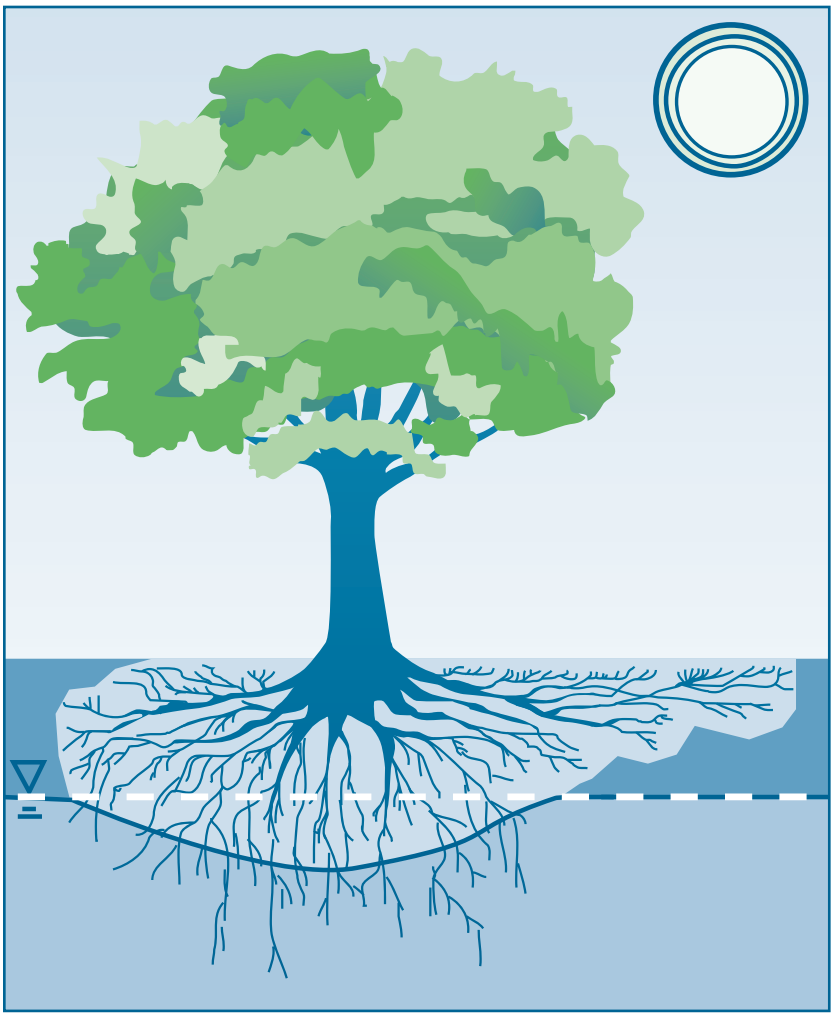
Technical/Regulatory Guidance

Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised



February 2009

Prepared by
The Interstate Technology & Regulatory Council
Phytotechnologies Team

Tech Reg Update

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PHYTO-3

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We appreciate the patience of the team members, EPA, and ITRC during this process and will pass on our lessons learned for updating ITRC guidance documents.

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EXECUTIVE SUMMARY

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

This document provides guidance for regulators, who evaluate and make informed decisions on phytotechnology work plans, and for practitioners, who have to evaluate any number of remedial alternatives at a given site. This document is an update to *Phytoremediation Decision Tree* (PHYTO-1, 1999) and *Phytotechnology Technical and Regulatory Guidance Document* (PHYTO-2, 2001) and replaces the previous documents entirely. It merges the concepts of both previous documents and includes new and, more importantly, practical information on the process and protocol for selecting and applying various phytotechnologies as remedial alternatives.

The technical descriptions of phytotechnologies in this document concentrate on the functioning mechanisms: phytosequestration, rhizodgradation, phytohydraulics, phytoextraction, phytodegradation, and phytovolatilization. For example, the application of phytotechnologies as a hydraulic control for groundwater is described as phytohydraulics (transpiration). This approach was selected to provide both scientific accuracy and a basic understanding of these mechanisms to the reader. Decision trees (Remedy Selection, Groundwater, Soil/Sediment, and Riparian Zone) help guide the user through the application of phytotechnologies to a remediation project.

Frequently Asked Questions and Rules of Thumb ( )

Often, the best response that can be provided to some of the most common questions encountered about phytotechnologies is, "It depends…." Many factors influence phytotechnologies, such as soil conditions, climate, suitable plant species, and associated rhizosphere microbes. Therefore, every project is unique and must be custom designed, installed, and operated. The following answers to frequently asked questions provide a brief, generalized understanding and direct the reader to the relevant sections of the document for further information.

> During the implementation/ growth stage of a remediation project using phytotechnologies, the project should clearly focus on managing potential exposure.

Mechanisms

Q: What is the difference between the terms "phytoremediation" and "phytotechnologies"?
From the regulatory perspective, cleanup goals can be remediation, containment, or both. Phytotechnologies include containment strategies in addition to (phyto-)remediation strategies. Other remedial goals also include prevention, polishing, and restoration/end use (Section 2.2.1).

Q: How do phytotechnologies work?
They use vegetation to sequester, extract, or degrade toxic chemicals located in soils, sediments, groundwater, surface water, and air. There are six major mechanisms associated with phytotechnologies: phytosequestration, rhizodegradation, phytohydraulics, phytoextraction, phytodegradation, and phytovolatilization (Section 1.2).

Q: What contaminants can be treated with phytotechnologies?
Typical organic contaminants ("organics") such as petroleum hydrocarbons, gas condensates, crude oil, chlorinated compounds, pesticides, and explosive compounds can be remediated using phytotechnologies. Typical inorganic contaminants ("inorganics") that can be addressed include salts (salinity), heavy metals, metalloids, and radioactive materials. Extensive databases are available covering a wide range of contaminants treated using phytotechnologies (Section 2.3.1).

Q: Do the plants become contaminated in this process?
For organic contaminants, the octanol-water partition coefficient (log K_{ow}) typically needs to be between 1 and 3.5 for uptake by plants to occur (Section 1.2.4). For inorganic contaminants, including essential plant nutrients, uptake is specific to the element and plant species (Sections 1.1.1 and 1.2.3). According to the current research, there is little or no accumulation of volatile contaminants in plant roots, wood, stems, leaves, or fruit. Plants may accumulate metals or other toxic materials that reach contaminated levels, but several mechanisms exist that often limit the uptake and/or persistence of nonessential compounds in the plant (Sections 1.2 and 2.5.1.3).

Q: Do plants release contaminants into the air? If so, how much and how often?
Possibly; there is an established mechanism known as phytovolatilization (Section 1.2.6) whereby volatile chemicals are taken up by a plant and released through leaf surfaces. However, extensive samplings in the field show that minimal amounts of volatile contaminants are emitted from plants (Section 2.5.3.3).

Q: If fruit and nuts are produced, are they safe for humans and animals?
Probably, but test them to be sure (Section 2.5.3.3).

Efficacy

Q: Will phytotechnologies work on my site?
It depends; however, decision tees have been developed which will help to determine whether a phytotechnology would be applicable at a site (Section 2.3.2)

Q: How deep do plant roots grow?
Typical rooting depths for herbaceous, upland species such as grasses and forbs are 1–2 feet; however, depths down to 5 feet have been reported as within the range of influence under some situations (Section 1.3). Furthermore, prairie grasses have root systems that can reach 10–15 feet below ground surface (bgs). Regardless, in general, 70%–80% of the root structure will be within the top 1–2 feet of soil (including tap-rooted species) with exploratory roots sent deeper and laterally. However, local soil conditions (nutrient content, moisture, compaction, etc.) will dictate the ultimate depth to which any plant will reach. Furthermore, the depth of penetration may

progress as the plants grow year over year (Section 2.3.2.3). For wetland species, typical depths are less than 1 foot due to oxygen limitations (Section 1.3). For trees, typical depths are 10–15 feet but often require special culturing practices (Section 2.4.3.2). Typical penetrations can be 3–5 feet per year when planted into a borehole or trench. The maximum practical depth is generally down to 25 feet bgs using these practices, although deeper depths can be reached under certain circumstances. The deepest influence of a phytotechnology system was measured at 40 feet bgs. A general rule of thumb, however, is that trees will not access deeper than 5 feet into the saturated zone (Section 2.3.2.2).

Q: How fast do plants grow? How long do they live?
Plant growth rate and longevity depend on species, soil, and climate. "Annual" species grow and die within a single season. Others, such as trees and other herbaceous perennials, continue to grow over years. Fast-growing species such as hybrid poplars can grow 5–10 feet (2–3 m) per year in the first few years. However, in general, those species that grow rapidly tend to be shorter lived (Section 2.5.2.1).

Q: How long does it take for the system to become effective?
In some cases, the application of phytotechnologies can have an immediate effect on contaminant concentrations upon planting. In other cases, it may require several seasons before the plant can interact with a contaminated zone at depth. Furthermore, it may depend on whether the plant itself is directly or indirectly involved with remediating the contaminant (i.e., phytodegradation or simply stimulating biodegradation in the rhizosphere—rhizodegradation; Section 1.2).

Q: What happens in winter when the plants are dormant?
Water consumption and contaminant uptake essentially stop when plants are dormant. Degradation by microbes and the rhizosphere effect continue but at a reduced rate. Efforts to estimate the rate of remediation should account for the dormant conditions (Section 2.4.1).

Q: How long until cleanup is achieved?
It depends on the criteria set forth in defining the cleanup objectives for the site. Furthermore, it depends on the type, extent, and concentration of contamination, continuing sources, obstructions, soil conditions, hydrologic/groundwater conditions, and other site characteristics, the plant species, growth rate, and climate conditions (Section 2.2). Complete restoration will depend on the type of phytotechnology applied at the site (Section 1.3).

Design and Implementation

Q: Which plant species should be used? How are plants selected for a remediation?
All plant selections must be made based on site-specific conditions. Climate, altitude, soil salinity, nutrient content, fertility, location, depth, concentration of contaminant, commercial availability, plantability, and plant hardiness are some of the determining elements (Sections 2.3.1 and 2.4.3). A variety of approaches and information resources can be used, including databases, site-specific vegetation surveys, and specifically designed tests to evaluate species (Section 2.3.1 and Figure 2-1). In addition to selecting species for the remediation, end-use

considerations can be included in the initial plant selection (Section 2.3.4). Typically, 10%–15% climax species might be included in the initial design.

Q: When should planting be done?
Planting season is generally in the early spring (after the last frost), the most desirable period to establish a phytotechnology system (Section 2.2.3.2). Seeding should be done whenever is most appropriate for the species, also typically in the early spring (Section 2.4.3.1). Tree cuttings for propagation should be taken while the source tree is still in winter dormancy and should be maintained dormant (stored under refrigerated conditions) until planted into the ground. In many cases, survivability hinges on the timing of the planting, which should be planned appropriately in the design.

Q: How much or how much area should be planted?
It depends on the extent of contamination and the characteristics of the site (Section 2.2.2). A general rule of thumb for a very preliminary design during the remedy selection phase of a project is a planting density of 75 ft^2 per tree (Section 2.3.2.2). Seeding rates for common grass species (ryegrass, fescue, etc.) are typically higher than prairie species. For example, 400 pounds of a fescue/perennial ryegrass seed mix is needed to cover one acre, while only 10 pounds of a prairie grass seed mix is needed to cover the same acre. The spacing between potted plants depends on the size of the specimens, but for plants that come in palettes, typically 1–2 feet, greater for larger specimens (Section 2.4.3.1). A standard landscaping rule of thumb is that 10% of recently planted trees or potted plants will not survive the first year (Section 2.5.4).

Q: How much does it cost?
It depends. Various cost items will need to be considered, such as earthwork, labor, planting stock, planting method, field equipment, heavy machinery (typically farming or forestry equipment), soil amendments, permits, water control infrastructure, utility infrastructure, fencing, security, etc. (Section 2.4).

Operation, Maintenance, and Monitoring

Q: Isn't this just a "Do something quick and cheap in the field and then walk away" approach?
No. Like any remediation system, phytotechnologies require significant operation, maintenance, and monitoring for several years after planting. Costs can include labor, sampling, analytical, materials, field equipment, utilities, waste handling, and disposal. Once the plantation becomes established, however, the operation and maintenance (O&M) costs tend to diminish (Section 2.5). Furthermore, additional sampling and monitoring will typically be required during the initial phases compared to subsequent years. Phytotechnologies are generally long-term remedial solutions.

Q: What do you have to do for operations and maintenance?
Phytotechnology plantations may require irrigation, fertilization, weed control (mowing, mulching, or spraying), and pest control. At the onset of a planting, which too may be a reoccurring O&M event, some percentage of replanting may be required due to the lack of

establishment. As a general rule of thumb, 10%–15% of the initial capital costs should be added as a contingency for replanting.

Q: In general how much water is required?
A general rule of thumb is that during establishment (i.e., before trees have reached a groundwater source) and perhaps throughout the growth of the vegetation (i.e., groundcover systems), plants should receive a total of 1–2 inches of water per week, including both precipitation and supplemental irrigation (Section 2.4.2.2). Another rule of thumb for a very preliminary design during the remedy selection phase of a project is that a tree plantation uses 10 gal per day per tree, annualized over the year (Section 2.3.2.2).

Q: When should fertilization be done? What fertilizers should be used?
Typically, regular fertilizations can be done in early spring to help the new growth and in late fall to prepare the vegetation for winterization. The formulation of the fertilizer depends on the site-specific soil conditions (Tables 2-9 to 2-11). Soil fertility can be analyzed by a local agriculture extension service using established methods (Table 2-12).

Q: What happens if the plants die as a result of a natural catastrophe or infestation?
If the plants die or are damaged, the beneficial effects are lost or greatly diminished. However, the effect can be temporary, depending on the ability of the vegetation to regrow. Contingency plans should be established for different degrees of loss (Section 2.5.3.4).

Q: If plants have to be harvested, how can one tell whether or not a plant is safe?
Analysis of plant and core tissue sampling (leaves and stems) can determine whether the plant is safe (Section 2.5.3.3).

Q: What is the easiest tissue to sample?
The aboveground tissues such as leaves, needles, stems, branches, and fruits/seeds/nuts are easiest. These are collected simply by pulling or cutting sufficient material from the plant and storing it in sealed plastic bags. For most analyses, samples of 20 g dry weight (10–15 average leaves) should be sufficient. As general rules of thumb, to estimate the wet-to-dry weight ratio for field sample collection, green stems typically contain 95% water weight, leaves 90%, fruits 85%, hardwood stems 50%, and nuts and seeds 5%. Once collected, the tissues should be stored on ice for transport to the laboratory (Section 2.5.3.3).

Q: Is the harvested material usable for commercial payback?
Yes, but it may depend on the use, harvested material, and contaminant. The material may need to be tested (Section 2.5.3.3).

Q: How do you know it is working?
Phytotechnology systems should be monitored using the same primary lines of evidence as any other alternative (i.e., concentration trends, hydrology, soil effects, etc.). That information may need to be supported by secondary lines of evidence, which generally entail analyzing the plants in some manner (Sections 2.5.2 and 2.5.3).

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1. DESCRIPTION OF PHYTOTECHNOLOGIES

Phytotechnologies use plants to remediate various media impacted with different types of contaminants. While phytotechnologies are typically applied in situ, hydroponics allows for ex situ application. Typical organic contaminants ("organics") such as petroleum hydrocarbons, gas condensates, crude oil, chlorinated compounds, pesticides, and explosive compounds can be remediated using phytotechnologies. Typical inorganic contaminants ("inorganics") that can be addressed include salts (salinity), heavy metals, metalloids, and radioactive materials. Phytotechnologies can potentially treat soils, sludge, sediments, groundwater, surface water, wastewater, and storm water. This document includes guidance for remediating soils, sludge, sediments, groundwater, and storm water. The reader is also referred to other Interstate Technology & Regulatory Council (ITRC) guidance for wastewater, surface water, and storm water control (ITRC 2003b, 2005a). Likewise, the reader is referred to similar ITRC guidance on alternative waste containment and management strategies (ITRC 2003c, 2003d, 2006a, 2006b).

The particular phytotechnology mechanisms used to address contaminants depend not only on the type of contaminant and the media affected, but also on the cleanup goals. Typical goals include containment through stabilization or sequestration, remediation through assimilation, reduction, detoxification, degradation, metabolization or mineralization, or both. To achieve these goals, the proper phytotechnology system must be selected, designed, developed, implemented, and operated using detailed knowledge of the site layout, soil characteristics, hydrology, climate conditions, analytical needs, operation and maintenance (O&M) requirements, economics, public perspective, and regulatory protection of the environment.

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

1.1 Basic Plant Physiology

Plants typically grow by sending their roots into the soil and producing leaf and woody material (Figure 1-1). To accomplish these basic growth habits (Taiz and Zeiger 1991), plants use carbon dioxide to harvest light energy, convert it into chemical energy, and produce carbon biomass through the processes of photosynthesis in the leaves and cellular respiration. Plants also take up liquid water and dissolved inorganic nutrients through the root system, transport them throughout the plant in the xylem, and transpire the water through the leaves as vapor. While carbon dioxide and water vapor are being exchanged, oxygen is also being released to the environment. Likewise, photosynthetic chemicals (photosynthates or phytochemicals) are transported throughout the plant in the phloem, even into the root to be exuded into the surrounding soil. The upward transport in the xylem and downward transport in the phloem, collectively termed "translocation," depend on the continuous water column that exists throughout the plant. Each

biological process contributes to the remediation or containment of contaminants as described in the following subsections.

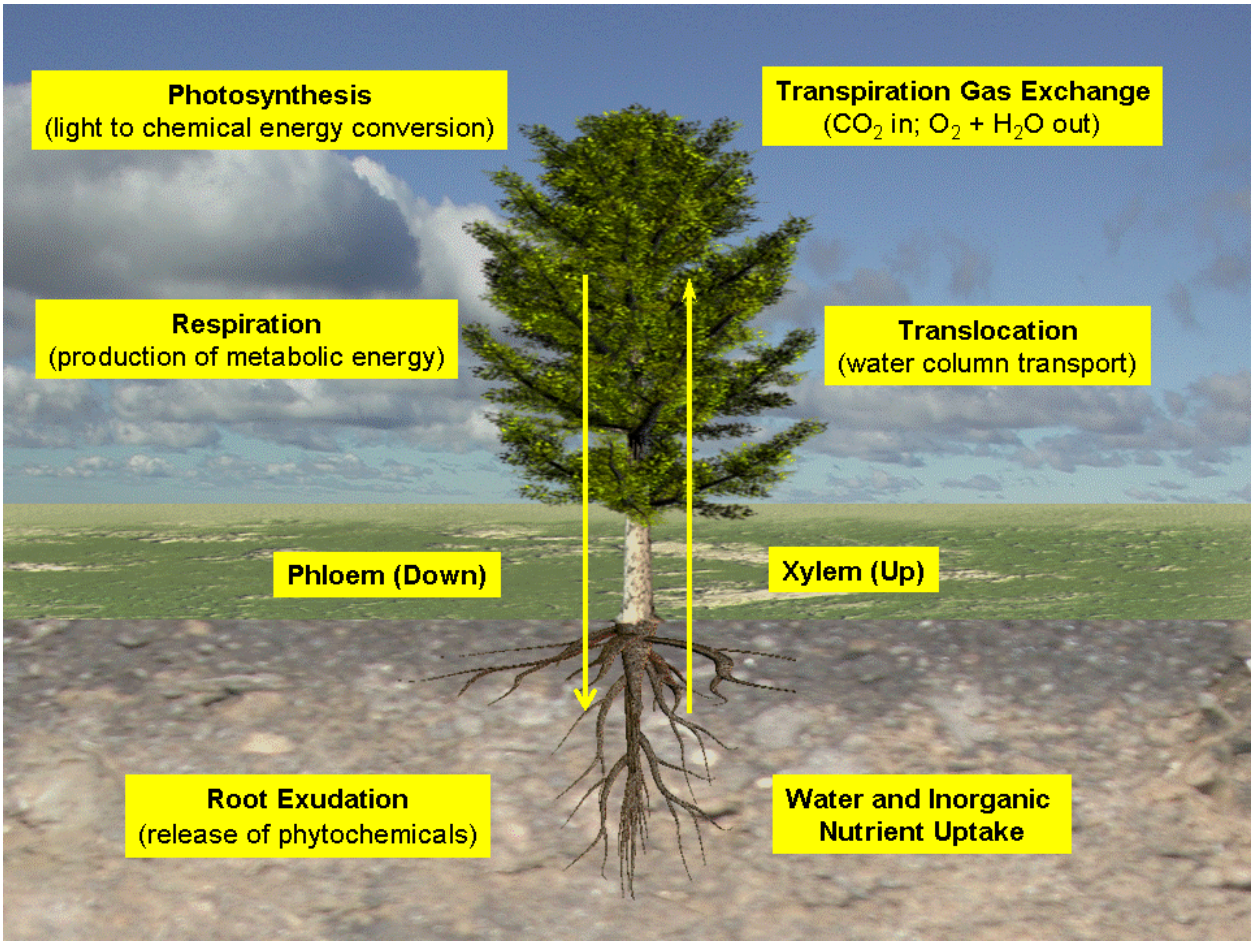


Figure 1-1. Plant physiological processes.

1.1.1 Inorganic Nutrition

Thirteen 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 (Table 1-1). 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 (xylem).

In addition to these essential nutrients, other nonessential inorganics such as various common contaminants (salts, 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. These processes are relevant to phytoextraction (see Section 1.2.4) and certain applications of phytoremediation groundcovers (see Section 1.3.3). 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 transport into the more sensitive tissues of the plant. These processes are relevant to phytosequestration mechanisms (see Section 1.2.1) and certain phytostabilization covers (see Section 1.3.1).

Table 1-1. Typical plant tissue concentrations and available forms of essential nutrient elements

	Nutrient element	Symbol	Tissue concentration (ppm)	Available forms
Organic biomass	Carbon	C	450,000	CO_2
	Oxygen	O	450,000	CO_2, H_2O
	Hydrogen	H	60,000	H_2O
Inorganic macronutrients	Nitrogen	N	15,000	NO_3^{2-}, NH_4^+
	Potassium	K	10,000	K^+
	Calcium	Ca	5,000	Ca^{2+}
	Phosphorus	P	2,000	HPO_4^{2-}, $H_2PO_4^-$
	Magnesium	Mg	2,000	Mg^{2+}
	Sulfur	S	1,000	SO_4^{2-}
Inorganic micronutrients	Iron	Fe	100	Fe^{2+}, Fe-chelate
	Chlorine	Cl	100	Cl^-
	Manganese	Mn	50	Mn^{2+}

1.1.2 Photosynthetic Production of Plant Materials

Photosynthesis is the conversion of light energy into chemical energy and consists of two light-induced reaction centers, photosystem I and II (PSI, PSII). These centers operate at 700 and 680 nm (far red and red light), respectively, by harvesting light energy through chlorophyll and other carotenoids. During the reactions of PSI, a strong reductant (P700*, Eh –1.3V) and a weak oxidant (P700, Eh +0.48V) are produced, while PSII produces a strong oxidant (P680, Eh +1.1V) and a weak reductant (P680*, Eh –0.78V). These processes are relevant to phytodegradation mechanisms (see Section 1.2.5) and both phytoremediation groundcover (Section 1.3.3) and tree stand (Section 1.3.5) applications. Furthermore, there is a chain of intermediate electron acceptor/donor compounds with varying redox potentials that facilitate the photosynthetic reactions. The ultimate electron donor in the photosynthetic process is water taken up through the process of transpiration (see Section 1.1.3).

Atmospheric carbon dioxide enters plants through stomata (microscopic openings in the leaves) and is incorporated into plant chemicals (phytochemicals) using the reductants generated during photosynthesis. The carbohydrate (CHO) skeleton and energy needed to produce these phytochemicals are generated during respiration when plant sugars and starches (also phytochemicals generated in photosynthesis) are oxidized to liberate the stored energy. While respiration is often thought of as the opposite of photosynthesis, the net gain in phytochemicals between production in photosynthesis and consumption in respiration is approximately 25%–75% of the original carbon from CO_2, depending on the species and environmental conditions. This net carbon gain, plus the metabolic energy from respiration, is used to produce biomass,

transport nutrients (see Section 1.1.1), and reproduce. The excess oxygen is released through the leaf stomata (countercurrent to the carbon dioxide influx). The interrelation between photosynthesis, respiration, and metabolism is shown in Equations (1-1) to (1-3), respectively.

Photosynthesis:

Light energy + CO_2 + H_2O + CHO skeleton $\rightarrow$ chemical energy (as a phytochemical) + O_2 (1-1)

Respiration:

Phytochemical (stored chemical energy) + O_2 $\rightarrow$ CHO skeleton + metabolic energy + CO_2 (1-2)

Growth and metabolism:

Metabolic energy + cell biomass $\rightarrow$ biomass production and metabolism (1-3)

Once produced, phytochemicals such as amino acids, enzymes, proteins, organic acids, carbohydrates, and other cellular materials can be transported throughout the plant through another vascular system, the phloem. This distribution system can send these phytochemicals down into the root system, where they can be exuded into the root zone. The exudation of carbon into the soil 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. Furthermore, the root system typically resides in an oxygenated environment either by creating channels where atmospheric oxygen can diffuse or by exuding oxygen through the plant tissues (e.g., aerenchyma in wetland species). This region of soil, roots, and organisms is known as the "rhizosphere" (Figure 1-2) and extends approximately 1–3 mm from the root surface (Shimp et al. 1993, Schnoor 1997). The proliferation of soil organisms in the rhizosphere can be 3 or 4 orders of magnitude greater than the population of soil organisms in comparison to nonvegetated soils. 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. These processes are relevant to rhizodegradation (see Section 1.2.2) and phytoremediation applications for soil and groundwater (Sections 1.3.3 and 1.3.5, respectively). Furthermore, the soil organisms can also enhance the uptake of essential plant nutrients (see Section 1.1.1) and extend the effective root system for enhanced water uptake into the plants (see Section 1.1.3).

1.1.3 Evapotranspiration

"Evapotranspiration" (ET) is the term for combined evaporation and transpiration of water from plant systems. These processes are relevant to phytohydraulic mechanisms (see Section 1.2.3) and tree hydraulic barrier (see Section 1.3.4) and certain phytostabilization cover (see Section 1.3.2) applications.

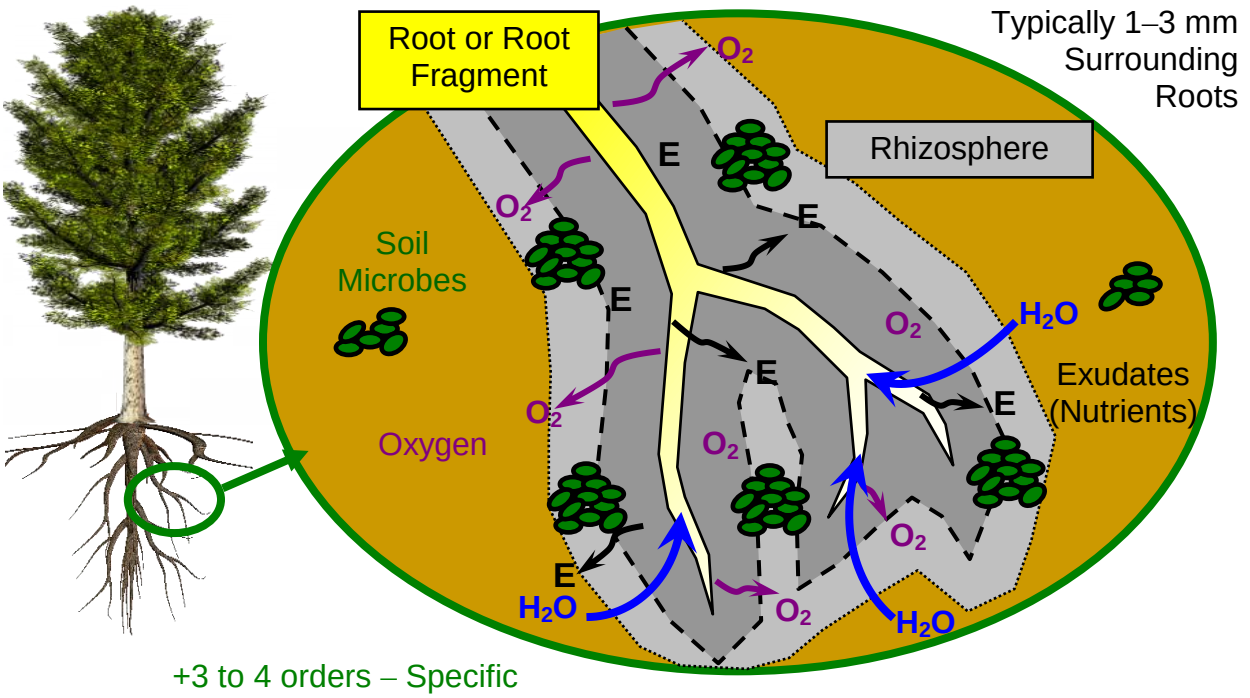


Figure 1-2. Rhizosphere.

For evaporation, plants have the ability to intercept a significant portion of rain (and irrigation) on their leaf surfaces, as depicted in Figure 1-3. This intercepted water is evaporated directly back into the atmosphere, preventing the water from reaching the ground surface (Viessman, Lewis, and Knapp 1989). This discharge effectively reduces the amount of infiltration and can be used to limit groundwater recharge. The differences in water interception capacities are due to morphological factors of the aboveground plant portions such as structure (vertical vs. horizontal profile), leaf cuticle (hairy vs. waxy), and density (number of branches and leaves). Key factors in determining the amount of canopy coverage provided by specific plants are the leaf area index (LAI) and area coverage (see Section 2.5.2.1). Table 1-2 shows typical water interception capacities.

If falling water is not intercepted by the plant and manages to infiltrate into the soil, it is then subject to the transpirational uptake by the plant root system, also depicted in Figure 1-3 (C). If the water is able to percolate below the root zone, it is available to recharge the groundwater. The transpirational "stream" begins with soil moisture being drawn from the soil into the root system and ends when the water evaporates into the atmosphere through the leaf stomata (countercurrent to the carbon dioxide influx, see Section 1.1.2). This whole process occurs primarily by the equilibrium driving force between liquid water in the leaves and the gaseous water (humidity) in the atmosphere. Other climate conditions, as well as the health and condition of the plant, greatly impact the transpiration capacity (see Sections 2.4.1.2 and 2.5.3.1). Typical plant transpiration rates are provided in Figures 1-4a to 1-4c. The rates in grasses and herbaceous species are estimated on a per area basis and in trees, on a per tree basis.

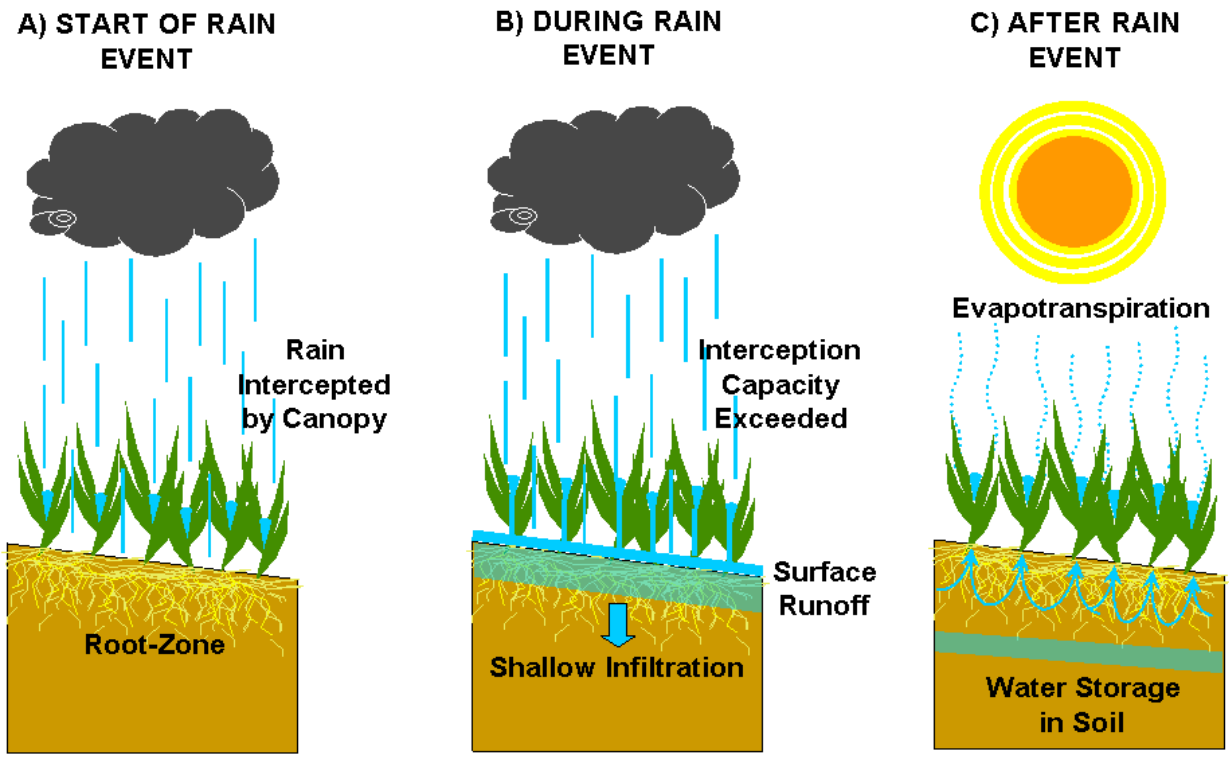


Figure 1-3. Evapotranspiration and phytostabilization cover for infiltration control application.

