throughout the experiment can provide an indication of the potential to accumulate the contaminant in the plant biomass. The RCF and TSCF values can be calculated during this level of treatability studies. A common method to assess the fate of organic compounds in a phytotechnology system and to differentiate it from other natural processes is to use the ^{14}C-labeled organic compound. ^{14}C-labeled carbon can be easily measured in the plant tissues as well as in the media in assessing the fate of organic chemicals in the phytotechnology system. Some of these studies can be undertaken in the field. This information is used to determine if the plant biomass must be treated as a hazardous waste if harvested.

Mass Balance Studies: An additional level of complexity can be added to the fate and transport studies by performing a more rigorous mass balance on the system. These studies are typically conducted in sealed plant chambers where all media (air, water, and soil) are controlled and subject to radiolabeled contaminants. In this case, the intensity as well as the distribution of the radiolabel throughout the plant system is assessed in order to evaluate the amount of organic compound present. GC/MS analyses of the radiolabeled tissues can also be conducted to determine the speciation of the contaminant. This may be required by regulators, as a mass balance will help not only assess the uptake of contaminants by the plants, but also determine if toxic products or byproducts are released to the environment during the phytotechnology application. Specifically, calculations can also be made during these studies to predict the amount and type of material transpired by the plants. Conflicting results have been obtained in several studies, which indicate that certain organic chemicals are either phytovolatilized by the plants as the parent compound, taken up and phytotransformed, or enzymatically degraded in the rhizosphere prior to removal from the soil (Anderson and Wilson, 1995). These studies can help clarify the mechanisms that are involved in the phytotechnology. In any case, these mass balance studies not only identify the parent and daughter products, but also provide information on the fate of the contamination.

Microbial Screening Studies: These studies determine the amount of naturally occurring bacteria that may be capable of degrading contaminants. Soil samples are taken to an off-site lab, and microbial plate counts determine the number of colony-forming units (CFU) of heterotrophic bacteria. The presence of a large quantity of heterotrophic bacteria indicates that rhizosphere degradation can occur. These results can be compared to planted soils. An increase in heterotrophic bacteria near the root zone is an indication of rhizodegradation.

Most published phytotechnology studies utilize a randomized block design involving all possible combinations (including controls) of several key factors such as different plant species, contaminant concentrations, and soil conditions (pH ranges, fertilizer additions, chelates, etc.). However, because the number of factors examined causes the number of trials to expand exponentially, a series of tests can be proposed that focus on a few factors first, which are then optimized during subsequent tests. For example, an initial experiment could be performed to determine which plant species are tolerant of a particular contaminant or group of contaminants with fixed concentration. During this phase, minimal sampling and analyses will be necessary because the primary objective is to identify the tolerant species. Once these species are determined, they can then be evaluated in a second set of experiments using different concentrations of the contaminant in combination with different soil conditions (soil type, pH, etc.) and amendments (adequate nutrients and water). These experiments will require more sampling than the previous set in order to determine tolerant species that promote the remediation of the contaminants. Finally, a third set of experiments can be conducted on the species that can tolerate the maximum contaminant concentrations expected to be encountered at the site while subject to various soil amendments designed to optimize growth and remediation. This final set of experiments will require much more sampling and analyses in order to determine whether these species are capable of meeting the remedial objectives for the project. This type of sequential experimental design allows for an efficient use of time and funds by assessing several factors simultaneously while minimizing unnecessary experiments on species that cannot tolerate the expected concentrations of contaminants at the site.

Conducting treatability studies may be seen as time-intensive, but the valuable information gained may directly affect the success or failure of the project. The time spent on testing is generally a few months to a year and does not significantly impact the overall restoration time frame of the project. Furthermore, these studies can be performed during the off-growing season, and adequate results can be obtained prior to the next available planting season.

3.3.1 Plant Selection Criteria

Plant selection is probably the one most important factor determining the success or failure of the phytotechnology project. Once the growing conditions at the site have been identified, the next goal of the plant selection process is to choose plants with appropriate characteristics for growth under site-specific conditions that also meet the objectives of the phytotechnology project (Rock, 2000). A screening test or knowledge from the literature of plant attributes will aid the design team in the selection of plants. Typical information needed for plant selection includes the species name (common and scientific), various tolerances (temperature, moisture, diseases, pests, etc.), growth habit (annual, perennial, biennial, evergreen vs. deciduous), United States Department of Agriculture (USDA) climate zone, and general form (grass, leafy plant, shrub, tree, etc.). Information can be gathered from local, state, or federal agencies and offices, or from universities. Furthermore, the Internet has abundant information on plants. One very useful source is the Plant Materials Program of the USDA Natural Resources Conservation Service (http://Plant-Materials.nrcs.usda.gov/). Another is the USDA national plants database (http://plants.usda.gov/). Additionally, the long-term establishment of vegetation at a site is also dependent on the planned future uses of the site. If no-maintenance vegetation is to be eventually established as part of a long-term ecosystem restoration, it is likely that this will occur through a succession of plants at the site. If so, this succession could be planned by considering the types of vegetation established initially and the timing of any future planting events.

In general, the use of a mixed variety of vegetation is preferred over monostands due to several advantages including the following:

- Monostands can be susceptible to diseases that can destroy the entire phytotechnology system, while mixed stands may only lose one or two species.
- Mixed stands support more diverse microbial communities (promoting potentially more complete rhizodegradation by further breaking down by-products).
- Synergistic effects such as nutrient cycling can be obtained in mixed stands.
- Mixed stands contain a more naturalized appearance.
- Mixed stands promote biodiversity and potential habitat restoration qualities.

Treatability studies such as greenhouse studies and pilot tests can establish the plants that are most applicable to contaminant and site conditions. The plant selection process begins by examining (listed in order of suitability) pre-existing species; literature species found in phytotechnology databases; native species that are already populating the region; hybrid species related to or grafted from pre-existing, literature, or native species; and genetically engineered species that are designed specifically to conduct the desired phytotechnology. These categories of potential candidate species are discussed in detail below.

Pre-Existing Species: These are species that are already growing at the site and, in some cases, in the contaminated media and have already exhibited tolerance to site conditions. However, tolerance does not equate necessarily to the ability to remediate. Therefore, the efficacy of these plants for phytotechnologies would need to be confirmed through treatability studies (laboratory, greenhouse, or field studies). These results could also be added to the growing database of phytotechnology species. Ideally, if the species that are already growing at the site also appear in the phytotechnology literature database, then species selection becomes relatively simple.

Literature Species: The number of species that have actually been evaluated for phytotechnologies is very small. Therefore, in most cases, the subset of plants that appear in the database that exhibit the necessary phytotechnology capabilities will have to be selected and established at the site in order to accomplish the remedial objectives. Lists of appropriate plants can be found in literature and by consulting phytotechnology experts. These species can be extrapolated from phytotechnology research, inferred from unrelated research, or other site-specific knowledge. Several extensive phytotechnology databases (Tsao, 1998; Frick, et al., 1999; Frick, et al., 2000; McIntyre, 2001) have been published and include the remediation of metals, radionuclides, petroleum hydrocarbons, halogenated compounds, surfactants, and pesticides. The proposal should contain sufficient detail on the contaminants that were tested, the concentrations that were examined, the climatic regions of the sites in the literature, and a list of references that provide additional details on the species used in the phytotechnology applications cited in the document.

Native Species: Besides those actually growing on the site, native species from surrounding areas can be evaluated because these are acclimated to the climatic conditions of the region. This can include native, crop, forage, and other types of plants that grow under the regional conditions. A list of these plants can be obtained from a local agricultural extension agent.

Even though a native species may not appear in the phytotechnology databases, there are several advantages of pursuing these species as potential candidates rather than introducing a new species to the region. Specifically, two Executive Orders address the protection and use of native plants. The first was signed on April 12, 1994, and requires all federal agencies to use regionally native species whenever federal funds are expended for landscaping. It promotes recycling of green wastes, reducing fertilizers and pesticides, and directs agencies to create outdoor demonstration projects using native plants. The second Executive Order specifically addresses invasive species and was signed on February 3, 1999. It requires federal agencies to prevent the introduction of invasive species and to detect and respond rapidly to control established populations of invasive non-native species.

Native, nonagricultural plants are desirable for ecosystem restoration. In most applications, plants that are adapted to local conditions will have more chance of success than nonadapted plants. The use of mixed species of vegetation can also lead to greater chance of success than the use of monocultures. Care should be taken to avoid introducing plant species that are invasive or a nuisance. In cases where the spread of the plant is undesirable, sterile varieties should be chosen to prevent plant reproduction.

The cleanup of Superfund (CERCLA) sites provides opportunities to use native plants during restoration or in phytotechnology applications. Native plants are especially important in critical habitat areas such as wetlands, riparian corridors, and other disturbed lands. As part of the

Superfund Redevelopment Initiative, many sites are being returned to beneficial reuse. Over 100 Superfund sites (totaling over 13,000 acres) have been recycled and are now in ecological or recreational use. Native species should be considered for use on phytotechnology projects.

Cultivated Species: If suitable pre-existing, literature, or native species cannot be found, cultivated species can be considered. Forage, crop, and horticultural species have been used extensively for landscaping and re-vegetation efforts and serve as a primary source of selected plant materials for species propagation and cultivation (see hybrid species below). The seed and planting stock of this group is readily available and less expensive than native species. Furthermore, through years of selection, growers have found varieties that contain natural resistances to diseases, various climate conditions, pests, and other potential growth deterrents. Native species are important for long-term plantings; but in many cases, vigorous, locally adapted varieties of mostly non-native forage grasses, legumes, or other species may be the most appropriate choices. These cultivated species can be considered initially with the eventual succession toward native species over time.

Hybrid Species: Hybrids are plant species that have been developed either naturally or artificially by combining tissues together from related varieties of a particular genus or species. These are also referred to as crossed species. Methods of hybridization include grafting tissues and cross-pollination from one variety to another. Many hybrid species have been utilized for decades in landscaping, agriculture, horticulture, and forestry. Hybrids have also been used successfully in phytotechnologies, including the hybrid poplars and willows that are extensively used. The advantage of using hybrid species is that these are usually selected for specific characteristics that can optimize the phytotechnology system. For example, a fast growing variety can be combined with a disease-resistant variety to incorporate the qualities of both in the hybrid.

Because of public concern, hybrids should not be mistaken for genetically engineered plant species. These differ from genetically engineered species (described below) since genetic manipulation is conducted at the cellular level (transferring DNA from one species to another), whereas hybridization occurs at the tissue level (typically within a species). Hybridization (particularly cross-pollination) is an occurrence in nature itself.

Genetically Engineered Species: Only if all other means of selecting a suitable plant species for a phytotechnology application have been expended, should the use of genetically engineered species be considered. In recent years, it has become possible to insert genes for desirable characteristics into the DNA of plant cells and produce plants that express the product of the gene. This technology has been used to successfully incorporate disease resistance into crop species. Experiments to use genes to create plants that manufacture their own insecticide have been developed. The genes, which produce enzymes that break down, detoxify, or sequester contaminants, could be incorporated into plants used for phytotechnologies. Research is currently ongoing to determine the feasibility of inserting genes for the production of cytochrome P450s into the hybrid poplars and tobacco plants used in phytotechnologies (Gordon et al., 1998) to enhance the breakdown of chlorinated compounds such as TCE and ethylene dibromide. Other researchers are investigating the plants that may already contain genes that code for peptides such as phytochelatins, which naturally bind and detoxify metals, so that these properties can be enhanced in the plants to increase their ability to remediate contamination.

Currently, the regulatory status of plants in which genetic material has been inserted (transgenic plants) is somewhat unclear. A number of aspects of the use of these plants could be regulated under various existing USDA plant regulations, such as the Federal Plant Pest Act (7 United States Code [U.S.C.] 150 aa et seq.), the Plant Quarantine Act (7 U.S.C. 2801 et seq.), and the Federal Noxious Weed Act (7 U.S.C. 2801 et seq.). While USEPA does not currently regulate plants used for commercial bioremediation, it may have the authority to do so under the Toxic Substances Control Act (TSCA). This authority could be invoked to regulate these plants if USEPA believed such regulation was necessary to prevent unreasonable risk to human health and the environment. USEPA does currently regulate microorganisms under Section 5 of TSCA. Plants that are altered to contain genes that enhance resistance to pests (by coding for gene products that have pesticide-like qualities) could be regulated under the statutes that regulate pesticides. These statutes are the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and the Federal Food, Drug, and Cosmetic Act (FFDCA) (Rock and Sayre, 1999).

One drawback of using genetically engineered plants is public concern that they may interbreed with wild plants to create undesirable variants or that the altered plants themselves may be harmful. Use of genetically altered plants in phytotechnologies may entail substantial public education. Regulators should confirm whether extensive testing prior to utilization has been conducted in the context of ecological compatibility in compliance with all applicable state, federal, and local regulations.

3.3.2 Agronomic Optimization

As part of the design requirement, initial treatability field studies should be conducted to determine if site conditions can support the plant growth. Soil samples should be used to assess the concentration of contaminants in the soil surrounding any plants that are growing at the site. Soil samples should also be analyzed for soil parameters influencing plant growth. These soil parameters may consist of soil pH, soil fertility and nutrient content, soil structure, soil texture, soil temperature, and soil depth. Saline groundwater/surface water conditions may adversely affect plant growth of some species of plants. The site soils should be amended as necessary to optimize plant growth conditions. The need for an irrigation system should be evaluated.

Agronomic inputs include nutrients necessary for vigorous growth of vegetation and rhizosphere bacteria. Soil samples will establish the natural conditions at the site. The soil may require fertilization (nitrogen, phosphorous, potassium, and other mineral nutrients), carbon addition, and soil conditioners, such as aged manure, sewage sludge, compost, straw or mulch (Schnoor, 1998). The site soil must have sufficient water-holding capacity to sustain vegetation. The pH of the soil may have to be altered to improve the efficiency of the system. Some states are now requiring agricultural operations (loosely defined) to develop and comply with a nutrient management plan. The possible need for this type of study/document should be considered. While remedial activities are not classic agricultural operations, the loose definition that some states are applying encompasses golf courses, parade/athletic fields, and other large grassed areas. Phytotechnology operations or activities need to check with local regulations for applicability.

The presence of microbial populations in the soils near the roots of the plants presently at the site may provide a source of inoculant for microbial seeding of soils, seeds, or roots during subsequent remediation studies.

3.3.3 Modeling

Since phytotechnologies are long-term remedial strategies, the use of modeling will be necessary to estimate a cleanup time and demonstrate that the contamination will not migrate to sensitive receptors during the projected cleanup time. Furthermore, modeling can be used to determine the general trends achieved throughout the life of the project as well as optimize the system parameters. For applications involving groundwater remediation, simple capture zone calculations (Javandel and Tsang, 1986; Domenico and Schwartz, 1997) can be used to estimate whether the phytotechnology can be effective as a biological pump to entrain the contaminant plume. Similarly, hydrologic modeling may be required to estimate the rate of percolation to groundwater when plants are irrigated. Typical models used for these purposes include EPIC (Erosion/Productivity Impact Calculator) and HELP (Hydrologic Evaluation of Landfill Performance). These models can be correlated to a weather station at the site in order to model the evapotranspiration capabilities of various plants and trees. The equations of Penmen-Monteith or Penmen-Van Bavel can be used to calculate the evapotranspiration rates given meteorological data (Allen, et al., 1989; Van Bavel, 1966).