Table 1-2. Typical water 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

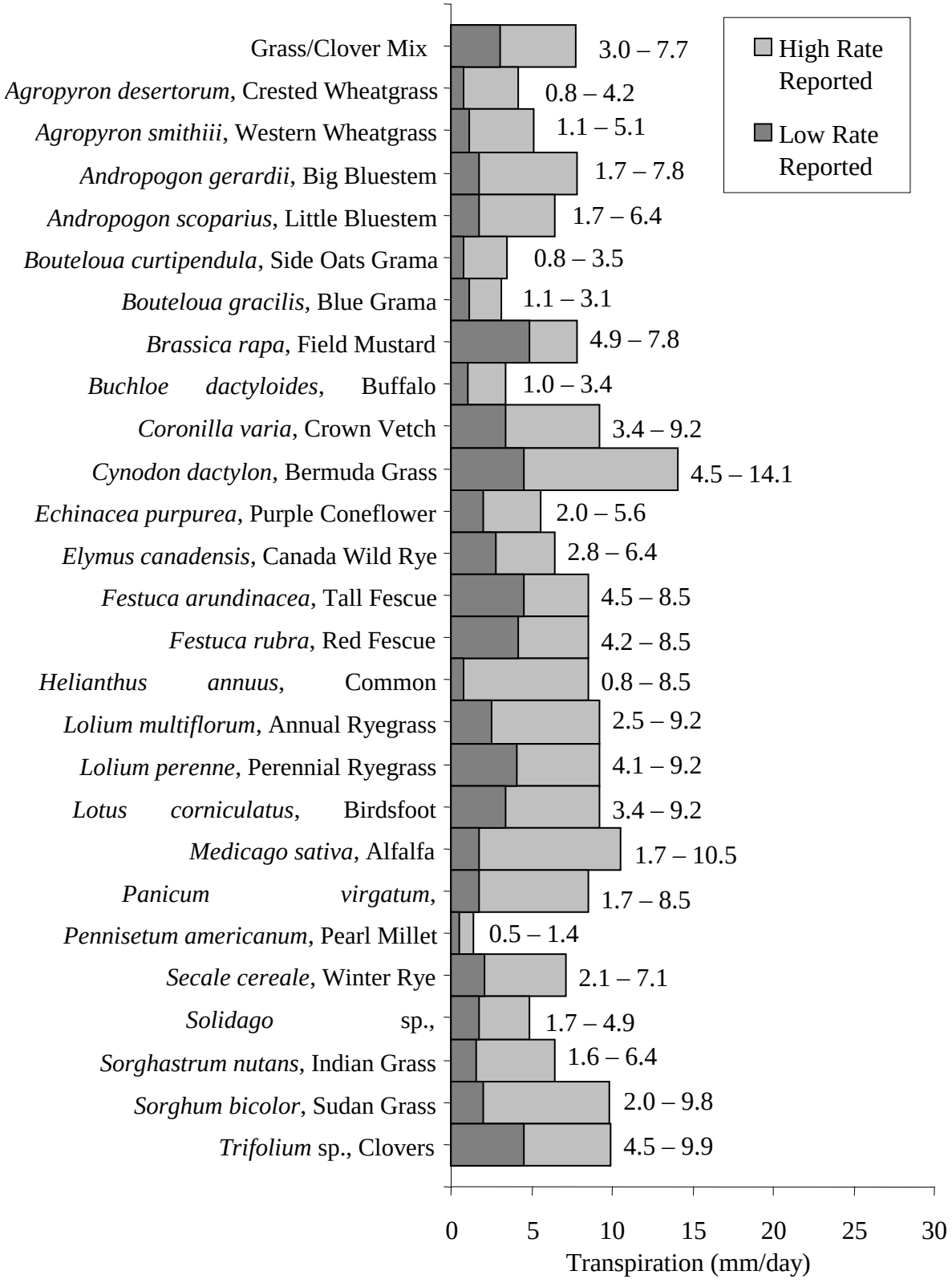


Figure 1-4a. Rates of transpiration of various grasses and herbaceous species.

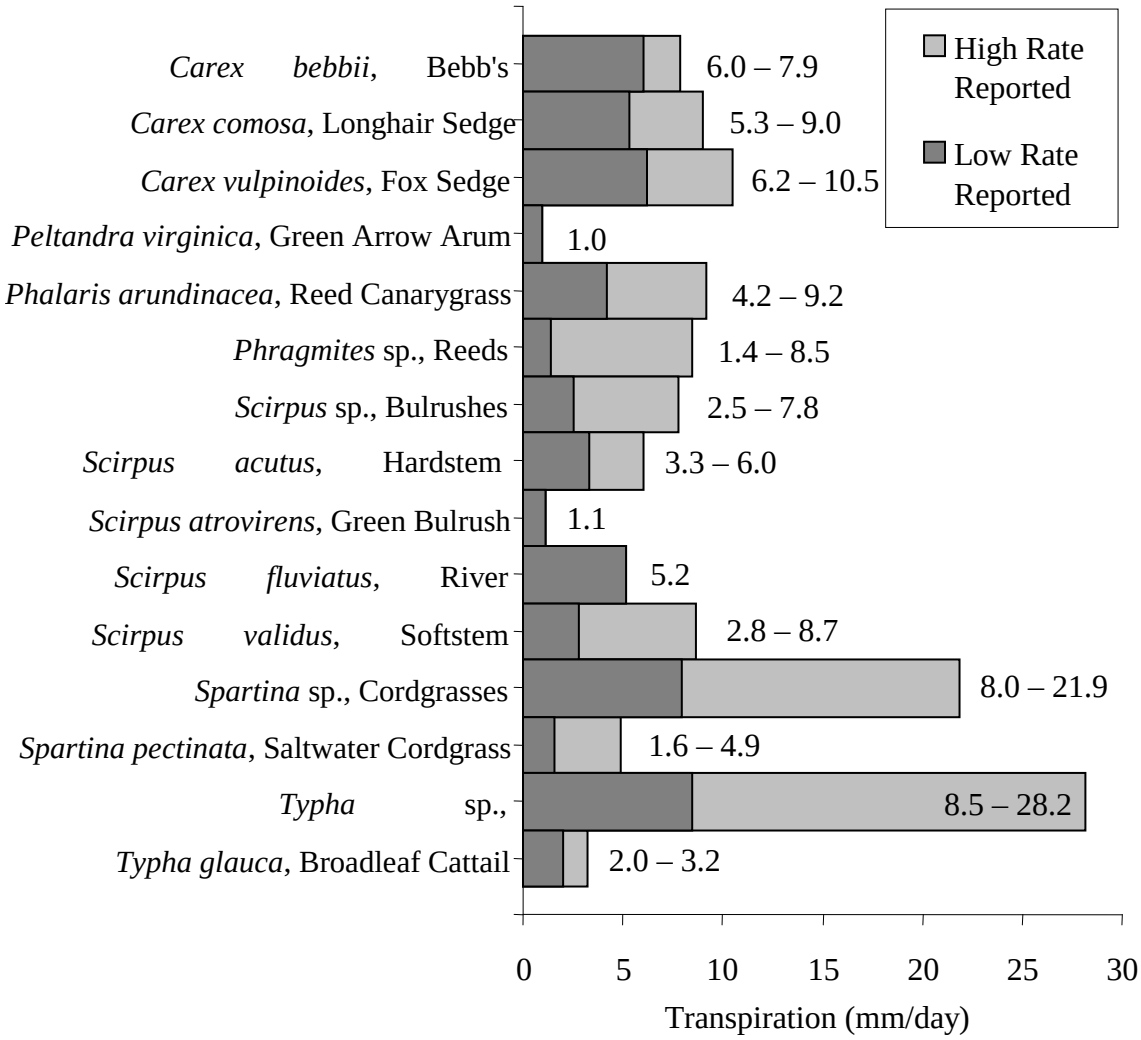


Figure 1-4b. Rates of transpiration of various herbaceous wetland species.

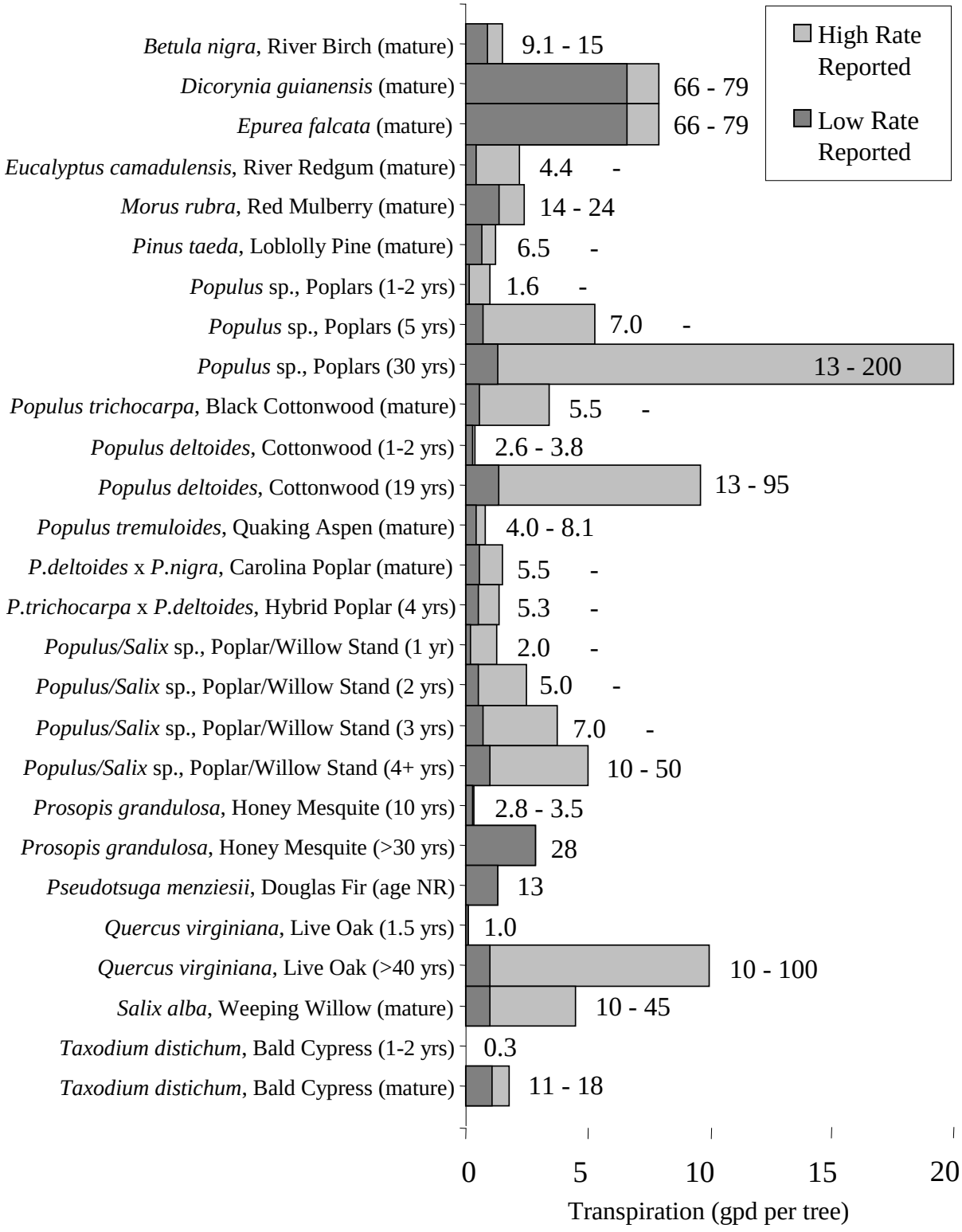


Figure 1-4c. Rates of transpiration of various woody species.

1.2 Mechanisms

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. Table 1-3 summarizes the specific mechanisms along with the applicable cleanup goals. The mechanisms are listed in the same order as the sequence of how contaminants come into contact with the transpiration stream, rhizosphere, and plant system. These mechanisms are interrelated and dependent upon the precursors. Therefore, in any given phytotechnology application, multiple mechanisms may be involved and can be exploited depending on the designed application (see Section 1.3).

Table 1-3. Summary of phytotechnology mechanisms

Mechanism	Description	Cleanup goal
1. Phytosequestration	The ability of plants to sequester certain contaminants in the rhizosphere through exudation of phytochemicals and on the root through transport proteins and cellular processes	Containment
2. Rhizodegradation	Exuded phytochemicals can enhance microbial biodegradation of contaminants in the rhizosphere	Remediation by destruction
3. Phytohydraulics	The ability of plants to capture and evaporate water off the plant and take up and transpire water through the plant	Containment by controlling hydrology
4. Phytoextraction	The ability of plants to take up contaminants into the plant with the transpiration stream	Remediation by removal of plants
5. Phytodegradation	The ability of plants to take up and break down contaminants in the transpiration stream through internal enzymatic activity and photosynthetic oxidation/reduction	Remediation by destruction
6. Phytovolatilization	The ability of plants to take up, translocate, and subsequently transpire volatile contaminants in the transpiration stream	Remediation by removal through plants

1.2.1 Phytosequestration

As shown in Figure 1-5, the three mechanisms of phytosequestration that reduce the mobility of the contaminant and prevent migration to soil, water, and air are as follows:

- Phytochemical complexation in the root zone: Phytochemicals can be exuded into the rhizosphere, leading to the precipitation or immobilization of target contaminants in the root zone. This mechanism of phytosequestration may reduce the fraction of the contaminant that is bioavailable.
- Transport protein inhibition on the root membrane: Transport proteins associated with the exterior root membrane (see Section 1.1.1) can irreversibly bind and stabilize contaminants on the root surfaces, preventing contaminants from entering the plant.

- Vacuolar storage in the root cells: Transport proteins are also present that facilitate transfer of contaminants between cells. However, plant cells contain a compartment (the "vacuole") that acts, in part, as a storage and waste receptacle for the plant. Contaminants can be sequestered into the vacuoles of root cells, preventing further translocation to the xylem.

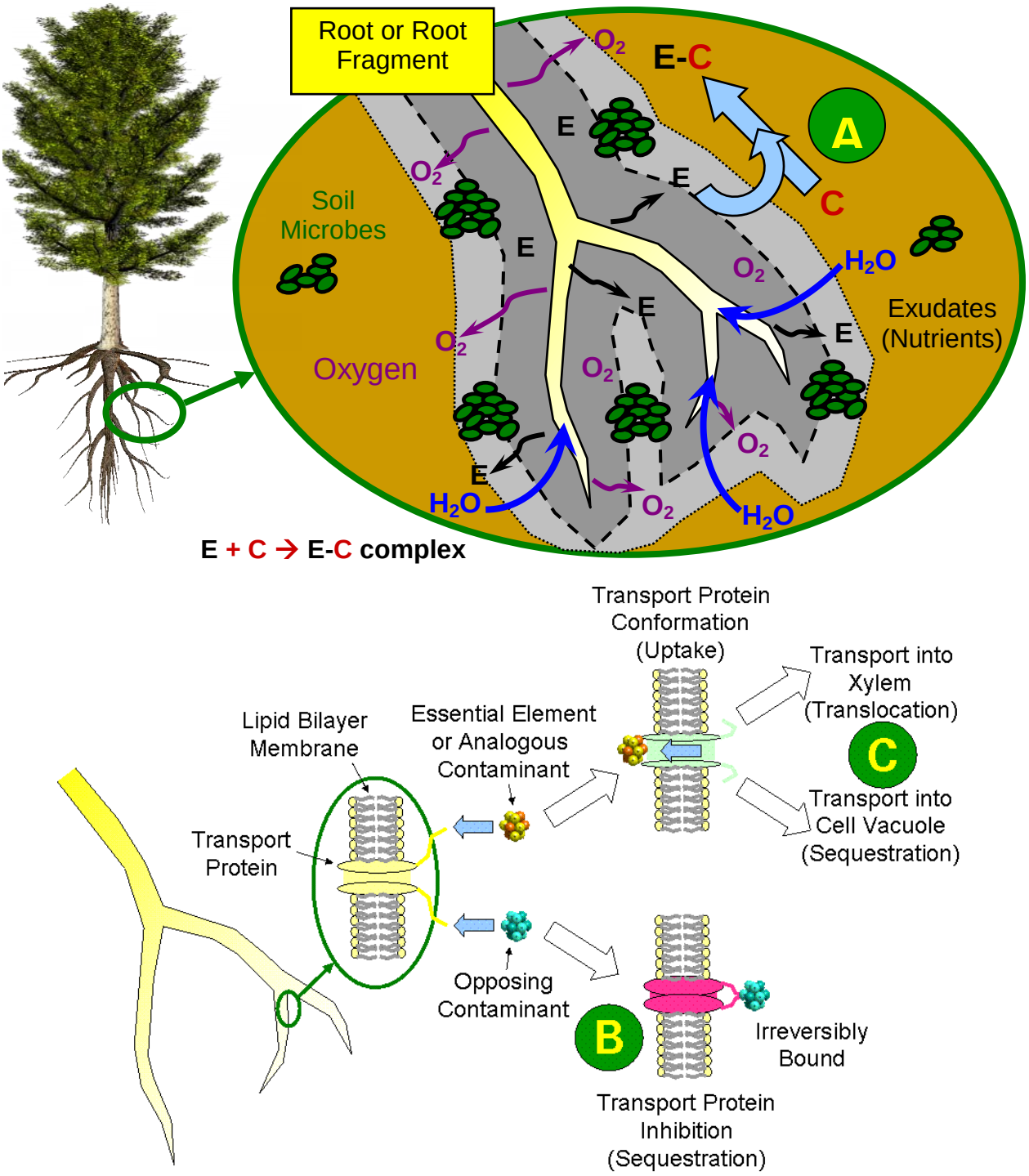


Figure 1-5. Phytosequestration mechanisms. A: phytochemical complexation, B: transport protein inhibition, C: vacuolar storage.

1.2.2 Rhizodegradation

The presence of a contaminant in a soil tends to naturally select organisms such as bacteria, yeast, and fungi that prefer that chemical as a source of food and energy. Microbial populations of specific organisms selected by using the contaminant as a primary food source can be several orders of magnitude higher than other organisms that do not metabolize the contaminant. The rate of degradation, metabolization, or mineralization of the contaminant in the soil depends on the bioactivity in the soil that is derived primarily from the proteins and enzymes from the soil organisms. However, contaminant breakdown is often limited by the availability of electron acceptors or donors, cometabolites, inorganic nutrients, plant vitamins and hormones, pH, and/or water.

In general, a symbiotic relationship evolves between plants and soil microbes in the rhizosphere. Plants provide nutrients necessary for the microbes to thrive, while the microbes provide a healthier soil environment where plant roots can grow. Specifically, plants loosen soil and transport oxygen and water into the rhizosphere. Furthermore, plants exude specific phytochemicals (sugars, alcohols, carbohydrates, etc.) that are primary sources of food (carbon) for the specific soil organisms that aid in providing the healthier soil environment. Alternatively, the exuded phytochemical may be an allelopathic agent meant to suppress other plants from growing in the same soil. In return for exporting these phytochemicals, plants are protected from competition, soil pathogens, toxins, and other chemicals that are naturally present or would otherwise be growing in the soil environment. Microbial populations can be several of orders of magnitude higher in a vegetated soil compared to an unvegetated soil.

Rhizodegradation, sometimes called phytostimulation, rhizosphere biodegradation, or plant-assisted bioremediation/degradation, is the enhanced breakdown of a contaminant by increasing the bioactivity using the plant rhizosphere environment (see Figure 1-2) to stimulate the microbial populations. This enhanced bioactivity represents the primary means through which organic contaminants can be remediated, including into harmless products that can be converted into a source of food and energy for the plants or soil organisms (Donnelly and Fletcher 1994). Specifically, the contaminants themselves may be analogs to the phytochemical naturally exuded by the plant and fortuitously metabolized as a substitute to the primary carbon source. Alternatively, the exuded phytochemicals may be cometabolites to organisms that are able to breakdown the contaminants as the primary metabolite. In this case, the contaminant is still metabolized (i.e., biodegraded) but at a slower rate or through a less efficient metabolic pathway than when the cometabolite is present. Similarly, the specific proteins and enzymes, or analogs to those produced by the soil organism needed to breakdown the contaminant, may be produced and exuded by the plant itself. Figure 1-6 depicts these mechanisms.

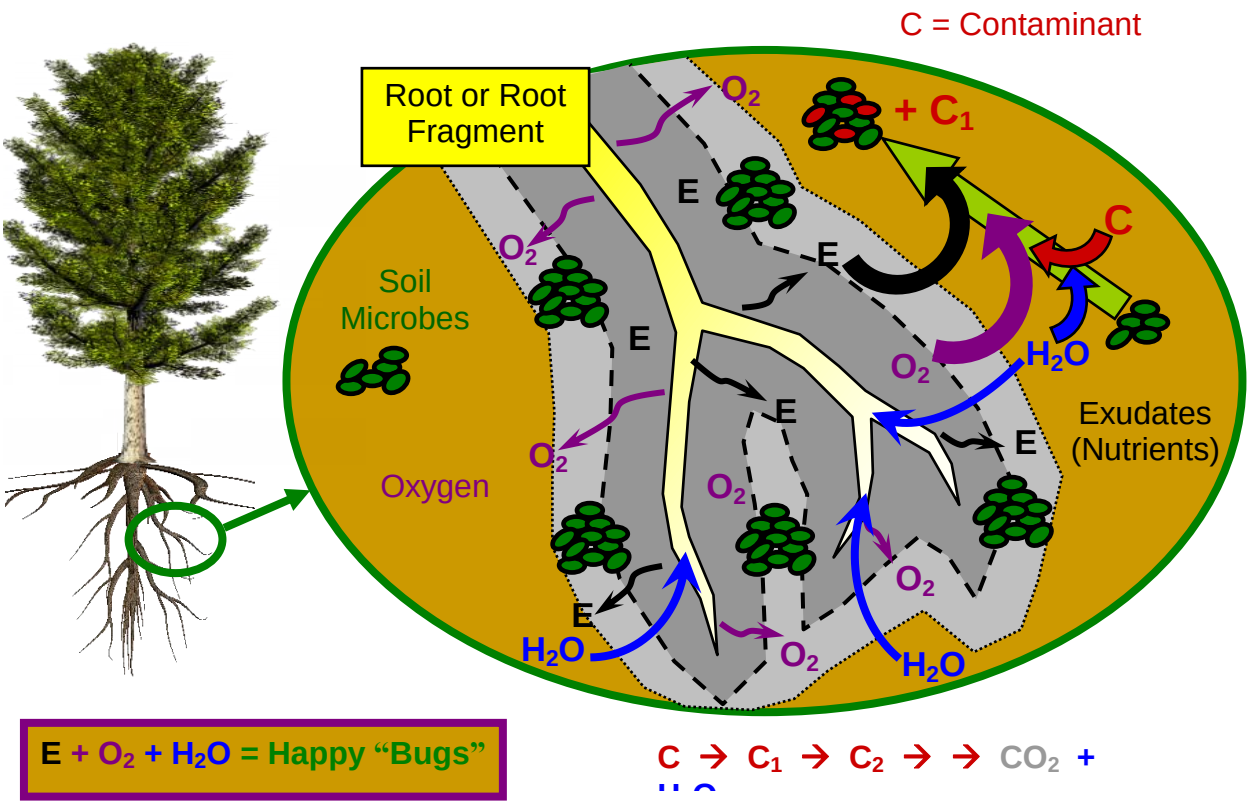


Figure 1-6. Rhizodegradation mechanisms.

1.2.3 Phytohydraulics

Plants significantly affect local hydrology. Phytohydraulics is the ability of vegetation to evapotranspire (see Section 1.1.3) sources of surface water and groundwater. The vertical migration of water from the surface downward can be limited by the water interception capacity of the aboveground canopy and subsequent evapotranspiration through the root system. This process was depicted in Figure 1-3. If water infiltrating from the surface is able to percolate below the root zone, it can recharge groundwater. However, the rate of recharge depends not only on the rooting depth of the species, but on the soil characteristics as well (see Section 2.2.3.1). The horizontal migration of groundwater can be contained or controlled (USEPA 2000) using deep-rooted species such as prairie plants and trees to intercept, take up, and transpire the water, as depicted in Figure 1-7. One class 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 species within the *Salicaceae* family such as cottonwoods, poplars, and willows.

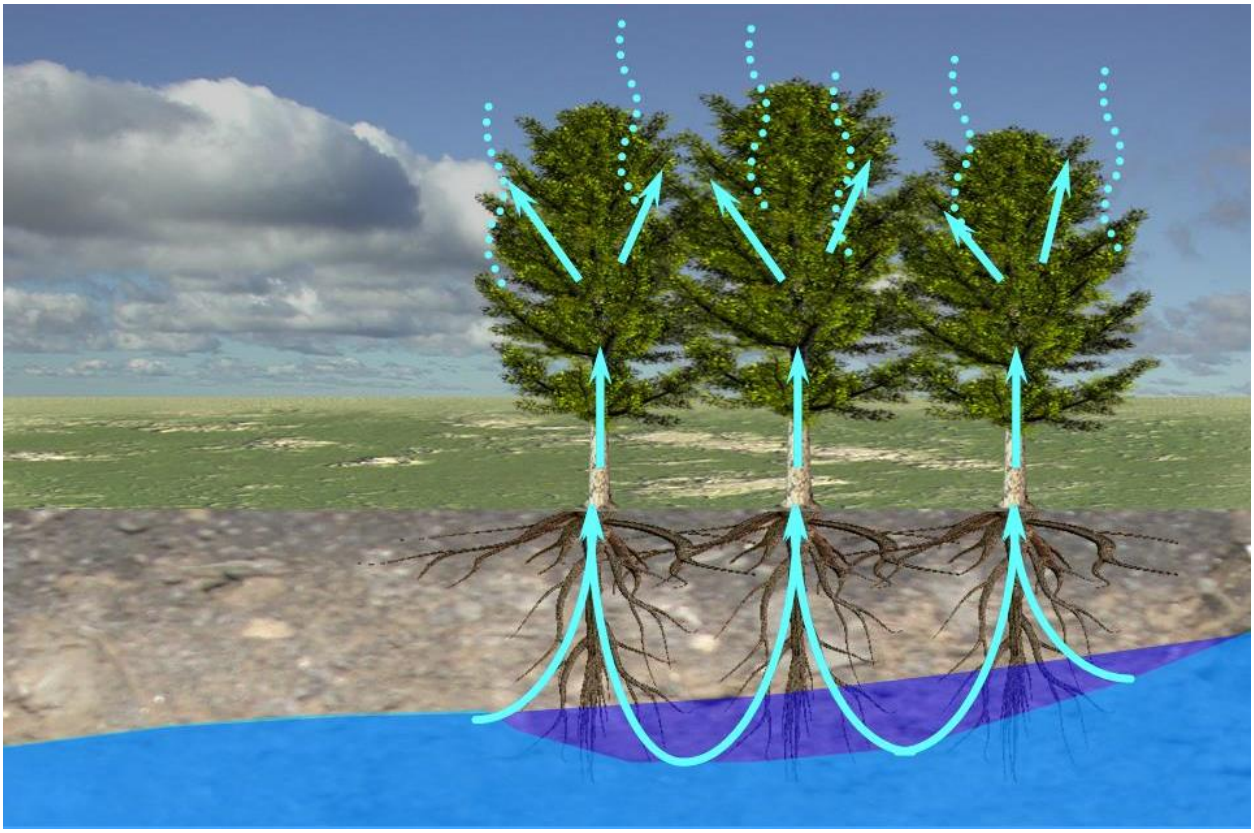


Figure 1-7. Phytohydraulics and groundwater hydraulic depression.

1.2.4 Phytoextraction

Phytoextraction refers to the ability of plants to take up contaminants into the roots and translocate them to the aboveground shoots or leaves. For contaminants to be extracted by plants, the constituent must be dissolved in the soil water and come into contact with the plant roots through the transpiration stream. Alternatively, the uptake may occur through vapor adsorption onto the organic root membrane in the vadose zone. Once adsorbed, the contaminant may dissolve into the transpiration water or be actively taken up through plant transport mechanisms. Figure 1-8 depicts both of these uptake pathways.

Once a chemical is taken up, the plant may store the chemical and/or its by-products in the plant biomass via lignification (covalent bonding of the chemical or its by-products into the lignin of the plant), sequester it into the cell vacuoles of aboveground tissues (as opposed to in root cells as part of phytosequestration, see Section 1.2.1). Alternatively, the contaminant may be metabolized through phytodegradation mechanisms (see Section 1.2.5) and/or phytovolatilized in the transpiration stream exiting the plant (see Section 1.2.6).

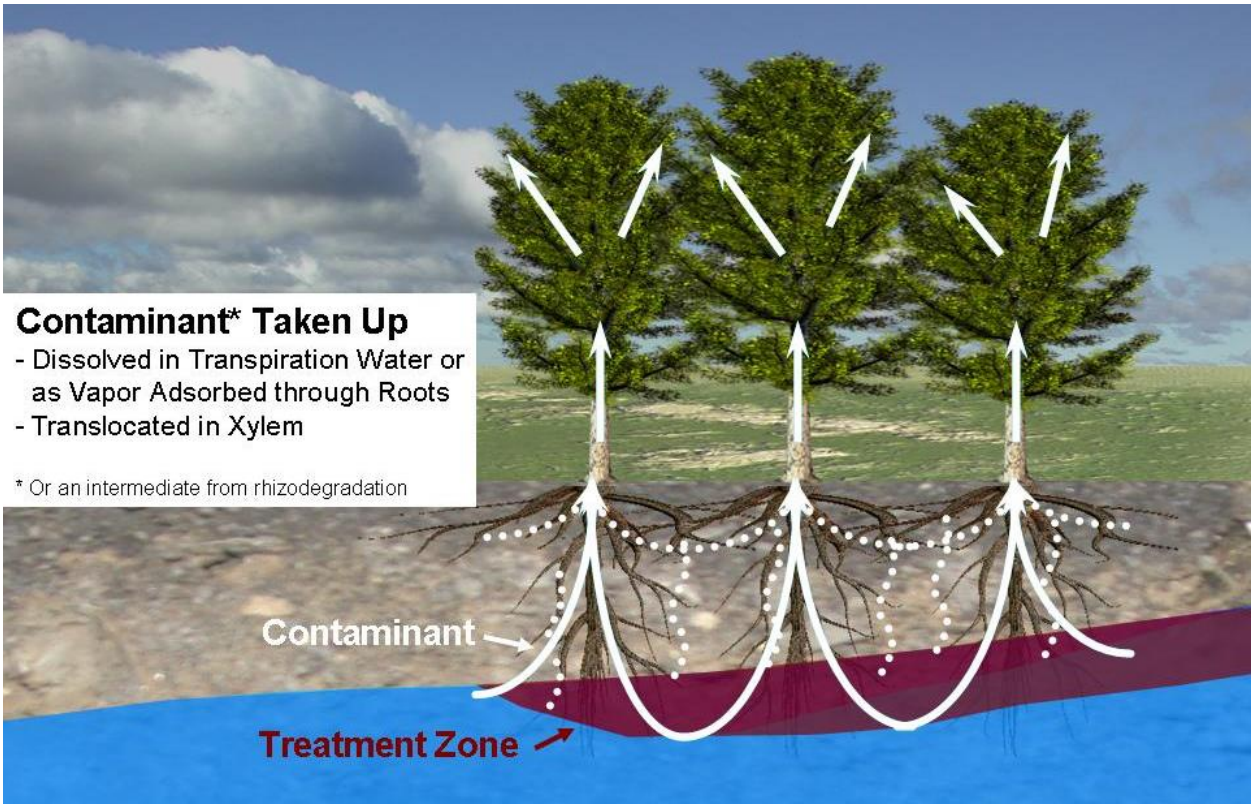


Figure 1-8. Phytoextraction mechanisms.