In addition to modeling the hydrologic effects of phytotechnologies on a site, the rates of remediation can be modeled as well. Results from treatability field studies can be used in models to estimate contaminant uptake, accumulation, and/or degradation rates. These are generally modeled using zero- or first-order rate equations and are reasonably accurate for estimation purposes when calculating cleanup times. More sophisticated fate and transport models may be necessary as data is generated and used to refine the predictions. In addition, models are also utilized to estimate the mass transport limitations in the subsurface (transferring the inorganic to the roots) during calculation of the rates of uptake and the rates of remediation of inorganic contaminants by plants (phytostabilization and phytoaccumulation). These mass transfer limitations can be estimated using Darcy's equation for transport in porous media and taking into account the retardation of elements in the soil environment (Dragun, 1998).

Conservative biodegradation rates for many organic chemicals have been published in the literature from both bench-scale and field-scale work (Dragun, 1998). For rhizodegradation, these rates will be similar because this mechanism relies on microbial activity to degrade the contaminants. These rates are also limited by mass transfer effects in the soil environment. For phytodegradation and phytovolatilization, there is an additional limiting step during the uptake of the contaminant into the plant tissues, assuming the log K_{ow} is within the range of 1 to 3.5 (see Sections 1.2.4 and 2.4.3). Results from treatability studies can also be utilized in a model to determine the fate and transport of the contaminant in the soil-water-plant system (see Section 2.4).

3.3.4 Ecological Risk Assessment

During treatability studies, it is important to assess the hazard from consumption of these plants and the transfer of the contaminant through the food chain because the contaminant could accumulate in the plants. Specifically, for phytotechnology projects where the contaminant will be accumulated or transported into the plant (i.e., phytoaccumulation, phytodegradation, and phytovolatilization), it is important to assess the hazards from consumption of these plants and the transfer of the contaminant through the food chain. According to the guidance document published by USEPA (USEPA, 1999), an ecological risk assessment compares the levels of contaminants in the soil at a site to threshold toxicity levels when low-level physiological effects on various species have been exhibited in the literature. These toxicity levels are based on a large number of assumptions about exposure, species, and sensitivity and should be discussed in the proposal as related to the site conditions. The amount to which each receptor is exposed is then calculated and compared to the best available wildlife toxicity data to assess whether the levels present at the site represent a risk to ecological receptors. Details on the specific calculation procedure were provided earlier in this document (see Section 2.4.3).

This approach to ecological risk can be very useful when developing phytotechnology proposals. Estimating the levels in the plants prior to beginning the project could assist in determining the time scale needed to complete the project and the potential changes in the levels of contaminants in plants during the course of the project. Estimating the exposure to wildlife that could be incurred by ingesting the plants can reassure regulators and the public that the project itself will not represent a conduit to further environmental exposures. These calculations can also be used to target the species that may be exposed to potential risk so that institutional controls for the site can be targeted toward those species. For example, calculations may show a possible risk to grazing mammals but not to insectivorous or carnivorous birds; therefore, fencing alone may be adequate protection for such a site. Ecological risk calculations for some sites may show no risk to wildlife that trespasses onto the site; therefore, this information could be used to reduce costs for the project by demonstrating that institutional controls are unnecessary.

3.4 Proposal Development

When treatability studies are completed, the Phytotechnologies Team will review the results and develop a proposal to ensure a viable option to achieve the cleanup within the specified time.

3.4.1 Remediation Objectives and Closure Criteria

The system designer and design team should develop the remediation objectives from the standpoint of the expected outcomes by the site owner, regulators, stakeholders, and the public. Interviews with regulators, site owners, and system designers should establish that all parties share the same objectives and cleanup criteria. The ARARs for the site will be constant regardless of the remediation technology applied and must be met or exceeded for the technology to be considered an alternative. The remediation objective can either be to contain/control (stabilize, sequester, remove, transfer) or remediate (degrade, reduce, metabolize, mineralize) the contaminant of concern. The phytotechnology mechanism will vary depending upon these objectives. Once the objectives have been defined and the treatability studies have been performed, it is essential to estimate the probability of success that the specific phytotechnology application will meet the remediation objective. The team should also determine if there have been other similar phytotechnology projects (contaminant, environmental conditions, plants, etc.) from which operational and closure data is available.

Closure criteria specifying target contaminant concentrations should be identified. The target concentration for each contaminant may be driven by environmental regulations such as RCRA, CERCLA, or the Clean Water Act, or state-specific cleanup requirements. Surface water discharges, if any, from the site may be required to meet NPDES limitations. If water is removed from the site and treated or disposed off-site, RCRA standards are applicable. The closure criteria are the objectives that must be fully achieved before closure can be granted.

The performance criteria (objectives for successful ongoing operation of the phytotechnology system) for the system must be established through predefined data collection and monitoring protocols developed for the project. There must be a process established to compare the observed monitoring data and site conditions to the performance criteria and closure criteria. Scientists and engineers must be able to develop and present data in periodic reports that the system will work. Site inspections, visits by the public and stakeholders, and the records of inspections should be established. If the plants used are to be harvested, the procedures for harvest and ultimate disposal will need to be established. Site owners and system designers must determine if plant harvest reports are to be submitted to the regulatory authorities. The site owner, system designer, regulator, and stakeholder must come to a consensus on how, when, and where the data will be collected and analyzed and how the results and data will be documented and reported. Performance evaluation results and closure requirements should be included in this documentation. A protocol for the submission of a request for no further action at the site must be established and must have the consensus or approval for this request by the regulating authority.

3.4.2 Data Review and Background Information

Prior to developing a proposal, the design team should have gathered sufficient background information and conducted an initial site characterization (see Section 3.1), including a review of the data applicable to the site such as from the ROD, design analysis report, operating permits, and site history. A review of the sampling and analysis data (site characterization) for the contaminated media should be included in the proposal. These data should include a site description, contaminant assessment, soil conditions, hydrogeological data, aerial conditions, and risk assessment criteria. The proposal should also discuss the regulatory concerns with the proposed phytotechnology design and remediation timeline developed during the comment-and-response period.

3.4.3 Public Acceptance

A Public Involvement Plan, if needed, should be prepared to inform the public of phytotechnologies. It is important to inform and educate the public on the phytotechnologies in early stages. One favorable view on phytotechnologies would be that they are natural and less-intrusive technologies. However, an unfavorable perception could be that phytotechnologies are merely a beautification effort and not a rigorous cleanup effort. Scientific information supporting the effectiveness of phytotechnologies would be beneficial in increasing the public's acceptance and understanding of phytotechnologies.

3.4.4 Supplementing or Replacing Existing Remediation Systems

In some instances, phytotechnologies can be proposed as supplements or replacements of an existing system in operation at a site (including natural attenuation). Under these conditions, the site owner and system designer must document the reasons why the proposed phytotechnology will increase the likelihood of meeting remedial objectives for the site. The information used to present the case for supplementing or replacing an existing remediation system will be similar to the information required for any other site. Regulators, stakeholders, and the public will need to evaluate the proposal using similar criteria as well. In many cases, these phytotechnology proposals will be easier to evaluate than those proposed for sites without existing systems. Specifically, the other remediation systems can be continuously operated until the phytotechnology system has reached the stage where the plants are effective. On the other hand, the existing system can be reactivated if monitoring shows that the phytotechnology system is not achieving performance criteria.

Several examples of how phytotechnologies may be proposed as a supplement or replacement for existing remediation systems are listed below.

- Vegetative covers for infiltration control as a replacement or supplement to conventional landfill covers, particularly those with a net accumulation of liquid.
- Vegetative covers for surface soil remediation as a replacement for land farming while maintaining biodegradation rates.
- Tree stands for groundwater hydraulic barriers as a supplement to natural attenuation for added plume migration control.
- Tree stands for soil and groundwater remediation as a supplement or replacement to pump and treat, air sparging, or extraction systems that are inefficiently remediating residual contaminants.
- Constructed wetlands for surface/wastewater remediation as a supplement (secondary or tertiary treatment) to traditional (primary) wastewater treatment systems.
- Riparian buffers for runoff control as a replacement for drain tiles used to redirect runoff instead of treat the runoff.
- Hydroponic systems for treating water streams (rhizofiltration) as a replacement or supplement for the treatment portion of a low-flow pump-and-treat system.

3.4.5 Project Costing

Project costing should include all components necessary to develop, design, implement, monitor, and operate a phytotechnology system through all stages of the project up until site closure. These components include

- Site characterization and background investigation costs,
- Design and proposal development costs,
- Setup and construction costs,
- Operating, maintenance, and monitoring costs, and
- Closure and final report generating costs.

The design team should have reasonable experience with phytotechnology systems so they can accurately estimate the costs and ensure that all cost items are captured in the project estimate. The design team should confirm these estimates by contacting various vendors and suppliers (if necessary).

Typical phytotechnology costs will be similar to any other remediation project and will include capital costs such as earthmoving, excavation work, well drilling, piezometer installation, initial site characterization, land clearing, security measures, health and safety equipment, etc. Similarly, engineering cost items such as proposal writing, labor, travel, report writing, shipping, permitting, agency interactions, meetings, etc., should also be identified. Finally, reoccurring operation, maintenance, and monitoring costs include soil and groundwater sampling, analytical, site visits, inspections, etc., which will also be included in the overall cost.

There are some cost items that are more unique for a phytotechnology project than other remediation technologies. These are listed below and should be included in the proposal.

- Plant or tree stock, seeds
- Fertilizers, pesticides, and other soil amendments
- Equipment for applying amendments, tilling fields (typical farm equipment)
- Surface irrigation system (pipes, hoses, rain bird sprayers, etc.)
- Subsurface irrigation system (pipes, connectors, screens) and breather tubes
- Water for irrigation, connection to an external water line
- Tubes or similar material for inducing deep root growth by trees (collars)
- Mulch, trunk guards for trees, other pest control devices
- Plant tissue sampling supplies and analyses
- Agronomic sampling and analyses
- Soil microbial sampling and analyses
- Weather station (temperature, humidity, and solar radiation sensors, wind gauge, and rain bucket)
- Sap flow sensors, soil moisture probes
- Leaf area meters, stem gauges, dendrometers
- Solar panels and automated data loggers for remote locations
- Lysimeters or moisture collection devices
- Weirs, gates, other flow control devices
- Plant litter collection, maintenance, pruning, mowing, etc.
- Disposal of plant wastes

3.5 Setup Construction

When the results of the above studies show that phytotechnology is a viable option, plans should be made to design a full-scale treatment system.

3.5.1 Securing Approvals and Notification

All regulatory authority (federal, state and local) should be notified and all approvals should be obtained prior to designing the treatment. These include obtaining all federal, state and/or local permits. In addition, all regulatory authority and the public should be notified of the start date and any modification to the original plan. All necessary personnel including nearby neighbors should be apprised of site activity, including safety precautions that should be taken when entering the site.

3.5.2 Site Preparation

Site preparation includes all activities necessary to prepare the site to be planted with a phytotechnology system. This could include marking the site, restructuring surfaces, removing obstructions, and amending the soils for optimum conditions. A proposal to apply phytotechnologies should contain detailed plans for conducting these tasks if called for in the design of the system.

Prior to the majority of activities being conducted to actually prepare and plant the site, the system designer, environmental engineer, and field manager/health and safety officer should walk the site and mark any relevant landmarks. This should include the boundaries of the phytotechnology system, areas to be resurfaced, potential obstructions, and sampling locations. These areas should be clearly delineated in the phytotechnology proposal and referred to during the discussion of the site preparation plans.

Some surface restructuring may be required for the site and generally calls for earthmoving machinery to be used. One reason is to deal with the potential runoff from irrigation systems. During these operations, dust generation will have to be addressed in the site preparation plans. Typically, this can be dealt with by moistening the soil prior to being moved. However, the runoff from spraying the soils will have to be addressed as well. Similarly, the volatilization or release of contaminants in the runoff, or leachate, will have to be accounted for during these operations as well. If deeper excavations are required, such as for removing subsurface or embedded obstructions, then these activities will also require additional measures to ensure the safety of the workers involved with the project. If dermal contact or significant concentrations of materials are anticipated, then the level of personal protective equipment (PPE) should be specified in site preparation plans as well.

3.5.3 Soil Preparation

Soil preparations include physical modification, such as tilling and creating a drainage control system. Agronomic inputs such as fertilizer, soil conditioners, and pH control agents are added to improve plant growth. Once any major earthmoving is completed, the soils where the phytotechnology system is to be planted will generally require the addition of soil amendments. During the initial site characterization, the soil conditions and hydrogeological data should have been assessed for the ability to support plant growth. These analyses will determine whether the site conditions are supportive of plant growth or whether the soil needs amending with fertilizers or other materials. Biosolids and/or treated effluents may be used if acceptable. The amendments should be geared toward optimizing the growth and remedial capabilities of the plants or soil organisms.

In many cases, the soil will require fertilization or pH adjustments by applying inorganic nutrients (N, P, K, etc.), organic matter, lime, etc. Chelating agents may be added to improve the ability of plants to uptake metals. The proposal should outline the type of soil amendment to be used as well as the method of application. If in a powder form, dust generation will have to be addressed. Similarly, if in a liquid form, then runoff of the soil amendment should be addressed as well. The site soil must also have sufficient water-holding capacity to sustain vegetation. Therefore, organic matter addition or other soil conditioners such as aged manure, sewage sludge, compost, straw, or mulch may have to be added (Schnoor, 1998).

3.5.4 Infrastructure

Each phytotechnology project will have different infrastructure requirements. Construction of a wetland to treat surface water will have much different infrastructure requirements than planting a riparian buffer to treat surface runoff. Irrigation systems may need to be installed to ensure a vigorous start to the phytotechnology system. Irrigation systems will prevent the loss of plants during drought conditions. Water requirements are on the order of 10–20 inches per year. When the phytotechnology system is properly established, it may be possible to remove the irrigation system.

Wetland systems may require fences for safety. Fencing may be required on other phytotechnology systems to mitigate ecological risk. Fencing will prevent animals from eating the plants and destroying the system. Monitoring wells and other semi-permanent monitoring devices may be required at the site.

3.5.5 Planting

The design team must establish the planting density and stage of plants (i.e., seeds, seedlings, plants) for the site. The design plan will describe the planting technique and labor required for the site. Special protection may be needed to prevent animals, vectors, and disease from harming the plants. Any needed special protection should be identified in the work plan.

After the soil has been exposed and the utilities and other structures have been removed or reconfigured, the soil should be prepared for planting. For proper root development, the uppermost 18 inches of the soil profile will need to be loose. Following the tilling of the soil, soil amendments identified to be necessary for plant growth should be worked into the soil. The plants should be planted, utilizing the optimal plant density identified in the system design process. Blowing dirt and dust may be a problem and can be controlled by keeping the surface of the soil moist. It may be advantageous to monitor the air for possible volatilization of contaminants.

Utilizing information gained during the plant selection process and the preliminary studies, an optimal planting depth and plant spacing can be identified. Initial planting densities may be greater than required, and the plants may be thinned after reaching a specific height.

During the plant selection process and site investigation, nutrient deficiencies in the soils at the site should have been identified. An initial fertilizer application can be made at planting time and tilled directly into the soil. Care should be given to monitor the growth of the plants closely to determine when additional fertilization is necessary. Fertilizer can be applied in granular form, which is broadcast on the ground, or in liquid form, which is applied directly through the irrigation system.

Weed control may be necessary for the first few years of a project. Weed control can be accomplished by mechanical methods or through the use of herbicides. When using herbicides, care should be taken to select a herbicide that is not detrimental to the desired plant, and the application time and methods should minimize drift to areas off site. If the selected plant is prone to insect infestations or disease, it may be advantageous to apply pesticides. It may be advantageous to select plants that are disease- and insect-resistant, such as hybrid poplars.

If trees are selected, proper pruning at regular intervals will keep the plantation healthy and minimize damage from storms. Replanting plants that die from disease or rootstock that doesn't survive for other reasons may be necessary to sustain the plantation.

3.5.6 Irrigation System

An irrigation system may be necessary to establish the plants and sustain their growth. Irrigation water may either be clean water or contaminated groundwater, depending on regulatory approval. Contaminated water from the site may actually be preferred because it will allow the plant to adapt to the contaminant concentrations in the groundwater. To utilize the contaminated groundwater, it may be necessary to install wells with sufficient yields to supply irrigation. For contaminants that may volatilize or transfer to the air, a drip irrigation system may be preferred over sprinkler irrigation.

Per the discussion provided earlier in Section 2.2.6, excessive irrigation can mobilize contamination from soil to ground or surface water. Therefore, in these cases, evapotranspiration estimates should be used to estimate the amount of water necessary to sustain growth without recharging the groundwater. Automated soil moisture monitoring systems are also available to control when irrigation is necessary.

3.5.7 Health and Safety Plan

A site health and safety plan is required for any remediation project. The health and safety plan will list the requirements for indoctrination and training; construction safety; emergency planning; personal protective and safety equipment; and hazardous substances, agents and environments, as well as hazardous waste activities and operations. Many of these will include the standard operating procedures already established by the industry, remediation companies, and construction and engineering firms. Field workers should typically be 40-hour Occupational Safety and Health Administration (OSHA) Hazardous Waste Operations and Emergency Response (HAZWOPER) trained.

Possible health and safety issues for both the workers dealing directly with the phytotechnology project as well as surrounding areas and communities are listed below. However, it should be possible to reduce or eliminate any adverse impacts by selecting the appropriate plant species as well as properly managing the project. Possible solutions to these potential issues are listed as well (see Table 3-2).

On the positive side, vegetation may be a visual, odor, dust, and noise barrier to block other site activities from surrounding areas.

Table 3-2 Potential Health and Safety Issues with Phytotechnologies

Problems	Possible Solutions
Dusts generated during operations involving earth work	Moisten soil prior to working, mist sprayers
Volatile contaminants released during operations involving earth work	Air samplers and alarms, PPE (respirators, self-contained breather apparatus).
The migration of soil amendments, fertilizers, and pesticides during or after application	Mist sprayers (powders, sprays), runoff control (liquids), scheduling.
Animals, insects, and other pests that can lead to bites, stings, and other natural dangers	Fencing, traps, repellents, etc.
Animals, insects, and other pests contacting the contaminant in the media or bioaccumulated in the plants	Fencing, traps, repellents, etc.
Pollen, allergies, odors, and other irritants produced by the plants	Inventorying the species present and noting seasonal susceptibilities
Dermal contact with the contaminated media or bioaccumulated in the plants	PPE (protective clothing, environmental suits)
Altered contaminant transport characteristics	Modeling, monitoring and contingency plans
Growth of invasive or noxious species or plant diseases affecting surrounding vegetation	Maintenance plan including weed control, pesticide applications, etc.
Root damage to foundations, underground utilities, or other structures	Maintenance plan including periodic inspections, control, repairs, and notifications
Blocked or obstructed vision or other concealment due to limbs, overgrowth, and thatch buildup	Maintenance plan to include pruning, trimming, mowing, etc.
Fire hazards due to the accumulation of dry plant matter	Maintenance plan to clear and contain or remove
Trespassers	Institutional controls and security measures

3.5.8 Site Security

Entry into the site may need to be restricted. Small animals such as rabbits and deer may need to be fenced out to prevent destruction of the plants. Fencing will also prevent large animals and/or people from destroying the new plants. Wetland area may be a danger to animals and small children. To ensure protection of human health and the environment, hazardous waste sites should be fenced to prevent unauthorized entry.

It may be necessary to secure the site by constructing a fence to prevent wildlife from damaging or destroying the plants. For phytotechnology mechanisms that translocate the contaminant to the plant material, it may be necessary to protect wildlife from exposure to contaminated biomass by preventing their access to the area. Posting signs on the fence that explain the project can inform the public regarding the potential for exposure to the contaminant.

3.6 Monitoring Requirement

The growth rate of a plant will directly affect the rate of remediation and should be monitored closely. Monitoring must be done to assess the performance and optimize phytotechnologies as well as to prevent and/or minimize any possible ecological risk. The following parameters should be monitored during phytotechnology applications to assess the performance of the system:

- Agronomic conditions
- Field measurements, including pH, salinity, available nutrients and climatic conditions
- Organic compound contaminant and degradation product concentrations, including byproduct composition and concentrations in all media
- Transpiration gases
- Biomarkers
- Microbial analysis

In addition, regulatory agencies may require sampling of all media until it is demonstrated that media transfer does not occur at the site. The use of established and published sampling protocols such as USEPA/American Society for Testing and Materials (ASTM) methods during any remediation project is highly recommended. Table 3-3 lists sampling methods applicable to typical phytotechnology projects.

Location, duration, and frequency of groundwater monitoring are determined from site characterization data. The exact sampling protocol and frequency will be determined on a site-specific basis. A recommended sample frequency for phytotechnologies is as follows:

- At initial site characterization to capture characterization baselines for vertical and horizontal depth and levels of contamination
- Before planting and after seed germinates
- At regular intervals and at the end of each growing season until site closure

Table 3-3 Methods for Typical Phytotechnology Monitoring

Parameter to be Monitored	Analytical Methods
Dissolved Oxygen (electron acceptor)	Standard Method # 421 or equivalent
pH	Standard Method # 423 or SW-846, Method 9040
Ammonia-N	Standard Method # 417 or equivalent
Nitrate-N	Standard Method # 418 or equivalent
Kjeldahl-N	Standard Method # 420 or equivalent
Available Phosphorus	Check with State Dept. of Agriculture
Total Phosphorus	Standard Method # 424 or equivalent
Temperature	Standard Method # 212 or equivalent
Metals such as Fe, Mg, Ca and other elements	Standard Method # 300 series or equivalent
Conductivity	Standard Method # 205 or SW-846, Method 9050A
Water table	Field instruments such as inter-phase probe
Microbes	Standard Method # 900 series or equivalent
Toxicity Tests for Microbes	Standard Method # 800 series or equivalent
Carbon dioxide	Standard Method # 406 or SW-846, Method 9060
Total Organic Carbon	Standard Method # 505 or equivalent
Total Organic Halogen	Standard Method # 506 or equivalent
Biochemical Oxygen Demand	Standard Method # 507 or equivalent
Redox Potential	Eh measurements
Contaminant of concern	Applicable USEPA methods

The growing seasons depend on the season and the climatic conditions. Since phytotechnologies can take longer times to achieve the target cleanup goal or standard, a long-term monitoring plan may be necessary. A reduction in the frequency for monitoring can be instituted after establishing that there is a contamination reduction during the first few growing seasons. Evaluation should occur on a yearly basis to determine the adequacy of monitoring frequencies and locations. In addition, the monitoring frequency should take into account seasonal and diurnal variation.

Transpiration monitoring of leaves, branches and the air can show that contaminants or byproducts do not present a hazard to human health or the environment. The processes that plants use to break down contaminants are not well understood. More samples may be required for phytotechnology projects to prove contaminant destruction.

Plant sampling (roots, shoots, stems, leaves) will demonstrate if uptake of the contaminant is occurring. Plant sampling is needed to determine if the plants are a hazardous waste.

Water monitoring at a phytotechnology site may include soil water, groundwater, and surface water runoff and effluent (from a wetland). The frequency and types of water tests will be site-specific depending upon the contaminant and site conditions.

3.6.1 Monitoring Plan

The major objective of any monitoring design system is to ascertain compliance with applicable state and federal standards. A monitoring plan should be developed for site-specific applications, and as such, monitoring plans are different for each application of phytotechnologies. The monitoring plan will collect information applicable to the remedial objectives. The monitoring plan should collect data to optimize the phytotechnology system, monitor the adverse impacts to the ecosystem, and measure the progress toward the remedial objectives. The monitoring plan should contain the following elements:

- Parameters or items to be monitored
- Frequency and duration of monitoring
- Monitoring/sampling methods
- Analytical methods
- Monitoring locations including media
- Quality assurance/quality control (QA/QC) requirements
- Target reduction goals

The monitoring plan also should address possible exposure pathways to ecological receptors at the site. Sampling of wildlife at the site should be performed to validate the calculations and assumptions made in the ecological risk assessment. The sampling should use species that contain levels of contaminants that reflect the current conditions at the site. These are species such as bees and nematodes that interact with the contaminated media and the plants, have short life spans, reproduce quickly, and have a habitat range that consists primarily of the site. In some areas where other heavily contaminated sites exist, samples of wildlife from other areas may be needed to assess the influence of contaminants from outside the site.

The monitoring plan must address basic issues affecting plant health, including soil nutrients, soil pH, soil microbial activity, and tree sap flow monitoring. The monitoring plan should also ensure that the fate and transport of the contaminant can be determined. A QA/QC plan describes how the monitoring plan will be implemented and sampling will be conducted. Data should be collected to demonstrate that the contaminant is being contained or destroyed in accordance with the remediation objectives. In addition, a long-term monitoring plan for the phytotechnology system should be prepared to collect data to optimize the operation of the system, monitor the adverse impacts to the ecosystem, and measure the progress toward the remedial objectives.

The sampling and analysis plan should confirm that the technology is meeting the regulatory objectives and requirements. The monitoring should use all established sampling and analytical protocols whenever possible. However, modification of established protocols or non-established methods including analytical screening methods are acceptable in most states, provided that such methods are scientifically valid, have a known and demonstrated level of precision and accuracy, and are completely documented.

3.6.2 Monitoring System Success

Monitoring must continue for the life of the phytotechnology project to ensure the target reduction goal is achieved. Periodic monitoring will measure remediation progress. Contaminant and degradation product concentrations measure system performance. Phytotechnologies are emerging technologies, and standard performance criteria for these systems have not been developed.

Monitoring the ecosystem for potential adverse effects may be necessary for some phytotechnology systems. If the system utilizes phytovolatilization, air sampling may be necessary to address concerns about compounds or degradation products that may be released to the environment. Extraction of contaminants by plants with uptake to edible portions of the plant such as leaves and seeds may require monitoring of the food chain for bioaccumulation of the contaminant.

Climatic indicators, such as temperature, precipitation, relative humidity, and solar radiation data, should be monitored to ensure that the plants' irrigation needs are being met. Water balance studies can be performed to estimate evapotranspiration rates, so that the proper amount of irrigation water can be estimated. Moisture sensors placed in the soil surrounding the root zone can automatically tell the irrigation system when the plants need watering, then apply the necessary amount of water. Lysimeter sampling of vadose zone soil moisture will determine if irrigation water is migrating downward past the root zone of the plants to avoid over-watering. To evaluate processes designed to impact water movement, the transpiration rate should be determined.

The plants should be monitored for signs of stress or damage from insects, so that the appropriate action can be taken, such as applying fertilizers or pesticides. The tissue composition (roots, leaves, shoots, etc.) of the plants should be monitored to quantify any contaminant byproducts that may be present. It may also be necessary to monitor off-gas emissions from the plants to ensure that any transpiration gases are not detrimental to human health or the environment. Some of the plant sampling will include

- Concentration and partitioning of contaminants in plants' roots (sorbed or bound and internal), shoots, stems, and leaves;
- Nutrient partitioning in plants, when under stress, resulting from contaminants;
- Root depth, distribution, density, and diameter;
- Plant abundance (density, cover, frequency, etc.), species richness, diversity;
- Mortality, health and vigor of plants (stress indicator);
- Classification of plants as indicators, excluders, and accumulators (determined by looking at concentrations in soil and plants);
- Proportion of plant species sensitive to contaminants versus tolerant of contaminants; use to manipulate the seed bank species planted as indicators, excluders, and accumulators;
- Chlorophyll levels in leaves; photosynthetic rates;
- Comparison of changes in plant community structure relative to nearby contaminated area; and
- Leaf area and evapotranspiration (measured by sap flow).

Soil moisture tension should be measured periodically using water content measurements or tensiometers. This information is related to water content through site-specific calibration. The soil surrounding the plants should be monitored for geochemical parameters, such as pH, nutrient concentrations, soil moisture, microbial populations, and contaminant breakdown products. Information gained can optimize vegetative, root, and microbial growth; quantify contaminant byproducts; and predict system operation. Soil samples can identify migration of the contaminant if it moves deeper into the soil due to irrigation.

Monitoring wells must be optimally located to contribute to a successful monitoring effort. Monitoring wells installed up gradient and down gradient from the planting areas should be monitored for contamination, degradation products, and other chemical parameters. Groundwater/surface water flow velocity is a key component in designing and establishing a monitoring schedule. Rates of groundwater/surface water flow can vary widely among sites across the states. If the groundwater/surface water flow rate is high, a more frequent schedule is applicable as the contamination is transported rapidly. Periodically, groundwater/surface water levels should be gauged. Gauging groundwater/surface water level data is a relatively inexpensive analysis, which can provide a great deal of information regarding the performance of the system. During the first year after implementation of phytotechnologies, groundwater/surface water levels should be gauged more frequently to determine the variations in the water levels due to seasonal fluctuations. In addition, groundwater/surface water velocity, direction, recharge rate, and volume should be monitored to evaluate the success of hydraulic control. This information can be used to evaluate compliance with remedial objectives and predict system operation.

3.7 Operations and Maintenance

Phytotechnology systems are like any other remediation system in that they require maintenance and upkeep. Failure can occur due to killing frosts, windstorms, drought, flood, animals (voles, deer, beaver), disease or infestation (fungus, insects), and latent toxicity. Part of the maintenance plan costs should include funding for periodically replanting a certain percentage of the site (Schnoor, 1998).

3.7.1 Operations and Maintenance Plan

An operations and maintenance plan will ensure optimal performance of the phytotechnology system. The level of detail in an operations and maintenance plan will be a function of the type of phytotechnology being used. Obviously a much more detailed operation and maintenance plan will be required for wetland operations than for a riparian buffer. The operation and maintenance plan for a phytotechnology project should address a wide variety of requirements, including

- Irrigation system that may be needed to start plants or keep them growing.
- Monitoring the soil conditions for pH, fertilizer requirements, needed soil amendments and required chelating agents.
- Site maintenance plan to address plant pruning, thinning, mowing, harvesting, and plant and litter removal. Harvested plants and litter from plants may be considered a hazardous waste.
- Animal and pest control. The site may need fencing to keep out people and animals.
- Replanting (if necessary).

The primary operation and maintenance requirements for a phytotechnology system consist of weed control, plant maintenance, and disposal of plant material. Weeds are controlled to reduce competition between the weeds and the selected plants and to prevent the spread of nuisance plants. Weeds are controlled by mechanical methods or through the application of herbicides. Weed control is of greater importance early in the phytotechnology project, before the canopy limits sunlight penetration to the ground surface and the understory growth is vigorous.

When trees are used in phytotechnologies, they need to be thinned and pruned to strengthen the structure of the plant. Replanting should be conducted as necessary at locations where initial plantings did not survive or to replace plants that have completed their life span. During the fall season, leaves that are fallen need to removed and disposed of properly.

Depending on the primary mechanism (phytoextraction or rhizofiltration) of the phytotechnology project, biomass removal may be necessary to reduce the potential risk of exposure to the contaminant or reintroduction of the contaminant to the environment. An appropriate disposal facility should be identified, and proper handling and disposal procedures will be required. In some cases, RCRA or state-specific hazardous waste regulations may apply. If the phytotechnology project does not result in contaminated biomass, the plant material may be harvested and sold as a cash crop to offset some of the remedial costs. Prior to selling the material, it must be verified that plant materials do not contain hazardous substances.

Phytotechnologies introduce large numbers of plants into an area, which can serve as a resource for both desirable and undesirable wildlife. Two issues should be examined during the planning stages of a phytotechnology project to minimize undesirable impacts on costs and feasibility:

- Preventing damage to the phytotechnology system by wildlife and vectors.
- Avoiding the introduction of noxious insects and diseases associated with the plants used in the project.