For organic chemicals, factors that affect the potential uptake into plants through the transpiration stream include hydrophobicity, polarity, sorption properties, and solubility. One characteristic that has been shown to correlate to uptake into a plant is the octanol-water partition coefficient, log K_{ow}. Specifically, organic chemicals having log K_{ow} values between 1 and 3.5 have been shown to enter into plants (Burken and Schnoor 1997a). The plant root is an organic membrane consisting of a lipid bilayer (see Figure 1-5). The organic characteristics of the lipids make the root partially hydrophobic while the bilayering aspects make it also nonpolar. Therefore, hydrophobic chemicals (log K_{ow} >3.5) are generally not sufficiently soluble in the transpiration stream or are bound so strongly to the surface of the roots that they cannot be easily translocated into the plant xylem. 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, Bromilow, and Evans 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 phytoextraction. Table 1-4 shows several examples.

The vapor uptake pathway into plants was specifically identified for chlorinated solvents such as perchloroethene (PCE, also known as "tetrachloroethene"), where partitioning coefficients between plant tissue and air and between plant tissue and water were measured to be 0.0081 L/g and 0.049 L/g, respectively (Struckhoff, Burken, and Schumacher 2005). Volatile hydrocarbons

such as BTEX constituents are often rhizodegraded to an extent that limits measurable phytoextraction (Fiorenza et al. 2005).

Table 1-4. Chemical properties for typical contaminants

Chemical	Log K_{ow}[a] (unitless)	Solubility[a] (mol/L)	Henry's constant[a] (unitless)	Vapor pressure[a] (atm)	TSCF[b] (unitless)	RCF[c] (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
Trichloroethene	2.33	2.04	0.4370	1.01	0.74	3.9
Aniline	0.90	0.41	2.2×10^5	2.89	0.26	3.1
Nitrobenzene	1.83	1.77	0.0025	3.68	0.62	3.4
Phenol	1.45	0.20	$>1.0 \times 10^5$	3.59	0.47	3.2
Pentachlorophenol	5.04	4.27	$1.5 \times 10^{4\,(d)}$	6.75[d]	0.07	54
Atrazine	2.69	3.81	$1.0 \times 10^{7\,(d)}$	9.40[d]	0.74	4.5
1,2,4-Trichlorobenzene	4.25	3.65	0.1130	3.21	0.21	19
RDX[e]	0.87	4.57	-	-	0.25	3.1

[a] Physical chemical properties (Schwarzenbach, Gschwend, and Imkboden 1993) at 25°C unless otherwise noted.
[b] Transpiration stream concentration factor (TSCF) = $0.75 \exp\{-[\log K_{ow} (-2.50)]^2/2.4\}$.
[c] Root concentration factor (RCF) = $3.0 + \exp(1.497 \log K_{ow} - 3.615)$.
[d] From Schnoor 1997.
[e] 1,3,5-trinitroperhydro-1,3,5-triazine, an explosive.
Source: Burken and Schnoor 1997a.

The relative ability of a plant to take up a chemical from the soil or groundwater into their roots is described by the root concentration factor (RCF), measured as the ratio of the concentration in the root (mg/kg) to the concentration in the external solution (mg/L). Furthermore, translocating the chemical to its shoots is described by the transpiration stream concentration factor (TSCF), measured as the ratio of the concentration in the xylem sap (mg/L) to the concentration in external solution (mg/L). These are also presented in Table 1-4 for the various chemicals although field values will typically depend on soil properties, chemical partitioning, and the plant species. Higher RCF and TSCF values are an indication of enhanced contaminant uptake by plants and vary directly with the log K_{ow} of the chemical. Contaminants in solution with the highest TSCF contained a log K_{ow} in the range of 1–3.5 (Briggs, Brimilow, and Evans 1982; Schnoor 1997). Equations describing the potential uptake are provided in Section 2.4.1.1 (see Equations 2-3 and 2-4).

For inorganic constituents such as salts, metals, and radionuclides, the uptake into plants and translocation into the aboveground tissues depends on the redox state, chemical speciation in the soil, sediment or groundwater, and the plant species. As a general rule, readily bioavailable inorganics for plant uptake include As, Cd, Cu, Ni, Se, and Zn. Moderately bioavailable metals are Co, Fe, and Mn, whereas Cr, Pb, and U are not very bioavailable (Bañuelos et al. 1998; Cipollini and Pickering 1986; Hinchman, Negri, and Gatliff 1997; Keiffer 1996; Keiffer and Ungar 1996; Kumer et al. 1995; Martin et al. 1996; Salt et al. 1995; Spier, August, and Feltham 1992). Several of these constituents, often considered as environmental contaminants in sufficient concentration, are also essential plant nutrients (see Section 1.1.1). Furthermore,

inorganic nutrients that make up various salts such as Ca, Cl, Mg, N, P, and K are readily taken up in available forms as well (see Table 1-1).

Certain plants called "hyperaccumulators" (McIntyre 2001) absorb unusually large amounts of metals in comparison to other plants and the ambient metal concentration. 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, Brooks, and Reeves 1998). Similarly, "halophytes" are plants that can tolerate and, in many cases, accumulate large quantities of salt (typically, NaCl but also Ca and Mg chlorides). Hyperaccumulators and halophytes are often discovered as being selected to grow at a site based on the metals or salts naturally present, forming their own niche through evolution. Some halophytes in tropical and near tropical environments such as salt cedars take up saline water and exude the excess salt through the stomata back onto the ground as a means to create the niche. Furthermore, some plants may produce and exude specific phytochemicals directly into the soil environment that alter the chemistry and speciation of constituents to promote the mobilization and uptake into the plant, particularly for enhancing the uptake of essential nutrients through the release of acidic phytochemicals.

1.2.5 Phytodegradation

Depending on factors such as the concentration and composition, plant species, and soil conditions, contaminants may be able to pass through the rhizosphere only partially or negligibly impeded by phytosequestration (see Section 1.2.1) and/or rhizodegradation (see Section 1.2.2). In this case, the contaminant may then be subject to biological processes occurring within the plant itself, assuming it is dissolved in the transpiration stream and can be phytoextracted (see Section 1.2.4). Specifically, phytodegradation, also called "phytotransformation," refers to the uptake of contaminants with the subsequent breakdown, mineralization, or metabolization by the plant itself through various internal enzymatic reactions and metabolic processes. Figure 1-9 depicts these mechanisms.

Plants catalyze several internal reactions by producing enzymes with various activities and functions (Newman 1995, Schnoor et al. 1995). Specifically, oxygenases have been identified in plants that are able to address hydrocarbons such as aliphatic and aromatic compounds. Similarly, nitroreductases are produced in some plants that can reduce and breakdown energetic compounds such as the explosives trinitrotoluene (TNT), 1,3,5-trinitroperhydro-1,3,5-triazine (RDX), and 1,3,5,7-tetranitro-1,3,5,7-tetrazocane (HMX). Although not known to be naturally produced in plants, dehalogenase-like activity has also been identified and isolated (Dhankher et al. 1999) that can remove halogen subgroups from compounds such as chlorinated solvents. Many of these plant enzymes may even be able to metabolize or mineralize these chemicals completely to carbon dioxide and water (Schnoor 1997). In addition, research has shown that the endophytic symbiotic bacteria *Methylobacterium populum* that lives within poplar can mineralize RDX and HMX (Van Aken et al. 2004).

In addition, the oxidation and reduction cycle operating during photosynthesis (see Section 1.1.2) offer additional contaminant breakdown potential. Stronger oxidants and reductants are produced in the plant system (from +1.1 V to –1.3 V) than are commonly available in biodegradation

processes (from +0.5 V to –0.3 V). Specifically, the redox potential for aerobic reactions with dissolved oxygen as the electron acceptor range +0.25 V and higher, possibly up to +0.5 V, while other electron acceptors (nitrate, iron-III, Mn, sulfate) range from +0.25 V down to –0.2 V. Below this redox potential, perhaps to –0.3 V, methanogenesis may occur. Therefore, organic chemicals (electron donors) in the transpiration stream reaching the photosynthetic centers of a plant are potentially subject to these strong redox conditions as well. This effect has been observed for RDX (Van Aken et al. 2004).

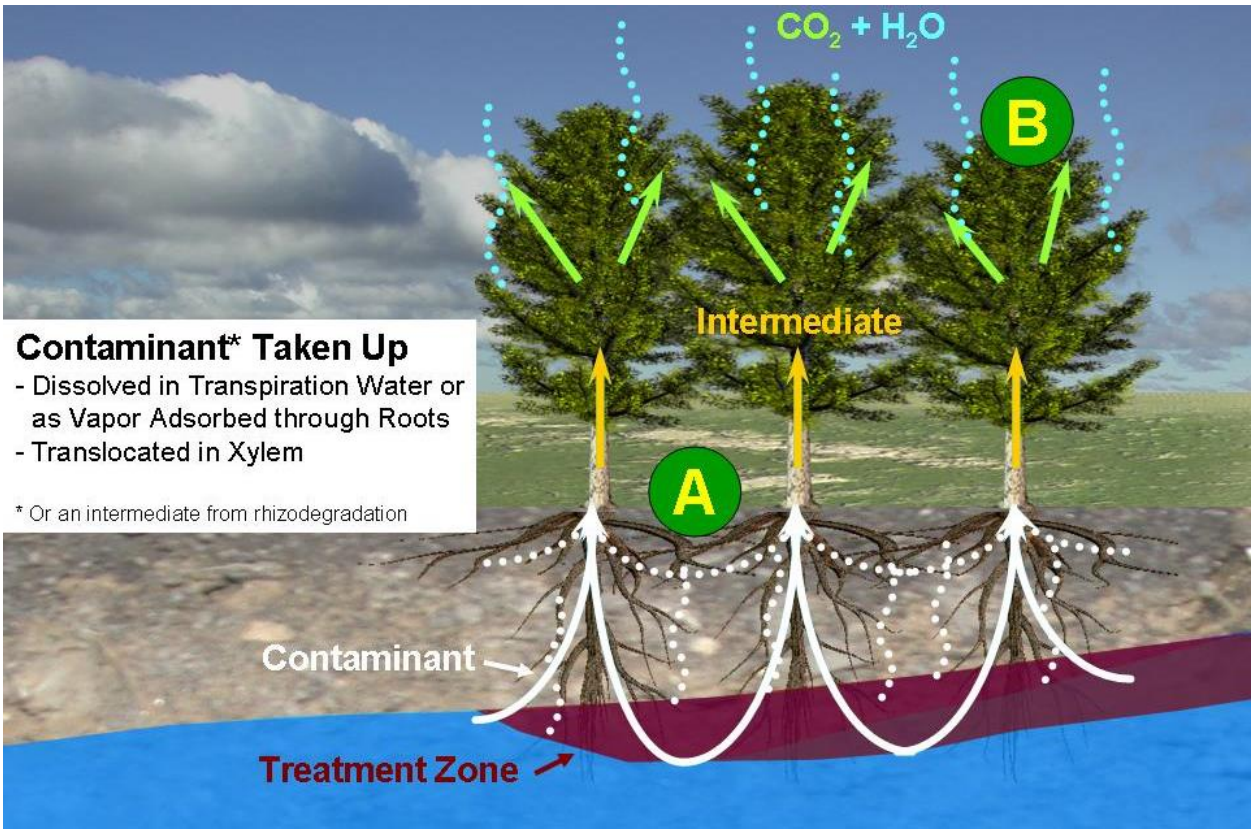


Figure 1-9. Phytodegradation mechanisms. A: plant enzymatic activity, B: photosynthetic oxidation.

1.2.6 Phytovolatilization

Phytovolatilization is the volatilization of contaminants from the plant either from the leaf stomata or from plant stems (Ma and Burken 2002), as shown in Figure 1-10. Chemical characteristics such as the Henry's constant and vapor pressure (see Table 1-4) dictate the ability of organic contaminants to volatilize. In some cases, a breakdown product derived from the rhizodegradation and/or phytodegradation of the parent contaminant along the transpiration pathway may be the phytovolatilized constituent. This effect was studied for the uptake and phytovolatilization of trichloroethene (TCE) or its breakdown products in poplars (Chappell 1998). Similarly, certain inorganic constituents such as mercury may be volatilized as well. Specifically, tobacco plants have been modified (see Section 2.3.1.5) 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). Once

volatilized, many chemicals that are recalcitrant in the subsurface environment react rapidly in the atmosphere with hydroxyl radicals, an oxidant formed during the photochemical cycle.

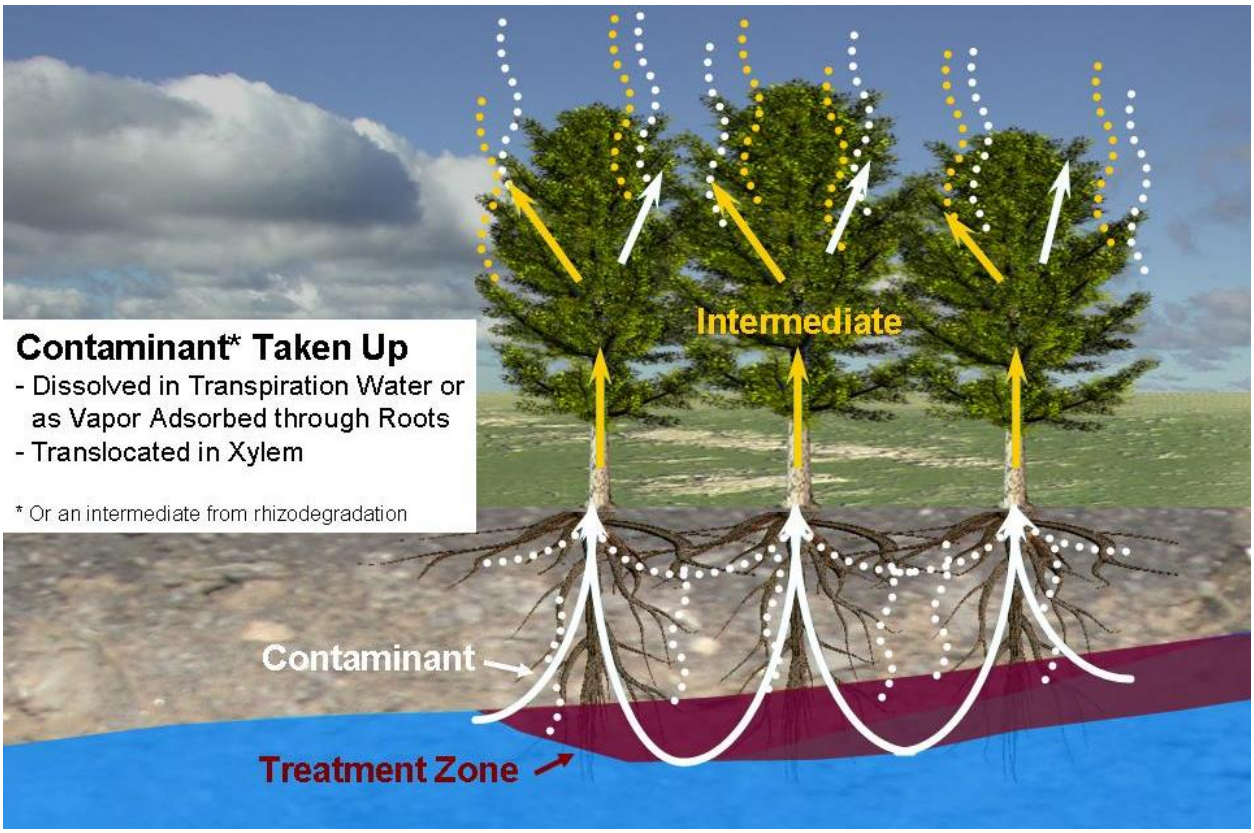


Figure 1-10. Phytovolatilization mechanism.

1.3 Applications

Applying phytotechnologies to environmentally impacted sites entails selecting, designing, installing, operating, maintaining, and monitoring planted systems that use the various mechanisms described in the previous section. The goal of the system can be broadly based on the remedial objectives of containment, remediation, or both. Furthermore, the target media can be soil/sediment, surface water, or groundwater, and these can be either clean or impacted. In some cases, groundwater transitioning to surface water (daylighting seep) can be addressed as a riparian situation where target media are combined. The possible combinations of treatment goal, target media, and applicable mechanisms are summarized in Tables 1-5a and 1-5b for each application. However, specific applications can be designed such that a particular mechanism is emphasized as the primary means of treatment either through plant selection, engineering and design, or method of installation or construction. Specific case study applications are summarized in Table 1-6, with additional information provided in Appendix C.

Table 1-5a. Summary of phytotechnology applications and potential mechanisms for containment treatment goals

Media	Application	Potential mechanisms	Comments
Soil/sediment (impacted)	**Phytostabilization cover**[a] (soil/sediment stabilization)	Phytosequestration Phytoextraction (no harvesting) Adsorption (abiotic) Precipitation (abiotic) Settling/sedimentation (abiotic)	Also controls soil erosion by wind/water See ITRC 2003b for sediment aspects.
Surface water (clean)	**Phytostabilization cover** (infiltration control)	Phytohydraulics (evapotranspiration) Runoff (abiotic)	Vertical infiltration control See ITRC 2003c, 2003d, 2006a, 2006b for alternative (evapotranspiration) covers.
Surface water (impacted)	Pond/lagoon/basin **Riparian buffer**	Phytosequestration Phytohydraulics (evapotranspiration) Phytoextraction (no harvesting) Evaporation (abiotic) Infiltration (abiotic)	See ITRC 2003b. Includes wastewater Also controls soil erosion by water runoff
Groundwater (clean)	**Tree hydraulic barrier** **Riparian buffer**	Phytohydraulics (evapotranspiration)	Lateral migration control
Groundwater (impacted)	**Tree hydraulic barrier** **Riparian buffer**	Phytosequestration Phytohydraulics (evapotranspiration) Phytoextraction (no harvesting)	Lateral migration control

[a] Applications in bold are covered in this document:

- Phytostabilization cover (for soil/sediment stabilization), see Section 1.3.1.
- Phytostabilization cover (for infiltration control), see Section 1.3.2.
- Tree hydraulic barrier, see Section 1.3.4.
- Riparian buffer, see Section 1.3.6.

Table 1-5b. Summary of phytotechnology applications and potential mechanisms for remediation treatment goals

Media	Application	Potential mechanisms	Comments
Soil/sediment (impacted)	**Phytoremediation groundcover**[a]	Rhizodegradation Phytoextraction (with harvesting) Phytodegradation Phytovolatilization Biodegradation (microbial) Oxidation/reduction (abiotic) Volatilization (abiotic)	Phytohydraulics (evapotranspiration) assumed for phytoextraction, phytodegradation, and phytovolatilization
Surface water (impacted)	Pond/lagoon/basin **Riparian buffer** Constructed treatment wetland	Rhizodegradation Phytoextraction (with harvesting) Phytodegradation Phytovolatilization Biodegradation (microbial) Oxidation/reduction (abiotic) Volatilization (abiotic)	See ITRC 2003b. Includes wastewater and extracted groundwater Phytohydraulics (evapotranspiration) assumed for phytoextraction, phytodegradation, and phytovolatilization
Groundwater (impacted)	**Phytoremediation tree stand** **Riparian buffer**	Rhizodegradation Phytoextraction (with harvesting) Phytodegradation Phytovolatilization Oxidation/reduction (abiotic) Biodegradation (microbial)	Phytohydraulics (evapotranspiration) assumed for phytoextraction, phytodegradation, and phytovolatilization

[a] Applications in bold are covered in this document:

- Phytoremediation groundcover, see Section 1.3.3.
- Phytoremediation tree stand, see Section 1.3.5.
- Riparian buffer, see Section 1.3.6

Table 1-6. Summary of case studies

Application	Contaminants treated[a]	Case study reference number and scale[b]
Phytostabilization covers (see Sections 1.3.1 and 1.3.2)	BTEX, PAHs, PCBs, PCE, TCE, DCE, VC, TPH, metals, acetone, MIBK (waste oil), refinery leachate, salinity, sodium (sodic soils), metals tailings, acid tar	1(F), 8(P), 18 (F), 29(F), 46(P), 47(F), 50(F), 51(F), 57(F), 60F
Phytoremediation groundcovers (see Section 1.3.3)	Organic compounds, TPH, TCE, PCE, PAHs, PCBs, PCE, TCE, DCE, VC, BTEX, MTBE, energetics, cyanide, metals (Ag, As, Au, Cd, Co, Cr, Cu, Fl, Hg, Mn, Mo, Ni, Pb, Zn), radionuclides (^{90}Sr, ^{137}Cs, ^{239}Pu, ^{234,} ^{238}U)	2(F), 3(P), 4(F), 5(F), 6(F), 7(B), 8(P), 9(F), 10(F), 11(F), 12(P), 13(F), 14(P), 16(F), 18(F), 19(F), 20(F), 23(F), 24(F), 27(F), 31(F), 34(F), 38(F)
Tree hydraulic barriers Phytoremediation tree stands (see Sections 1.3.4 and 1.3.5)	Dissolved organic and inorganic compounds (BTEX, MTBE, naphthalene, toluene, EDC, TDA, TPH, TCE and PCE), metals (Cu, Cd, Pb), salinity, pH	15 (F), 17(F), 18(F), 26(F), 33(F), 35(F), 37(F), 39(F), 40(F), 42(F), 43(F), 49(P), 55(F), 60(F)
Riparian buffers (see Section 1.3.6)	N, P, excess fertilizers, pesticides, TCE, PCE, BTEX, MTBE, DRO	2(F), 25(F), 36(F), 46(P)
Constructed treatment wetlands (see ITRC 2003b)	As, Cr, F, N, P, Se, cyanide, phenols, TPH, BTEX, TCE, municipal waste water, alkalinity, gray water, organic acids, crude oil, acid	21(F), 22(F), 30(F), 32(F), 41(F), 44(F), 48(F), 52(F), 53(F), 54(F), 56(F)

[a] DCE = dichloroethene, DRO = diesel-range organic, EDC = ethylene dichloride, MIBK = methyl isobutyl ketone, MTBE = methyl tertiary-butyl ether, PAH = polycyclic aromatic hydrocarbon, PCB = polychlorinated biphenyl, PCE = perchloroethene, TDA = toluenediamine, TPH = total petroleum hydrocarbons, VC = vinyl chloride.

[b] See Appendix C for additional case study information. Key to scale: B = bench, P = pilot/demo, F = full.

1.3.1 Phytostabilization Covers for Soil/Sediment Stabilization

Soil and sediment can mobilize (vertically and laterally) when exposed to uncontrolled water flows. Furthermore, soil can also mobilize (as airborne contamination) by blowing wind. Both of these modes of soil/sediment migration are known as "erosion" or "leaching." If the soil or sediment is impacted, the migration of the contaminants through these modes is generally considered nonpoint source (NPS) pollution. Phytostabilization covers provide a natural barrier and resistance to erosion and leaching and can be further used to minimize NPS pollution if the soil or sediment is impacted.

The main mechanism contributing to stabilizing erosion is the infusion of plant roots into the soil or sediment. Typically, plants with fibrous root systems are used, such as many grasses, herbaceous species, and wetland species. Typical rooting depths for these species are 1–2 feet for upland species and <1 foot for wetland species (see ITRC 2003b for upland to wetland characteristics). Common upland seed mixes are available through local Department of Transportation offices formulated for stabilizing roadsides.

When the soil or sediment is impacted, the contaminants can also be phytosequestered (see Section 1.2.1) by vegetation. Specifically, phytostabilization covers for soil or sediment control erosion to minimize bulk migration of the contaminated media, while phytosequestration mechanisms address the mobility of the contaminant itself. Therefore, phytostabilization covers are simply soil or sediment that are planted with vegetation selected specifically to control bulk soil migration (via infusion with fibrous root systems) and/or prevent contaminant migration through phytosequestration. In some instances, the same species can serve both purposes.

In addition to phytosequestering contaminants in the rhizosphere, other plants, such as halophytes and hyperaccumulators, can be selected based on their ability to phytoextract (see Section 1.2.4) and accumulate contaminants into the aboveground tissues. Obviously, additional risks are involved with moving contaminants into the plant; however, this aspect of a phytostabilization cover application for soil/sediments may still be acceptable, depending on the overall human health and ecological risks associated with the site. This is a decision factor to consider when selecting this phytotechnology application as the site remedy (see Section 2.3). If a harvesting and removal plan is implemented for the application to mitigate the additional risks, then the application is classified as a phytoremediation groundcover (see Section 1.3.3).

1.3.2 Phytostabilization Covers for Infiltration Control

Another method to stabilize contaminants in the subsurface is to prevent water from interacting with the waste, possibly leading to its migration. This is a common approach for landfill covers but can also be applied to minimize surface water recharge of groundwater plumes. Phytostabilization covers for infiltration control, also known as evapotranspiration, water-balance, or vegetative covers, use the ability of plants to intercept rain to prevent infiltration and take up and remove significant volumes of water after it has entered the subsurface to minimize the percolation into the contained waste (Veissman, Lewis, and Knapp 1989). This effect is illustrated in Figure 1-3, with typical water interception capacities listed in Table 1-2 and

transpiration capacities for various types of species presented in Figures 1-4a to 1-4c. The main phytotechnology mechanism for these applications is phytohydraulics (see Section 1.2.3).

Phytostabilization covers for infiltration control are composed of soil and plants that maximize evaporation from the soil and plant evapotranspiration processes (see Section 1.1.3) from the system. To allow these time-dependent (and climate-dependent) processes to occur and successfully remove water from the system, the soil component of the cover is specifically designed and installed such that the available water storage capacity in the soil is maximized. The vegetation component of the cover usually entails specially formulated seed mixes or mixed communities of plants/trees that can access the stored water as well as create the intercepting canopy. Furthermore, the entire cover is often contoured to promote runoff as another significant loss mechanism for the overall water balance. Different water balance models are available (see Equation 2-5) with additional information available in ITRC 2003c.

When minimizing infiltration, one of the potential outcomes is to create an anaerobic zone underneath the phytostabilization cover. In some cases, the subsurface conditions will be driven into methanogenic (methane-producing) conditions. These covers may not be appropriate for sites that can lead to the production of chronic, large, or uncontrolled amounts of this landfill gas. While the methane itself may or may not be toxic to the plants, the presence of the gas in the vadose zone may restrict the oxygen transport needed for cell respiration in the root system (see Section 1.1.2). Furthermore, these covers have not been shown to be able to prevent the diffusion of landfill gases to the surface. Therefore, these gases must be controlled through other means.

1.3.3 Phytoremediation Groundcovers

In addition to the ability of cover systems to stabilize soil/sediment and control hydraulics, densely rooted groundcover plants and grasses can also be used to phytoremediate contaminants. Phytoremediation groundcovers are one of the more widely used applications and have been applied at various bench- to full-scale remediation projects. It is the "classic" application often referred to as "phytoremediation" (distinguishing it from the nonremediation aspects of phytotechnologies such as phytostabilization covers, see Sections 1.3.1 and 1.3.2, and hydraulic tree stands, see Section 1.3.4). Furthermore, in the context of this document, phytoremediation groundcovers are vegetated systems typically applied to surface soils as opposed to phytoremediation tree stands (see Section 1.3.5), which refers to phytoremediation systems for deep soils and/or groundwater. The typical range of effectiveness for phytoremediation groundcovers is 1–2 feet below ground surface (bgs); however, depths down to 5 feet have been reported as within the range of influence under some situations (Olsen and Fletcher 1999).

Phytoremediation encompasses rhizodegradation, phytodegradation, and/or phytovolatilization mechanisms (see Sections 1.2.2, 1.2.5, and 1.2.6, respectively) to reduce contaminant concentrations at the site. Furthermore, phytoremediation also includes phytoextraction (see Section 1.2.4) as long as harvesting and contaminant removal is included in the application. The specific mechanisms that are emphasized in an application depend on the mobility, solubility, degradability, and bioavailability of the contaminant(s) of concern (COC). Phytoremediation groundcovers have been widely applied to soils impacted with recalcitrant compounds such as PAHs, PCBs, and other persistent organic pollutants that are typically less mobile, soluble,

biodegradable, and bioavailable. Reviews of these works can be found in the literature (Flathman and Lanza 1998; Frick, Farrell, and Germida 1999; Zeeb et al. 2006; Russell 2005). Furthermore, these groundcover systems can also be used as certain types of landfill covers that also promote the degradation of the underlying waste (USEPA 2000). These have been referred to as bioreactor landfills (see ITRC 2006a). Finally, phytoremediation groundcovers have been used to extract specific inorganic contaminants such as metals, salts, and radionuclides in concentrations higher than what existed in the soil. Typical concentration ratios of many such elements have been compiled by many scientists (Wang, Biwer, and Yu 1993). The remediation aspects for these constituents occur when the aboveground portions of the plant where the inorganic contaminant accumulates are harvested with conventional agricultural methods and removed from the site.

To enhance the phytoextraction capabilities, several strategies have been attempted. Lead can be made much more bioavailable with the addition of chelating agents such as ethylene diamine tetra-acetic acid (EDTA) to soils (Schnoor 1997). Similarly, a considerable body of information exists on the uptake of radionuclides into plants, including laboratory and field studies where radionuclides from nuclear weapons complexes or test sites have been transferred into plants. Specifically, the availability of uranium and radio-cesium 137 has been enhanced using citric acid and ammonium nitrate, respectively (Dodge and Francis 1997, Riesen and Bruner 1996). However, adding these enhancing agents also increases the inherent risks associated with the application since they can also mobilize target contaminants and other constituents deeper into the soil or into groundwater. This is a decision factor to consider when selecting this phytotechnology application as the site remedy (see Section 2.3). Furthermore, the timing of the application should be thoroughly designed, planned, and managed during implementation (see Section 2.4).

1.3.4 Tree Hydraulic Barriers

Groundwater naturally migrates from higher to lower elevations in the subsurface, typically along the path of least resistance (i.e., higher permeable zones or aquifers). Contaminants present in the groundwater can likewise migrate in the subsurface, potentially impacting downgradient receptors. However, many contaminants can interact with the subsurface environment through adsorption and electrostatic forces to retard the contaminant plume compared to the bulk groundwater. To contain the hydraulic flow, groundwater extraction can be used to further limit the migration of groundwater plumes. When groundwater is extracted downgradient of the plume, the hydraulic gradient is reversed in a cone (or zone) of depression creating a capture zone. When groundwater is extracted upgradient of the plume, the hydraulic gradient within the plume is reduced, causing slower plume migration. Figure 1-11 illustrates both of these alternatives using trees to extract the groundwater and create the hydraulic containment barrier. Most tree hydraulic barrier applications concentrate the plantings above and at the downgradient edge of the plume (Matso 1995). All applications use the phytohydraulic mechanisms (see Section 1.2.3).