The latter issue is primarily a concern when exotic species or foreign cultivators of familiar species are used, but damage to the system by wildlife can greatly impact cost and feasibility of a project.

Tree-based phytotechnology systems would be most vulnerable to damage by browsing deer and elk or foraging beavers and jackrabbits. If these species are found near the site, substantial fencing may be required to protect the area. Systems using herbaceous plants (mustard, sunflower, etc.) are probably more susceptible to damage by insects, mice, gophers, prairie dogs, and moles. If the phytotechnology plants are being introduced to the site through seeding, protecting seeds from birds and ants is crucial. Mulch and spray binders can reduce the accessibility of seed to wildlife.

Any monostand (large area of the same type of plant) tends to attract insect and disease problems. Monitoring the site for insects and disease should be part of any phytotechnology project. The presence of an area of good habitat such as that provided by phytotechnology plants, particularly in a relatively urban area, is likely to attract animals. Many of these animals become a nuisance in areas surrounding the site. Mice, rats, and large flocks of starlings may have to be controlled in response to complaints from the public.

The use of pesticides should be addressed. If annual plants are used, replanting should be in the maintenance plan. Replanting will be required if plants are damaged or fail to grow.

The operations and maintenance plan should address drainage water from the site. Irrigation can cause water runoff, and runoff due to heavy rain or snow should be addressed. Monitoring wells will require some maintenance. If a pump-and-treat system is used during the trees' dormant period, pump system maintenance should be addressed.

Table 3-4 lists many parameters that will need to be part of an operations and maintenance plan for phytotechnology systems.

In addition, this plan will also address the measures that should be taken during a catastrophic event. During extreme weather conditions, plants can be damaged and destroyed. In such cases, it will be important to dispose of the destroyed plants and litter from plants as well as implement necessary steps to replace the destroyed plants.

Table 3-4 Operations and Maintenance Checklist

Operations Parameter	Maintenance Requirement
Soil Conditions	Maintain soil amendments, soil pH, fertilizer requirements and chelating agents.
Irrigation System	Irrigation system may be needed to start plants and may be needed during drought conditions.
Plant Maintenance	Plants may need to be thinned, pruned, mowed and treated to control weeds.
Fencing	Fencing may need to be installed to keep people and animals out. Fencing will be an important safety factor when wetlands are used.
Replanting	Replanting will be required for annual plants. Replanting trees will be required if they are damaged or fail to grow.
Vector Control	Phytotechnology systems will attract mice, rats, starlings and other vectors that may be a nuisance. A suitable control plan will be needed.
Monitoring Well Maintenance	Monitoring wells will be needed and they require some maintenance.
Disposal of Plant Material	Plant material may need to be collected and tested for contaminant accumulation. Plant material may need to be treated as a hazardous waste if contaminant concentrations exceed regulatory limits.
Stormwater Runoff	Ensure best management practices are used to control stormwater runoff from the site.
Mechanical Support Systems	Maintenance will be required for mechanical systems used during dormant periods (pumps for pump-and-treat systems).
Chelating Agents	When chelating agents are used to mobilize metals they will need to be added on a routine basis to ensure project success.
Wetlands Systems	Pond maintenance, plant harvesting, influent and effluent monitoring, and sediment control.

3.8 Contingency Plan

A contingency plan should define the actions taken if the phytotechnology system does not meet remedial objectives. The contingency plan may be required if there is large-scale failure of the plants (disease, flood, drought), if the system does not protect human health or the environment, or if remedial objectives are not met.

One of the important considerations in designing the phytotechnology system is a contingency plan if the phytotechnology does not meet the remediation goals. The plan should cover a wide range of possible failure mechanisms (drought, floods, disease, animals). It may take several years of monitoring to determine that the phytotechnology is not meeting the remedial goals. Each contingency plan will be site-specific depending upon numerous factors including

- Regulatory authority
- Funding to complete site cleanup
- Type of phytotechnology being applied
- Site environmental conditions (growing season, amount of rain, etc.)
- Time to complete cleanup

The remediation plan should contain a timeline that shows the expected reduction of the contaminant of concern over time. If the phytotechnology system is not achieving the expected goals, the site owner, system designer, regulator and stakeholders should review the remediation plan. Implementation of the contingency plan will be based upon many site-specific factors.

3.9 Reporting

Reports should document the status of implementing the phytotechnology project and should include monitoring data and a summary of construction activities. Reporting requirements may consist of quarterly reports early in the phase of the project. As the project approaches maturity, annual reports may suffice. Once remedial action objectives have been met, a final report can be prepared, summarizing the information gained during the life of the entire project.

4.0 NEW TECHNOLOGIES

Phytotechnologies have great potential. Although they has been extensively developed in the field, even those applications may not be fully understood on a mechanistic level. Furthermore, innovative applications of phytotechnologies are also being attempted that are continually expanding the range of usefulness. Phytotechnologies can be applied as either stand-alone technologies, as polishing steps, or in combination with other existing physical or mechanical technologies. This chapter discusses several “new” phytotechnologies that are still in the developmental or design phase but have great potential for future use. It is important that sufficient time be given to fully develop these systems and to better understand the mechanisms involved in these developing phytotechnologies.

4.1 Expanding Phytotechnology Mechanisms through Plant Biochemistry

One area where recent developments may prove to enhance the range of phytotechnology applications is within the plants themselves. Specifically, the chemicals, proteins, and enzymes produced by plants are continually being investigated for additional applications to remediate soil, sediments, surface water, and groundwater of organic and inorganic contaminants.

4.1.1 Plant Root Exudates

Plant root exudates play a significant role in nurturing rhizosphere bacteria. Furthermore, some bacteria are capable of living only in the root zone of certain plants where specific root exudates reside. However, plant exudates have the potential to do more than just increase microbial populations. Recent research indicates that plant exudates may, in fact, trigger the metabolic pathways that allow for the degradation of certain recalcitrant compounds. Specifically, plant-produced chemicals, such as morusin and catechin produced by mulberry and oak trees, respectively, may be responsible for the breakdown of PAHs and PCBs in sludges (Fletcher, 2000). In addition to studying the effects of the exudates on the degradation of contaminants, research is also being conducted to examine the effects of season and root turnover on microbial activities.

4.1.2 Plant Surfactants

Some plants, especially those adapted to growing in nutrient-poor regions, have developed the ability to produce root exudates that aid the plant in assimilating needed nutrients. For compounds with limited solubility/bioavailability, an alternative approach is being investigated that uses the natural surfactants produced and excreted by plants. Similar to the application of chelators or the production of phytochelators to increase the bioavailability of certain metals, surfactants loosen the bonds between soil and contaminants, facilitating plant uptake. Once inside the plant, contaminants can be phytodegraded. Furthermore, it might be possible to select plants that have the dual functions of nourishing soil bacteria to promote rhizodegradation, while exuding surfactants that make the contaminant more bioavailable for plant uptake and phytodegradation.

One drawback is that production of many plant surfactants evolved as a protection mechanism for the plant against soil microbial attack. Therefore, careful study of this area is warranted as it would detrimental to put plants on a site that would both mobilize the pollutant and kill off those bacteria that would be capable of degradation.

4.1.3 Plant Extracts and Plant Parts

While there are a few extracellular plant enzymes with documented phytotechnology capabilities, most plant enzymes are retained internally. In some cases, these intracellular enzymes may be able to phytodegrade organic contaminants but are never secreted into the surrounding soils where the contaminants reside. In addition, the limited uptake of organic contaminants by plants further limits the usefulness of these intracellular enzymes. Therefore, one area of research is to develop methods to introduce the intracellular plant enzymes without the need for direct plant uptake. To accomplish this, some researchers have experimented with plant extracts as well as ground or minced plant parts applied directly to an aqueous solution or contaminated soils

(Medina, et al., 2000). In all instances, higher levels of degradation were found compared to those seen in the presence of intact plants.

This raises the possibility of vegetating a site with plants that contain intracellular enzymes capable of degrading site contaminants. Once the plants have reached sufficient biomass, the plant material is finely tilled into the soil, releasing the enzymes to phytodegrade the contaminants. Alternatively, if the concentration of the contaminant proves to be toxic to the plant (through feasibility studies), the plants can be produced off site, harvested at the appropriate time, and then brought to the impacted site for incorporation into the soils.

4.2 Expanding Plant Capabilities through Genetic Engineering

There is great appeal in using plants as natural remediation systems. However, some metabolic pathways that are necessary for dealing with specific pollutants may not be present naturally in plants or present at sufficiently high activity rates. Although there is controversy surrounding its use, genetic engineering may provide additional or enhanced plant capabilities for phytotechnology applications. By incorporating genes identified as coding for certain characteristics such as metal tolerance or the production of desirable enzymes, plant species can be enhanced to achieve remediation activities beyond those found in nature.

4.2.1 Bacterial Genes

Naturally occurring bacteria have proven to be extremely useful in remediation. Some researchers have inserted genes involved in the metabolism of perchloroethylene (PCE) and TCE into root-colonizing organisms that thrive only in the root zone of certain plants (Wood, et al., 2000). By inoculating young plant roots with these engineered bacteria before planting, a phytotechnology system can be designed so that as the plants grow and send their roots deeper into the subsurface, the bacteria is carried along with them. Along the way, the bacteria would degrade the PCE and TCE contaminants. Since the bacteria can only survive and gain nutrients in the rhizosphere of the specific plant species, they would only be limited to those soils and would not represent any further genetic threat. Taking this a step further, other researchers are working to insert bacterial genes that code for the enzymes responsible for the detoxification of organic contaminants directly into plants.

4.2.2 Mammalian Genes

Several groups are focusing research on the metal uptake and accumulation pathways that can be enhanced in plants. There is a hope that a better understanding of the genetics of these pathways would allow for manipulation of the genes involved, resulting in “super-accumulating” plants. Specific work has included the insertion of mammalian metallothionein genes into plants. The resulting plants exhibited an increased ability to survive higher levels of metal stress. However, few showed significant increases in metal uptake and accumulation capabilities (Cai, et al., 1999).

Others have inserted the cytochrome P450 IIE1 gene into plants, resulting in variants that can metabolize TCE up to 640 times faster than normal (Doty, et al., 2000). Other researchers have inserted P450 genes into plants involved in the detoxification of pesticides but have received mixed results thus far.

4.3 Applying Phytotechnologies to New Contaminants

In addition to the development of new applications focusing on plant capabilities themselves, research is also being conducted on utilizing existing knowledge of phytotechnologies on other contaminants, including those that have traditionally been difficult or impractical to treat with current alternatives. In addition to those described in detail below, several research groups are developing phytotechnology applications for 1,4-dioxane, PCBs, carbon tetrachloride, fluorides, and metal cyanides.

4.3.1 Methyl Tertiary Butyl Ether

The characteristics that make MTBE difficult to treat with traditional methods may actually make it easier to treat with phytotechnologies. MTBE is readily taken up by species such as poplar, pine, and eucalyptus. Using dosages of ^{14}C-MTBE, several laboratory groups have seen the accumulation of the ^{14}C in plant tissue, while other groups have found MTBE in plant tissue collected from trees growing in an MTBE-contaminated aquifer (Newman, et al., 1999; Zhang, et al., 2000; Landmeyer, 2000; Rubin, 2000; others).

One potential problem of using phytotechnologies for MTBE remediation is that the fate of MTBE inside the plant is currently not fully understood. One potential fate is that the MTBE is phytovolatilized, while others indicate that it may be partially degraded in the rhizosphere and then taken up. Some preliminary studies have indicated that MTBE is phytodegraded within the plant in a manner consistent with cytochrome-P450 oxidation. In studies conducted in California, significant levels of tertiary butyl alcohol (TBA), a major metabolite of MTBE biodegradation, have been detected in the transpiration vapors of trees growing in contact with an impacted aquifer. Furthermore, it has been documented that low levels of CO_2 are produced from MTBE in poplar cell cultures (Newman, et al., 1999).

Part of the problem is that the analytical methods needed to analyze for MTBE and its metabolites are not sensitive enough to measure the concentrations in tissues, particularly when concentrations are close to the regulatory limit of 15 ppb. Until sufficient methods exist to understand the metabolic fate of MTBE in plants, there will continue to be questions by both the regulatory community and the public.

4.3.2 Perchlorate

Used extensively as a strong oxidizing agent in solid rocket fuel, perchlorate has recently become a groundwater concern. Researchers are currently investigating the use of parrot-feather (*Myriophyllum aquaticum*) as a means to cleanse impacted soil and water (Susarla, et al., 1999). Shown to successfully remediate TNT and chlorinated solvents, this species is being tested to determine the abilities to remove perchlorate from aqueous solutions and to determine the transformation products in the plant tissues. Initial results show a substantial reduction in concentrations, which also led to the decreased growth of the plant. Initial investigations in this toxic response indicate that the decreased growth was more of a response to the increased chloride content rather than the perchlorate itself.

4.3.3 Tritium

Groundwater impacted from nuclear research is currently being tested with deep-rooted trees as a potential method to capture and phytovolatilize tritium (Negri, et al., 2000). One of the potential concerns before this field project was initiated was that the uptake of tritiated groundwater could result in an elevated concentration of tritium in the air and/or within the plant biomass. This concern led to regulatory approval of the project to ensure that no significant increase in radiation to the most exposed individual would occur. Air modeling showed that even if all of the tritium were released into the air through phytovolatilization, the exposure levels would be below National Emissions Standards for Hazardous Air Pollutants (NESHAPS).

4.3.4 Arsenic

Arsenic contamination can result from the accumulation of naturally occurring arsenic or from the application of arsenic-based pesticides. Several studies have been initiated looking into the phytoaccumulation capabilities of various species (Koch, et al., 2000; Tossell, 2000). To date, however, the only known plant that has been identified as being able to accumulate high levels of arsenic is a fern (*Pteris vittata*) (Ma, 2001). Laboratory studies have shown that the plant is capable of accumulating arsenic 126 times higher than what is present in the soil. Field-based studies have shown that plants growing in soils with only background levels of arsenic are still able to accumulate high levels into the aboveground portions of the plants. These studies indicate that almost all of the arsenic was present in the fern fronds as inorganic trivalent arsenic. The major drawbacks to the application of this plant to clean up arsenic-contaminated sites are the limited root system of ferns and the potentially limited climate suitability. This plant may prove to be a source of genes to insert into other plants.

4.4 Applying Phytotechnologies to New Media

In addition to applying phytotechnologies to new contaminants, these technologies are also expanding into different impacted media. These areas of research are developing as changes in environmental laws dictate that these media be addressed.

4.4.1 Sediments (In Situ and Dredged)

Although not strictly a new media for phytotechnologies, the rapid increase in dredging operations that is expected over the next 10 years provides opportunities for the technology to be applied in novel ways. One of the current uses for sediments with low to minimal contamination levels is in construction as road-base material. However, the consistency of the sediments immediately after dredging makes it unusable, requiring treatment. One potential application of phytotechnologies is to utilize the evapotranspirative capabilities to de-water the sediments. Another area of research is to develop methods to change the consistency of the sediments through solidification and stabilization methods.

For sediments with higher levels of contamination, certain rooted aquatic species may be able to enhance the microbial biodegradation in situ (i.e., rhizodegradation). The evidence is certainly available that rooted aquatic species are capable of remediating contaminants (e.g. parrot-feather with TNT, chlorinated solvents, and perchlorate). However, no studies have been initiated that look specifically into the use of vegetation to treat the contaminated sediments themselves. Some researchers (Schwab, et al., 2000) are starting to examine this problem by looking to develop systems that would treat both the organic (pentachlorophenol, PAHs, petroleum hydrocarbons, others) and the inorganic (Hg, Sn, others) contaminants that are generally found.

4.4.2 Greenhouse Gas Mitigation

With rising concern over greenhouse gases in conjunction with the deforestation occurring around the world, several organizations are looking into the use of plants and trees to mitigate gaseous carbon emissions. Furthermore, the potential implementation of a worldwide carbon emissions trading system has prompted the development of large plantations dedicated to sequestering carbon dioxide (the primary greenhouse gas) into its tissues. Recent research has shown that newly planted forests can accumulate into the hardwood tissues approximately 10 tons of CO_2 per acre (CSIRO, 1999).

In addition to the ability of trees to sequester CO_2 into the terrestrial portion of plants, researchers have also been investigating the ability of plants to sequester carbon into the subsurface through exudation and humification (Post, et al., 1998). These processes can account for as much as 50% of the total metabolism of carbon dioxide in some plants. Furthermore, the stability of the soil organic fraction derived from these processes can be several centuries long.

Researchers are also looking into the potential effects of elevated CO_2 concentrations on plant growth (BNL, 1999). In a large forest of loblolly pines (*Pinus taeda*), elevated CO_2 levels are produced from blowers located amongst the trees. These blowers produced CO_2 levels as high as 560 ppm compared to the nominal levels of 360 ppm. The pines trees exhibited increased growth of 25% over controls by assimilating the additional carbon dioxide.

4.5 Combining Phytotechnologies with Other Treatment Technologies

Since phytotechnologies simply represent additional tools in the environmental toolbox for remediating contaminated sites, it can be applied in conjunction with other alternatives. In some cases, the alternative may be enhanced in the presence of plants and trees.

4.5.1 Non-Reactive Barriers

Non-reactive barriers such as slurry walls and sheet-pile walls are simply physical barriers that stop the movement of contaminated plumes. Since they do not have any degradation activity, water and contaminants can build up on the up-gradient side of the barrier. This can lead to an outward gradient that can potentially lead to the eventual permeation of contaminants through the barrier system. Typically, it becomes necessary to install some sort of pumping system to remove and/or contain the plume.

One method that is being considered is the installation of deep-rooted plants immediately up gradient of the barrier. The vegetation would function to remove the water that builds up behind the barrier plus phytoremediate the contaminants. If a sufficient rate of pumping can be achieved by the vegetation planted up gradient, an inward gradient may even be able to be maintained across the barrier.

4.5.2 Extraction Systems

Traditional pump-and-treat systems utilize an extraction system that sends the groundwater to a treatment system where the water is cleansed. A novel approach involving phytotechnologies is to use the extracted groundwater as irrigation on the planted plots. Several different variations of this technology have been devised. In the simplest system, the water is pumped from the aquifer and applied directly to the vegetation through spray irrigation. For volatile contaminants, this vigorous pulsing can lead to substantial evaporation, effectively reducing concentrations. This technique is similar to an air stripping treatment system. Once in the atmosphere, these stripped contaminants are subject to photodegradation. Those contaminants that are not stripped are subject to phytotechnology mechanisms if they're able to infiltrate into the root zone. Since the water will also used by the vegetation, this eliminates the need for re-injection.

To reduce potential exposures from the sprayed groundwater, irrigation lines may be used. These lines can be placed above ground or buried just below the surface. Aboveground systems are easier to install and maintain; however, since this method applies the contaminant on the soil surface at the base of the vegetation, it could contribute to lead exposure. By installing the irrigation line below ground, it will eliminate the release of the contaminant to the soil surface. However, this method is a bit more complex to install and leads to a trade-off with practicality.

4.5.3 Air Sparging, Soil Vapor Extraction, and Bioventing

Air sparging is a very effective technology for volatilizing contaminants in the subsurface. Once volatilized, the contaminant can either be released to the atmosphere or treated using an off-gas treatment method. A proposed strategy is to combine phytotechnologies with this technology. Specifically, a fast growing, densely rooted species could be grown directly over the zone of influence of the sparging system. As the contaminant vapors rise through the unsaturated soil layers, they would interact with both the plant roots and the rhizosphere bacteria where phytotechnology mechanisms may occur. Since the rhizosphere would contain an enhanced bacterial population, remediation rates may be enhanced compared to sparging alone.

Because this application of phytotechnology is still in the conceptual phase, several areas need to be addressed:

- Can the plants interact with the contaminant when presented in a vapor phase, as opposed to a dissolved phase?
- How will the air injection rates affect both root and bacterial growth in the soil?
- What mass loading rate of contaminant can the plant systems' handle and still maintain effectiveness?
- How will different soil types affect the efficiency of the system?

Similarly, the transpiration capabilities of plants can be used to lower the water level in areas where soil vapor extraction (SVE) or bioventing is being conducted. The increased exposure of unsaturated soils to the SVE or bioventing systems will enhance their overall efficiencies.

5.0 BIBLIOGRAPHY AND REFERENCES

Allen, R.G., M.E. Jensen, J.L. Wright, and R.D. Burman. 1989. "Operational Estimates of Reference Evapotranspiration." *Agron. Journal*, 81: 650–662.

Anderson, T.A. and B.T. Walton. 1991. "Fate of Trichloroethylene in Soil-Plant Systems." American Chemical Society Extended Abstract, Division of Environmental Chemistry, pp. 197–200.

Anderson, T.A. and B.T. Walton. 1995. "Comparative Fate of ^{14}C Trichloroethylene in the Root Zone of Plants from a Former Solvent Disposal Site." *Environmental Toxicology and Chemistry*, 14: 2041–2047.

Baker A.J. M., R.R. Brooks, and R.D. Reeves. 1998. "Growing for Gold and Copper and Zinc." *New Science*, 177: 44–48.

BNL, 1999. "Striking Results from Brookhaven Ecology Facility: Trees Grow Faster in Simulated Future CO_2-Rich Atmosphere." Brookhaven National Laboratory (BNL) Report 99-43. Available at: http://www.bnl.gov/bnlweb/pubaf/pr/bnlpr051399.html.

Briggs, G.G., R.H. Bromilow, and A.A. Evans. 1982. "Relationship Between Lipophilicity and Root Uptake and Translocation of Non-Ionized Chemicals by Barley." *Pesticide Science*, 13: 495–504.

Burken, J.G. and J.L. Schnoor. 1997 (submitted). "Estimating the Uptake of Organic Contaminants by Hybrid Poplar Trees." *Environment Science and Technology*.

Cai, X.H., C. Brown, J. Adhiya, S.J. Traina, and R.T. Sayre. 1999. "Growth and Heavy Metal Binding Properties of Transgenic *Chlamydomonas* Expressing a Foreign Metallothionen Gene." *International J. Phytoremediation*, 1: 53–66.

Campbell, R. and M.P. Greaves. 1990. "Anatomy and Community Structure of the Rhizosphere." *The Rhizosphere*. John Wiley & Sons, Ltd., West Sussex, England.

Chappell, J. 1998. "Phytoremediation of TCE in Groundwater Using Populus." Status report prepared for USEPA, Technology Innovation Office. February. Available at: http://clu-in.org/products/phytotce.htm.

Christensen-Kirsh, K.M. 1996. "Phytoremediation and Wastewater Effluent Disposal: Guidelines for Landscape Planners and Designers." M.A. Thesis, University of Oregon. December.

Cipollini, M.L. and J.L. Pickering. 1986. "Determination of the Phytotoxicity of Barium in Leach-Field Disposal of Gas Well Brines." *Plant and Soil*, *92*: 159–169.

Compton, H.R., D.M. Haroski, S.R. Hirsh, and J.G. Wrobel. 1998. "Pilot-scale use of trees to address VOC contamination." *Bioremediation and Phytoremediation*, *Chlorinated and Recalcitrant Compounds*, pp. 245–250. G.B. Wickramanayake and R.E. Hinchee (eds.) Battelle Press, Columbus, OH.

CSIRO, 1999. "Plantation Forests as Carbon Sinks." Commonwealth Science and Industrial Research Organisation (CSIRO) Forestry and Forest Products located at: http://www.csiro.au/csiro/ghsolutions/s6.html

Dodge, C.J. and A.J. Francis. 1997. "Biotransformation of binary and ternary citric acid complexes of iron and uranium." *Environ. Science and Technology*, 31: 3062–3067.

Domencio, P.A. and F.W. Schwartz. 1997. *Physical and Chemical Hydrogeology*. John Wiley, New York, NY.

Donnelly, P.K. and J.S. Fletcher. 1994. "Potential Use of Mycorrhizal Fungi as Bioremediation Agents." *Bioremediation Through Rhizosphere Technology*. T.A. Anderson and J.R. Coats (eds.), American Chemical Society, Washington, DC.

Doty, S.L., Q.-T. Shang, A.M., Wilson, J. Tangen, A.D. Westergreen, L.A. Newman, S.E. Strand, and M.P. Gordon. 2000. "Enhanced Metabolism of Halogenated Hydrocarbons in Transgenic Plants Containing P450 IIE1." Presented at the Second International

Conference on Remediation of Chlorinated and Recalcitrant Compounds, May 22–25, Monterey, CA.

Dragun, J. 1998. *The Soil Chemistry of Hazardous Materials. 2nd Edition*. Amherst Scientific Publishers, Amherst, MA.

Dushenkov, S., Y. Kapulnik, M. Blaylock, B. Sorochinsky, I. Raskin, and B. Ensley. 1997a. "Phytoremediation: A Novel Approach to an Old Problem." *Global Environmental Biotechnology*. pp. 563–572. D.L. Wise (ed.), Elsevier Science, B.V

Dushenkov, S., D. Vasudev, Y. Kapulnik, D. Gleba, D. Fleisher, K.C. Ting, and B. Ensley 1997b. "Removal of Uranium from Water Using Terrestrial Plants." *Environ. Science and Technology*, 31: 3468–3474.

Ferro, A.M. 1998. "Biological Pump and Treat Systems Using Poplar Trees." Presentation at IBC's 3rd Annual International Conference on Phytoremediation. Houston, TX, June 22–25, 1998.

Ferro, A.M., R.C. Sims, and B. Bugbee. 1994. "Hycrest Crested Wheatgrass Accelerates the Degradation of Pentachlorophenol." *Journal of Environmental Quality,* 23: 272–279.

Ferro, A.M., J. Kennedy, and D. Knight. 1997. "Greenhouse Scale Evaluation of Phytoremediation for Soil Contaminated with Wood Preservatives." Fourth International In-situ and On-Site Bioremediation Symposium. 3: 309–314, April 28–May 1, 1997, New Orleans, LA.

Flathman, P.E, and G.R. Lanza. 1998. "Phytoremediation: Current Views on an Emerging Green Technology." *J. Soil Contam*., 7: 415–432.

Fletcher J.S. 2000. "Biosystem Treatment of Recalcitrant Soil Contaminants." Presentation at the USEPA Phytoremediation State of the Science Conference, May 1–2, Boston, MA.

Frick, C., R. Farrell, and J. Germida. 1999. "Assessment of Phytoremediation as an In-Situ Technique for Cleaning Oil-Contaminated Sites." Petroleum Technology Alliance of Canada (PTAC), Calgary, AB.

Frick, C., R. Farrell, and J. Germida. 2000. "Phyto-Pet: A Database of Plants that Play a Role in the Phytoremediation of Petroleum Hydrocarbons." CD-ROM developed by the University of Saskatchewan in cooperation with Environment Canada and Petroleum Technology Alliance of Canada.

Gatliff, E.G. 1994. "Vegetative Remediation Process Offers Advantages over Traditional Pump-and-Treat Technologies." *Remediation*, Summer 1994: 343–352.

Glass, D.J. 1998. "The 1998 United States Market for Phytoremediation." D. Glass Associates, Inc., Needham, MA.

Gordon, M.P., S. Strand, and L. Newman. 1998. *Final Report: Degradation of Environmental Pollutants by Plants*. USEPA, National Center for Environmental Research, Office of Research and Development. Available at: http://es.epa.gov/ncerqa/final/gordon.html (accessed January 6, 2000).

Heaton, C.P., C.L. Rugh, N-J Wang, and R.B. Meagher. 1998. "Phytoremediation of Mercury- and Methylmercury-Polluted Soils Using Genetically Engineered Plants." *J. Soil Contam.*, 7: 497–509.

Hinchman, R.R., M.C. Negri, and E.G. Gatliff. 1997. *Phytoremediation: Using Green Plants to Clean Up Contaminated Soil, Groundwater, and Wastewater*. Report submitted to the U.S. Department of Energy, assistant secretary for Energy Efficient and Renewable Energy under Contract W-31-109-Eng-38.

Javandel, I. and C-F Tsang. 1986. "Capture-Zone Type Curves: A Tool for Aquifer Cleanup." *Groundwater*, 24: 616–625.

Kadlec, R.H. and R.L. Knight. 1996. *Treatment Wetlands*. CRC Press LLC, Lewis Publishers, Boca Raton, FL.

Keiffer, C.H. 1996. "Comparison of Salt Tolerance and Ion Accumulation of Halophytes and Their Potential Use for Remediating Brine Contaminated Soil." Ph.D dissertation, Ohio University, College of Arts and Sciences, Athens, OH.

Keiffer, C.H. and I.A. Ungar. 1996. *Bioremediation of Brine Contaminated Soils*. Final Report, PERF Project #91-18.

Koch, I., L. Wang, C.A. Ollson, W.R. Cullen, and K.J. Reimer. 2000. "The Predominance of Inorganic Arsenic Species in Plants from Yellowknife, Northwest Territories, Canada." *Environ. Science and Technology*, 34: 22–26.

Kumar, P.B.A.N., V. Dushenkov, H. Motto, and I. Raskin. 1995. "Phytoextraction: The Use of Plants to Remove Heavy Metals from Soils." *Environ. Science and Technology*, 29: 1232–1238.

Landmeyer, J. 2000. "Effects of Woody Plants on Ground-Water Hydrology and Contaminant Concentrations." Presentation at USEPA Phytoremediation State of the Science Conference, May 1–2, Boston, MA.

Licht, L.A. 1993. "Ecolotree Cap. Densely Rooted Trees for Water Management on Landfill Covers." Presentation at the Air and Waste Management Association, Denver, CO.

Ma, L. 2001. "Fern Soaks Up Arsenic with Staggering Efficiency." Environmental Data Interactive Exchange (EDIE) Weekly Summaries 02/02/2001 located at: http://www.edie.net/news/Archive/3762.html.

Ma, L., et al. 2001. "A fern that hyperaccumulates arsenic." *Nature*, 409: 579.

Martin, H.W., T.R. Young, D.I. Kaplan, L. Simon, and D.C. Adriano. 1996. "Evaluation of Three Herbaceous Index Plant Species for Bioavailability of Soil Cadmium, Chromium, Nickel, and Vanadium." *Plant and Soil*, 182: 199–207.

Matso, K. 1995. "Mother Nature's Pump and Treat." *Civil Engineering*, October: 46–49.

McCutcheon, S.C. 1995. "Phytoremediation of Hazardous Waste." July 23–26.

McIntyre, T. 2001. "PhytoRem: A Global CD-ROM Database of Aquatic and Terrestrial Plants that Sequester, Accumulate, or Hyperaccumulate Heavy Metals." Environment Canada, Hull, Quebec.

Meagher, R.B., C. Rugh, D. Wilde, M. Wallace, S. Merkle, and A.O. Summers. 1995. "Phytoremediation of toxic heavy metal ion contamination: expression of a modified bacterial mercuric ion reductase in transgenic *Arabidopsis* confers reduction of and resistance to high levels of ionic mercury." Proceedings/Abstracts of the 14th Annual Symposium on Current Topics in Plant Biochemistry, Physiology, and Molecular Biology — Will Plants Have a Role in Bioremediation? pp. 29–30. April 19–22, 1995, Columbia, MO. Interdisciplinary Plant Group, University of Missouri, Columbia, MO.