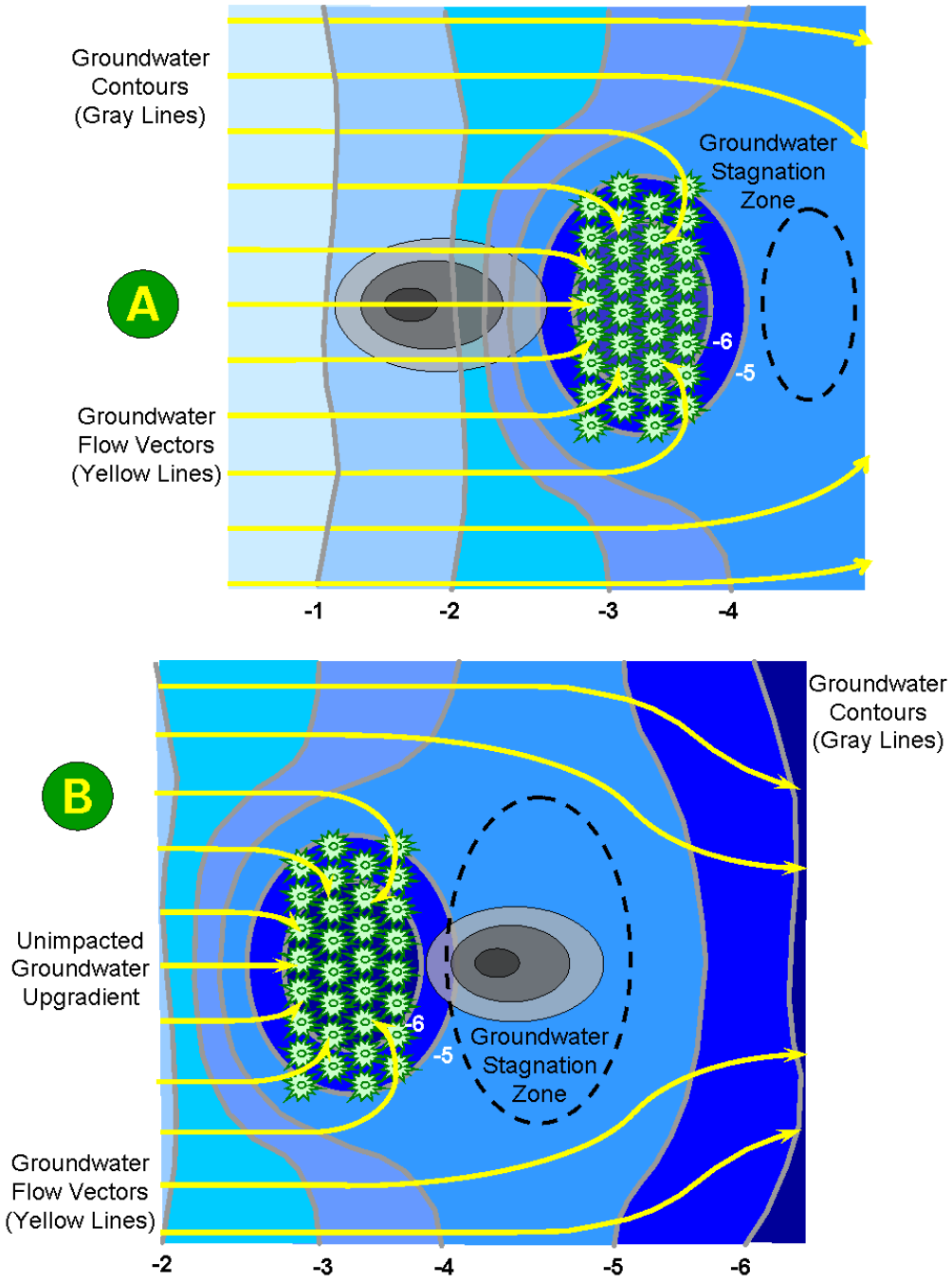


Figure 1-11. Tree hydraulic barrier application (plan view). A: downgradient plume, B: upgradient groundwater control.

In general, the deep-rooted, high-transpiring trees must be actively tapping into the groundwater to create the barrier. Furthermore, a relatively large number of trees (and associated area) are generally required to extract the volumes necessary to achieve containment. Typical transpiration rates were shown previously in Figure 1-4c for woody species (trees) of various ages. Although this type of phytotechnology application has generally focused on the use of trees, other species such as prairie grasses have root systems that can reach 10–15 feet bgs, given optimal soil and

moisture conditions (USEPA 1998). Furthermore, many of these species have high transpiration rates, as shown in Figure 1-4a. The range of values presented depends on many other factors, including the depth of groundwater, soil conditions, and climate in the region where the site is located. These factors must be considered when selecting and designing the technology (see Sections 2.3 and 2.4, respectively). Similar to other extraction systems, the influence of tree hydraulic barriers on groundwater plumes can be modeled (see Section 2.4.1.2).

1.3.5 Phytoremediation Tree Stands

In addition to the ability of deeper rooted plants and trees to take up and transpire groundwater, they can also be used to phytoremediate deeper soils and contaminated plumes that are located near the top of the water table. While phytohydraulics can be used to bring the contaminants into the root zone, rhizodegradation, phytodegradation, and/or phytovolatilization mechanisms (see Sections 1.2.2, 1.2.5, and 1.2.6, respectively) can reduce contaminant concentrations at depth. Furthermore, phytoremediation also includes phytoextraction (see Section 1.2.4) as long as harvesting and contaminant removal is included in the application. These mechanisms further reduce the migration of contaminated groundwater plumes through destruction.

Phytoremediation tree stands have been widely applied to soluble contaminants that commonly impact groundwater such as petroleum products (BTEX, MTBE, aliphatics, gasoline-range organics [GRO], DRO, and TPH) and chlorinated hydrocarbons (PCE, TCE, DCE, VC, etc.). The lighter fractions of these constituents are generally mobile, soluble, and bioavailable with log K_{ow} values in the range where uptake into plants is expected. However, the bioactivity in the rhizosphere (see Section 1.1.2) may limit or eliminate plant uptake since these constituents are also relatively biodegradable. Several reviews of these applications have been published (Chappell 1998, Van Den Bos 2002). Furthermore, some phytoremediation tree stand applications have been successful when planted into free-phase product, showing dramatic reductions in concentrations as the plume flowed through the root zone (Fiorenza et al. 2005).

1.3.6. Riparian Buffers

As agriculture and urbanization encroach upon downgradient surface water bodies, NPS pollution is often generated in the runoff. This can contain fertilizers, pesticides, and animal waste from agriculture; sediment from cleared, urbanized lands; and road salts, automotive fluids, and other urban chemicals from roadways and infrastructure. Riparian buffers are vegetated areas that protect adjacent water resources from NPS pollution. In addition, these buffers provide bank stabilization and habitat for aquatic and other wildlife. Figure 1-12 shows a cross-section of a typical riparian buffer, along with the types of vegetation according to the wetland indicator status (see ITRC 2003b for further definitions).

Similar situations that threaten surface water bodies are groundwater seeps that contain environmental pollutants. Typically, where these seeps daylight is just upgradient of a surface water body (i.e., a gaining water body) that then flows directly into the receptor. In some cases, including seasonal variations, the groundwater may not always daylight and may simply feed the surface water body through a subsurface hydrologic connection. Placement of a riparian buffer would be along and upgradient of the groundwater-surface water interface.

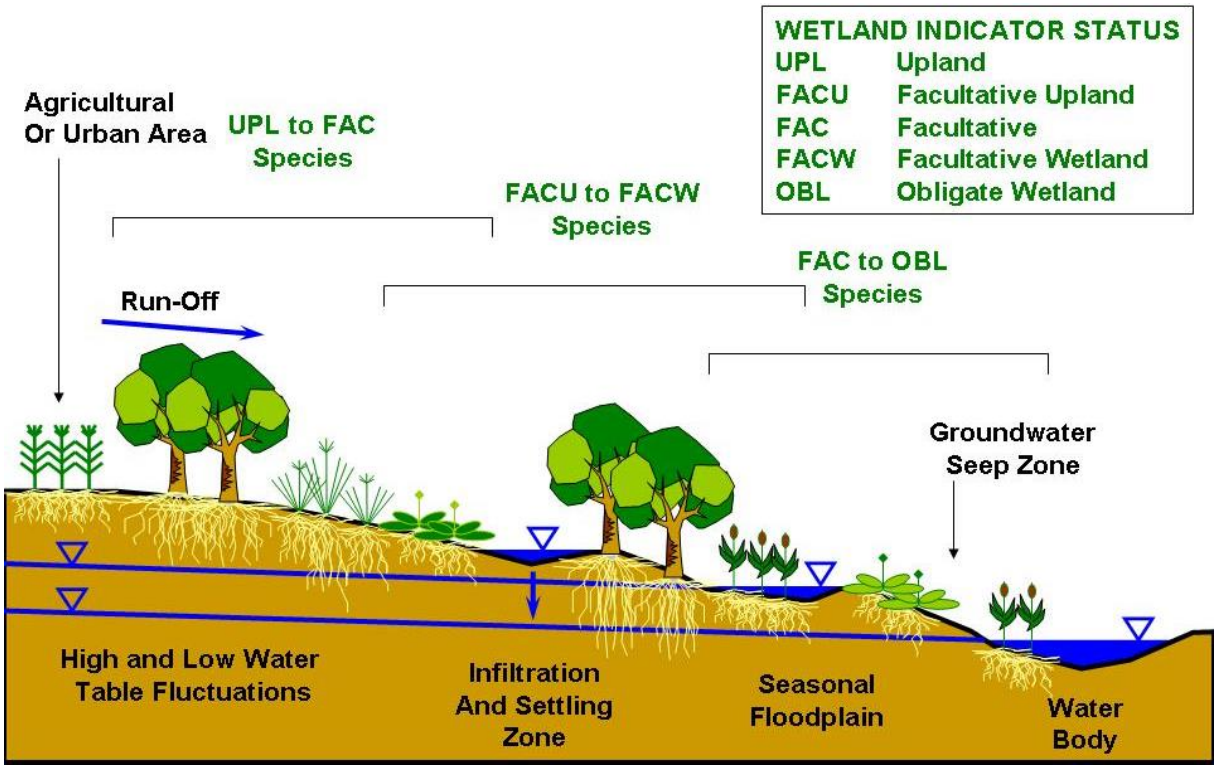


Figure 1-12. Riparian buffer application.

It has long been recognized that riparian buffers (also known as or similar to riparian corridors, riparian zones, vegetated swales, retention/detention basins, etc.) are vital to controlling the hydrology and cleansing the runoff and near-surface groundwater. Specifically, the surface runoff or seep requires that the flow of water be sufficiently slow or contained to allow sediments and other particulate matter to settle out. The rate of flow is often measured as the hydraulic retention time (HRT) and can be designed using the width, grade (vertical drop over horizontal distance), and contouring of the system as well as soil characteristics. Furthermore, runoff water must flow evenly across the buffer to be effective. If channels develop due to erosion, the effectiveness of the buffer is greatly reduced due to the water "short-circuiting" the system and reducing the HRT. For the contaminants in the runoff to be adequately remediated, the HRT must be sufficient to match the rates of attenuation from various mechanisms. Many of these can be abiotic, such as those mentioned in Tables 1-5a and 1-5b. Furthermore, the hydrology is affected by the vegetation in the riparian buffer with the same mechanisms driving phytohydraulics while their root systems promote phytosequestration, rhizodegradation, phytoextraction, phytodegradation, and/or phytovolatilization (see Section 1.2).

1.4 Advantages and Limitations

Phytotechnologies is a broad set of technologies that can be applied to a wide range of environmental conditions. In comparison to alternative cleanup technologies, it is one of the few that can be applied to both organic and inorganic contaminants and to soil/sediment, surface water, and groundwater. Furthermore, in some cases, it can be applied to various combinations of contaminant types and impacted media simultaneously. In most other remedial approaches, these

Example of Phytotechnologies' Broad Utility

Consider wood-treating facilities where creosote (organic contaminant) and copper-chromium-arsenic (inorganic contaminants) wood preservations were used. Often, surface releases directly impact the soil while leaching of the soluble components of both organic and inorganic contaminants can create commingled groundwater impacts. Assume the groundwater is relatively shallow but spread across a large area of the site. Different treatment options are possible:

Option 1. Conventional Treatment Train—To address soil impacts, excavation and off-site disposal can prevent further leaching. Once completed, the groundwater impacts might be addressed using extraction (groundwater pumping network) to remove contaminants and control plume migration. Once extracted, the organic constituents in groundwater might be treated through granulated activated carbon (GAC). For the dissolved inorganic constituents, a reverse osmosis (RO) system might be used as treatment. Once cleansed, the groundwater would be discharged through a permitted outfall. This scenario uses three steps (excavation, extraction, treatment) with two treatment technologies (GAC and RO).

Option 2. Phytotechnology Application—Deep-rooted trees planted over the impacted area can send roots through the impacted soil to access the groundwater. Phytohydraulics can be used to control plume migration (tree hydraulic barrier application). Phytosequestration of the inorganics and rhizodegradation of the organics can be used to treat the surface soils (phytostabilization cover and phytoremediation groundcover applications). The dissolved inorganic constituents can be phytoextracted or phytosequestered in the trees (phytostabilization cover application) while the organic groundwater constituents can be rhizodegraded and/or phytodegraded (would likely not be phytovolatilized given the chemical properties of heavier hydrocarbon typical of creosote) (phytoremediation tree stand application). No water is discharged. This scenario uses one step (planting) but with four phytotechnology applications.

Option 3. Hybrid Approach—Excavation and extraction as in Option 1, but treatment in a constructed treatment wetland that can address both the organic and inorganic constituents (see ITRC 2003c). This scenario uses three steps (excavation, extraction, treatment) with one treatment technology.

Of course, the final selection of the remedial approach depends on many other factors besides remedial technologies, including technical issues, economics, regulatory acceptance, community stakeholders, etc.

combinations would have to be addressed using a treatment train. This fact represents one of the main advantages of phytotechnologies. Other advantages are listed below:

- considered a green technology and sustainable
- solar-powered (The system itself does not require supplemental energy, although monitoring equipment may. See Section 2.5.)
- improves air quality and sequesters greenhouse gases
- minimal air emissions, water discharge, and secondary waste generation
- inherently controls erosion, runoff, infiltration, and fugitive dust emissions
- passive and in situ
- favorable public perception, including as an educational opportunity
- improves aesthetics, including reduced noise
- applicable to remote locations, potentially without utility access (critical utility is a supplemental source of irrigation)
- can be used to supplement other remediation approaches or as a polishing step
- can be used to identify and map contamination
- can be installed as a preventative measure, possibly as a leak detection system
- lower maintenance, resilient, and self-repairing
- creates habitat (can be a disadvantage—attractive nuisance)
- provides restoration and land reclamation during cleanup and upon completion

- can be cost-competitive

However, like all remediation technologies, phytotechnologies are appropriate only under certain conditions. The major limitations are depth, area, and time. The physical constraints of depth and area depend on the plant species suitable to the site (i.e., root penetration) as well as the site layout and soil characteristics. Phytotechnologies typically require larger tracts of land than many alternatives. Time can be a constraint since phytotechnologies generally take longer than other alternatives and are susceptible to seasonal and diurnal changes. These limitations should be considered along with several other decision factors when evaluating a phytotechnology as a potential remedy (see Section 2.3). Furthermore, these potential limitations should be considered when assessing the site (see Section 2.2) to determine immediate "No-Go" situations.

2. PHYTOTECHNOLOGIES PROJECT MANAGEMENT REQUIREMENTS

Developing and managing phytotechnology systems are similar to any in situ remediation system. To successfully remediate a particular site, six general phases exist which require specific skills necessary to understand the particular site conditions, treatment mechanism, design layout, and evaluation parameters:

- assessment
- remedy selection
- design
- implementation
- operation, maintenance, and monitoring (OM&M)
- closure

Though discrete, these phases form a continuum and sometimes an iterative process to design an optimal phytotechnology system for a contaminated site. The following sections describe unique characteristics and functions required for each of these phases to reliably apply phytotechnologies to address impacted soils, sediments, and/or groundwater.

2.1 Project Structure and Organization

2.1.1 Project Team

For any phytotechnology system, project team skills and roles should be established up front and should consist of the following disciplines (or have personnel on the team capable of completing these tasks). Table 2-1 identifies, in general, the required skills for each member of the project team for each phase of the project.

- ***Project Manager.*** Coordinate all of the information being gathered. Evaluate the phytotechnology system to meet cleanup objectives, including containment zones, contaminant remediation mechanisms, sampling and analysis plan, operation and maintenance plan, health and safety plans, schedules, compliance, and cleanup time.
- ***Soil Scientist/Agronomist.*** Evaluate the ability of the soil conditions to support plants. Develop a soil amendment plan to prepare and maintain the growth of plants throughout the duration of the phytotechnology application.

- ***Hydrologist/Geologist.*** 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 COC(s).
- ***Plant Biologist/Botanist.*** Evaluate a range of plant species suitable for the site soil, groundwater, and climatic conditions. Knowledge of species capable of remediating the COCs is desirable. Determine planting requirements, including density, patterns, field preparation, and equipment needs. Develop plans for planting.
- ***Environmental Scientist.*** Conduct greenhouse screening tests using water and/or soil samples from the site to ensure that the plants can survive the contaminated conditions. Conduct feasibility field studies to determine whether the plants will remediate the COCs.
- ***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 toxicity evaluations using relevant receptors.
- ***Regulatory Specialist.*** Determine the regulatory requirements, final cleanup limits, sampling and analysis requirements, data quality requirements, O&M 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.*** Evaluate engineered implementability of a phytotechnology system at the site (earthmoving, constructability, materials, etc). Design field systems: irrigation, pumping, water control, rooting, security, automated sensors, etc. Assemble relevant computer-aided design and drafting (CADD) drawings.
- ***Field Manager/Health, Safety, and Environmental 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.

Table 2-1. Required skills for project phases

Discipline	Assessment	Selection	Design	Implementation	OM&M	Closure
Project management	X	X	X	X	X	X
Soil sciences/agronomy	X	X	X	X	X	
Hydrology/geology	X	X	X		X	
Plant biology/botany	X	X	X	X	X	
Environmental sciences	X	X				
Risk assessment/ toxicology	X	X				
Regulatory interpretation	X	X				X
Environmental engineering	X	X	X	X		
Field and health, safety, and environmental management	X	X	X	X	X	
Economic analysis		X	X			

2.1.2 Project Checklists and Planning

Each project phase has a unique set of deliverables with each subsequent phase dependent on decisions of the previous phases. To ensure adequate information is available for the subsequent decisions, the project team should establish a series of checklists outlining data requirements, site needs, timetables, and expectations for each phase of the project. When transitioning from one phase to the next, the project team should meet to discuss the completeness of the current phase deliverables and prepare the checklist for the next phase. As the project progresses, these checklists become more detailed and site specific. These checklists can be used to align site owners, system designers, technology vendors, regulators, stakeholders, and the public on the plan, evaluation, and effectiveness of the phytotechnology system to achieve the cleanup goals for the site.

The checklists for all phases should, at a minimum, identify the composition, roles, and responsibilities of the phytotechnology team (who), outline a project level timetable (when), and outline the schedule and objectives (what) of site visits (where). Supplemental documentation may also be necessary such as work plans, health and safety plans, site security protocols, etc. (how). Specific phases may also require unique elements as summarized in Table 2-2.

2.2 Site Assessment

A complete site assessment is critical for the design and installation of a phytotechnology treatment system. But like any other assessment, it should provide answers to the following basic questions:

- What type and quantity of contamination exists at the site?
- Where and how is the contamination migrating?
- What hazards exist to public health or the environment?

Once these basic site assessment questions are answered, such as using the Triad approach (see ITRC 2007b), a risk assessment can be done, which then allows the phytotechnology project objectives to be defined should the technology be selected as part of the remedy. Selection of a phytotechnology as a potential remedy is described in Section 2.3 and incorporates much of the information gained during the assessment. However, other factors such as economics; wants/needs; and viewpoints from stakeholders, regulators, site owners, and community members are also included.

2.2.1 Project Objectives

Remediation objectives for phytotechnologies can be control and containment, contaminant removal and destruction, or both. When designed specifically for control and containment, there is the potential to remediate as well. Furthermore, other objectives such as preventative "phytoscaping," polishing in a treatment train, and long-term end use or closure care requirements may need to be considered, depending on the type or phase of the project.

Table 2-2. Checklist of deliverables by project phase

Italics indicate phyto-specific information

	Deliverable
Assessment	
☐	Baseline concentration data
☐	Risk assessment (receptor survey, exposure pathways, toxicology, etc.)
☐	Statement of the remedial objectives, governing regulatory framework, cleanup targets
☐	Site characterization data (topography, hydrogeology, obstructions, utilities, etc.)
☐	*Agronomic assessment data*
☐	*Existing vegetation survey, climate data*
Selection	
☐	Description of expectations of the site owner, regulators, stakeholders, and the public
☐	Description of the stakeholder/public concerns *with phytotechnologies*
☐	Closure criteria for the site
☐	Environmental impact assessment (if needed)
☐	*List of candidate species successfully screened in greenhouse/laboratory studies (if needed)*
☐	*Feasibility, fate and transport, or plant toxicity study results (if needed)*
☐	*Mechanistic description of how phytotechnologies will achieve the remedial goals*
☐	Preliminary time estimates *for phytotechnologies* to complete cleanup
☐	*Preliminary design of the phytotechnology system*
☐	Economic comparison *of the phytotechnology remedy* to other alternatives
Design	
☐	*Final proposed design of a phytotechnology system (layout, types and number of species, installation methods, construction time, irrigation system, etc.)*
☐	*Mass balance study results (if needed)*
☐	Plan to deal with waste generation and disposal during construction
☐	Site health and safety plan; security plan; environmental impact/spill prevention, control, and countermeasure plan
☐	Operations and maintenance plan; *plan to deal with secondary waste from the phytotechnology remedy (i.e., contaminated plants, plant parts)*
☐	Parameter list to evaluate effectiveness, monitoring schedule, milestones, data management plan
☐	Contingency plan if the *phytotechnology* remedy does not achieve the monitoring milestones
☐	Work plan for implementing the final design *of the phytotechnology system*
Implementation	
☐	*Map/drawings of the final planted layout*
☐	Manifest of total materials used *(seed/plant stock, fertilizer, mulch, amendments, backfill, etc.)*
☐	As-built drawings of engineered systems (i.e., *irrigation system,* storm water control systems, monitoring devices/wells, security system, etc.)
☐	Breakdown of final capital costs of installation
OM&M	
☐	System maintenance records, *replanting records, pest (insect/herbivore) control measures*
☐	Monitoring records, concentration trend data, *growth data*
☐	*Transpiration rate and composition data (if needed)*
☐	*Plant tissue data (contaminant uptake) (if needed)*
☐	*List of volunteer growth species; associated invasive species control measures*
☐	Revised/updated site-wide water balance (if applicable)
☐	Breakdown of annual operation, maintenance, and monitoring costs
	Where required, periodic harvesting, transportation and disposal of plant wastes
Closure	
☐	Post-closure monitoring and care plan
☐	Equipment decommissioning plan, plan to plug and abandon wells

If reducing contaminant mobility is the primary objective, the main focus should be on rain interception and/or groundwater uptake and the subsequent evapotranspiration from both processes. The contaminant physical state (solubility and availability) should be considered as well. The effects of the plants on contaminant fate and transport should be modeled, including, potentially, plume migration, plume stability, and/or surface flow or vadose zone models. Several models for these applications are available in the literature. See ITRC 2003c, 2008. Applications for control and containment include vegetated caps, vegetated soil stabilization covers, and hydraulic barriers (usually placed downgradient of a plume, but can be upgradient as well).

Phytotechnologies that remove contaminants from the media include phytoextraction and phytovolatilization. These typically require the development of mass flux equations or rates of extraction to model their effectiveness. Destruction of contaminants can be accomplished using rhizodegradation and phytodegradation and can be modeled using degradation rate constants. These remediation mechanisms can be combined with containment. Applications for removal or destruction include phytoremediation groundcovers, tree stands for remediating deeper soil and groundwater, constructed treatment wetlands, and riparian buffers. Closure criteria specifying the target contaminant concentrations should be identified. The target concentration for each contaminant may be driven by environmental regulations such as Resource Conservation and Recovery Act (RCRA); Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); and the Clean Water Act; or state-specific cleanup requirements. Surface water discharges from the site, if any, may be required to meet National Pollutant Discharge and Elimination System (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 applications of phytotechnologies that combine containment with remediation include covers that stabilize soils and phytoremediate contaminants, tree stands that create a hydraulic barrier while remediating impacted soil and groundwater, constructed wetland treatment systems, and riparian buffers.

2.2.2 General Information Relevant to Phytotechnologies

During any general site assessment, much of the information normally collected is useful in determining whether phytotechnologies are applicable to the site in much the same way other technologies are assessed. Site visits should be conducted to assess specific information. Furthermore, photographic records of relevant areas provide documentation for future reference as designs and plans are developed. Table 2-3 lists several categories of assessment information that are normally collected, indicates which discipline of the phytotechnology team uses the information, and describes why the information is relevant specifically for phytotechnologies. This list is not exhaustive and includes no descriptions of general purpose use for selecting any remedy but attempts to focus on the relevancy to phytotechnologies only.

Table 2-3. General assessment information

Information category	Discipline	Relevance to phytotechnologies
Site description and history	Soil sciences/agronomy	Surface features and obstructions to design the implementation and select planting equipment Historic use of pesticides at the site or on adjacent sites (spray drift) to evaluate plant establishment issues
	Hydrology/geology	Surface topography for determining runoff characteristics for irrigation
	Plant biology/botany	Location of water bodies, standing water, or inundation for plant selection
	Environmental engineering	Surface features, grade, and obstructions to determine area available for planting and constructability Infrastructure and utilities that can support the phytotechnology system
	Field and health, safety and environmental management	Utilities and surface grade to evaluate implementability (health and safety), utility clearance, slips/trips/fall potential, and personal protective equipment (PPE) requirements
Contaminant assessment	Hydrology/geology	Contaminant concentrations and composition to model fate and transport and determine contaminant mobility driven by transpiration water usage
	Plant biology/botany	Vertical and horizontal extent of contamination to evaluate the ability of plants to affect the entire contaminant mass
	Environmental sciences	Contaminant concentrations and composition for plant screening and testing
	Regulatory interpretation	Impacted media and contaminants to determine handling requirements of waste generated during construction and long-term OM&M
	Field and health, safety and environmental management	Impacted media and contaminants to determine PPE requirements
Hydrogeological conditions	Hydrology/geology	Groundwater flow direction, hydraulic conductivity, and soil types to design and model the effects of hydraulic phytotechnology systems
	Plant biology/botany	Depth to groundwater accessible by plants, soil classifications, and geological stratification affecting root growth and penetration Groundwater salinity and pH for plant selection Wetland indicators (surface water/groundwater interface) for plant selection Redox potential to determine degradability of contaminants within and outside of the rhizosphere of the plant species
	Environmental engineering	Soil classifications and geological stratification to determine competence for tree boreholes Depths of all clean and impacted water-bearing zones to determine target depths for hydraulic capture and exclusion
Exposure assessment	Hydrology/geology	Receptor survey for waterway and wetland characteristics to determine storm water management and runoff control
	Risk assessment/toxicology	Local/regional herbivores and migratory animals to determine potential attractive nuisance issues
	Field and health, safety and environmental management	Local community demographics to determine potential interaction and security issues

2.2.2.1 Site Description and History

A site description should include detailed maps of the location, including property boundaries, surrounding features, residential or public areas, water bodies, roadways or other accessways, 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, easements, and other obstacles that will need to be removed and/or accounted for in the phytotechnology design. These include buildings, structures, foundations, concrete pads, paved surfaces, tanks, pipes, drains, underground utility lines, monitoring/compliance wells, overhead power lines, and natural barriers. The current and suspected use of the various features should be included in a discussion by the project team such as active traffic areas, line-of-sight issues, and the effects of vegetation throughout the life cycle of the plants. Other useful information includes historical uses of the site, surrounding industrial or commercial sites, previous site investigations, previous remediation efforts, and records from the responsible regulatory agencies.

2.2.2.2 Contaminant Assessment

The location, extent, and concentrations of the COCs must be accurately determined and should include characterizing soil, sediment, surface water, groundwater, and air emissions from the site. Site owners and their consultants should work with the responsible regulatory agency to determine the methods and distribution of sampling to characterize the COCs. Information about the contaminant distribution in specific media is needed to properly design a phytotechnology system. Phytotechnologies may not remove all contaminants and may not work if the contaminant concentration is too high. Therefore, 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 residual and/or dissolved plume with phytotechnologies. Furthermore, the distribution of a plume dictates the location of plantings used to control hydraulics or remediate the impacted subsurface. Similarly, the location and flow of surface runoff drive the location of the plantings.

Phytotechnologies also offer some information on identifying contaminated zones. In some cases, the existing vegetation, patterns of growth, and overall health of the plants often provide an initial indication where contamination might exist. Furthermore, simple plant tissue sampling methods can be used to help refine those locations prior to conducting exploratory drillings and other more conventional investigative techniques. Specifically, certain plant species have evolved to grow on certain soils containing specific metals (McIntyre 2003). Similarly, leaf tissue sampling, transpiration gas sampling, or trunk core sampling can be employed to detect soluble contaminants in the transpiration stream such as TCE or MTBE (Schumacher, Struckhoff, and Burken 2004; Newman et al. 1999a; Arnold, Parfitt, and Kaltreider 2007).

The benefits of using the phytotechnology-based techniques are the relative lower costs, labor requirements, and safer operations compared to the more intensive and invasive conventional techniques. For example, drilling an exploratory boring to collect a sample for analysis may require more than an hour, while coring the trunk of a tree to collect a sample may take only 10

minutes. Furthermore, the sampling of plants simply provides a direction and refinement to future exploratory borings making the latter more efficient.

2.2.2.3 Hydrogeological Conditions

Control and/or treatment of groundwater using phytotechnologies is limited to the extent of the root zone. Root penetration is dictated by the nutrient content, moisture, and relative ease of or resistance to grow into the matrix. Tight formations (e.g., clayey, bedrock strata, or aquitards with smaller porosity and lower water transmissivity) are often more resistant to root penetration than permeable formations (e.g., sandy, silty, gravel strata or aquifers with higher porosity and water transmissivity). Regardless of the ability of roots to penetrate the subsurface, plants will grow root systems extensive enough only to supply the necessary nutrients and moisture to sustain itself. If this is achieved prior to accessing the target groundwater, then the performance of the system may be limited. If contaminated groundwater is deeper than the root zone, then the groundwater could be pumped to the surface and induced towards the root zone of the plant.

Plant roots generally follow the path of least resistance with the most optimal nutrient and water conditions for growth, including water available at the surface from infiltrating precipitation. Therefore, to target specific water-bearing zones or preferential flow paths, either clean for hydraulic control or impacted for remediation and control, special culturing and installation methods are usually employed (see Section 2.4.3). Similarly, methods are available to bring plant roots into contact with a targeted impacted groundwater located below clean water–bearing zones or perched groundwater.

Although some plant species can tolerate some fluctuations in the water table, others species are less tolerant. Therefore, in addition to static groundwater conditions, adequate characterization is needed of dynamic changes both vertically and laterally from seasonal and tidal fluctuations, infiltration and recharge, and production wells (particularly backup wells that are used periodically). While the most desirable condition to model and predict the performance of a phytotechnology system is a stable water supply, these dynamic changes can be mitigated using supplemental and, often targeted, irrigation. These irrigation systems can be specifically engineered from the onset (see Section 2.4.2.1) but may not be required throughout the life of the phytotechnology system as the plants mature.

In addition to the depth and location of the groundwater relative to the root zone, the geochemistry should be evaluated for the potential to affect the function and performance of the phytotechnology system. Groundwater salinity and pH can limit plant selection or require modifications to properly implement a phytotechnology system. Redox potential and soil gases (oxygen, carbon dioxide, methane, etc.) can also indicate the likelihood to rhizodegrade groundwater contaminants. Similarly, the inorganic composition of the groundwater may contain elements that do not pose an environmental risk (not a COC, but naturally occurring), but may limit plant growth. To address these potentials, greenhouse or laboratory feasibility studies are often recommended using site-specific materials (see Section 2.3.3.1).

2.2.2.4 Exposure Assessment

Because phytotechnology systems use plants at a contaminated site, the potential ecological exposures posed by the species planted need to be considered. The level of detail required is site specific and varies with the application. Factors that should be incorporated into the risk assessment may include species-specific considerations of bioavailability (see USEPA 2008), ecological exposures, and the transformation of the chemical composition or physical state.

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 mercury to the ionic or elemental forms will render the metal less bioavailable and, therefore, less harmful. Similarly, barium is absorbed more by animals as barium chloride than as barium sulfate (the later form more prevalent in soils). There is generally limited information to assess the bioavailability of many contaminants. However, there is ongoing work, including through ITRC, to quantify bioavailability as affected by pH, soil moisture, organic matter content, and the presence (or absence) of other compounds in the soil. In addition, the stability of the bioavailable form can vary depending on the site conditions. Some chemicals can change form readily, while other chemical forms are stable/recalcitrant.