Meagher R.B. and C. Rugh. 1996. "Phytoremediation of Mercury Pollution Using a Modified Bacterial Mercuric-ion Reductase Gene", International Phytoremediation Conference, May 8–10, 1996, Arlington, VA.

Medina, V.F., S.L. Larson, W. Perez, and L.E. Agwaramgbo. 2000. "Evaluation of Minced and Pureed Plants for Phytotreatment of Munitions." Presentation at the Second International Conference on Remediation of Chlorinated and Recalcitrant Compounds, May 22–25, Monterey, CA.

Negri, M.C., R.R. Hinchman, and J.B. Wozniak. 2000. "Capturing a Mixed Contaminant Plume: Tritium Phytoevaporation at Argonne National Laboratory's Area 319." Presentation at USEPA Phytoremediation State of the Science Conference, May 1–2, Boston, MA.

Newman, A. 1995. "Plant Enzymes Set for Bioremediation Field Study." *Environment Science and Technology*, 29: 18a.

Newman, L.A., S.E. Strand, N. Choe, J. Duffy, G. Ekuan, M. Ruszaj, B.B. Shurtleff, J. Wilmoth, P. Heilman, and M.P. Gordon. 1997. "Uptake and Biotransformation of Trichloroethylene by Hybrid Poplars." *Environment Science and Technology,* 31: 1062–1067.

Newman, L.A., M.P. Gordon, P. Heilman, D.L. Cannon, E. Lory, K. Miller, J. Osgood, and S.E. Strand. 1999. "Phytoremediation of MTBE at a California Naval Site." *Soil & Groundwater Cleanup*, Feb/March: 42–45.

Nyer E.K. and E.G. Gatliff. 1996. "Phytoremediation." *Ground Water Monitoring and Remediation*, 16: 58–62.

Olsen, P.E. and J.S. Fletcher. 1999. "Field Evaluation of Mulberry Root Structure with Regard to Phytoremediation." *Bioremediation Journal*, 3(1): 27–33.

Orchard, B.J., J.K. Chard, W.J. Doucette, B. Bugbee. 1999. "Laboratory Studies on Plant Uptake of TCE." Presentation at the 5th International In-Situ and On-Site Bioremediation Symposium, Battelle, San Diego, CA.

Pais, István and J. Benton Jones, Jr. 1997. *The Handbook of Trace Elements*. pp. 223. St. Lucie Press, Boca Raton, FL.

Post, W.M., R.C. Izaurralde, L.K. Mann, and N. Bliss. 1998. "Monitoring and Verifying Soil Organic Carbon Sequestration." *Carbon Sequestration in Soils: Science, Monitoring, and Beyond*. Proceedings of the St. Michaels Workshop. N.J. Rosenberg, R.C. Izaurralde, and E.L. Malone (eds.), Battelle Press, Columbus, OH.

Riesen, T.K. and I. Brunner. 1996. "Effect of Ectomycorrhizae and Ammonium on ^{134}Cs and ^{85}Sr Uptake into *Picea abies* Seedlings." *Environ. Pollut.* 93(1): 1–8.

Rock, S.A. and P. Sayre. 1999. "Phytoremediation of Hazardous Wastes: Potential Regulatory Acceptability." *Environmental Regulations and Permitting,* Volume 8(3): 33–42. John Wiley & Sons, Inc., New York, NY.

RTDF. 2000. *Annual Report of the RTDF Phytoremediation Action Team - TPH Subgroup: Cooperative Field Trials*. Remediation Technologies Development Forum (RTDF). http://www.rtdf.org/public/phyto/phytodoc.htm

Rubin, E. 2000. "Potential for Phytoremediation of Methyl-Tert-Butyl-Ether (MTBE)." Presentation at the 10th Annual West Coast Conference on Contaminated Soils and Water, March 20–23, San Diego, CA.

Salt, D.E., M. Blaylock, N.P.B.A Kumar, V. Dushenkov, B.D. Ensley, I. Chet, and I. Raskin. 1995. "Phytoremediation: A Novel Strategy for the Removal of Toxic Metals from the Environment Using Plants." *Biotechnology*, 13: 468–474.

Schwab, P.A., L.E. Newman, M.K. Banks, and K. Nedunari. 2000. "Dewatering, Remediation, and Evaluation of Dredged Sediments." Center for Integrated Remediation Using Managed Natural Systems (CIRUMNS), USEPA Hazardous Substance Research Center, West Lafayette, IN.

Shimp, J.F., J.C. Tracey, L.C. Davis, E. Lee, W. Huang, L.E. Erickson, and J.L. Schnoor. 1993. "Beneficial Effects of Plants in the Remediation of Soil and Groundwater Contaminated with Organic Materials." *Critical Review in Environmental Science & Technology,* 23: 41–77.

Schnoor, J.L. 1996. *Environmental Modeling – Fate and Transport of Pollutants in Water, Air, and Soil*. John Wiley & Sons, New York, NY.

Schnoor, J.L. 1998. *Phytoremediation*. Technology Evaluation Report TE-98-01. Prepared for Ground-Water Remediation Technology Analysis Center.

Schnoor J.L., L.A. Light, S.C. McCutcheon, N.L. Wolfe, and L.H. Carriera. 1995. "Phytoremediation of Organic and Nutrient Contaminants." *Environment Science and Technology*, 29: 318–323.

Schwarzenbach, R.P., P.M. Gschwend, and D.M. Imboden. 1993. *Environmental Organic Chemistry*. John Wiley & Sons, New York, NY.

Speir, T.W., J.A. August, and C.W. Feltham. 1992. "Assessment of the Feasibility of Using CCA (Copper, Chromium and Arsenic) -Treated and Boric Acid-Treated Sawdust as Soil Amendments. I. Plant Growth and Element Uptake." *Plant and Soil*, 142: 235–248.

Susarla, S., S.T. Bacchus, N.L. Wolfe, and S.C. McCutcheon. 1999. "Phytotransformation of Perchlorate Using Parrot-Feather." *Soil & Groundwater Cleanup*, Feb/March: 20–23.

Taiz, L. and E. Zeiger. 1991. *Plant Physiology*. The Benjamin/Cummings Publishing Company, Inc., Redwood City, CA.

Thomas, F., J. Reider, A. Ferro, and D. Tsao. 1998. "Using Trees as a Barrier Strip to Metals-Contaminated Saline Groundwater." Presentation at the 3rd Annual International Conference on Phytoremediation, June 22–25, Houston, TX.

Tossell, R.W. 2000. "Uptake of Arsenic by Tamarisk and Eucalyptus Under Saline Conditions." Presentation at the 2nd International Conference on Remediation of Chlorinated and Recalcitrant Compounds, May 22–25, Monterey, CA.

Tsao, D. 1998. *Phytoremediation Technologies.* BP Amoco Technology Guidance Document. Naperville, IL.

USEPA, see United States Environmental Protection Agency.

United States Environmental Protection Agency. 1993. *Wildlife Exposure Factors Handbook*. Volume 1. EPA/600/R-93/187.

United States Environmental Protection Agency. 1998. "Green Landscaping with Native Plants." http://www.epa.gov/greenacres/

United States Environmental Protection Agency. 1999. *Phytoremediation Resource Guide*. EPA/542/B-99/003. June. Available at http://www.epa.gov/tio.

United States Environmental Protection Agency. 1999. *Screening Level Ecological Risk Assessment Protocol, Appendix C. Media-to-Receptor BCF Values and Appendix D. Wildlife Measurement Assessment Receptor BCF Values.*

United States Environmental Protection Agency. *Introduction to Phytoremediation*. 2000. EPA/600/R-99/107. http://www.epa.gov/clariton/clhtml/pubtitle.html

Van Bavel, C.H.M. 1996. "Potential Evapotranspiration: The Combination Concept and Its Experimental Verification." *Water Resources Research*, 2: 445–467.

Vasudev, D., T. Ledder, S. Dushenkov, A. Epstein, N. Kumar, Y. Kapulnik, B. Ensley, G. Huddleston, J. Cornish, I. Raskin, B. Sorochinsky, M. Ruchko, A. Prokhnevsky, A. Mikheev, and D. Grodzinsky. 1996. "Removal of Radionuclide Contamination from Water by Metal-Accumulating Terrestrial Plants." Presentation at the In-Situ Soil and Sediment Remediation Conference, New Orleans, LA.

Viessman, W., G.L. Lewis, and J.W. Knapp. 1989. *Introduction to Hydrology, 3rd Edition*. Harper & Row Publishers, New York, NY.

Wood, T.K., H. Shim, D. Ryoo, J.S. Gibbons, and J.G. Burken. 2000. "Root-Colonizing Genetically-Engineered Bacteria for Trichloroethylene Phytoremediation." Presentation at the 2nd International Conference on Remediation of Chlorinated and Recalcitrant Compounds, May 22–25, Monterey, CA.

Zhang, Q., L. Davis, and L. Erickson. 2000. "Transport of Methyl Tert-Butyl Ether (MTBE) Through Alfalfa Plants." Presentation at USEPA Phytoremediation State of the Science Conference, May 1–2, Boston, MA.

APPENDIX A

Groundwater Capture and Transpiration Rates

Groundwater Capture and Transpiration Rates

The information in this Appendix is from Schnoor, 1998.

A simple capture zone calculation (Domenico and Schwartz, 1997) can be used to estimate whether the phytotechnology pump can be effective at entraining the plume of contaminants. Trees can be grouped for consideration as average withdrawal points. The goal of the phytotechnology effort is to create a water table depression where contaminants will flow to the vegetation for uptake and treatment. Organic contaminants are not taken up at the same concentration as in the soil or groundwater, rather there is a transpiration stream concentration factor (a fractional efficiency of uptake) that accounts for the partial uptake of the contaminant (due to membrane barriers at the root surface). The uptake rate is given by the following equation:

$$U = (TSCF)\ (T)\ (C) \tag{1}$$

where

U = uptake rate of the contaminant, mg/day
TSCF = transpiration stream concentration factor, dimensionless
T = transpiration rate of vegetation, L/day
C = aqueous-phase concentration in soil water or groundwater, mg/L.

If the plants do not take up the dissolved contaminants, then the plume that emerges may become concentrated (i.e., the mass of contaminant in the plume will be the same, but the concentration remaining will actually be greater due to the reduction in water volume by vegetation). This is a potential concern during the application to groundwater plumes or created wetlands, where a relatively hydrophilic contaminant can be concentrated on the downstream side of the phytotechnology system.

A method for estimating the Transpiration Stream Concentration Factor (TSCF) for Equation (1) is given in Table A-1. The Root Concentration Factor is also defined in Table A-1 as the ratio of the contaminant in roots to the concentration dissolved in soil water (µg/kg root per µg/L). It is important in estimating the mass of contaminant sorbed to roots in phytotechnology systems.

Mature phreatophyte trees (poplar, willow, cottonwood, aspen, ash, alder, eucalyptus, mesquite, bald cypress, birch and river cedar) typically can transpire 3 to 5 acre-feet of water per year (36–60 inches of water per year). This is the equivalent to about 600 to 1,000 gallons of water per year for a mature species planted at 1,500 trees per acre. Transpiration rates in the first two years would be somewhat less, about 200 gallons per tree per year, and hardwood trees would transpire about half the water of a phreatophyte. Two meters of water per year is a practical maximum for transpiration in a system with complete canopy coverage (a theoretical maximum would be 4 m/yr based on the solar energy supplied at 40^0N on a clear day which is required to evaporate water).

If evapotranspiration of the system exceeds precipitation, it is possible to capture water that is moving vertically through soil. Areas that receive precipitation in the wintertime (dormant season for deciduous trees) must be modeled to determine if the soil will be sufficiently dry to hold water for the next spring’s growth period. The Corps of Engineers HELP model (Waterways Experiment Station, Vicksburg, Mississippi) and other codes have been used to estimate vertical water movement and percolation to groundwater.

Table A-1 estimates the Transpiration Stream Concentration Factor (TSCF) and Root Concentration Factor (RCF) for Some Typical Contaminants (from Burken and Schnoor, 1997). The TSCF and RCF for metals depend on their redox state and chemical speciation in soil and groundwater.

Table A-1 Transpiration Stream Concentration Factor (TSCF) and Root Concentration Factor (RCF).

Chemical	**$^{+}$Log K_{ow}**	**$^{+}$Solubility – Log C_w^{sat}@ 25^0C, (mol/l)**	**$^{+}$Henry's Constant K_H, @25^0C (dimensionless)**	**$^{+}$Vapor Pressure –Log P_0 @ 25^0 C (atm)**	**Transpiration Stream Concentration Factor (TSCF)***	**Root Concentration Factor RCF$^{\#}$ (L/kg)**
benzene	2.13	1.64	0.2250	0.90	0.71	3.6
toluene	2.69	2.25	0.2760	1.42	0.74	4.5
ethylbenzene	3.15	2.80	0.3240	1.90	0.63	6.0
m-xylene	3.20	2.77	0.2520	1.98	0.61	6.2
TCE	2.33	2.04	0.4370	1.01	0.74	3.9
aniline	0.90	0.41	$2.2\text{x}10^5$	2.89	0.26	3.1
nitrobenzene	1.83	1.77	0.0025	3.68	0.62	3.4
phenol	1.45	0.20	$>1.0\text{x}10^5$	3.59	0.47	3.2
pentachlorophenol	5.04	4.27	$1.5\text{x}10^{4(a)}$	$6.75^{(a)}$	0.07	54
atrazine	2.69	3.81	$1.0\text{x}10^{7(a)}$	$9.40^{(a)}$	0.74	4.5
1,2,4-trichlorobenzene	4.25	3.65	0.1130	3.21	0.21	19
RDX	0.87	4.57	- - -	- - -	0.25	3.1

[+] Physical chemical properties (Schwarzenbach, et al., 1993) unless otherwise noted.

TSCF = 0.75 exp $\{-[(\log K_{ow} - 2.50)^2/2.4]\}$ Burken & Schnoor, 1997.

[#] RCF = 3.0 + exp $(1.497 \log K_{ow} - 3.615)$ Burken & Schnoor, 1997.

(a) Source: (Schnoor, 1996).

Computing Contaminant Uptake Rate and Cleanup Time

From equation (1) above, it is possible to estimate the uptake of rate of the contaminant(s). First-order kinetics can be assumed as an approximation for the time duration needed to achieve remediation goals. The uptake rate should be divided by the mass of contaminant remaining in the soil:

$$k = U/M_0 \tag{2}$$

where

k = first-order rate constant for uptake, yr^{-1}
U = contaminant uptake rate, kg/yr
M_0 = mass of contaminant initially, kg

Then, an estimate for mass remaining at any time is expressed by equation 3 below:

$$M = M_0\ e^{-kt} \tag{3}$$

Solving for the time required to achieve cleanup of a known action level:

$$t = -(\ln M/M_0)/k \tag{4}$$

where

t = time required for cleanup to action level, yr
M = Mass allowed at action level, kg
M_0 = initial mass of contaminant, kg.

EXAMPLES

Equations (1 through 4) can be applied to most sites where soil cleanup regulations are known for metals or organic contaminants. Two examples follow, one for TCE treatment by phytodegradation (phytotransformation) and another for lead removal by phytoextraction, which demonstrates the use of design equations.

Organics—Example 1

TCE residuals have been discovered in an unsaturated soil profile at a depth of 3 meters. From lysimeter samples, the soil water concentration is approximately 100 mg/L. Long cuttings of hybrid poplar trees will be planted through the waste at a density of 1,500 trees per acre for uptake and phytodegradation of the TCE waste. By the second or third year, the trees are expected to transpire 3 acre ft/yr of water (36 in/yr) or about 600 gal/tree per year. Estimate the time required for cleanup if the mass of TCE per acre is estimated to be 1,000 kg/acre, and the cleanup standard has been set at 100 kg/acre (90% cleanup).

$$U = (TSCF)\ (T)\ (C)$$

where

TSCF = 0.74 from Table A-1
$T = (600\ \text{gal/tree-yr})\ (1500\ \text{tree/acre})\ (3.89\ \text{L/gal}) = 3.5\text{x}\ 10^6\ \text{L/acre-yr}$
C = 100 mg/L (given)

$U = 2.59 \times 10^8$ mg/acre-yr = 259 kg/acre-yr
$k = U/M_0$
$k = (259 \text{ kg/yr})/1000 \text{ kg}$
$k = 0.259 \text{ yr}^{-1}$
$t = -(\ln M/M_0)/k$
$t = -(\ln 100/1000)/0.259 \text{ yr}^{-1}$
$t = 8.9$ yr.

Most of the TCE that is taken up by the poplars is expected to volatilize slowly to the atmosphere. A portion will be metabolized by the leaves and woody tissue of the trees.

Metals—Example 2

Lead at a lightly contaminated Brownfield Site has a concentration of 600 mg/kg to a depth of 1 foot. The cleanup standard has been set at 400 mg/kg. Indian mustard (*Brassica juncea*) will be planted, fertilized and harvested three times each for phytoextraction. Using small doses of EDTA, it is possible to achieve concentrations in the plant of 5,000 mg/kg (dry weight basis), and harvestable densities of 3 tons dry matter per crop. Estimate the time required for cleanup.

U = Uptake Rate = (5,000 mg/kg) (9 tons/acre-yr) (908 kg/ton)
= 4.09×10^7 mg/acre-yr = 40.9 kg/acre-yr

M_0 = Mass of Pb in soil at a dry bulk density of 1.5 kg/L
$M_0 = (600 \text{ mg/kg}) (1.5 \text{ kg/L}) (1 \text{ ft}) (43{,}560 \text{ ft}^3\text{/acre-ft}) (28.32 \text{ L/ft}^3) \{10^{-6} \text{ mg/kg}\}$
M_0 = 1,110 kg/acre (initial mass in soil)
M = 740 kg/acre (cleanup standard of 400 mg/kg).

This is assuming zero-order kinetics (constant rate of Pb uptake each year) because EDTA will make the lead continue to be bioavailable to the Indian mustard.

$$T = (M_0 - M)/U = 9.0 \text{ yr}$$

The time to cleanup may actually be somewhat less than 9 years if Pb migrates down in the soil profile with EDTA addition, or if tillage practices serve to "smooth out" hot spots. Regulatory cleanup levels are usually based on a limit that cannot be exceeded, such as 400 mg/kg, and soil concentrations would need to be analyzed to ensure compliance at the end of each year.

APPENDIX B

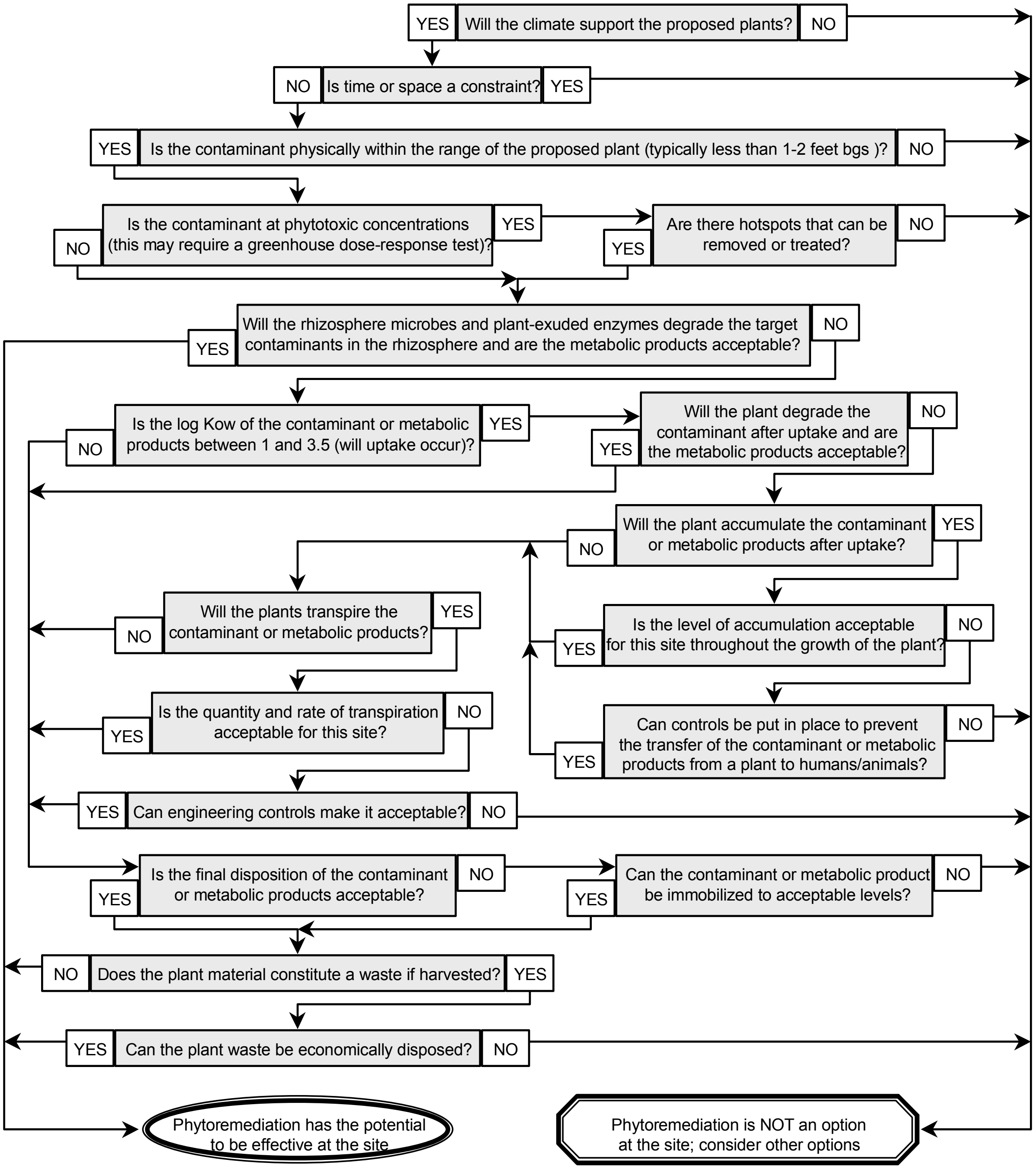
Phytoremediation Decision Trees

Phytoremediation Decision Trees

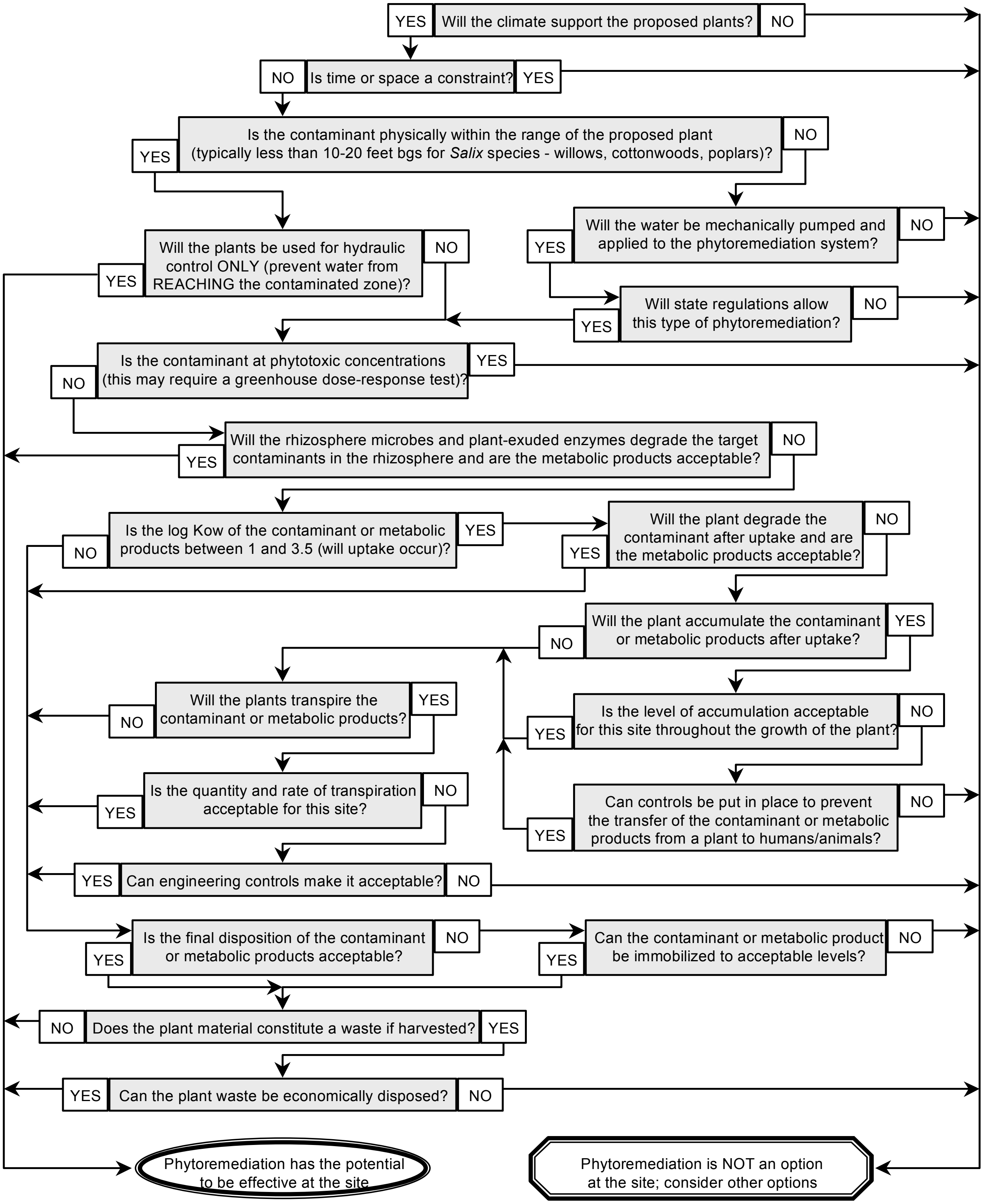
The intent of this Appendix is to provide a tool that can be used quickly to determine if phytotechnologies have the ability to be effective at a given site. The decision trees allow the user to take basic information from a specific site and, through a flowchart layout, decide if phytotechnologies are feasible at that site. These decision trees are from the Interstate Technology Regulatory Cooperation (ITRC) Phytotechnologies Team's 1999 ***Decision Tree Document***.

ITRC's Phytotechnologies Team has provided separate decision trees for three types of contaminated media (i.e., soil, groundwater, and sediments).

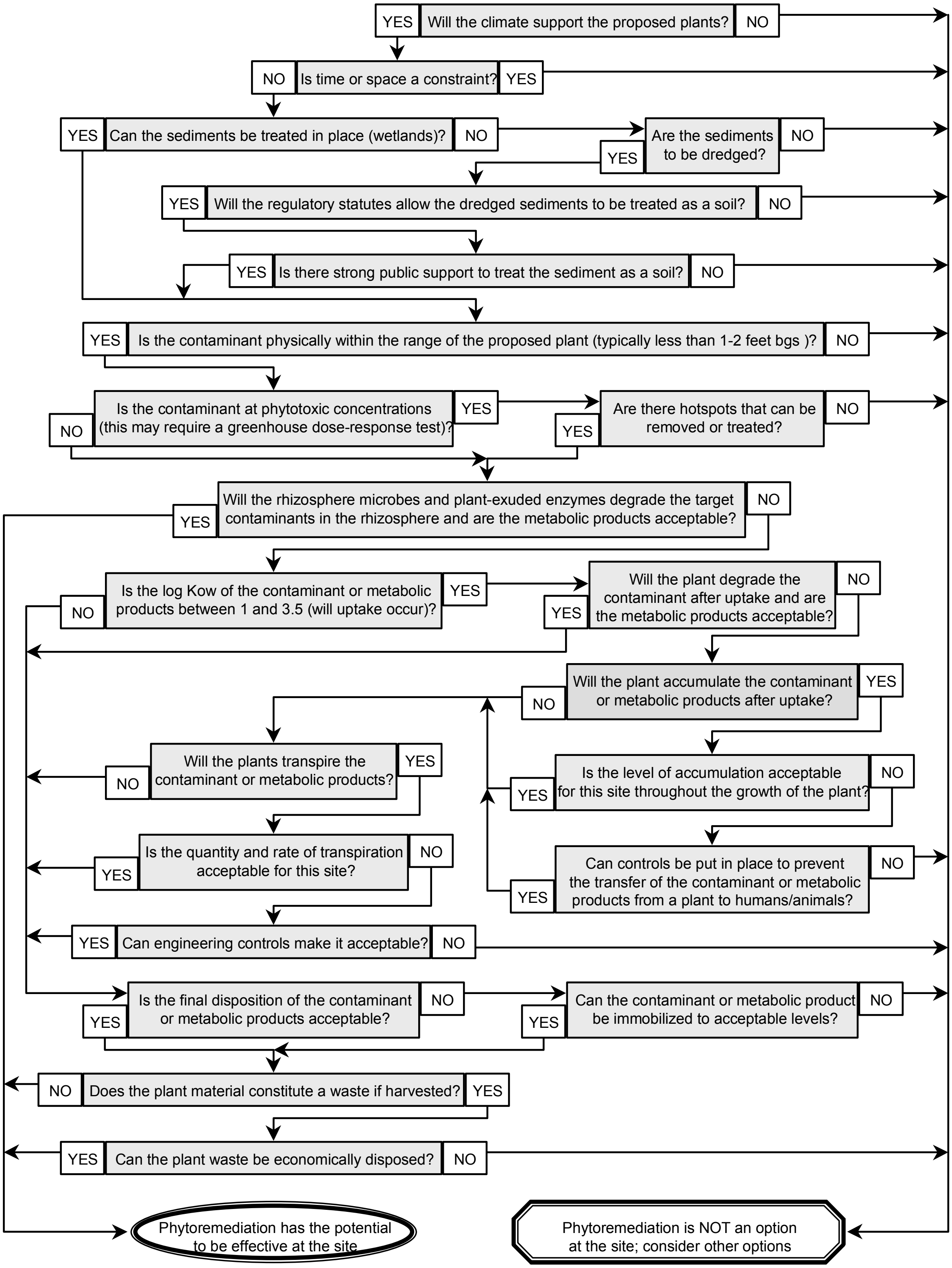
Decision Tree for Phytoremediation
Soil



Decision Tree for Phytoremediation
Groundwater



Decision Tree for Phytoremediation
Sediments



APPENDIX C

Cost Estimates for Phytotechnologies

Cost Estimates for Phytotechnologies

Tables C-1 through C-3 provide three estimates for phytotechnologies versus competing technologies (Schnoor, 1998). In Table C-1, a five-year cost comparison is made for a phytotechnology design versus a pump-and-treat system with reverse osmosis for nitrate-contaminated groundwater. The phytotechnology system is less than half the cost of the pump-and-treat technology.