Bioavailability is controversial in both regulation and remediation. Site owners and system designers must address bioavailability on a site-specific basis since it depends on the contaminant composition, type of phytotechnology application, and site conditions. The effort could include educating concerned parties regarding bioavailability and issues specific to the site. The routine assumption of 100% bioavailability of contaminants to plants often overestimates the impacts of the contaminant. Actually, the solubility of the contaminant or by-product plays a major role. Research has shown that many organic contaminants do not accumulate in plant tissue since they are minimally water soluble. However, some organics can be taken up, particularly those that are phytovolatilized. For inorganics, increasing the bioavailability to plants using amendments or soil conditioning may be the designed approach. This increases the uptake into plants (i.e., phytoextraction), which can subsequently be harvested for recovery or disposal. However, adding chelating agents, surfactants, or pH adjustments, for example, to solubilize a contaminant could result in contamination of underlying soils and groundwater.

Furthermore, the phytotechnology mechanism being used (rhizodegradation, phytoextraction, phytovolatilization, etc.) affects the risk assessment. For example, a risk assessment for phytosequestration or rhizodegradation should address the roots and soilborne receptors (i.e., insects, worms, burrowing animals, etc.) that may ingest or contact them. If a contaminant enters into the terrestrial portion of the plant (leaves, stems, branches, etc.) during phytoextraction, phytodegradation, or phytovolatilization, then pathways through those plant structures will need to be assessed as well. However, the ecological exposure may not be directly from the consumption of the plant. Specifically, the U.S. Environmental Protection Agency (EPA) estimated that 2%–10% of the total mass ingested by animals might be soil (USEPA 1993). This percentage corresponds to 1–40 g/kg body weight per day. Therefore, enhancing the bioavailability of chemicals can potentially impact wildlife that resides at or nearby even if the animals do not consume the vegetation.

Contaminants may also be moved from soil and groundwater to air through plant transpiration. Plants have been noted to transpire volatile contaminants such as PCE, TCE, and MTBE (Compton et al. 1998; Newman et al. 1997b; Arnold, Parfitt, and Kaltreider 2007). This occurrence may raise health concerns even though most of these organics rapidly phytodegrade or the vapor concentrations from transpired gases are extremely low. Other contaminants may be volatilized, given the proper plants and conditions. 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). 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. Data must be provided demonstrating that the transfer of contaminants to the air poses a lesser risk for exposure than other remedial options. In some cases, it may be acceptable to allow a phase transfer to occur provided that this mechanism results in a higher level of protection to human health and the environment. 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 also affects 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.

EPA guidance for the preparation of ecological risk assessments (USEPA 1999b) should be used to evaluate any potential exposure pathways created or enhanced by using phytotechnologies. The bioconcentration factors used in this document are based on limited studies so may not be completely representative to the phytotechnology application being proposed. However, the data generated in the phytotechnology project may contribute to expanding that base of information.

The EPA 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 (see USEPA 2007a). These calculations can also be used to target which species 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 (see EPA 2007a).

2.2.3 Information Specifically Collected for Phytotechnologies

In site visits to conduct a general assessment, additional information specific to evaluating the applicability of phytotechnologies should also be collected. The general categories of information are provided in Table 2-4 along with which member of the phytotechnology project team would

use the information and why the information is relevant. This list is not exhaustive, but focuses on the relevancy to phytotechnologies only.

Table 2-4. Assessment information specific for phytotechnologies

Information category	Team member	Relevance
Soil conditions	Soil sciences/agronomy	Soil structure, compaction, and fertility to determine ability to support plants and develop fertilization and soil amendment plans Presence of fill material to determine implementability with field equipment
	Hydrology/geology	Soil structure to determine erosion and infiltration potentials
	Plant biology/botany	Nutrient content (see Table 1-1), pH, salinity/conductivity, moisture capacity and retention, and organic matter content to determine sustainable growth Compaction to determine rooting penetration and patterns Wetland indicators (i.e., hydric soil type) for plant selection
	Environmental sciences	Soil characteristics to replicate conditions for plant screening and testing
	Environmental engineering	Presence of fill material to determine implementability
Climate conditions	Hydrology/geology	Precipitation patterns, relative humidity, and pan evaporation rates for water management
	Plant biology/botany	Temperature ranges, frost dates, precipitation patterns and forms for plant selection
	Environmental sciences	Climate characteristics to replicate conditions for plant screening and testing
	Environmental engineering	Adverse weather conditions (i.e., 25-, 50-, 100-year flood, drought, storm events, etc.) to design and develop contingency plans and systems
	Field and health, safety and environmental management	Climate characteristics and planting season to schedule implementation
Existing vegetation	Plant biology/botany	Scientific and common names for plant selection, herbicide management, and controlling invasive or noxious species Wetland indicator status for plant selection
	Risk assessment/toxicology	Habitat form (prairie, arboreal, deciduous/evergreen forest, etc.), relative abundance, and locations to determine potential ecological receptors
	Regulatory interpretation	Scientific and common names to determine protected or species of interest
	Field and health, safety and environmental management	Type of vegetation (herbaceous, shrub, woody, vine, etc.), abundance, and locations to determine clearing and grubbing

2.2.3.1 Soil Conditions

The immediate condition of the surface soils may have a large impact on the entire phytotechnology system, particularly soil systems but also deeper, groundwater systems to some extent. Typically contaminated industrial sites are built on fill material and/or soil with low to nonexistent fertility, which needs to be considered during implementation. Furthermore, the soils are usually highly compacted, representing limitations to root penetration. In these cases, significant effort are required to condition (e.g., till, disk, plow, etc.) and amend the soils (e.g., add fertilizer, organic matter, fertile soil, etc.) to sustain plant growth. The level of effort and materials involved affect the time and cost of the overall project.

Special considerations often found at contaminated sites include high salinity measured as chloride content, electrical conductivity (EC), and/or total dissolved solids (TDS) in the soil pore water, acidic or alkaline soil pH, poor structure, elevated sodium content measured as sodium adsorption ratio (SAR), adverse cation exchange capacity (CEC), and the presence of residual herbicides from historic use. Many of these conditions may not favor the use of phytotechnologies due to the limitations on plant selection and the ability to cultivate and grow the vegetation. Again, many of these conditions can be evaluated using greenhouse or laboratory feasibility experiments (see Section 2.3.3.1).

If soil covers for phytoremediation are being considered, additional characterization of the microbial community may be needed. This information is generally not conducted during standard site assessments. These can include measurements of most probable numbers, specific degrader counts, and/or more sophisticated characterization techniques. Additional information on specific techniques is discussed in other documents, including ITRC 1998, 1999, 2007a, and 2008.

2.2.3.2 Climatic Conditions

All information related to climate conditions, including temperature, humidity, precipitation (rain and snow), wind (speed and prevailing direction), altitude, and the probabilities of flood or drought (25-, 50-, 100-year events, etc.) should be obtained from local weather stations (nearby cities, airports, major operating facilities). These site characteristics affect the design (planting density, modeling evapotranspiration, etc.), plant selection (tolerances to extreme temperatures, flood/drought, altitude, etc.), and maintenance (irrigation, mowing, debris, etc.) of the system.

In general, average seasonal lengths are dictated by the first and last frost dates for the region (check with the local agricultural extension service). The early spring is generally planting season and the most desirable period to establish a phytotechnology system. Therefore, planning to implement a system is often scheduled based on growing season in addition to other timing considerations such as regulatory process, permitting, gaining approvals, etc. In addition, changes in climate based on seasons also affect the performance of phytotechnologies. For example, during winter months, plants generally slow metabolic processes or go dormant altogether. Depending on the phytotechnology mechanism being used in the remedy, some or all of the performance may be seasonal as well.

2.2.3.3 Existing Vegetation

Conducting an initial plant species survey should include an identification of the major plant species (scientific and common names), their relative abundance, general locations at the site, and whether the roots are in contact with the contaminated media. In many cases, these species represent the starting point for determining potential applicable species for the phytotechnology application (see Section 2.3.1). Additional relevant information to note in the species survey includes habitat form, type of vegetation, and wetland indicator status. All of these may contribute to developing the type of phytotechnology application by matching the plant information to the location and extent of the contamination. Furthermore, habitat form considers potential ecological receptors that might be attracted to the area and is supplemented by determining the wetland indicator status. These include obligate wetland (OBL), facultative wetland (FACW), facultative (FAC), facultative upland (FACU), and upland (UPL) categories (for further definitions, see ITRC 2003b). The indicator status also aides in identifying species to be further screened or considered in the phytotechnology application. The type of vegetation (herbaceous, woody, vines, etc.) can also help develop the design, implementation, and O&M plans (see Sections 2.4 and 2.5).

2.3 Remedy Selection

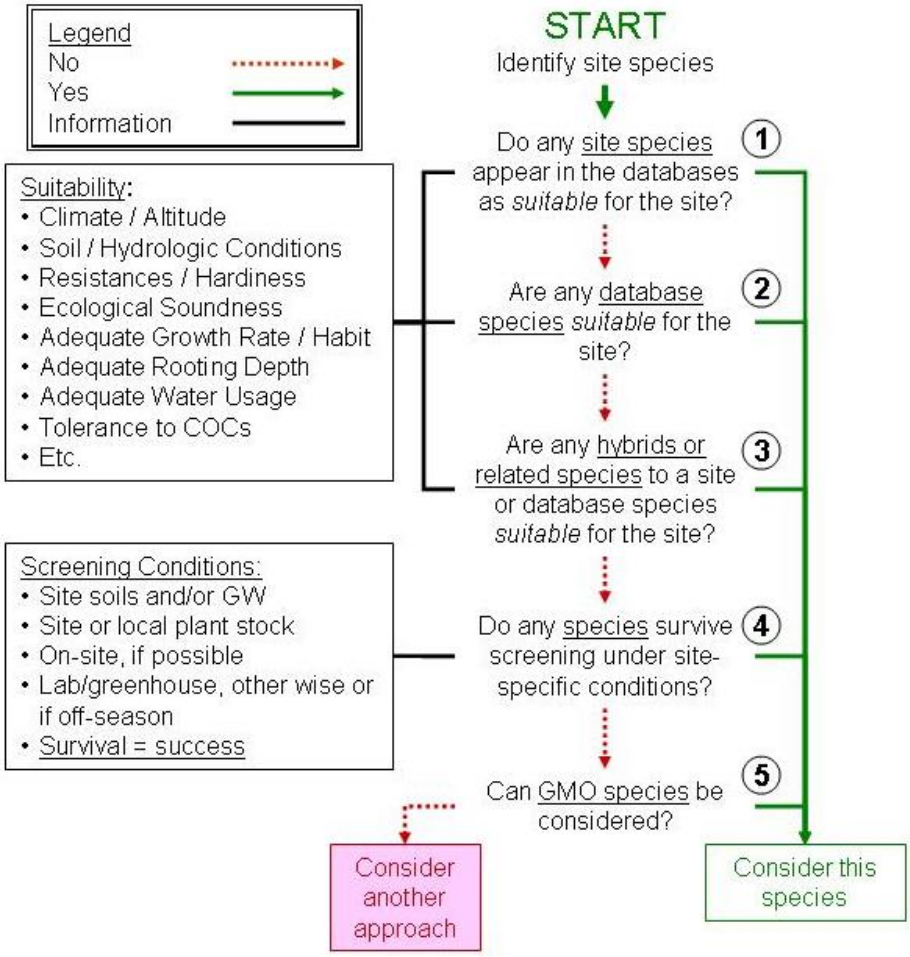
Phytotechnologies should simply be added to the broader list of options project teams need to consider to address the risks associated with a contaminated site. In general, remedies are often selected based on the media that is impacted, the COCs, and the behavior of the contaminants in the impacted media. To aid in the decision process, a decision tree for identifying potential phytotechnology applications based on these general criteria is provided in this section. Furthermore, decision trees for groundwater, soil/sediments, and riparian zones are also provided should these applications be identified as potential remedies. At sites where multiple media are impacted, additional decision trees contained in this document as well as other ITRC or similar decision documents should be consulted. Other impacted media or contaminated situations such as surface water and landfills are covered in other references, including ITRC 2003b and 2003c.

Using these decision trees, in conjunction with the remainder of the document, will assist regulators, site owners, technology vendors, and the public in determining whether phytotechnologies are applicable to a contaminated site. However, these decision trees are primarily for making technical decisions; the ultimate remedy selected for the site will also depend on other factors, including remedial objectives; cleanup targets; expected outcomes; stakeholder, site owner, regulator, and community acceptance; economics; and other applicable or relevant and appropriate requirement (ARARs). Furthermore, adding a phytotechnology to a site with an existing system can also be considered as either a supplement or eventual replacement. In these cases, the effects of both systems need to be considered in combination with each other and over time as the phytotechnology system matures at the site.

2.3.1 Plant Species Screening Process

Prior to running through the decision trees, a basic question that needs to be answered is simply whether any species exist that can survive the contaminated site conditions. To answer this basic

question, a plant screening exercise needs to be conducted. Figure 2-1 shows the process for screening plant species. The output of this screening process is simply a list of candidate species, if any, that may be applicable; it does not lead to a final list for the site. Generating a final list is done once a phytotechnology remedy is selected for the site and when the design is being conducted (see Section 2.4). If the output of the screening process does not generate any candidate species, then phytotechnologies is not appropriate for the site and another remedy



should be sought.

Figure 2-1. Plant species screening process.

The plant screening process assumes that the existing species at the site have been characterized and begins by examining:

1. species found in phytotechnology databases and currently growing at the site
2. species found in phytotechnology databases and suitable to the region but not currently growing on the site
3. hybrid or species related to a species identified as a candidate in either #1 or #2
4. species NOT found in the databases (or test conditions that are too dissimilar) but currently growing at the site or in the region

5. genetically modified organism (GMO) species designed specifically to conduct the desired phytotechnology

These categories are discussed in detail below. The *suitability* of a species, which is considered in the first three categories, is determined based on the ability of a species to grow and survive the site conditions (soil, contamination, climate, U.S. Department of Agriculture [USDA] hardiness zone, altitude, etc.). Furthermore, the ecological soundness should also be considered to prevent introducing nonnative and/or aggressive species that may disrupt the local ecology. Finally, general operability factors such as growth rate, habit (perennial, annual, biennial, deciduous, evergreen), form (grass, herbaceous, shrub, tree, etc.), ability to reach desired depths, water usage, disease/pest resistances, and tolerances can be considered at this stage as well. This information can be gathered from local, state, or federal agencies and offices or from universities. Several Internet resources are also available that provide this type of information, including the Plant Materials Program of the USDA Natural Resources Conservation Service (http://Plant-Materials.nrcs.usda.gov) and the USDA PLANTS national database (http://plants.usda.gov).

Furthermore, these categories and the entire screening process rely on access to and knowledge contained within existing phytotechnology databases. Although the number of species that have actually been evaluated for phytotechnologies is very small, several extensive phytotechnology databases have been published (Tsao 1998; Frick, Farrell, and Germida 1999, 2000 [www.phytopet.usask.ca/mainpg.php]; McIntyre 2001). A periodically updated database of plant species according to contaminant can be accessed on the ITRC website at http://www.itrcweb.org/Team/Public?teamID=40. These databases include species to address metals, radionuclides, petroleum hydrocarbons, halogenated compounds, explosives, surfactants, and pesticides and generally include information on climate conditions, contaminant composition and concentrations, type of application, scale of the test, performance, etc. Some recent contaminants studied include MTBE, tertiary butyl alcohol (TBA), arsenic, cyanide, perchlorate, tritium, PCBs, and explosives (TNT, RDX, HMX). Other contaminants and species may be found in more recent phytotechnology research (as of this publication), extrapolated from unrelated research, or other site-specific knowledge. *International Journal of Phytoremediation* is a dedicated journal on phytotechnologies. EPA hosts a web page exclusive to phytotechnologies: www.clu-in.org/techfocus/default.focus/sec/Phytoremediation/cat/Overview.

Database information on evapotranspiration rates is less common; although data on the transpiration portion (separating it from interception and evaporation) of common phytotechnology species are being continually generated by phytotechnology projects. Even less common are the interception and evaporation rates that various plant canopies create. Some evapotranspiration estimates are reported in this document (see Table 1-2 and Figures 1-4a to 1-4c). However, when reviewing the literature, the basis for the reported values should be noted since shorter-duration measurements are highly dependent on the conditions of the study. Transpiration estimates can be reported as annualized rates (total gallons pumped in a season divided by 365 days), seasonal rates (total volume pumped in a season divided by the length of the season), or as a single event occurring within a single day. Typically, values for trees are reported in units of volume per day per tree (i.e., gallons per day [gpd] per tree). Furthermore, reported values should note the age, growth stage, or growth characteristic (such as basal trunk

area) of the tree as reference to the maturity. Similarly, groundcover plants (grasses, herbaceous species, crops, etc.) are typically reported in volume per unit area per unit time (i.e., gal/acre-day, or gpd/acre), or if converted, in length per time (i.e., feet/day). Again, the duration, study conditions, and plant age should be noted. Rain interception capacities for both tree and groundcover systems are often reported as a percentage of the total precipitation event captured by the canopy. Therefore, these values are highly dependent on the duration and magnitude of the precipitation event.

If a species appears in a phytotechnology database or other reference, the conditions described in the source reference should be compared to those of the site. If these are sufficiently similar to the site conditions, then these species may be considered candidate species. If the conditions are significantly dissimilar, then the efficacy of those plants may need to be confirmed through additional screening studies (see Section 2.3.1.4). These results could also be added to the growing database of phytotechnology species.

2.3.1.1 Database Species Currently at the Site

Species that are found in the phytotechnology databases or literature should be compared to the list of species found at the site during the site assessment phase. If the species appears in both lists, then species selection becomes relatively simple. Since the species is already growing at the site, and in some cases, in the contaminated media, it already exhibits tolerance to the site conditions (climatic and contamination). Since there is also confirmation in the literature that the species is able to address the specific contaminants at the site, it becomes one of the most likely candidates for future consideration.

2.3.1.2 Database Species Suitable to the Region

In some cases, species that are growing in the region may, for some reason or another, not be growing at the site. These 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. Since these species also appear in the phytotechnology databases or other references, their inclusion for future evaluation is highly recommended. These species already exhibit tolerance to the climate conditions necessary for a successful phytotechnology application. In most applications, plants that are adapted to local conditions have more chance of success than nonadapted plants. While the species may simply be naturally selected based on the current contaminated conditions, other reasons may exist unrelated to the contamination altogether. These could include adverse soil conditions, inappropriate hydrology, selective predation, or exclusion by more aggressive plant species. Given the proper management and cultivation during implementation and operation of the phytotechnology system, these species may proliferate at the site and conduct the desired remediation once these conditions are alleviated. However, it may be recommended to conduct screening experiments (see Section 2.3.1.4) to determine whether a species in this category is truly a candidate.

Species identified as native (not just existing) in the region deserve special consideration. Specifically, an Executive Order signed on April 12, 1994, requires all federal agencies to use regionally native species whenever federal funds are expended for landscaping. It promotes

recycling of green wastes and reducing fertilizers and pesticides and directs agencies to create outdoor demonstration projects using native plants. Secondly, native, nonagricultural plants are desirable for ecosystem restoration in critical habitat areas such as wetlands, riparian corridors, and other disturbed lands. Furthermore, the cleanup of Superfund (CERCLA) sites provides opportunities to use native plants during restoration or in phytotechnology applications. As part of the Superfund Redevelopment Initiative, more than 100 Superfund sites (totaling more than 13,000 acres) have been recycled and are now in beneficial ecological or recreational use. Native species are highly recommended for consideration on phytotechnology projects.

2.3.1.3 Hybrid or Related 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. Hybrids should not be mistaken for genetically modified or engineered species (see Section 2.3.1.5). Hybridization (particularly cross-pollination) occurs in nature itself. Artificially induced methods of hybridization include grafting tissues and cross-pollination from one variety to another.

Plant hybrids, including many of the forage, crops, and horticulture species, have been used for decades in landscaping, agriculture, horticulture, and forestry. One advantage is that the seed and planting stock of this group is readily available and typically 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. Similarly, fast-growing varieties can be selected and subsequently combined with other desirable characteristics. Because of these advantages, hybrids such as from poplars and willows have been extensively and successfully used in phytotechnologies.

However, because of these resistant and/or fast-growing characteristics, care should be taken to avoid introducing plant species that are noxious, invasive, or considered a nuisance. Designating species into these classifications varies among states. A second Executive Order specifically addressing invasive species 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 nonnative species. In cases where the spread of the plant is undesirable, sterile varieties, if available, should be chosen to prevent reproduction.

2.3.1.4 Species Screened in Experiments

Screening experiments are generally carried out in a greenhouse or laboratory setting, designed to mimic the site conditions as much as possible. This usually entails small-scale, replicated plantings using soils and/or water from the site grown under climate conditions typical for the region. In some cases, particularly for larger or older test stock, the screening experiments may be conducted at the site under field conditions (outdoors, natural climate conditions). However, the effects of other uncontrolled adverse conditions may result in confounding results. In general, screening experiments are needed to evaluate species already growing at the site but currently not appearing in the phytotechnology databases, species that do appear in the databases but under test conditions too dissimilar to the site conditions, or when other mitigating site conditions are

preventing the growth of species that under normal circumstances would be present (i.e., regionally present, but not at the site).

The objective of these screening experiments is simply to evaluate and demonstrate survivability, although combining these experiments with other, more quantitative objectives such as feasibility (see Section 2.3.3.1) or even treatability studies (see Section 2.3.3.3) can be done. The criteria for *survivability* should be clearly identified prior to conducting the experiments. *Survivability* is a qualitative result and generally encompasses a broad range of outcomes in a plant. High concentrations of contaminants may completely inhibit plant growth and eliminate phytotechnologies as remedial options for site cleanup. On one extreme, a plant can be severely stunted in growth, visually stressed (yellowing leaves, curling leaves, wilting stems/branches, etc.), and necrotic (tissue necrosis, cellular death) and still be considered to be surviving. In fact, the highly stressed condition may make the species more conducive to achieve the remedial cleanup objectives because the plant may initiate its secondary metabolic processes that provide protection and detoxification to the plant. It is this protection and detoxification that may also remediate environmental contaminants.

In most cases, plants grown under optimal control conditions should also be considered to compare the results. In some instances, plants have been shown to have enhanced growth compared to these controls (ARRIBPP 2004). Furthermore, plants may respond differently at different stages of their growth. Patterns include immediate or delayed stressed growth symptoms followed by recovery or normal growth followed by stress symptoms appearing later, possibly resulting in death (Tsao and Tsao 2003). To address these variable outcomes, the length of the plant screening experiment should be discussed and may need to be based on the annual life cycle of the species being tested.

2.3.1.5 Genetically Modified Organism Species

GMOs are species manipulated at the cellular level by transferring DNA, typically from a completely unrelated species into another. For example, GMO plants, also known as GM, genetically engineered, or transgenic plants, may have genes from a reptile, mammal, or insect inserted into the DNA of plant cells and then expressed within the host plant. These should not be confused with hybrids, which are manipulated at the genus or species level only (see Section 2.3.1.3).

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, are incorporated into plants used for phytotechnologies. There has been ongoing research to determine the feasibility of inserting genes for the production of cytochrome P450s into the hybrid poplars and tobacco plants used in phytotechnologies to enhance the breakdown of chlorinated compounds such as TCE and ethylene dibromide (Gordon, Strand, and Newman 1998). 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. Similarly, the expression of genes which enhance the phytodegradation of energetic compounds such as TNT, RDX, and

HMX is being researched, with the goal of enhancing this genetic expression in plants which are suitable to active military ranges (Rylott et al. 2006). It should be noted that in cases where transgenic plants have been developed to remove/degrade pollutants, their capabilities increase about tenfold over those found in naturally occurring plants (Doty et al 2007).

However, the current regulatory status of GMO 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 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 EPA 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 EPA believed such regulation necessary to prevent unreasonable risk to human health and the environment. EPA does currently regulate microorganisms under TSCA Section 5. The Animal and Plant Health Inspections Service oversees the development and introduction through importation, interstate movement, and environmental release of genetically engineered organisms. This arm of the USDA, responsible for regulating transgenic plants, reviews about 1000 applications each year from biotechnology companies wishing to field test new transgenic plants or petitioning to have a plant deregulated altogether (Lazaroff 2002). These statutes are the Federal Insecticide, Fungicide, and Rodenticide Act and the Federal Food, Drug, and Cosmetic Act (Rock and Sayre, 1999). A field trial in Oregon halted the use of genetically engineered creeping bentgrass (USDA 2007).

In Europe, the coexistence of GMO plants with conventional and organic crops has raised many concerns. One concern is the public perception that they may interbreed with wild plants to create undesirable variants or that the altered plants themselves may be harmful. Since there is separate legislation for GMO crops and a high demand from consumers for the freedom of choice between GMO and non-GMO foods, measures are required to separate GMO, conventional, and organic plants and the food and feed derived from those plants. At the field level, biological containment methods, isolation distances, and pollen barriers can be employed.

In a survey conducted in Great Britain, transgenic plants were more readily accepted for controlling contamination compared to food production (Gaskell 2000). Further surveys might prove worthwhile to generate, address, and educate the public on concerns and truths associated with GMO species used to benefit of society outside of food production. Regardless, regulators should confirm whether extensive testing prior to use has been conducted in the context of ecological compatibility in compliance with all applicable state, federal, and local regulations. Therefore, it is recommended that GMO plants should be considered in phytotechnologies only after all reasonable public and stakeholder concerns have been addressed.

2.3.2 Phytotechnology Decision Trees

The majority of the information necessary to run through the groundwater and soil/sediment decision trees should have been collected during the assessment phase of the project (see Section 2.2). Therefore, proposals to apply a phytotechnology at a site should include all information necessary to demonstrate a successful outcome when run through the decision trees. The initial decision tree attempts to generate phytotechnology options based on the candidate plant species

(as determined in Section 2.3.1), COC(s), impacted media, and the chemical behavior in the soil-plant-atmosphere continuum. Two additional decisions are also provided that are specific to groundwater and soil/sediment applications, should these be identified as potential remedies through the initial decision tree. Furthermore, the user is reminded that some applications can be used to address multiple media and multiple contaminants.

Each of these decision trees is meant as a general screening of phytotechnologies to arrive at simple "Yes" (solid lines) or "No" (dotted lines) type of evaluation. In some cases, the answer to a specific question may be "Maybe" or "I Don't Know." In those situations, the user is advised to consider those results as "Yes" until additional information can be collected that would provide clearer answers to those questions. In some cases, bench- or pilot-scale feasibility studies may need to be conducted to answer these questions (see Section 2.3.3.1). Some results lead to a "Yield" which provides additional instructions to the user prior to proceeding (dashed lines).

2.3.2.1 Remedy Selection Decision Tree

The following information from the assessment phase (see Section 2.2) is needed to run through the Remedy Selection Decision Tree (Figure 2-2):

- COC(s) and its/their general chemical properties
- impacted media and location and extent of impact(s)
- exposure assessment results and acceptable risks

Additional knowledge of the behavior of the COC(s) with the candidate plant species identified through the plant screening process is also needed. This information may be available in the phytotechnology databases used during the plant species screening process (see Section 3.3.1). Discussions of specific questions within the decision tree are provided as well.

Will the plant take up the contaminant or by-product*?* For organic contaminants, the octanol-water partition coefficient (log K_{ow}) typically needs to be between 1 and 3.5 for uptake by plants to occur (see Section 1.2.4). For inorganic contaminants, including essential plant nutrients, uptake is element- and plant species–specific (see Sections 1.1.1 and 1.2.3).

Will the contaminant or by-product accumulate in the plant? This is mainly a concern with inorganic contaminants since these do not degrade. However, uptake of inorganic constituents is highly regulated by the plant in the root system, typically limiting the amounts that can accumulate. On the other hand, after organic contaminants are taken up, they are also susceptible to the phytodegradation processes (see Section 1.2.4) or even phytovolatilization (see Section 1.2.5) and generally do not accumulate.

Is the level of accumulation acceptable throughout the life of the plant? Some plants live and die within a season while others grow and continue to mature year after year. The acceptability of contaminants that accumulate may be dictated by the growth habit of the plant species. Consideration should be given for the entire life cycle of the phytotechnology project, which may include all or part of the growing life of the plant species. How to deal with plants that

accumulate contaminants to unacceptable levels depends on the type of application and the corresponding growth habit of the species employed in the application. Therefore, this situation may need to be readdressed after the type of application is determined.

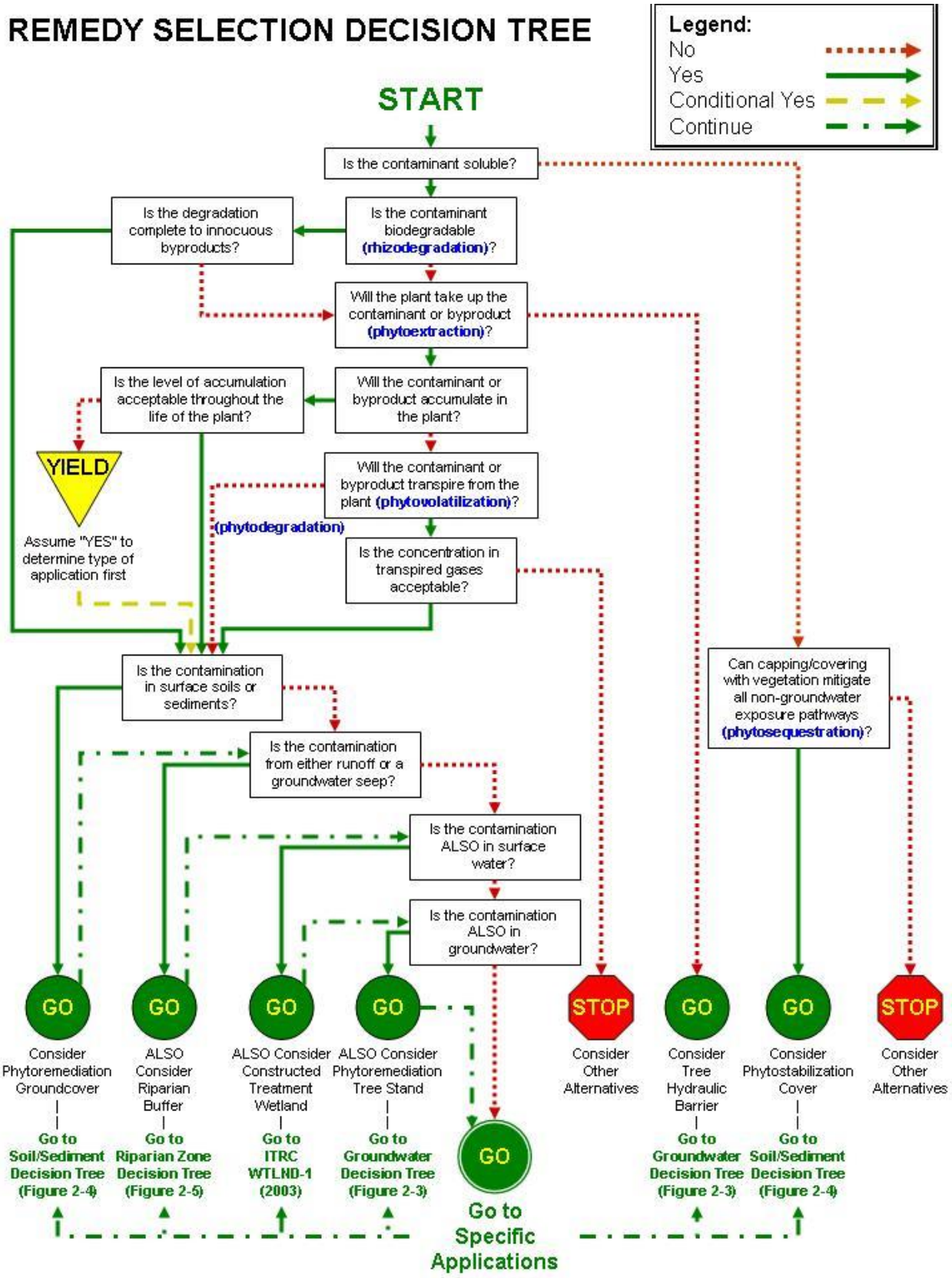


Figure 2-2. Remedy Selection Decision Tree.

Will the contaminant or by-product transpire from the plant? If highly volatile organic contaminants can pass through the rhizosphere (rhizodegradation) and through the plant itself (phytodegradation), traces may be present in the transpiration gas stream (see Section 1.1.1). Similarly, certain metals such as mercury may be able to translocate completely through a plant; however, the total amount transpired is again regulated by the root system. The acceptability of transpired contaminants depends on the associated risks and regulatory requirements.

2.3.2.2 Groundwater Decision Tree

If the Remedy Selection Decision Tree (Figure 2-2) recommends either a hydraulic barrier and/or phytoremediation tree stand, the Groundwater Decision Tree (Figure 2-3) should be consulted. The following information from the assessment phase (see Section 2.2) and plant species screening process (see Section 2.3.1) is needed to run through this decision tree. Furthermore, preliminary design and implementation considerations are required to complete the evaluation. Specific discussions of questions within the decision tree are provided as well.

- site description, layout, sources of irrigation, and available planting area
- hydrogeology and groundwater geochemistry
- concentration of COC(s) and location and extent of impact
- climate conditions
- growth habit of candidate plant species, tolerances to the COC(s), tolerances to groundwater geochemical conditions

Is the target groundwater within 15 feet of surface or 15–25 feet bgs? Depending on the stratigraphy of the subsurface, the target groundwater may not be the uppermost water-bearing zone. Special installation methods may allow access to groundwater at depths below the uppermost level (see Section 2.4.3.2). Depths within 15 feet of the surface are generally accessible by most deep-planted applications. In some cases, plant stock (in the *Salicaceae* family) can be directly installed to this depth and produce a viable tree. The maximum practical depth is generally 25 feet bgs; deeper depths can be reached under certain circumstances.

Can the target depth be easily/rapidly accessed by boring or trenching? Will the boreholes or trenches collapse upon themselves? Two common methods for installing large plantations of trees to produce deep root systems are either through boreholes or trenches (see Section 2.4.3.2). Because many trees typically need to be installed for phytotechnology applications, the sheer number of boreholes or trenches may impact the decision to continue with a phytotechnology application. Furthermore, the relative ease of creating the excavations, labor requirements, and installation time are common criteria for selecting the installation method. If conditions are too difficult or unsafe due to obstructions, limited access, or inappropriate or difficult geologies, they may limit whether phytotechnologies are appropriate.

Is time a constraint? Phytotechnologies may take longer than traditional methods to reach final cleanup levels. Time of treatment must include time to establish the plant community, which can take months and in some cases more than a year to reach optimal operational conditions. This period should be thoroughly understood and included in the treatment time frame.

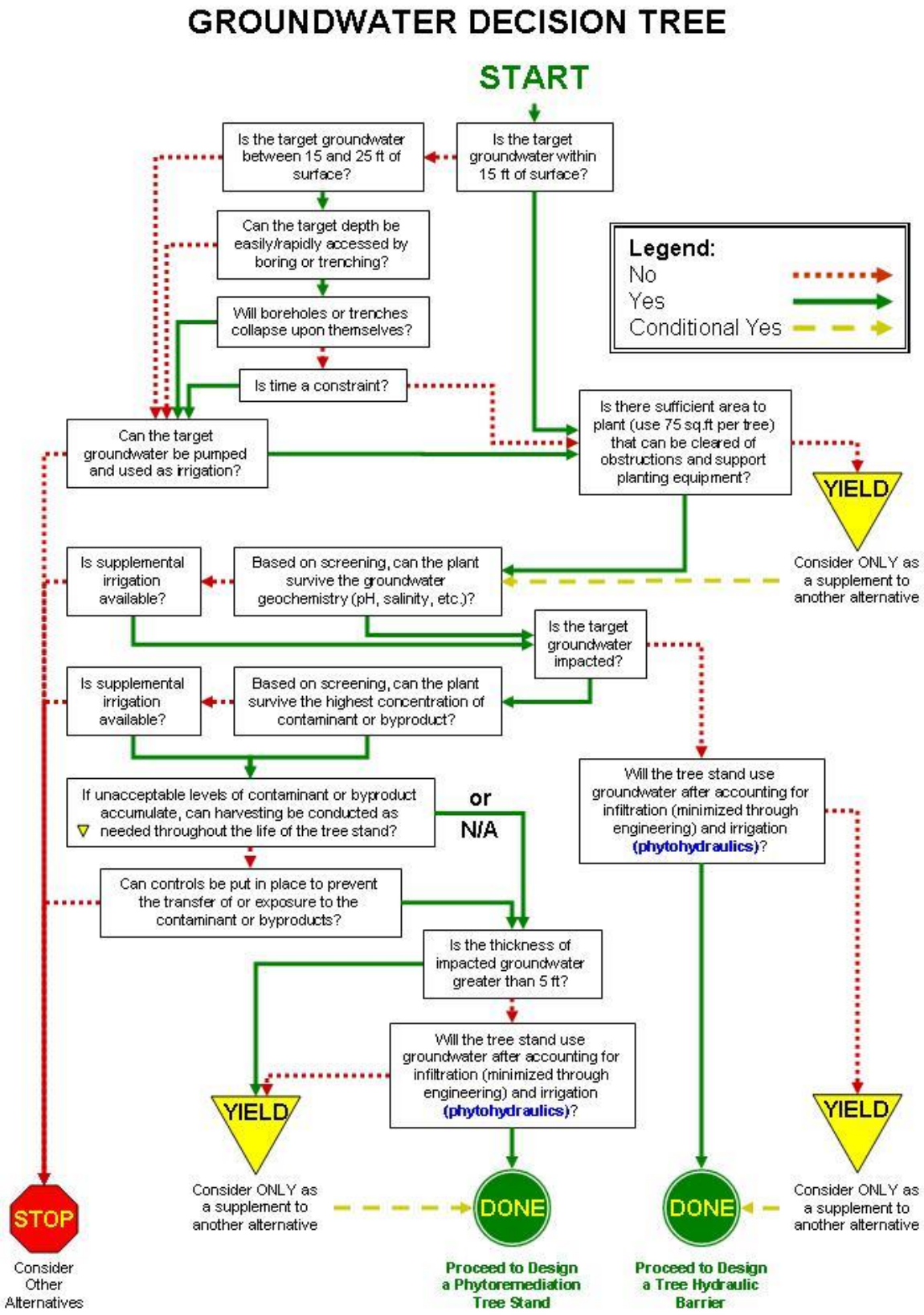


Figure 2-3. Groundwater Decision Tree.

Can the target groundwater be pumped and used as irrigation? In many ways, this process is similar to using a constructed wetland to receive and treat extracted groundwater. However, if groundwater is pumped to the surface, a permit may be required (see Section 3). Using groundwater in an irrigation system (see Section 2.4.2.1) on a phytotechnology plantation may satisfy reinjection exemptions. Subsurface irrigation systems are available and may be acceptable if the extracted groundwater is plumbed directly into it and never reaches surface. Furthermore, spray irrigation methods may result in significant volatilization where the potential air emissions and permit requirements should be considered as well.

Is there sufficient area to plant (use 75 square feet per tree) that can be cleared of obstructions and support planting equipment? A general rule of thumb for a very preliminary design during the remedy selection phase of a project is a planting density of 75 square feet per tree, based on planting trees on an average 10-foot centers using staggered rows. Trees planted at this density will fill the area with a radius of 5 feet and will essentially create a full canopy with adjacent trees. To determine whether sufficient trees can be planted, another rule of thumb at this phase of a project is to use 10 gpd per tree, annualized over the year. This value has been achieved in many field applications but may take several years to reach depending on many site-specific conditions. This pumping rate, along with the planting density, can be used (Equation 2-1) to calculate a total rate of removal for a planted area.

$$\text{Removal rate (gpd)} = \frac{10 \text{ gpd/tree}}{75 \text{ ft}^2\text{/tree}} \times \text{area planted (ft}^2\text{)} \qquad (2\text{-}1)$$

More detailed designs (see Section 2.4.1.2) should use tree pumping rates that are based on the annual tree growth rather than a single value. Furthermore, other sources of water such as rainwater and irrigation need to be considered when determining the total number of trees needed. At this stage, simply using percentages of the total volume to estimate factors such as the contribution of rain, irrigation, and runoff is generally sufficient.

Typical planting equipment for installing tree systems includes medium to heavy machinery (bobcat to drill rig). The ground surface should be able to support the equipment and the area free of obstructions such that it can be operated safely.

Is supplemental irrigation available? When groundwater conditions (geochemical and/or contaminant concentrations) are toxic to plants, controlled irrigation systems (see Section 2.4.2.1) can be used to provide dilution water to the plants to reduce the toxicity. Similarly, when establishing the vegetation, supplemental irrigation may be needed, particularly if the area or climate just after planting is arid. Furthermore, in many cases, the supplemental irrigation may not be needed once the trees are established or have reached the desired depths or maturity to withstand the toxic conditions. Decisions to use supplemental irrigation are usually based on the economics involved with plumbing in the system, O&M requirements, benefits to survivability, and potentially reducing replanting.

If unacceptable levels of contaminant or by-product accumulate, can harvesting be conducted as needed throughout the life of the tree stand? Can controls be put in place to prevent the

NOTE: The triangular symbol in the decision tree is a reminder that this is a follow-on question from the Remedy Selection Decision Tree (Figure 2-2). If the question is not applicable (N/A), then it should be answered as a "Yes" response.

transfer of or exposure to the contaminant or by-products? For tree systems, the need to harvest plant materials may depend on the species selected. Leaves may be harvested from deciduous trees prior to autumn leaf drop without significant damage or reduction in growth. Evergreen species may or may not shed needles naturally, but they too can be collected without significant long-term effects on the plant. Furthermore, only portions of the plantation or on each tree may be harvested. Harvesting whole branches is more detrimental to the tree and is generally not recommended but may be necessary depending on where the contaminant accumulates in the plant. Harvesting whole trees is also not recommended unless using species able to be coppiced. These trees, typically in the *Salicaceae* family, are able to regrow from cut stumps and can be harvested, typically in a rotation over several years. Harvesting, collecting, and handling woody material may entail chipping.

If natural leaf or needle drop is a concern in terms of potential exposures or media transfer, collection protocols may need to be implemented as part of the operation and maintenance (see Section 2.5.1.3). Alternatively, fencing or netting can be used to capture the plant material and would be incorporated within the design (see Section 2.4.2.2). Whether these methods are acceptable depends on many factors, including the economics, safety, regulatory requirements, and potential exposure of workers conducting the harvesting or collection.

Is the thickness of impacted groundwater greater than 5 feet? Some deep-rooted trees, known as "phreatophytes," can take up water from the capillary zone within the water table. Fluctuations in the water table due to seasonal and diurnal changes can allow access to deeper depths within the saturated zone. In many cases, trees produce roots through this fluctuating zone to maintain a constant supply of water. These characteristics are often used when selecting species for phytotechnologies (see Section 2.4.3). A general rule of thumb, however, is that trees do not access deeper than 5 feet into the saturated zone. Only under special circumstances or tidally influenced conditions where fluctuations greater than 5 feet occur on a daily basis are depths greater than 5 feet accessed. If the contamination resides below these depths, those impacted zones may not be affected by the vegetation. Depending on the method and design of installation (see Section 2.4) such as overplanting the area or cased boreholes at specific depths, this situation may be acceptable as a standalone remedy or as a supplement to an alternative groundwater capture system.

Will the tree stand use groundwater after accounting for infiltration (minimized through engineering) and irrigation? The ultimate target for groundwater phytotechnology systems is to access and take up groundwater. However, water available at the surface from infiltrating precipitation (other surface water sources) or irrigation may be more readily accessible to the trees and will reduce the volume of groundwater that is needed. If sufficient surface water is available, groundwater uptake may not occur, and/or roots may not need to penetrate to the desired depths. To address this possibility, different designs and methods of installation (see Section 2.4.2.1) such as grading or use of low-permeability surface materials can be used to minimize these surface water sources. If these can be reasonably applied at the site, then the

phytotechnology application may be acceptable as a standalone remedy. If not, then the phytotechnology may be acceptable but only as a supplement to an alternative groundwater capture system. Surface water management also needs to be considered in modeling the effects of tree installations on groundwater systems.

2.3.2.3 Soil/Sediment Decision Tree

If the Remedy Selection Decision Tree (Figure 2-2) recommends either a phytostabilization cover or phytoremediation groundcover, then the Soil/Sediment Decision Tree (Figure 2-4) should be consulted. The following information from the assessment phase (see Section 2.2) and plant species screening process (see Section 2.3.1) is needed to run through this decision tree:

- site description, layout, sources of irrigation, and available planting area
- hydrology
- soil/sediment agronomic conditions and fertility
- COC(s) and location and extent of impact
- climate conditions
- growth habit of candidate plant species, tolerances to the COC(s), tolerances to soil/sediment conditions

Preliminary implementation considerations are also required to complete the evaluation. Specific discussions of questions within the decision tree are provided as well.

Is the entire area able to be cleared of obstructions and support planting equipment? Typical planting equipment for installing groundcover systems may include heavy machinery (tractor, tiller, seed spreader, seed driller, etc.). The ground surface should be able to support the equipment, and the area should be free of obstructions for safe operations.

Can amending the soil or sediment enable the plant to survive? Can amending the soil or sediment immobilize the contaminant or by-product? Typical soil amendments are generally similar to what is commonly used in agricultural applications and may include lime, gypsum, fertilizers, organic matter, etc. (see Section 2.4.2.3). These changes in the soil conditions can alter the contaminant mobility and the ability of the soil to sustain plant growth. In some cases, plant survival may have been evaluated during the screening process where the addition of amendments was considered (see Section 2.3.1.4). Recommendations for soil amendments may often be obtained from a local agricultural extension service, which can evaluate the soil fertility. For the effects of amendments on contaminant behavior, feasibility studies may be needed (see Section 2.3.3.1 and USEPA 2007b).

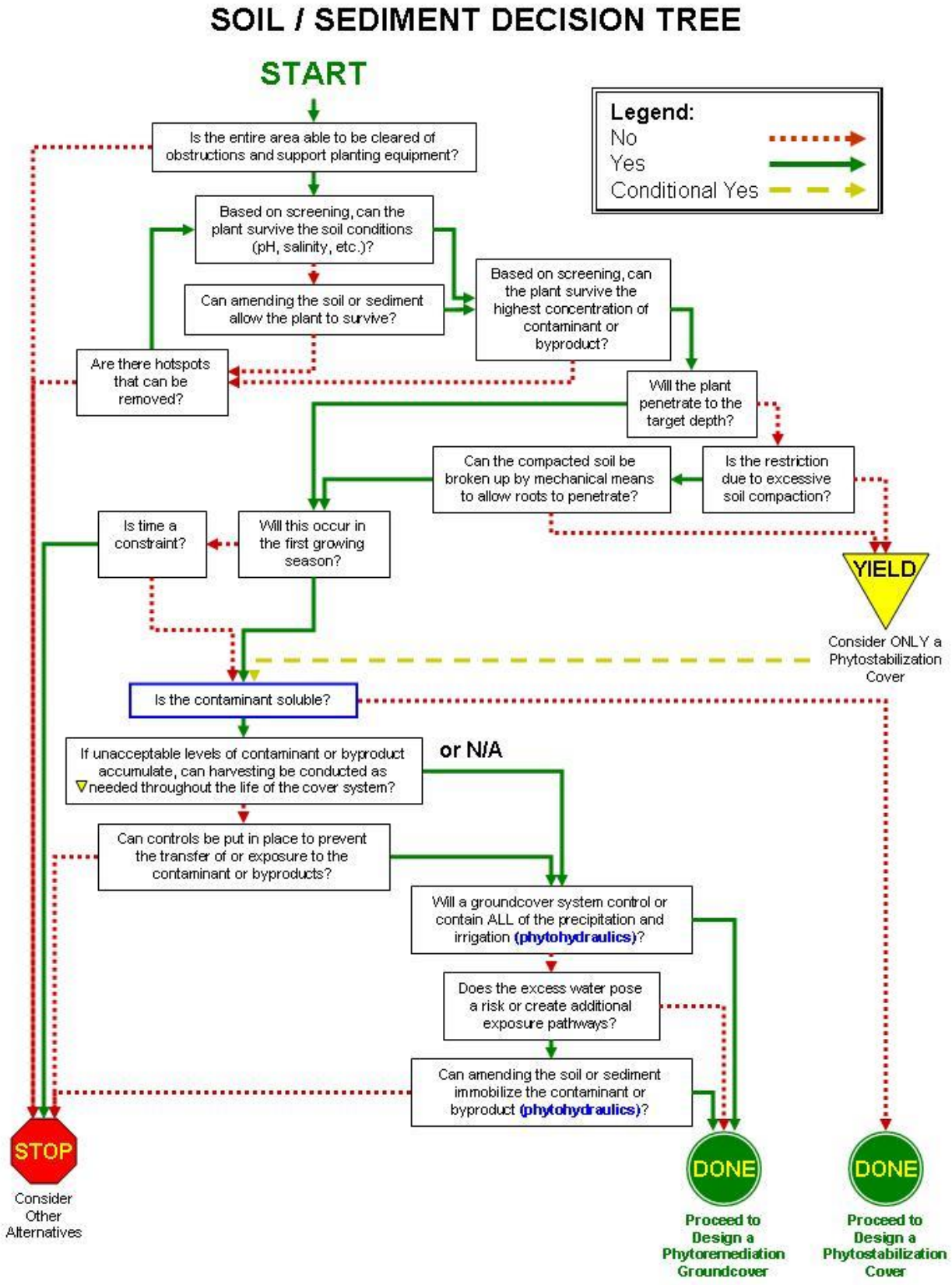


Figure 2-4. Soil/Sediment Decision Tree.

Will the plant penetrate to the target depth? Is the restriction due to excessive soil compaction? Will this occur in the first growing season? The effective range for plants to influence contaminants depends on the rooting depth of the plant system. In general, the roots must come into contact with the contaminated media for the remediation to occur. Conversely, containment strategies may consider the opposite, where roots should not come into contact with the contaminated media. A general rule of thumb for the rooting depth of herbaceous species such as grasses and forbs is 2 feet. However, some species, such as the native prairie species illustrated in Figure 1.8 and tap-rooted species such as alfalfa, are able to penetrate deeper (Shimp et al. 1993, Nyer and Gatliff 1996). However, local soil conditions (nutrient content, moisture, compaction, etc.) dictate the ultimate depth to which any plant will reach. Furthermore, the depth of penetration may progress as the plants grow year over year. In contaminated soil, the term "phytoremediation front" has been used (Olsen and Fletcher 1999) to describe the interface between clean soil at the surface and impacted soil underneath. The bulk of the root mass resides in the clean soil while exploratory roots are sent into the impacted soil. Over time this front moves downward.

It is recognized that these questions are difficult to answer conclusively since the ability of roots to penetrate over time is site-, soil-, and climate-specific under the actual, immediate conditions experienced by the vegetation. The user is reminded that answers "Maybe" and "I Don't Know" should be considered as "Yes" until additional information can be collected, perhaps through a field feasibility study (see Section 2.3.3.1).

Is time a constraint? Phytotechnologies may take longer than traditional methods to reach final cleanup levels. Time of treatment must include time to establish the plant community, which can take months and in some cases more than a year to reach optimal operational conditions. This period of plant establishment should be thoroughly understood and included in the treatment time frame.

Is the contaminant soluble? This question is repeated and should result in the same answer as was given in the Remedy Selection Decision Tree.

If unacceptable levels of contaminant or by-product accumulate, can harvesting be conducted as needed throughout the life of the tree stand? Can controls be put in place to prevent the transfer of or exposure to the contaminant or by-products? For groundcover systems, harvesting plants is generally relatively easy and entails the use of mowers or threshers (see Section 2.5.1.3). Once cut down, collection may be conducted using balers or even manually. Some equipment, such as a harvester, combines combine the cutting and collection. For woody species such as shrubs, see the Groundwater Decision Tree discussion (Section 2.3.2.2). Whether these methods are acceptable depends on many factors, including the economics, safety, regulatory requirements, and potential exposure of workers conducting the harvesting or collection.

NOTE: The triangular symbol in the decision tree is a reminder that this is a follow-on question from the Remedy Selection Decision Tree (Figure 2-2). If the question is not applicable (N/A), then it should be answered as a "Yes" response.

Will a groundcover system control or contain ALL of the precipitation and irrigation? Does the excess water pose a risk or create additional exposure pathways? Water that cannot be captured and controlled by ET may pose additional site risks or exposure pathways, particularly if the soil or sediment contain contaminants that are soluble in water. A reasonable estimate for the rate of ET from a groundcover system is the local pan evaporation rate. Estimates of this rate are available from the local agricultural extension service. If other control measures are available or the site can be enhanced during design and construction (see Section 2.4.2.1), these should be considered as well in answering these questions.

2.3.2.4 Riparian Zone Decision Tree

If the Remedy Selection Decision Tree (Figure 2-2) recommends a Riparian Buffer, then the Riparian Zone Decision Tree (Figure 2-5) should be consulted. The following information from the assessment phase (see Section 2.2) is needed to run through this decision tree:

- site description and layout
- hydrology and hydrogeology
- location and extent of impact
- climate conditions

The output of this decision tree directs the user to the Groundwater and/or Soil/Sediment Decision Tree for further consideration. These may already have been used, depending on the extent of the impact. Specific discussions of questions within the decision tree are provided as well.

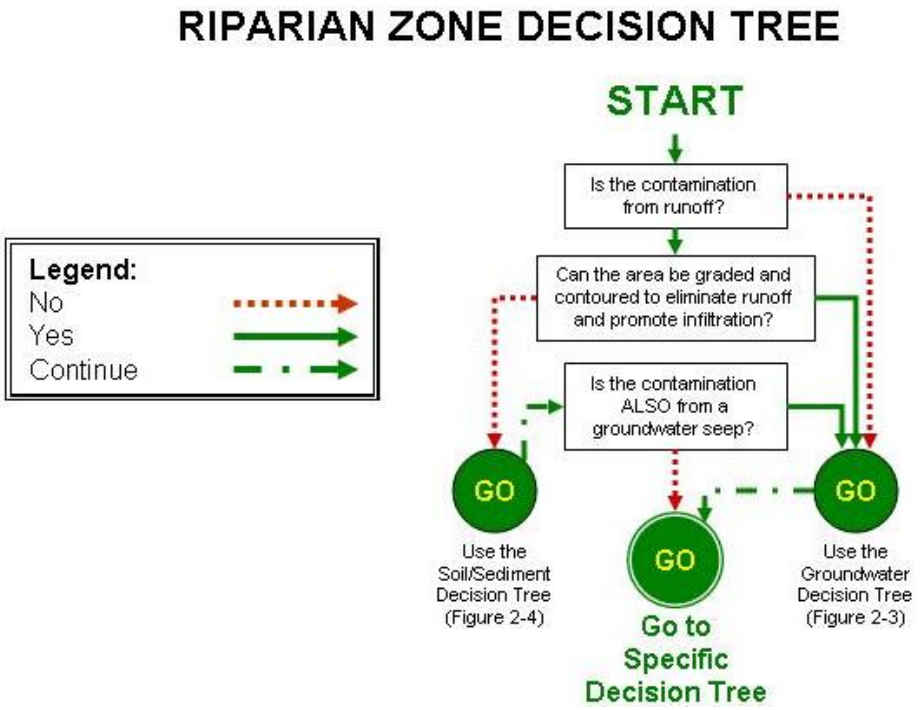


Figure 2-5. Riparian Zone Decision Tree.

Can the area be graded and contoured to eliminate runoff and promote infiltration? Promoting infiltration will enhance the treatment of the contaminants by increasing the contact time with the riparian plant system. Plants should be selected based on the final hydrologic conditions created at the site. Surface grading may entail substantial earthmoving activities, which may or may not be able to be conducted at the site. Constructability is covered in the Groundwater and Soil/Sediment Decision Trees. Furthermore, soil conditions may dictate the success of promoting infiltration over runoff and/or the evaporation of ponded water. Hydrologic modeling may be needed to answer this question (see Section 2.4.1.1).

2.3.3 Regulatory Decision Factors

When selecting a phytotechnology as the remedy for the site, additional regulatory factors must be considered that are directly linked to the technical factors evaluated in the decision trees. These are in addition or complementary to all ARARs for the site that must be met or exceeded for the technology to be considered an alternative. Phytotechnologies do not and will not work on all contaminants. One of the absolute requirements is to demonstrate to regulators that the COC(s) can be contained and/or remediated using the phytotechnology. This is often demonstrated in feasibility studies conducted specifically for the site or extrapolated from literature results that are sufficiently similar to the site conditions. Furthermore, the proposed remedy must ensure that the fate and transport of the contaminant(s) and/or by-products are acceptable through all potential exposure pathways.

Once feasibility is demonstrated, the ability of the phytotechnology system to reasonably and in high confidence achieve cleanup goals in a satisfactory time frame must also be demonstrated for regulatory acceptance to be granted. This is often demonstrated in treatability studies, which can often be planned and conducted in concert with feasibility studies, including using the same experimental setup (scale, materials, duration, techniques, etc.). The primary difference between treatability and feasibility is the level of quantitative evaluation included in the study. For example, a feasibility study examines whether a specific plant species is capable of treating the contaminant regardless of the time or rate of concentration or mass reduction, whereas a treatability study compares the effectiveness of the treatment in relation to the remedial objectives and ARARs set forth for the site. Treatability results are often compared to other remedial alternatives to ultimately select the technology that can best meet the site remedial objectives. In many cases, contingency conditions must be established that either trigger a continuation of the phytotechnology solution or initiate one of these other alternative remedies. Furthermore, these contingencies can be addressed if there is an existing system in place that the phytotechnology solution is meant to supplement or eventually supplant at the site.

2.3.3.1 Demonstrating Feasibility

Demonstrating the feasibility of a phytotechnology remedy to address a contaminated site condition initially depends on whether vegetation can influence the behavior of the COC(s). The initial clues as to whether the vegetation can influence the contaminant behavior may come from the initial evaluation conducted to screen plant species (see Section 2.3.1). During this process, the phytotechnology literature may have produced sufficient information allowing feasibility to be demonstrated. In general, the five categories of species identified in Figure 2-1 serve as an

initial ranking system for whether additional laboratory or greenhouse feasibility studies need to be conducted. Database species found at the site (see Section 2.3.1.1) represent one extreme where these have sufficient literature information available indicating that further studies may not be needed. On the other extreme, genetically modified plants (see Section 2.3.1.5) generally require additional study. The intermediate categories may or may not require further demonstration with their acceptance based on the amount of supporting evidence that can be provided to the regulatory authority. Many factors in addition to the proposed species—such as the COC, contaminated media, size of the site or study, and type of phytotechnology employed—are factors in determining the type and amount of supporting information needed to be summarized and provided to the regulator.

If additional feasibility studies are required, the goal should be to demonstrate the ability of the proposed plant species to alter the contaminant behavior in ways that are aligned to the remedial objectives of the site. These would be conducted while other alternatives are likewise being evaluated. Feasibility studies can be conducted in the laboratory, greenhouse, or in the field and involve hydroponics, potted plants, or test plots established on site. Typically, these tests should be carried out for at least one growth cycle, including dormancy. These experiments should use site-specific data previously obtained during the initial characterization, including duplicating field conditions (climate, sunlight, and soil moisture) as much as possible since 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, unimpacted soils can be artificially contaminated with a representative, properly weathered or aged sample of the contaminants to assess the maximum concentrations that can be tolerated by the plants before health and growth rate are adversely impacted. 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.

A feasibility study may include evaluating agronomic inputs such as fertilization, carbon addition, and other soil conditioners to learn whether the site soil conditions can be sufficiently altered to allow the phytotechnology to be a possible remedy. Another objective of a feasibility study might be to evaluate the potential fate and transport of the parent or by-products that might develop in relation to the growth of the plant. These could include evaluating the composition of the transformation by-products, bioavailability, toxicity, food web accumulations, ecological exposures, and/or transfer to other media. As long as these factors remain acceptable, the proposed phytotechnology remedy remains feasible as a remedy for the site.

Most published phytotechnology studies use a randomized block design. 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 optimized during the subsequent tests. Each subsequent test should build on the results obtained from the previous set with refinements made to the subsequent test conditions. Conducting these 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 outside the growing season, and adequate results can be obtained prior to the next available planting season. Also, this type of sequential experimental design allows for an efficient use of funds by assessing broader factors first and in a simultaneous manner while minimizing unnecessary experiments that are not aligned to the remedial objectives for the site. In general, data need to be generated that support the ability of the vegetation to control the infiltration of precipitation, flow of surface or groundwater, and/or reduce contaminant concentration or mass. The techniques to measure these characteristics are similar to those required to monitor a full-scale system (see Section 2.5.3). Monitoring requirements are also likely to contain elements specific to phytotechnologies that would not be necessary for feasibility studies for other alternatives, including plant growth assessments, plant tissue sampling for COCs, and measurements of transpiration and root penetration.

2.3.3.2 Fate and Transport Studies

Since phytotechnologies are remediation systems that use natural systems, ecosystems that develop as a result are subject to fate and transport issues. Specifically, fate and transport studies may be needed that evaluate whether the contaminant becomes more mobile, can transfer to other media, becomes more bioavailable to the plant and/or animals, or accumulates in specific plant tissues that represent likely exposure pathways (e.g., edible fruits, seeds, leaves). Furthermore, if the contaminant is transformed by the vegetation itself or during the phytotechnology application, the transformation by-products may need to be evaluated as well, particularly if they are more toxic, soluble, bioavailable, or mobile compounds.

However, a distinction should be made between these types of fate and transport feasibility studies and ecotoxicity studies, which would include chemically dosing representative receptors (laboratory animals). For example, increasing bioavailability of a chemical into a plant can also increase the potential for ecological exposure to animals that may consume that plant. If animals known to inhabit the site might normally consume the vegetation, a fate and transport feasibility study might focus on whether the contaminant or transformation by-product accumulates in the edible portions of the plant such as the fruits, seeds, and leaves, or just in the roots or stems, where the potential for consumption is reduced. A fate and transport feasibility study would not examine the toxicity (dose-response conditions, epidemiology, etc.) of the contaminant or by-products to the animal receptor. These ecotoxicity studies are outside the scope of this document but may be required when ultimately selecting the remedy for the site.

Many phytotechnology applications use plant transformation mechanisms (rhizodegradation, phytodegradation, natural chelation/solubilization in phytoextraction, etc.) to conduct remediation. Unfortunately, conflicting results have been obtained in several studies where certain contaminants are transformed in the rhizosphere prior to removal from the soil, taken up and transformed in the plant, or phytovolatilized by the plant as the parent compound. In general, researchers have not clearly identified complete contaminant transformation pathways that lead to innocuous compounds that incorporate into organic matter (McCutcheon et al. 1995), sequester into the soil matrix, get metabolized into plant matter, or no longer represent an environmental or human health risk. However, an additional level of complexity can be added to the fate and transport studies to help clarify the mechanisms and daughter products, if deemed

necessary. Specifically, a more rigorous mass balance can be performed on the system. However, this will typically need to be conducted in sealed plant chambers where all media (air, water, and soil) are controlled and subject to radioactively labeled contaminants. In this case, the intensity as well as the distribution of the radiolabel throughout the plant system is assessed to evaluate the mass distribution. Gas chromatography/mass spectrometry (GC/MS) analyses of the radiolabeled tissues can also be conducted to determine the speciation of the contaminant. Furthermore, calculations can also be made during these studies to predict the amount and type of material transpired by the plants. However, strong caution is recommended in making absolute decisions based on the results of these mass balance studies. The test conditions are suboptimal, very restrictive to plant growth and metabolism, and not representative of how the plants will respond in a field-scale system. Therefore, when considering phytotechnologies in absence of this information, it is recommended that equal consideration be given to transformation products as to the original contaminant.

Furthermore, several other mechanisms may also contribute to changes in the fate and transport, including many farming practices used during soil preparation and plant cultivation. For example, soil amendments are designed to alter the general soil chemistry and change the bioavailability of constituents. Tilling or disking soil can expose, aerate, and volatilize contaminants or cause wind drift of soilborne contaminants. Similarly, excessive irrigation can create or enhance off-site runoff and the potential leaching to groundwater. Because of all these factors, the fate of the parent or by-product will remain an issue until more research is completed. The overall site risk assessment should include these considerations when evaluating whether the phytotechnology is feasible for the site. If the risk is greater and it cannot be reasonably mitigated, the application would not be considered feasible for the particular site.