Table C-1 **Five-Year Cost Comparison of a Phytotechnology System Using Hybrid Poplar Trees Versus Conventional Pump and Treat (Schnoor, 1998)**

Phytodegradation			
	Design and Implementation		$ 50,000
	Monitoring Equipment		
		Capital	10,000
		Installation	10,000
		Replacement	5,000
	5-Year Monitoring		
		Travel and Administration	50,000
		Data Collection	50,000
		Reports (annual)	25,000
		Sample Analysis	50,000
TOTAL			**$250,000**
Pump and Treat (3 wells and Reverse Osmosis System)			
	Equipment		$100,000
	Consulting		25,000
	Installation/Construction		100,000
	5-Year Costs		
		Maintenance	105,000
		Operations (electricity)	50,000
		Waste disposal	180,000
		Waste Disposal Liability	100,000
TOTAL			**$660,000**

Table C-2 Cost Advantage of Phytoextraction for Metals (Schnoor, 1998)

Type of Treatment	Cost/m^3 ($)	Time Required (months)	Additional factors/expense	Safety Issues
Fixation	90-200	6-9	Transport/excavation Long-term monitoring	Leaching
Landfilling	100-400	6-9	Long-term monitoring	Leaching
Soil extraction, leaching	250-500	8-12	5,000 m^3 minimum Chemical recycle	Residue disposal
Phytoextraction	15-40	18-60	Time/land commitment	Residue disposal

Table C-3 Cost Advantage of Phytoremediation (Enhanced Rhizosphere Bioremediation) of Soils Using Fine-Rooted Grasses Compared to Other Techniques (Schnoor, 1998)

Type of Treatment	Range of Costs $/Ton
Phytoremediation	$10–35
In-situ Bioremediation	$50–150
Soil Venting	$20–220
Indirect Thermal	$120–300
Soil Washing	$80–200
Solidification/Stabilization	$240–340
Solvent Extraction	$360–440
Incineration	$200–1,500

APPENDIX D

Case Studies

Evapotranspirative Landfill Cover

1. Site name: Operating Industries, Inc. (OII).
2. Site location: Southern California.
3. Former site use: Landfill.
4. Site Principal Investigator: Jorge Zornberg.
5. Size of area: 25 acres.
6. Climate: Semiarid.
7. Primary contaminant(s) and concentration(s): Various municipal and hazardous waste.
8. Media and properties: Groundwater.
9. Cleanup goals: Protection of groundwater.
10. Performance objectives: Equivalent performance to RCRA cover.
11. Mechanism: Evapotranspiration.
12. Vegetation: Native grasses and other vegetation.
13. Date planted: 1999-2000.
14. Planting technique: Standard seeding.
15. O&M requirements: Irrigation.
16. Monitoring systems: Perimeter groundwater monitoring wells.
17. Regulatory status: Superfund.
18. Project status: First ROD accepting ET cover on Superfund site, construction complete.
19. Results: Monitoring under way.
20. Costs:
21. References:

Vegetative Cover to Rhizodegrade TPH/PAHs in Surface Soils

1. Site name: RTDF phytoremediation of TPH/PAH in surface soils.
2. Site location: Various (11 sites across the U.S., including Alaska).
3. Former site use: Various (petroleum facilities, manufactured gas plants, etc.).
4. Site Principal Investigator: Members of the RTDF phytoremediation subgroup (facility owners, USEPA TIO& ORD, Kansas State University, consultants).
5. Size of Area: Variable; 12 20x20-foot plots – 3 treatments, 4 replicates (minimum).
6. Climate: Variable.
7. Primary contaminant(s) and concentration(s): TPH and PAHs (methylated PAHs optionally analyzed); TPH concentrations range from 1,400 to 45,000 mg/kg (shallow layer) and 600 to 57,000 mg/kg (deep layer); PAH concentrations (as benzo (a) pyrene equivalents) average 72 mg/kg (shallow layer) and 138 mg/kg (deep layer).
8. Media and properties: Variable soil types.
9. Cleanup goals: Local standards.
10. Performance objectives: This is a three-year study into the use of a standardized seed mix planted in different climate and soil conditions to phytoremediate TPH and PAH-impacted surface soils. Fertilized and vegetated plots with the standard mix are compared to site-specific vegetation as well as a do-nothing control. Additional treatments can include fertilizer-only and vegetation-only plots.
11. Mechanism: Rhizodegradation.
12. Vegetation: Fescue, ryegrass, and legume mix standard at each site plus site-specific vegetation ranging from grasses, to herbaceous species, to trees.
13. Date planted: 1999 & 2000.
14. Planting technique: Seeding (with some tree plantings).
15. O&M requirements: Irrigation and fertilization on a site-specific basis.
16. Monitoring systems: Initial samples taken over the entire site to determine individual plot locations; baseline soil samples (0-15 and 15-45 cm) taken at the time of planting; time-series soil samples taken at the end of each season. Samples of vegetation are taken at the end of the three-year study for chemical analyses. Soil microbial sampling and analyses conducted as optional monitoring.
17. Regulatory status: Variable.
18. Project status: Ongoing (but study designed for 3 years).
19. Results:
20. Cost: $40,000 (standard sampling alone); additional cost data compiled for the final report.
21. References: RTDF, 2000

Vegetative Cover to Phytoaccumulate Heavy Metals

1. Site name: Magic Marker.
2. Site location: Trenton, NJ.
3. Former site use: Battery recycling.
4. Site Principal Investigator: Phytotech Inc. (Edenspace Inc.).
5. Size of area: >1 acre.
6. Climate: 40+ inches/year, May-Sept growing season.
7. Primary contaminant(s) and concentration(s): Lead, 24,000- 0 ppm, heterogeneous distribution in top 12" of soil, decreasing dramatically with depth.
8. Media and properties: Soil, and former gravel parking lot. Difficult to till, poor water holding and nutrient characteristics.
9. Cleanup goals: 400 ppm Pb in soil, NJ residential standard.
10. Performance objectives: Accumulate 2% lead in plant material (dry weight), plant three crops each year for two years, and reduce average concentrations from 1,400 to 400 - not targeting the highest concentration areas, which will be removed by excavation.
11. Mechanism: Phytoextraction; uptake into plant shoots and leaves, harvest and disposal of vegetation. Vegetation dried, tested and sent to landfill.
12. Vegetation: Indian mustard and sunflower.
13. Date planted: 1997 & 1998.
14. Planting technique: Standard agricultural cropping techniques with chelate addition before harvest.
15. O&M requirements: Irrigation system installed.
16. Monitoring systems: Pre- and postseason sampling and analysis.
17. Regulatory status: City-owned Brownfield site. Former owner not able to pay taxes, so property reverted to city.
18. Project status: Complete.
19. Results: Phytotech was able to achieve plant concentrations as anticipated, and to reduce concentration in top 12 inches of soil. Only two crops per season for two seasons were fielded due to weather. Soil concentrations were reduced in some area, though results were not consistent across site. Some concern about dilution through tilling. Generally considered a successful project.
20. Cost: $150,000 (developer estimate).
21. References:

Hydraulic Barrier to Phytostabilize Chlorinated Solvents

1. Site Name: J-Field Poplar Grove
2. Site Location: Aberdeen Proving Ground, MD.
3. Former Site Use: Open Burning Pit for chemical contained weapons and unusable chemicals.
4. Site Principal Investigator: U.S. Environmental Protection Agency Region III Environmental Response Team.
5. Size of Area: 1 acre.
6. Climate: 37+ inches/ year, May-Sept growing season.
7. Primary Contaminant(s) and Concentration(s): 1,1,2,2-tetrachloroethane, 170,000 ppb; TCE, 61,000 ppb; Cis-1,2-Dichloroethene, 13,000 ppb; PCE, 9,000 ppb; Trans-1,2-dichloroethene, 3,900 ppb; and 1,1,2-trichloroethane, 930 ppb.
8. Media and Properties: Variable Soils. High water table in coastal plain deposits.
9. Cleanup Goals: Institutional control of the area, Monitored Natural Attenuation, and Phytotechnologies.
10. Performance Objectives: The main remedial reductions in contaminant levels are to be accomplished by long-term natural attenuation of the plume. The objective of the phytotechnology portion of the project was to contain the contaminants and prevent further migration.
11. Mechanism: Phytostabilization.
12. Vegetation: Popular Trees.
13. Date Planted: 1996.
14. Planting Technique: The trees were planted by augering to a depth of 10 feet, lining the hole with plastic on the hole walls to encourage downward growth, and backfilling the hole with a soil fertilizer mixture. This procedure led to an increased susceptibility for the trees to lodge in moderate wind speeds.
15. O&M Requirements: Spring and fall fertilization are the only maintenance requirements.
16. Monitoring Systems: semiannual sampling and analysis.
17. Regulatory Status: Active military installation.
18. Project Status: ongoing.
19. Results: Phytotech was able to achieve containment during the growing season along with some degradation of the contaminants. Generally this project is considered successful.
20. Cost: $90/tree (purchase and planting of trees). This is considered high but necessary due to the possibility of encountering unexploded ordnance during the planting.
21. References:

Tree Stands to Phytostabilize and Phytoaccumulate Heavy Metals and Salts

1. Site Name: C-Plant (Area H)
2. Site Location: Texas City, TX.
3. Former Site Use: None (groundwater impact from neighboring site)
4. Site Principal Investigator: BP Amoco, Phytokinetics, KMA Environmental.
5. Size of Area: 22 acres.
6. Climate: 45+ inches/year, Feb. to Nov. growing season.
7. Primary Contaminant(s) and Concentration(s): Salts: Na, Ca, and Mg chlorides up to 3x seawater salinity levels (110 mmhos/cm); Heavy Metals: Cd, Cu, and Pb above MCLs.
8. Media and Properties: Heavy Clay Soils.
9. Cleanup Goals: Institutional Control of the Area, Barrier Wall, and Phytotechnologies.
10. Performance Objectives: Impacted groundwater that migrates off site will be addressed under the voluntary cleanup program. Institutional Controls and Barrier Walls installed to prevent movement and cut off the incoming plume from neighboring site. Phytotechnologies are being investigated as potential measures that may be installed should off-site migration occur.
11. Mechanism: Phytostabilization and phytoaccumulation.
12. Vegetation: Eucalyptus and Salt Cedar Trees.
13. Date Planted: 1999 (field trial).
14. Planting Technique: The trees were planted by augering to a depth of 20 feet, backfilling the hole with a mixture of sand, peat, and fertilizer to create a conduit for root growth and promote the up-welling of groundwater (to ~5 ft bgs). Drip-irrigation system installed with each test tree to maintain dilution of high-saline groundwater to tolerable levels.
15. O&M Requirements: Maintain drip-irrigation system
16. Monitoring Systems: Field trial: sap flow sensors, excavation of tree to determine root penetration, isotope ratio study to determine groundwater vs. rainwater uptake
17. Regulatory Status: Texas Natural Resources Conservation Commission Voluntary Cleanup Program.
18. Project Status: Greenhouse studies completed, field trials ongoing.
19. Results: Salinity up to 2x seawater levels (66 mmhos/cm) tolerated by trees. Cd and Pb phytostabilized in root zone while salts phytoaccumulated into terrestrial plant tissues.
20. Cost: $390,000 including greenhouse, field trials, and full-scale implementation (if required)
21. References: Tsao, 1998; Thomas, et al., 1998

Wetland Treatment System to Phytodegrade Explosive Residues

1. Site name: Milan Army Ammunition Plant.
2. Site location: Milan, Tennessee.
3. Site use: Ammunitions, artificial wetlands.
4. Site Principal Investigator: Darlene Bader.
5. Size of area: Two constructed wetland systems: Gravel Bed Lagoon Cell 1 36' x 106'; 2 Cells @ 31' x 78'; Cell 2 36'x 36'.
6. Climate:
7. Primary contaminant(s) and concentration(s): TNT (1.8 mg/L), RDX (2.2 mg/L), HMX (0.13 mg/L).
8. Media and properties: Groundwater and sediments.
9. Cleanup goals: >90% removal.
10. Performance objectives:
11. Mechanism: Phytodegradation.
12. Vegetation: Canarygrass; elodea; woolgrass; water stargrass; sweetflag; sago pondweed; parrot-feather.
13. Date planted: June 1996.
14. Planting technique:
15. O&M requirements:
16. Monitoring systems:
17. Regulatory status:
18. Project status:
19. Results:
20. Costs:
21. References:

Riparian Buffer for Non-Point Pollution Control

1. Site name: Amana.
2. Site location: Amana, Iowa.
3. Site use: agricultural field.
4. Site Principal Investigator: Lou Licht.
5. Size of Area: 1,000 ft corridor.
6. Climate: 35 inches of rain.
7. Primary contaminant(s) and concentration(s): Herbicides, pesticides, excess fertilizer.
8. Media and Properties: Surface and shallow groundwater.
9. Cleanup Goals: Protect stream from Ag chemicals and nutrients.
10. Performance Objectives: Drinking water quality in stream.
11. Mechanism: Rhizofiltration in riparian buffer.
12. Vegetation: Hybrid poplar trees.
13. Date planted: 1989.
14. Planting technique: Trench with bare root whips 4-6 feet long, four rows 8 feet apart.
15. O&M Requirements: Minimal.
16. Monitoring systems: Screened wells between tree rows, grab samples from stream.
17. Regulatory status: Voluntary.
18. Project status: Ongoing.
19. Results: Successful in achieving water quality goals.
20. Cost:
21. Reference

APPENDIX E

Acronyms

Acronyms

AOC	Area of Contamination
ARAR	Applicable or Relevant and Appropriate Requirement
ASTM	American Society for Testing and Materials
BCF	Bio-Concentration Factor
bgs	below ground surface
BTEX	Benzene, Toluene, Ethylbenzene, and (o-, m-, p-) Xylenes
CAMU	Corrective Action Management Unit
CEC	Cation Exchange Capacity
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CFU	Colony Forming Units
EC	Electrical Conductivity
ECOS	Environmental Council of the States
EDTA	Ethylene Diamine Tetra-acetic Acid
EPIC	Erosion/Productivity Impact Calculator
ERIS	Environmental Research Institute of the States
ET	Evapo-Transpiration
FFDCA	Federal Food, Drug, and Cosmetic Act
FIFRA	Federal Insecticide, Fungicide and Rodenticide Act
GC/MS	Gas Chromatography/Mass Spectrometry
gpd	gallons per day
ITRC	Interstate Technology and Regulatory Cooperation Work Group
HAZWOPER	Hazardous Waste Operations and Emergency Response
HELP	Hydrologic Evaluation of Landfill Performance
HW	Hazardous Waste
LAI	Leaf Area Index
MSW	Municipal Solid Waste
MTBE	Methyl Tertiary-Butyl Ether
NPDES	National Pollutant Discharge and Elimination System
NESHAPS	National Emissions Standards for Hazardous Air Pollutants
NPL	National Priorities List

OSHA	Occupational Safety and Health Administration
PAH	Polycyclic Aromatic Hydrocarbon
PCE	Per-Chloro-Ethylene
PPE	Personal Protective Equipment
QA/QC	Quality assurance/Quality Control
RCF	Root Concentration Factor
RCRA	Resource Conservation and Recovery Act
ROD	Record of Decision
RTDF	Remediation Technologies Development Forum
SSEB	Southern States Energy Board
SVE	Soil Vapor Extraction
TBA	Tertiary Butyl Alcohol
TCE	Tri-Chloro-Ethylene
TCLP	Toxicity Characteristics Leaching Procedure
TDS	Total Dissolved Solids
TNT	Tri-Nitro-Toluene
TSCA	Toxic Substances Control Act
TSCF	Transpiration Stream Concentration Factor
U.S.C.	United States Code
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
UST	Underground Storage Tank
UV	Ultra-Violet
VOC	Volatile Organic Compound
WGA	Western Governors' Association

APPENDIX F

ITRC Contacts, ITRC Fact Sheet, ITRC Product List, and User Survey

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