The feasibility studies that examine these fate and transport outcomes should be thoroughly designed from the onset. In general, chemical analysis is required not only for the media (soils, site water, irrigation water, and/or air), but also of the plants or even specific tissues. Standard analytical methods should be employed for the media, while the plant matter may require specialized techniques to sample and analyze. These would be similar to those required in a full-scale system (see Section 2.5.3.3). 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 the media to assess the fate of organic chemicals in the phytotechnology system. Harvesting the planted system may be conducted at several times throughout the experiment to provide temporal trends. RCF and TSCF values can be calculated during the feasibility study to provide an indication of the potential to accumulate the contaminant in the plant biomass, if applicable. This information may also be used to determine whether the plant biomass must be treated as a hazardous waste if harvested.

2.3.3.3 Demonstrating Treatability

Demonstrating treatability is quantifying the probability of success of an approach to achieve cleanup targets that reduce risks to acceptable levels in a reasonable time frame. Treatability studies are performed to present technical evidence validating the proposed treatment scenario, optimize the design data, and assure concerned parties that the phytotechnology will achieve the

desired results under existing site conditions. These are typically demonstrated using performance data that show that the approach can meet predefined criteria identified as success. Establishing performance criteria is generally independent of the remedial approach undertaken at the site. Therefore, phytotechnologies do not really warrant any special considerations. However, a consensus will need to be reached on how much and what kind of data are required and how, when, and where they will be collected, analyzed, documented, and reported. Typically, demonstrating treatability relies mainly on conventional data such as concentration trends, groundwater conditions, hydrologic modeling, etc. These will often, although not necessarily, require sampling and analytical techniques unique to phytotechnologies (see Section 2.5.3).

Similar to feasibility studies, the literature review undertaken as part of the plant screening process (see Section 2.3.1) may contain sufficient information to meet the objectives of treatability studies. Typically, a rate of remediation must be established either from the literature or from the treatability study results. This rate of remediation is then incorporated into some form of predictive modeling to estimate the time necessary for the phytotechnology to reach the predefined criteria of success. Part of the definition of success is a consensus on the length of time considered reasonable to complete the cleanup. Furthermore, the seasonal nature of phytotechnologies also needs to be considered when estimating the amount of time required to accomplish cleanup objectives. Sufficient data must be provided to regulators and stakeholders that describe how the contaminant will be contained or treated during the dormant period. Therefore, the treatability study should be designed such that it incorporates the full impact of plant growth and maturity, including dormancy and other seasonal changes. In many cases, it may be suitable to include the treatability test in the field as the first year or more of the remedial application and eventually incorporated into the final design. Typically, additional sampling and monitoring are required during this initial pilot phase compared to subsequent years.

Based on an ongoing treatability study, the probability of success of the proposed remedy needs to be continually evaluated. Furthermore, the expected outcomes and potential pitfalls should be discussed and presented along with the contingencies for failed outcomes. Again, criteria should be defined in advance that indicate what a successful outcome is and what a failed outcome is, particularly the triggers that would initiate a contingency alternative.

2.3.3.4 Supplementing or Supplanting Existing Remediation Systems

One of the best and common applications of phytotechnologies is when a conventional (typically mechanical, but even natural attenuation) remedy needs to be supplemented or eventually replaced. The reasons for this change could be inefficient operation, high long-term costs, frequent system down-time, reaching the operational life of a system, or incomplete remediation. Under these conditions, the reasons why the proposed phytotechnology will increase the likelihood of meeting remedial objectives for the site must also be documented. Examples of how phytotechnologies may be proposed as a supplement or replacement include the following:

- vegetative covers for infiltration control as a replacement or supplement to conventional landfill covers, particularly those with a net accumulation of liquid (see ITRC 2003c)

- vegetative covers for surface soil remediation as a replacement for land farming while maintaining biodegradation rates
- tree stands for groundwater hydraulic barriers as well 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 vapor extraction systems that are inefficiently capturing or remediating residual contaminants, including in the off-gas
- constructed wetlands for surface/wastewater remediation as a supplement (secondary or tertiary treatment) to traditional (primary) wastewater treatment systems (see ITRC 2003b)
- riparian buffers for runoff control and treatment as a replacement for drain tiles used simply to redirect runoff (see ITRC 2003b)

For the phytotechnology system, this approach often offers an automatic backup for when contingency conditions are triggered during the evaluation of the phytotechnology in the field. Regulators will more easily accept a supplemental or replacement remedy if an existing conventional system is either still operating or can be switched back on should the phytotechnology system not meet performance criteria. Furthermore, the conventional system may be needed during specific times of the year based on the growing season or when adverse climate conditions impact overall plant growth and performance.

2.3.4 Stakeholder Decision Factors

In addition to the technical and regulatory factors that are considered when selecting a remedy for a site, other concerns of stakeholders such as the public, community members, adjacent property members, nongovernment organizations (NGOs), and site owners may need to be considered as well. These concerns include aesthetics, operability, future property reuse options, timing, long-term stewardship, sustainability, and the final disposition of the site. Involvement of other stakeholders early in the process is crucial to the final selection of a phytotechnology remedy.

The general perception is that "green" technologies are natural, environmentally friendly, and less intrusive. Phytotechnologies create sustainable greenspace and can also provide visual screening, reduce noise, and require less intense human interaction to install and operate in the long term. Furthermore, phytotechnologies also create a barrier to odors, noise, and dust generated from other site activities as well. Therefore, the public perception of phytotechnologies can be quite favorable. However, a perception could be that phytotechnologies are merely beautification and not cleanup, particularly since phytotechnologies can take longer than other alternatives to meet objectives. In some cases, community members may also express opinions on certain species based on personal preferences or medical conditions including allergies, asthma, perceived nuisances (i.e., cotton-like seeds from cottonwoods, excessive leaf, branch, or seed drop), wildlife use, type of wildlife attracted, etc.

Furthermore, it is also important to consider how phytotechnologies fit into the designs of future land uses and stewardship of the property to be remediated, as well as the areas surrounding the site. Future land uses are largely determined by zoning where changes will need to be proposed and accepted by a community board or city council before the phytotechnology remedy can be

ultimately selected. Similarly, many communities have restrictions or ordinances on the type, form, and sometimes species that can be used in any landscaped area. In some cases, these restrictions or ordinances may be based on the commercial use, including those on neighboring properties, where creating a fire hazard may be controlled by the local fire department, or visual contact with field workers must be maintained at all times for safety reasons, as examples. Some communities may also have restrictions on species they consider noxious or invasive even if not listed at the state or national level.

In some cases, commercial redevelopment may not have a future occupant lined up yet, which makes planning the future layout difficult. City planners and architects are often reluctant to finalize plans until the future property use itself has been defined, including the layout of greenspace, storm water control areas, and other vegetated areas that might also serve as phytotechnology plantations. In general, the decision on the final property disposition often outweighs the decision to select and implement a phytotechnology application. Therefore, selecting the final remedy for the site is often delayed until the disposition is solidified.

Related to the final disposition of the site is the long-term stewardship and sustainability of the remediation system. In some cases, the new property owner or occupant may be willing to take on or negotiate the care and maintenance of the planted areas since this function typically impacts its public image. In other cases, the current liability owner may retain all care and maintenance activities if significant monitoring requirements are also to be conducted along with other O&M activities. Furthermore, long-term stewardship may be negotiated with third parties such as state departments of natural resources, the Bureau of Land Management, U.S. Department of Interior, NGOs, nature conservancies, etc. Similarly, easements may be placed on the property to prevent future land changes and/or trust funds set up to ensure the solvency of the long-term management plan.

Before proceeding with designing the phytotechnology application, these concerns and issues must be addressed. Addressing these may include an education program that provides information on how phytotechnologies work in general, what specific mechanisms would be used 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 approval, scientific information supporting the effectiveness of phytotechnologies must be provided to gain public understanding and acceptance. Furthermore, phytotechnology projects often offer educational opportunities in areas such as botany, ecology, horticulture, and biological sciences for local schools and boys/girls clubs that can increase the appeal and utility of the application.

2.3.5 Economic Decision Factors

While not always a consideration of regulators or stakeholders, an economic comparison of the phytotechnology option to other alternatives generally needs to be conducted to satisfy the liability owner(s) who must ultimately fund the remediation. This economic evaluation should be based on the life cycle of the various options and use the net present costs of each remedy. During the remedy selection phase, typically only a rough (±50%) cost estimate is needed, which should include capital, engineering and design, labor, and long-term OM&M costs. A more detailed cost estimate is conducted during the design phase (see Section 2.4). In addition to costs

incurred for any remediation project, such as report writing, permitting, travel, soil or groundwater sampling and analytical, etc., there are cost items specific to phytotechnologies summarized in Table 2-5 for groundcover and tree systems. Other than the sunk costs, all of these items may be considered optional, depending on the local conditions, availability, and the technical, regulatory, and stakeholder needs of the project. Reasonable experience with phytotechnology systems is needed to accurately estimate the costs and ensure that all necessary cost items are captured in the estimate. Otherwise, these costs may need to be confirmed.

Table 2-5. Optional cost items specific to phytotechnologies

	Groundcover systems	**Tree systems**
Sunk costs	Site assessment, literature review, feasibility/treatability studies	
Capital	• Earthwork, land clearing/grubbing, nonpersistent herbicide • Soil amendments, fertilizer • Equipment for applying amendments, tilling/disking fields (typical farm equipment) • Plant/seed stock, including cover crop • Seed drillers, spreaders • Surface irrigation system (pipes, hoses, rain bird sprayers, etc.) • Weirs, gates, other surface flow control devices	• Earthwork, land clearing/grubbing, boring/ trenching equipment • Tree stock (whips/poles, potted, balled and burlapped), storage fees, down payment • Soil amendments, fertilizer, backfill soil, cover mulch, equipment to distribute • Tubes or collars for inducing deep root growth, breather tubes • Trunk guards, fencing (perhaps electrical), other animal-control devices • Surface irrigation system (pipes, hoses, rain bird sprayers, etc.) • Subsurface irrigation system (pipes, connectors, screens, etc.)
Engineering and design	Irrigation system plumbing, connection to water supply	CADD maps of tree layout (by species and locations)
Labor	• Plant litter collection, mowing, harvesting, and associated equipment • Irrigation management • Spot reseeding/replanting (rule of thumb +5%–10% capital costs) • Botanist/horticulturist to assess growth/health	• Irrigation system plumbing, connection to water supply, automated controls • Plant litter collection, tree maintenance, pruning • Tree replanting (rule of thumb +10%–15% capital costs) • Arborist/horticulturist to assess growth/health
OM&M	• Irrigation water, electrical utility • Fertilizer, pesticides, equipment for applying • Weed, noxious/invasive plant control • Lysimeter, soil moisture probes, datalogger, solar panels/batteries (if remote) • Dedicated or local meteorological station (temperatures, humidity, solar radiation, wind, precipitation) • Soil agronomic sampling supplies, and analyses • Soil microbial sampling supplies and analyses • Plant tissue sampling supplies and analyses • Disposal of plant wastes, haulage, off-site	• Irrigation water, electrical utility • Fertilizer, pesticides, equipment for applying • Weed, noxious/invasive plant control • Sap flow sensors, datalogger, solar panels/batteries (if remote) • Dedicated or local meteorological station (temperatures, humidity, solar radiation, wind, precipitation) • Leaf area meter, stem gauges, dendrometers • Plant tissue sampling supplies and tissue analyses • Transpiration gas sampling supplies and analyses • Disposal of plant wastes, haulage, off-site disposal fees

	disposal fees	

In addition to a direct net present cost comparison, full cost-benefit analyses should also be conducted on each of the remedial alternatives. ITRC established a comprehensive list of economic elements affecting the cost and value of a site remediated using phytotechnologies (ITRC 2006c). However, the concepts are applicable to any remedial approach. These cost elements can be broken down into quantifiable, semiquantifiable, and nonquantifiable (or qualitative) values. Table 2-6 categorizes the various elements impacting the cost-benefit analyses. As mentioned in the stakeholder decision factors (see Section 2.3.4), phytotechnology projects often generate community goodwill through their aesthetics, green approach, and sustainability, which are often not available through other remedial alternatives. This goodwill, while difficult to quantify, can translate into very real and tangible benefits for a business due to the improved corporate reputation within the community. This increased reputation can facilitate new ventures and business opportunities by continuing and open dialogue with the community initiated through the phytotechnology project.

Table 2-6. Value elements for cost-benefit analyses

Quantifiable values	Semiquantifiable	Qualitative
Project design and development • Meet remedial goals • Alternative end points • Cost recovery • Risk/site assessments • Permitting and contracting • Security • Attractive nuisance	***Stakeholder*** • Community engagement • Social mores • NGO engagement • Regional needs/compatibility • Education opportunity • Recreational opportunity • Avoid property condemnation • Corporate shareholder value	***Livability*** • Aesthetic appearance • Noise, odor, visibility • Health, safety, security • Community character/ sense of place
Capital • Technology development • External funding • O&M • Monitoring • Reporting • Property tax payments • Project length	***Regulatory*** • Innovative approach • Reimbursement solvency • Relationship status • Precedence	***Corporate values*** • Core values and policies • Company pride • Moral/ethical responsibility • Cultural alignment • Enhanced reputation • Employee morale
Environmental liabilities • Natural resource damage offsets • Future use liabilities • Supplemental environmental projects • Long-term cost liabilities	***Ecological*** • Biodiversity benefits • Erosion control • Storm water management • Conservation or mitigation • Greenhouse gas effects	***Strategic planning*** • Public and government relations • License to operate • Sustainable legacy

Source: ITRC 2006c.

2.4 Design and Implementation

Prior to major design and implementation activities being conducted, the design team should walk the site and note any relevant landmarks, including boundaries, planting areas, areas to be resurfaced/regraded, potential obstructions, infrastructure/utilities, and any additional sampling locations. While these were likely noted during the site assessment phase, they should be clearly delineated at the site (staking, flagging) as well as on CADD drawings for future design development and refinements. Furthermore, the site health and safety plan should be developed and revised based on information gathered during the initial site walks. Table 2-7 lists potential health and safety issues to look for specifically associated with phytotechnology systems. Many of these hazards can be reduced or eliminated by engineering them out in the design or through proper management during implementation and subsequent O&M (see Section 2.5).

When designing a phytotechnology system, several options generally exist that depend on whether the system is a soil/sediment groundcover system, groundwater tree system, or riparian buffer system (see Section 2.3.2.1). Simplistic to highly complex models may be developed in this phase to design the system as well as to reasonably predict the long-term performance. Furthermore, each type of system will generally require infrastructure to support the long-term functioning of the system, the proper plant selection and stock, and particular culturing and installation methods to promote vigorous growth. Each of these components will need to be incorporated into the final design and subsequent work plans. The final engineering design will typically depend on a more detailed economic evaluation (±10%) than previously done during the remedy selection phase. In addition to a refined capital cost estimate for installing the system, an estimate of the life-cycle duration for the system should also be developed.

2.4.1 Modeling Phytotechnology Systems

Phytotechnology systems (excluding wetlands) can address soil/sediment, groundwater, or both. While riparian systems often combine components of soil/sediment systems with groundwater systems, there are also components of surface water systems (i.e., wetlands) that are beyond the scope of this document (see ITRC 2003b). Furthermore, modeling the groundwater-surface water interface in riparian systems requires complex hydrogeological models that can consider tidal influences, salt water intrusion, mixing zones, changes in redox conditions, etc. These too are beyond the scope of this document. Regardless of the type of system, however, the remedial objective of the application may be containment, remediation, or both. Once the system and objective are defined for the site, different models are needed that are based on both defining factors and generally describe the hydraulics (i.e., water flow or water balance) and/or the remediation (i.e. rate of degradation or attenuation).

Table 2-7. Potential health and safety issues specific to phytotechnologies

Site condition or activity	Potential health and safety issue	Possible solutions
• Prevailing wind direction, speed, and patterns	• Dermal contact or inhalation of soil amendments, fertilizers, and pesticides • Dermal contact or inhalation of dust generated from tilling, plowing, mowing, harvesting	• Scheduling • PPE • Air sampling • Eyewash station
• Biohazards—insects, small animals attracted to the newly planted site	• Stings, bites • Allergic reactions	• Inventorying/surveying species • Fencing, traps, repellents • Precondition medical check, first aid kit, snake bite kit, EpiPen/prescription medication • Mowing
• Biohazards—large/game animals attracted to the newly planted site	• Maulings, attacks	• Fencing, traps, repellents • Avoidance, notification/evacuation
• Biohazards—poisonous plants, thorns, pollen	• Puncture wounds, scrapes, cuts • Allergic reactions	• Inventorying/surveying species • Precondition medical check, first aid kit, EpiPen/ prescription medication
• Growth of plants on contaminated soil/water • Plant tissue sampling, inventorying/ surveying species	• Dermal contact with plants containing contaminants or by-products • Inhalation of transpired contaminants or by-products	• Plant selection criteria for final design • PPE
• Overgrowth of vegetation canopy	• Visual obstruction, line-of-sight issues	• Mowing, trimming, cutting, pruning, felling trees
• Overgrowth of limbs, branches	• Puncture wounds, scrapes, cuts • Overhead plant litter drop	• Trimming, cutting, pruning • PPE
• Trimming, cutting, pruning	• Puncture wounds, scrapes, cuts	• PPE
• Felling trees	• Falling objects, overhead plant litter drop	• Staging, exclusion areas • PPE
• Buildup of dry plant matter	• Fire hazard	• Mowing
• Shallow/surface root growth, low branches, plant litter	• Slips, trips, and falls	• PPE • Maintenance plan to remove/handle plant waste
• Uneven ground surfaces from tilling, plowing, mowing	• Slips, trips, and falls	• Job site control • PPE
• Tilling, plowing, mowing, felling trees	• Noise	• PPE
• Irrigation hoses, tubing, sprinkler heads	• Slips, trips, and falls	• Job site control, avoid placement in walkways • PPE

2.4.1.1 Soil/Sediment Systems

Soil/sediment systems can either be phytostabilization (containment) or phytoremediation (remediation) covers. In general, phytostabilization systems are designed to prevent infiltration and usually entail a water balance model that considers the hydraulic load into the contaminated soil/sediment. Dedicated hydrologic models, including EPIC (Erosion/Productivity Impact Calculator, www.wiz.uni-kassel.de/model_db/mdb/epic.html) and HELP (Hydrologic Evaluation of Landfill Performance, www.scisoftware.com/products/help_interface/help_interface.html), correlate to weather station data to model infiltration (P + I – R + q; defined in Section 2.4.1.2) and runoff (R). This modeling is performed by the hydrologist/geologist. Generally, for systems 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 also be considered in the design. Specifically, there should be a net reduction of infiltration during the primary growing season that compensates for the heavy infiltration after the thaw.

In addition, phytostabilization covers can also include systems designed to control the chemical stability of a contaminant by influencing the physical state, speciation, complexation, etc. (phytosequestration). Therefore, it may include a model that demonstrates the permanency of the attenuation. This would include estimates of partitioning coefficients, solubilities, and contaminant availability as influenced by soil pH, organic matter content, cation exchange capacity, alkalinity, etc. (Barnett and Hawkins 2007). This modeling would likely be done by the soil scientist/agronomist. Much of the information needed to generate these models may have been developed during fate and transport or treatability studies (see Sections 2.3.3.2 and 2.3.3.3).

Similarly for phytoremediation systems designed to remediate soils/sediments, results from treatability studies should have generated reasonable estimates of contaminant mass transport, uptake, accumulation, and/or degradation rates. The mass transport limitations can be estimated using Darcy's equation for transport in porous media while taking into account the retardation of contaminants in the soil environment (Dragun 1998). Uptake and accumulation (during phytoextraction, phytodegradation, and phytovolatilization) may be modeled based on the RCF and TSCF (see Section 1.2.4), which incorporate other mass transfer limitations due to the interaction of the contaminant with the plant tissues and cellular transport mechanisms. These rates can also account for mass transfer effects in the soil environment. Calculating the rate of contaminant uptake (Schnoor 1997) into aboveground tissues, U_{above} (mg/day), entails multiplying the TSCF (unitless) by the rate of transpiration, T (L/day), and the contaminant concentration in the soil water or groundwater, C_{GW} (mg/L).

$$U_{above} = TSCF \times T \times C_{GW} \quad (2\text{-}1)$$

Alternatively, for contaminants that are phytosequestered or phytoextracted only in the roots, the RCF (mg/kg root per mg/L) can be used to calculate the rate of contaminant uptake and sorption onto the root, U_{root} (mg/kg/day).

$$U_{root} = RCF \times T \times C_{GW} \quad (2\text{-}2)$$

Other uptake models exist that correlate the apparent permeability of plant root tissues to the octanol-water partition coefficient (log K_{ow}) of the compound (Trapp 2003). Degradation can occur in the soil environment prior to uptake (i.e., rhizodegradation) or after uptake has occurred (phytodegradation). Conservative biodegradation rates for many organic chemicals broken down by microbial activity have been published in the literature from both bench-scale and field-scale work (Dragun 1998). These are similar for modeling rhizodegradation. However, complexities such as the annual dormant cycle may need to be considered since a large influx of available carbon into the subsurface is provided to the soil microbes to feed upon and continue remediation during winter. This carbon comes from the turnover of roots when plants go dormant (Olsen and Fletcher 1999). For phytodegradation and phytovolatilization, attenuation occurring within or through the plant is often developed empirically mainly because there is incomplete knowledge of the active mechanisms causing the reduction in contaminant concentrations. Specifically, Equations (2-1) and (2-2) do not explicitly account for the attenuation occurring within plant tissues and simply rely on empirical tissue concentration data (see Section 2.5.3.3) used to generate the TSCF or RCF. Similarly, the overall rates of attenuation, k, of the contaminant throughout the entire soil-plant-atmosphere continuum are generally modeled using zero- or first-order rate equations. In Equations (2-3) and (2-4), C(t) is the concentration at time, t, and C_0 is the initial concentration.

Zero order: $C(t) = C_0 - kt$ (2-3)

First order: $C(t) = C_0 e^{-kt}$ (2-4)

Either of these equations may be appropriate to estimate the time to achieve cleanup by substituting the action level for C(t) and solving the equations for t.

2.4.1.2 Groundwater Systems

Groundwater systems can be simple hydraulic control systems (tree hydraulic barriers) to maintain containment, or they can be systems that also remediate contaminants (phytoremediation tree stands). For hydraulic control systems, a site-wide water balance will be needed that contains components quantifying the inputs and outputs of water associated with the site. The general mass balance shown in Equation (2-5) consists of three components: net storage in the aquifer = [aquifer flow characteristics] + [net recharge]. Note that recharge is defined as the net surface infiltration (P + I – R + q) minus the amount removed through ET.

$$S\,(\delta h/\delta t) = [\nabla \bullet (Kb\nabla h)] + [P + I - R + q - ET] \quad (2\text{-}5)$$

where

S = subsurface storage capacity		Section 2.2.2
h = hydraulic gradient (3-dimensional)	(input & output)	Section 2.2.2
K = hydraulic conductivity (3-dimensional)	(input & output)	Section 2.2.2
b = aquifer boundary thickness (3-dimensional)		Section 2.3.2.2

t = time		
P = precipitation	(input)	Section 2.5.2
I = irrigation	(input)	Sections 2.5.2 and 2.5.1.1
R = net surface runoff	(output)	Sections 2.4.1.1 and 2.5.2
q = other surface water sources or sinks	(input or output)	Section 2.2.2
ET = total canopy evapotranspiration*	(output)	Sections 2.5.2 and 2.5.3.1
∇ = partial differential operator ($\delta/\delta x + \delta/\delta y + \delta/\delta z$)		

* ET can be further divided into evaporation (E) and transpiration (T) components.

Quantifying the individual parameters in this general water balance relies on information and data collected from various sources and methods. The subsurface storage capacity, S, is a function of the soil characteristics collected during the site assessment phase (see Section 2.2.2). Similarly, the hydrogeological parameters—h, K, and b—are likewise collected during this initial phase. Other water sources or sinks, q, should also be part of the site characterization. Net surface runoff, R, is usually a modeled parameter (see Section 2.4.1.1) using climate data (see Section 2.5.2) but is based on site characterization information as well. Precipitation, P, and supplemental irrigation, I, are typically measured or controlled through on-site monitoring and control devices (see Sections 2.5.2 and 2.5.1.1) while quantifying evaporation, E, relies on both monitoring climate conditions and the resulting rain interception capacity of the canopy planted at the site (see Section 2.5.3.1). Similarly, climate conditions are used to determine the theoretical transpiration rate, T, although direct measurements on individual specimens can also be used and extrapolated to the entire stand (see Section 2.5.3.1).

For groundwater situations, Equation (2-5) is often simplified using several assumptions. First, the groundwater characteristics, h and K, are assumed to be constant. Second, groundwater flow is conserved such that input into the boundary area equals output. Third, the vertical (z) and lateral (y) flows are negligible compared to the predominant groundwater flow direction (arbitrarily defined in the x direction). Essentially, these assumptions reduce the [aquifer flow characteristics] term to zero. Therefore, the resulting simplified water balance, shown in Equation (2-6), is more often used, where ΔS is the change in groundwater storage.

$$\Delta S = P + I - R + q - ET \qquad (2\text{-}6)$$

For groundwater to be consumed, ΔS must be less than zero (groundwater storage must decrease). Solving Equation (2-6) for ET quantifies the amount of evapotranspiration that must be achieved by the plant canopy for groundwater to be consumed beyond the net amount supplied from surface infiltration ($P + I - R + q$).

$$\Delta S = P + I - R + q - ET < 0 \quad \text{or} \quad ET > P + I - R + q \qquad (2\text{-}7)$$

To determine the total ET needed from the entire plantation, the number of trees for a final engineering design can be calculated in a number of ways. Standard groundwater models such as MODFLOW from the U.S. Geological Survey or others (Javandel and Tsang 1986, Domenico and Schwartz 1997) can be used to estimate the total groundwater removal rate needed to provide

plume capture. However, models used for phytotechnology systems should also account for complexities such as seasonal variations of the trees, groundwater fluctuations, and the preferential use of surface water (precipitation and/or irrigation) over groundwater. Specifically, the model needs to account for variations in contaminant migration during the dormant season versus when the trees are actively extracting water. The output of the model needs to demonstrate that the leading edge of the plume will not travel beyond or below the influence of trees by the end of the dormant season. Similarly, hydrologic model inputs may be required to estimate the rate of percolation of rain or irrigation water as an additional source of water to the trees instead of just groundwater. Similarly, the output from hydrologic models such as EPIC and HELP may also be used to determine the water from the surface that will contribute to the total water needing to be removed for a groundwater plume to be captured.

This total water removal rate (ET) can then be converted into the equivalent number of trees using empirical water usage models that correlate annualized transpiration (sap flow) data specific to the species to some measure of the growth such as height, girth, or basal trunk area (see Sections 2.5.2.1 and 2.5.3.1). Figure 2-6 shows an example of this empirical correlation. However, these empirical water usage models do not account for canopy closure since the measurements are performed on individual trees rather than on an entire canopy. The concept of canopy closure is when adjacent trees within a stand have branches that begin overlapping one another and all of the solar energy (and wind) driving the ET from the system is captured by the system. This represents a theoretical maximum in the pumping capacity of the system. At this level, the FAO Penman-Monteith equation, available at www.fao.org/docrep/X0490E/x0490e06.htm, can be used to calculate the ET rates given meteorological data (Allen et al. 1998).

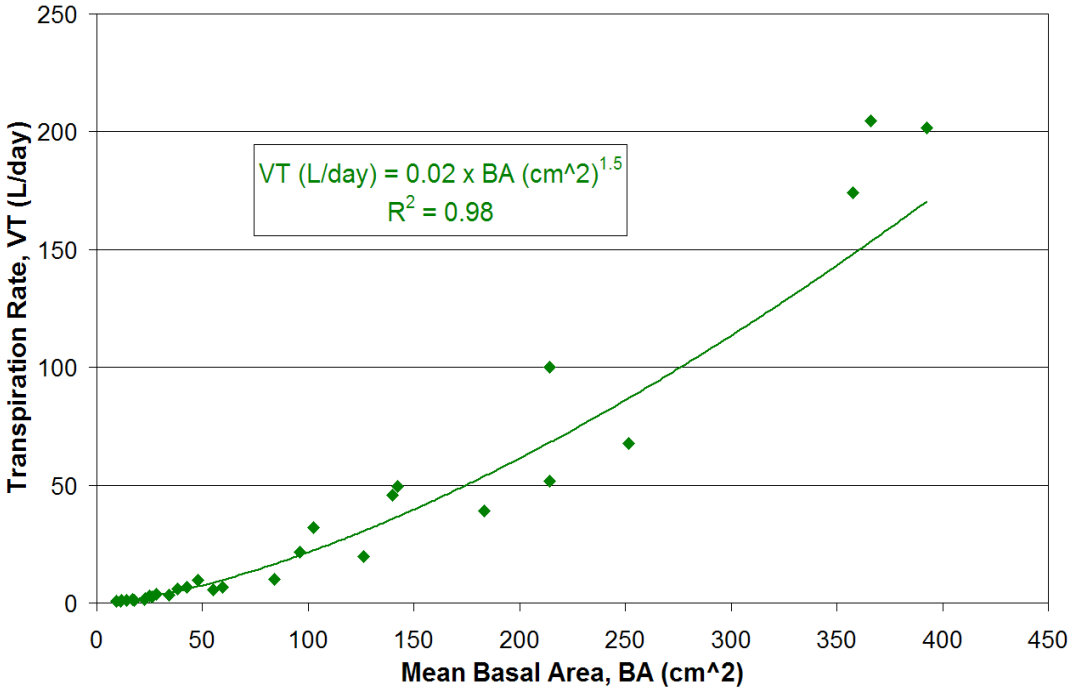


Figure 2-6. Empirical correlation of annualized transpiration rate (V_T, L/day) to basal trunk area (BA, cm^2). For poplars (*Populus* L.) growing in USDA hardiness zones 5–6.

At this step in the calculation, multiple designs (number of trees) are possible as a higher number of younger trees pumping less water each may be equivalent to fewer, older trees that pump more on a per tree basis, particularly if their canopies are equivalent. Initial planting densities may be greater than required and the trees may be thinned after reaching a specific height. With the total removal rate and various numbers of trees based on relative age determined (see Table 2-8), planting densities can be calculated for each design and compared to what is reasonable for the species and the site. Recommended planting densities are available from sources such as the USDA PLANTS national database (http://plants.usda.gov). However, stands planted at higher densities than recommended either thin naturally or can be thinned to optimize the total pumping capacity. Other factors should be considered when selecting the final design, including installation costs, O&M requirements including thinning, timing to achieve the total required removal rate, canopy closure, continued operation of an existing system (if present), etc.

Table 2-8. Range of basal trunk areas and corresponding trunk diameters for trees of different ages. For poplars (*Populus* L.) growing in USDA hardiness zones 5–6.

Age (years)	Basal trunk area (cm^2)	Trunk diameter	
		(cm)	(inches)
0–3	1–50	1.0–7.5	<1–3
3–5	50–200	7.5–15	3–6
5–10	200–500	15–25	6–10
10+	500+	25+	10+

Similar to soil/sediment phytoremediation cover systems, the rate of attenuation in groundwater systems can be based on models describing the various relevant steps in the transport, uptake, accumulation, and/or degradation of the contaminant. Some additional considerations in tree groundwater systems versus soil/sediment groundcover systems include lateral diffusional losses through the trunks of trees (Schumacher, Struckhoff, and Burken 2004), changing rates as the tree develops year over year, and changes in redox conditions in the root zone during extended periods of inundation or desiccation. In many cases, the issue is less about the specific details of how and where the attenuation occurs in the soil-plant-atmosphere continuum and more about the fact that it does and can be quantified. Therefore, much of these complexities can be accounted for in a simple rate constant or empirical relationship rather than individual models accounting for each complexity.

2.4.2 Infrastructure and Site Preparation

Phytotechnology systems have similar infrastructure and site preparation requirements to what most remediation projects require, such as earthwork, clearing and grubbing, storm water management, accessibility, fencing/security, etc. Furthermore, even though phytotechnology systems are less energy-intensive than other alternatives, there is still a need for basic utilities to run pumps, controllers, automated sprinkler systems, monitoring equipment, etc. Whether the infrastructure already exists at the site or needs to be brought in for the phytotechnology system

Example Calculation

Assume a site is located in a temperate climate in USDA hardiness zone 5–6 and has 1 acre available for planting. Furthermore, assume a standard groundwater model (e.g., MODFLOW) estimates that plume capture can be achieved as long as 5 gpm (7200 gpd, 365 days/year) of groundwater is extracted along the entire plume width perpendicular to the direction of flow. However, hydrologic models that account for rain and irrigation percolating into the root zone results in an additional 1 gpm that must be included in the total removal. Therefore, the total removal rate needed for plume capture is 6 gpm (8640 gpd) extracted continuously throughout the year. The total number of trees required to meet this pumping capacity depends on the individual annualized rate per tree.

Design Option 1: Within a year or two after planting, each tree may pump around 10 L/day (~2.5 gpd). This rate converts to approximately 3500 trees to capture the plume. Using Figure 2-6, this represents tree basal trunk areas around 50 cm^2, and according to Table 2-8, these would be around 3 years old and 8 cm (~3 inches) diameter.

Design Option 2: As each tree matures, it may pump 60 L/day (~15 gpd). At this rate, approximately 600 trees would be required. Using Figure 2-6 and Table 2-8, this rate can be achieved by 5-year-old trees that are approximately 15 cm (6 inches) diameter with basal trunk areas of 200 cm^2.

Based on information from the USDA PLANTS national database for poplars (*Populus* L.), the typical planting density is 170–800 trees per acre. Therefore, 3500 trees on 1 acre would represent a very dense planting design (planted on 4-foot centers). Over time, this stand would become overcrowded and would need to be thinned. Alternatively, 600 trees planted at the site would be a reasonable design but at the expense of the additional time to achieve the total required removal rate.

to operate should have been developed during the site assessment and remedy selection phases (see Table 2-3 and Figures 2-2 through 2-5). However, how these infrastructure and site preparation activities support the phytotechnology system may be somewhat different. For example, earthwork activities would be described in a detailed work plan, but would also include how to prepare and plant soils to support the desired phytotechnology plantings. Similarly, storm water management must account for the additional irrigation used in a phytotechnology project. Because phytotechnology systems change and grow over time, access onto parts of the site may become restricted, visual obstructions to traffic flow may develop, or solar-powered systems may become shaded due to overgrowth of the remediation system itself. Therefore, either the system should be designed and laid out so that these issues do not develop, or an O&M plan should be developed that addresses these issues as they develop in the future (see Section 2.5).

2.4.2.1 Irrigation Systems, Infiltration Control, and Storm Water Management

Irrigation systems may need to be installed or modified to ensure a vigorous start to the phytotechnology system. If existing infrastructure is being considered to be used for an irrigation supply system, it should be checked to ensure it can supply adequate water volumes and pressures. Irrigation water may be clean water, treated effluent, or contaminated groundwater, depending on the need, availability, and regulatory restrictions. 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 use the contaminated groundwater, it may be necessary to install wells with sufficient yields to supply irrigation. Pumping groundwater contaminated with hazardous constituents may require special approval to apply the contaminated groundwater to the soil. Such application could be defined as disposal and subject to landfill requirements. However, as is the case for contaminated groundwater used to mix and inject amendments for in situ bioremediation, when contaminated groundwater is

extracted and injected as part of the remedial process, it does not constitute disposal and is allowed (see RCRA 3020(b) as discussed in ITRC 2007a). However specific state requirements should be consulted. For contaminants that may volatilize or transfer to the air, a drip irrigation system may be preferred over sprinkler irrigation.

The main types of irrigation systems are rain bird or distribution sprayers, soaker hoses, and drip irrigation. Spraying type systems are generally used for groundcover systems although they may be needed for tree systems in highly humid and hot climates simply to cool the plants under these conditions. These can be fixed plumbing or temporary hose systems depending on the need, frequency, and distribution requirements. Soaker hoses can also be used if excessive volatilization of contaminants is a concern; however, the use of these may be limited by the size of the plantation. Soaker hoses need to be laid out in a fairly tight pattern such that the distribution encompasses the entire area needing irrigation. Hoses in general can pose additional slip/trip/fall hazards, which should be considered in the initial design. Furthermore, constantly moving and redistributing the hoses can also pose additional risks (biohazards, contaminant exposure, etc.) and potential ergonomic issues to workers. Drip irrigation systems also need a fairly tight distribution pattern; however, the materials such as silicone rubber, fluoropolymer, or polyvinyl chloride (PVC) tubing can be designed and semipermanently or permanently installed at the site. Furthermore, these can be buried to avoid associated hazards, although secondary containment issues may need to be addressed, particularly if impacted groundwater is used as the irrigation source. Another advantage of drip irrigation systems is that multilevel (vertical) distribution can also be designed into the system. Using multilevel drip irrigation systems in association with borehole or trench plantings, tree root systems can be "trained" to grow deeper by providing the irrigation at successively deeper depths over time. This irrigation design does require additional plumbing and distribution control (including associated cost and O&M) but can be combined with other methods to promote deeper root systems (see Section 2.4.3.2). Furthermore, determining the depth of root systems can be difficult although several methods are available and continually being developed (see Section 2.5.2.2).

A general rule of thumb is that during establishment (i.e., before trees have reached a groundwater source) and perhaps throughout the growth of the vegetation (i.e., groundcover systems), plants should receive a total of 1–2 inches of water per week, including both precipitation and supplemental irrigation. Once vegetation is properly established, it may be possible to remove the irrigation system. However, once an irrigation system has been installed, it provides a backup in case of severe drought. Furthermore, future applications of a liquid fertilizer may best be applied using the irrigation system (see Section 2.4.2.3). However, some states are now requiring a nutrient management plan to be developed for loosely defined "agricultural operations." While remedial activities are not classic agricultural operations, the loose definition has been applied to golf courses, parade/athletic fields, and other large grassed areas. Phytotechnology operations or activities need to check with local regulations for applicability.

One concern for phytotechnology systems is that excessive irrigation can mobilize contamination from soil to ground- or surface water. Therefore, in these cases, ET estimates (see Figure 1-7 and Tables 1-2 and 1-3) may be needed to estimate the amount of water necessary to sustain growth

without infiltrating through the soil and root zone and recharging the groundwater. Automated soil moisture monitoring systems are also available to control flow when irrigation is necessary (see Section 2.5.3.2).

In terms of controlling hydraulics, different methods applied at the surface or in ground may be employed. For controlling infiltration, soil mounding, contouring/grading, and impermeable or semipermeable barriers can restrict or control total infiltration. Common barrier materials include compacted clay, low- and high-density polyethylene liners and landscape tarp (polypropylene mesh). For liners and tarps, holes need to be cut (a simple "X" cut) to accommodate desired plants. The use of these should be included in any hydrologic modeling done in the design (see Section 2.4.1). Other storm water (and irrigation) management control features such as conveyance ditches and retention/detention basins may also be designed into the site but may also include the storage capacity in the soils themselves (see ITRC 2003c). To minimize runoff, higher-permeability materials such as sand, gravel, or cobble placed in layers or along boundaries can be used to capture, store, and/or convey the storm water as desired based on management requirements. These too may be lined with a low-permeability material. In some cases, if these conveyances lead to a discharge point, they may be subject to NPDES permits. In some cases, these management systems may be planted with species capable of remediating or transpiring the runoff (see ITRC 2003b and also riparian systems in this document).

2.4.2.2 On-Site Access, Fencing, and Security

By definition, phytotechnology systems are growing and ever-changing systems. Thus, special design considerations should be given to accommodate how the system will change the appearance and accessibility throughout the site over time. Certain requirements may have to be considered, such as easements approaching traffic intersections to prevent visual obstructions, locating and accessing monitoring wells and other infrastructure located within the planted area, and future mobilization of equipment and heavy machinery to various parts of the site. On a day-to-day basis, visual contact with field workers conducting routine OM&M activities may need to be maintained. This specific requirement may impact the final design by limiting the species selected to those that do not grow over a certain height. Similarly, access for mowing may dictate the spacing of trees to accommodate the equipment.

Entry into the site may need to be restricted either to minimize potential exposures to human and ecological receptors or to protect the plantation from vandalism and damage caused by the public. Fencing provides a minimum level of protection for these needs but can also serve other purposes in addition to providing security for the site. Fencing or netting can also be used to capture plant debris and leaves from blowing off site. Large animals such as deer and beavers can be restricted from entry provided the fencing is tall enough and/or has small enough openings. Alternatively, electrified fencing can also be used to deter these larger animals. Smaller fences or wire mesh ("chicken wire") can be used for smaller animals and rodents such as rabbits and mice; however, complete control of these animals using fencing can be difficult. An alternative or supplement to this approach includes maintaining an adequate mowing program around the periphery in addition to establishing raptor perches. Burrowing animals such as moles and groundhogs can be controlled by installing a trench around the perimeter of the plantation and filled with larger material such as cobble that cannot be burrowed through. The depth of this

trench need be only a couple of feet deep but below the normal burrowing depth of the animal. In extreme cases, overhead netting can be used to restrict migratory birds from accessing the plants although this can also cause entangling issues.

In addition to fencing around the site, individual plants, particularly trees, may need to be protected through additional means such as trunk guards, guide lines, ties, and stakes. Grazing animals (e.g., voles, beavers, rabbits) as well as various animals that rub up against trees (e.g., deer rubbing off antler felt) can do considerable (often irreversible) damage to a newly planted stand. Plastic, expandable trunk guards may be placed around each tree until the stand matures to a point where it can withstand these events. It is recommended to consult a local forestry, arborist, or natural resources department for other alternatives. Trees planted into boreholes or trenches, with or without casings (see Section 2.4.3.2), will not have the same stability as a normal tree since lateral root growth, which provides much of the stability during high wind events, can be restricted. Stakes, guide lines, and ties can be used to help provide the stability, but care should be given such that the guide lines and ties do not restrict the growth of the tree. Once a stand matures, particularly towards canopy closure, the innermost trees are often shielded from these effects, and these aids may not be needed in the long term.

2.4.2.3 Soil Preparation, Amendments, Fertilizers

All systems will require some form of soil preparation, either the entire field for a groundcover system or the soil that will be used as backfill into boreholes or trenches for trees. Soil preparation for a phytotechnology plantation is similar to that undertaken in agriculture, including tilling, fertilizing, planting, and irrigating, and should be done according to application guidelines and rules. These are usually conducted in conjunction with or after major earthmoving activities are conducted, such as surface contouring/grading, creating drainage control systems, and removing obstructions. The specific requirements to prepare a soil are site-specific and should rely on the soil characterization information collected during in the assessment phase (see Section 2.2.3.1).

At many former industrial facilities, soil compaction tends to be an issue when installing a phytotechnology system. Compact soils can restrict root penetration, as shown in Figure 2-7, and need to be dealt with using tilling or harrowing. The depth and associated equipment of tilling/ harrowing depend on the compaction; the goal is to loosen the soil to be more conducive to support vegetation. In general, the uppermost 18 inches of the soil profile need to be loose for proper root development. For borehole or trench installations, the entire depth may need to be loose within the excavation to optimize root penetration. The cuttings may be able to be used as all or part of the backfill. If the soils were impacted, some regulatory authorities allow the material to be used as long as it passes any required soil tests. In addition to building a better environment to support plants, the tilling or harrowing also aerates the soil in a manner identical to landfarming. For organic contaminants, this can be desirable to stimulate aerobic biodegradation and should be considered as part of the remedy. However, possible volatilization of contaminants may need to be monitored or addressed. Blowing dirt and dust generation may need to be addressed during these activities.

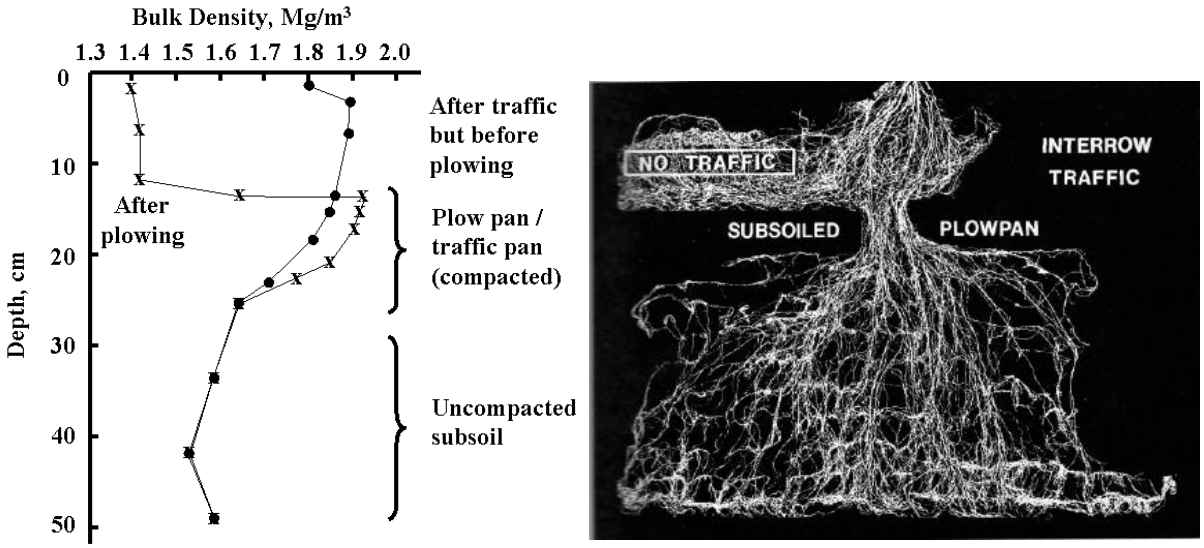


Figure 2-7. Effects of soil compaction on root penetration.

Another condition that often develops after major earthmoving or tilling is volunteer plant growth due to the seed bank stored in the soils. While many of the plants that develop may provide some remedial benefit, particularly for remediating soils/sediments, these are typically annual varieties. In some cases, this effect can be designed into the entire remedial strategy; however, the specific species that will develop are difficult to predict as are coverage and potential fate and transport issues. Methods to address this prospect, if deemed necessary, include a series of applications of nonpersistent herbicide, mowing (done before the annual species produce seed), and covering with landscape tarp or liner material. Care should be given to spray drift and/or dust generation during these activities. The best method also depends on the area to be prepared.

Either during or after the soil is tilled, soil amendments and an initial fertilizer application can be added into the matrix. Different compositions can be considered based on the soil condition or affect desired to promote vigorous plant growth. Several of these are listed in Table 2-9. Although this list is incomplete, a general recommendation is to use local materials whenever possible. Fertilizers are commercially available in powder (or granular), liquid, or tablet forms. Powders are generally mixed into the soil matrix; however, dust generation may have to be addressed. Liquids are spray-broadcast over the entire planting area but may similarly require runoff to be addressed. Alternatively, liquid fertilizers can be applied through the irrigation system (see Section 2.4.2.1) or deep-injected into the soil at the base of the plant. Mist sprayers (powders, sprays), runoff control (liquids), and scheduling can be used to properly manage these applications.

Another alternative often used for trees immediately prior to planting is the use of "root dips," which are also commercially available or can be custom-designed. These root dips usually comprise specific nutrients and, oftentimes, mycorrhizal fungi inoculants, made into a slurry using a hydrophilic gel (acrylamide-based polymer). Slow-release (2–3 year) fertilizer tablets of various formulations of inorganic nutrients are also available commercially, with some also containing plant growth hormones. These are can be added to an excavation prior to planting. For trees, several of these may be placed at various depths throughout a borehole or trench.

Table 2-9. Potential amendment remedies for various soil conditions/growth needs

Soil condition or effect	Soil amendment
General fertility	Balanced (10-10-10 NPK) fertilizer, biosolids, sewage sludge
Root development/growth	Phosphate fertilizer, ectomycorrhizal fungi
Foliar growth	Nitrogen fertilizer
Nutrient regulation	Potassium fertilizer
Essential metals uptake	Ectomycorrhizal fungi, chelating agents, weak acids
Acidity (pH <5)	Lime
Alkalinity (pH >9)	Gypsum, sulfur
Salinity (EC >2 or 4 mS/cm[a]) Sodicity[b] (SAR >12 meq/L)	Gypsum, calcium/magnesium fertilizer (+ irrigation)
Water-holding capacity	Compost/mulch mixed in (see Table 2-11)
Moisture retention Temperature regulation	Compost/mulch on surface (see Table 2-11)
Aeration	Earthworms

[a] USDA defines water with an EC >4.0 mS/cm as saline. The horticulture industry frequently uses a standard of 2 mS/cm to define saline water.

[b] SAR = Na / √ [(Ca + Mg) / 2]. (These values are in meq/L.)
SAR = (Na × 0.043) / √ {[(Ca × 0.05) + (Mg × 0.083)] / 2}. (These values are in ppm or mg/L.)

When dealing with sites impacted with biodegradable organic contaminants, the inorganic nutrient demand from the microbes also needs to be considered along with the demand from vegetation. Different target ratios of nitrogen, phosphorus, and potassium (NPK) to the total carbon content (C) in the soil, including both natural organic matter and contaminant, can be targeted. Relative high and low ratios are shown in Table 2-10. However, there are no specific levels of NPK to carbon that must be achieved or maintained since contaminants (e.g., concentration, breakdown products), microbes (e.g., community diversity, populations), plants (e.g., species, maturity, growth conditions), and time (e.g., season, climate) all constantly change.

Table 2-10. Target nutrient ratios based on total carbon content

Target Ratio	Carbon	Nitrogen	Phosphorus	Potassium
High	100	25	10	5
Low	100	5	2	1

Furthermore, excess fertilizers applied to achieve a certain nutrient ratio, particularly C:N ratios, can have detrimental effects if not managed properly. Excess nitrogen fertilizers have been shown to impact receiving water bodies located downgradient and can have a detrimental affect if not managed carefully. Most chemical fertilizers should not be applied immediately before a heavy rain event and/or before storm water management systems have been installed. Table 2-11 shows alternatives to chemical fertilization that slow the release of nitrogen nutrients. These sources of compost or mulch may be mixed into the soil matrix, added as part of the backfill, or applied on the surface (see Table 2-9) to slowly biodegrade over time, releasing both the carbon and inorganic nutrients. Furthermore, several of these are known to degrade through specific organisms also capable of affecting contaminants (e.g., white rot fungi for wood chips). Likewise, some research has shown that the intracellular enzymes produced by some species that

are effective in breaking down contaminants are also effective when added as organic matter to a site (Medina et al. 2000). However, as these materials decompose, one should consider the potential subsidence issues, particularly for trees planted into boreholes or trenches containing these materials.

Table 2-11. Carbon and nitrogen (C:N) ratios from different sources of compost/mulch

Compost/mulch	C:N ratio	Compost/mulch	C:N ratio
Manure (fresh)	15:1	Leaves (fresh)	40:1
Legumes (peas, etc.)	15:1	Weeds (dry)	90:1
Grass clippings	20:1	Straw, cornstalks	100:1
Manure (w/weeds)	23:1	Pine needles	110:1
Weeds (fresh)	25:1	Sawdust	500:1
Hay (dry)	40:1	Wood chips	700:1

2.4.3 Plant Selection, Plant Stock, and Planting Methods

Many of the plant selection options are identified during the assessment and remedy selection phases (see Sections 2.2 and 2.3, respectively). The final selection of plants during the design phase includes additional, more practical considerations, such as commercial availability and plantability. Related to the commercial aspects, the type of stock that the species is typically sold as dictates the planting method and the ultimate design of the phytotechnology system. For all stock, cost is relatively proportional to the size of the specimen. Since price is dependent on limited availability, it is highly recommended to order well in advance of the planting date (i.e., the winter before). Using locally available stock is highly recommended since it is acclimated to local climate conditions. Growing seasons generally run from the average first to last frost dates for the region (check local agricultural extension service). Planting is typically done in late winter  or early spring although exceptions and alternatives exist, as discussed for each of the different types of stock.

In general, the use of a variety of vegetation leads to a greater chance of success and is preferred over monocultures due to several advantages, including the following:

- Mixed stands may lose only one or two species to a disease, while monocultures may be entirely susceptible so that one event can destroy the entire phytotechnology system.
- 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 occur in mixed stands.
- Mixed stands contain a more natural appearance.
- Mixed stands promote biodiversity and potential habitat restoration qualities.

Additionally, the planned future use of the site can be considered during the design phase. If a vegetated stand with little or no maintenance is to be eventually established as part of a long-term ecosystem restoration, it is likely that this will occur through a succession of species. This succession could be planned by considering the types of vegetation established initially and the timing of any future planting events. Similarly, slower growing, longer-lived climax species can

be included in the initial design such that faster-growing, shorter-lived species conduct the remediation until the climax species succeed. Typically, 10%–15% climax species might be included in the initial design.

2.4.3.1 Groundcovers

For groundcover systems (typically for soils/sediments), the design should consider seasonal variations, particularly between when the species are active versus when they are dormant. Cool season species typically grow in the spring and fall when it is cool and typically moist, while warm season species grow during the summer months when it is hot and dry. One can consider a mixture of warm and cool season species in the initial design. Furthermore, native species are important for long-term plantings, but in many cases, vigorous, locally adapted varieties of mostly nonnative forage grasses, legumes, or other species may be the most appropriate choices. These cultivated species can be considered initially with the eventual succession towards native species over time.

Species for groundcover systems are commercially available either as pure seed, in a mix of seeds, as bare-root plantlets, or as individually potted stock. If not commercially available, harvesting seeds, root runners from existing plants, or whole plants at or nearby the site may be done, although survivability of the plants, safety, potential contaminant exposure, and the intensity of the labor should be considered whether to select this species for the final design. The advantages and disadvantages of seeds are as follows:

Advantages:

- Lower costs for the stock (number of plants per unit cost)
- Easy installation (spreaders, seeders) and general labor
- Simple storage and transport of the stock

Disadvantages:

- Lower success of establishment and even coverage of site
- Higher predation and competition from volunteer growth
- Cover crop often required

In addition, some seeds require specific chemical, mechanical, or thermal conditions for germination to occur. For example, some prairie species require a winter freeze to break open the seed coat, which then allows water to enter for germination. Therefore, these may need to be planted at the site during the winter before the next growing season. Similarly, some seeds require an animal to digest the seed, break down the seed coat in the gut, and reintroduce the seed to the soil through fecal deposition for eventual germination. Typically, these species should be eliminated from contention. Species that fix nitrogen often need to have a rhizobial inoculum added to the seeds (typically supplied separately in powder form) prior to spreading. Seeding rates for common grass species (ryegrass, fescue, etc.) are typically higher than those of prairie species; although the costs on a weight of seed per unit area are often relatively equal. For example, 400 pounds of a fescue/perennial ryegrass seed mix is needed to cover 1 acre at a cost of $3/pound, or $1200/acre. Alternatively, 10 pounds of a prairie grass seed mix is needed to cover the same acre but at a cost of $100/pound, or $1000/acre. The method of seeding can depend on the species. It generally entails the use of spreaders (common for lawn/turf grass seeds but also usable for forbs such as clovers, vetches, trefoils, alfalfa, etc.) or seed drillers (common

for seeds of prairie species). In some cases, manual spreading is also sufficient. Seeding should be done whenever is most appropriate for the species, typically in the early spring. In many cases, survivability hinges on this timing, which should be planned appropriately in the design.

When using seed, some sort of cover is usually required protect the seeds from predation, provide moisture retention, and shade young plantlets as they emerge. The cover itself can be an annual crop such as an annual grass species added to the mix. For common lawn and turf grasses, overseeding is another common method. Other options include wetted sawdust (as a seed carrier and cover), coconut or straw fiber mats (some times impregnated with the seed itself), or nylon seed meshes. The advantages and disadvantages of bare-root or potted stock are as follows:

Advantages:

- Higher survivability since there is significant plant biomass available from which to grow
- Visual and remedial effects shortly after planting
- Greater ability to compete against or reduce volunteer growth

Disadvantages:

- Higher installation cost, time, and labor
- Proper storage and care required before planting
- Larger transport needs

The cost for bare-root stock is generally less than that of potted stock, perhaps by 25%, although both are more than seed (on a number of plants per unit cost basis). The costs for either vary widely depending on the species, size of the specimens, commercial origin, and size of the order. In general, however, the cost of the stock itself is minimal compared to the remaining costs to transport, store, maintain, install, and cultivate at the site. In some cases, the cost of the stock may only be 1%–2% of the total capital installation costs. Potted stock typically can range from small plugs in palettes of 32–128 individual plantlets to single plants of varying sizes in 1-, 2-, or 5-gal pots.

Methods of installation generally require extensive manual labor since each individual plant must be handled to be planted. A common method for small and medium-sized plantations is to use a crew of three field workers, one with a dibble bar or similar implement to create a hole sufficient to accept the plant (and soil if potted), a second worker to place the plant into the hole, and third following behind to replace the soil around the plant. The plants or palettes should be placed in appropriate locations throughout the area to be planted beforehand (and adequately watered). Optimal spacing between plants depends on the size of the specimens, but for plants that come in palettes, typically 1–2 feet, greater for larger specimens. With proficiency, a site up to several acres can be planted in a day using this method. Some equipment such as a shallow trencher can be used to increase the rate of planting or work with tighter soils or larger sites. Survivability is greater with potted stock since the potting soil is typically included when the plant is installed at the site. This additional soil provides a clean soil from which the plant can send out exploratory roots into a contaminated zone, similar to the concept of the "phytoremediation front" (see Section 2.3.2.3).

When using plugs or potted plants, some initial protection is generally needed to aid the plants as they establish. Volunteer growth and competition can be dealt with using landscape tarp placed

down prior to planting where individual holes are cut (a simple "X" cut) to accommodate each plant. Obviously, the size of the site may make this technique impractical. Moisture can be dealt with by including a layer of mulch or using coconut or straw fiber "logs" that contain the plant or plug.

2.4.3.2 Tree Stands

Trees are commercially available either as whips, poles, bare-root, potted, or balled and burlapped (B&B) trees. The advantages and disadvantages of each type center on the cost of the stock, storage, transport and handling requirements; the installation cost, time, and labor; and survivability. In general, larger specimens have a greater chance of survival but are also more costly in most aspects. In some cases, specimens can be collected from the site or nearby area instead of purchased commercially. Whips or poles can be cut assuming the species has the appropriate characteristic of being able to regrow from a cutting. These are typically, but not exclusively, in the *Salicaceae* family (willows, poplars, cottonwoods, etc.). Cuttings should be taken while the source tree is still in winter dormancy and should be maintained dormant (stored under refrigerated conditions) until planted into the ground. Other species that are not able to regrow from cuttings can be entirely removed (including the soil around the main root mass); however, survivability can be low, depending on the ability of the species to withstand transplantation shock. There are different methods of cutting, storing, preserving, and transplanting the stock. Information on a species ability to regrow from cuttings or other methods of propagation may be available on the USDA PLANTS national database (http://plants.usda.gov). Furthermore, recommendations can also be discussed with a local agricultural extension service or forestry department. Regardless of the stock, some initial protection is generally needed to aid the trees as they establish (see Section 2.4.3.1).

Whips and poles generally appear simply as unbranched (or debranched) sticks of varying size ranging from less than 1 foot (less than ½-inch diameter) to greater than 10 feet (½ to 2 inches in diameter). Whips can cost less than $1, while poles 3–6 feet long can be $10–20 each. Larger poles can cost even more and may entail special orders placed well in advance of the planting. The advantages of this type of stock include easy storage, transport, and handling; smaller diameter boreholes or smaller trenches needing to be excavated; and in most cases, the ability to be planted to significant depths with the majority of the material placed into the subsurface. For example, a 10-foot poplar pole can be planted 9 feet into the subsurface with only the remaining 1 foot above ground. A pole planted in this way can produce a viable tree because the growth primordia (shoot buds) located along the length of the pole produce branches if aboveground but can also produce roots if below ground. For this technique to be successful, at least one, but typically several, growth primordia need to be aboveground after the planting. The pole should be planted above the static water table to receive sufficient oxygen. In tighter geologies, breather tubes (perforated PVC) can be installed into the borehole along with the pole to supplement the oxygen diffusion from the surface. The benefit of this deep planting approach is that the portion placed below ground produces a root system that starts at depth (9 feet bgs in this example) instead of from the surface downward.

Note that most tree species cannot be planted using this approach and require other methods to promote deeper root systems. These include several design features discussed previously, such as

surface covers and grading, multilevel drip irrigation systems, and designed backfill materials conducive to root penetration (see Sections 2.4.2.1 and 2.4.2.3). Additional measures to promote deeper root systems include physical barriers installed into a borehole or along trench walls that restrict lateral root growth and force/allow only vertical root penetration. These may be installed the entire length down to the saturated zone or installed only at specific zones in the vertical profile (i.e., to isolate a clean aquifer from being accessed above an impacted one). Different casing materials have been tried: some persistent (corrugated pipe or plastic, concrete, polyethylene sleeves, etc.), some biodegradable or semipermeable (cardboard, Sonotubes®, etc.). Several of these methodologies have been patented. However, in some cases, soils compacted during excavation or simply tight native soils may be sufficient to restrict lateral root growth, particularly if a backfill or soil matrix can be designed that is more conducive to root growth and penetration. Again, root penetration is restricted by the saturated conditions eventually encountered in the subsurface; although breather tubes can likewise aid oxygen diffusion.

The speed and labor requirements for planting whips or poles depend on several design factors, including depth to be reached, soil type and compaction, size of the stock, method of installation (boreholes or trenches), and additional engineering designed into the installation such as subirrigation systems, breather tubes, casings or other root growth barriers, backfill and other amendments, etc. The diameter of the borehole or width of the trench also depends on the additional engineering included in the design. In complex, highly engineered installations, an experienced team can plant 50–100 trees per day. In relative simple, shallow installations where a ripper or trencher is used without soil needing to be backfilled, an experienced team can plant thousands of cuttings per day.

Whole tree specimens come in a variety of sizes and measures. Smaller trees with an intact root system are available as bare-root specimens or potted in soil. The pot size generally correlates to the size of the tree; therefore, a 2-gal (pot) tree will be larger (taller, additional branching, wider trunk girth, bigger canopy, etc.) than a 1-gal tree of the same species. Similarly, larger trees are often measured in terms of their trunk girth and can be either potted or B&B. The common measure is the caliper (diameter) of the main trunk. A 3-inch-caliper tree is a larger specimen than a 2-inch-caliper tree. However, the pot size or caliper of one species is not an equal measure for another species. It is recommended to discuss the tree size with the supplier. Generally, the cost of these trees also correlates with the size. Bare-rooted stock is relatively inexpensive (around $10 or less each). Potted stock (up to 10 gal) ranges approximately $10–100, while larger stock (potted or B&B up to 4-inch caliper) costs $100–500 per tree.

The advantage of these more expensive trees—increased survivability—needs to be compared to the cost of replanting smaller stock such as whips or poles. Furthermore, installing a rooted tree generally requires additional excavation, including larger boreholes or trenches for species able to be deep-planted (see above). These also add to the installation cost in terms of additional backfill material, time required to advance a larger borehole or cut a wider trench, and the associated labor. Furthermore, transport, storage, and handling of the larger stock also incur additional costs in the form of larger vehicles and facilities to accommodate the stock. If the trees need to be maintained after they arrive at the site but before they can be put into the ground, the larger stock also requires larger amounts of water.

2.4.3.3 Riparian Transitions

In addition to the species and stock used in groundcover and tree systems, riparian systems may also include aquatic (OBL) species and/or different transitional (FACW, FAC, FACU) species based on the tolerance to flooded conditions in the riparian zone. Stock for these transitional species depends on the form (tree, grass, herbaceous, etc.) and can likewise be available as seed, plugs, bare-root plantlets, potted plants, cuttings, or B&B stock. For aquatic species, there are three categories: floating, emergent, and submerged. Floating species are not rooted into a solid matrix and acquire their nutrients from the liquid medium. Emergent and submerged species generally are rooted in the sediment but differ in the wavelength of solar radiation where they conduct photosynthesis (full spectrum for emergent species versus filtered below the water surface for submerged species). Emergent species transpire water and are easier to harvest if required, while submerged species do not transpire but provide more biomass for contaminant uptake and sorption.

Most aquatic species used in a phytotechnology system are harvested from or nearby the site. However, some species are commercially available from nurseries that specialize in aquatic species, such as aquaculture, aquascaping, and aquarium supply vendors. Other than seed, stock of these species typically come as bare-root specimens and require immediate attention since they are not shipped with sufficient water to sustain them. Costs are comparable to similar groundcover or tree species; however, shipping costs are likely to be higher due to overnight delivery and additional water weight. Furthermore, transport and handling of the plant stock also need to be addressed if the shipment cannot be sent directly to the site. The advantages and disadvantages of seed over actual plant stock are similar to those discussed for groundcovers.

Furthermore, the design of the plantings may depend on the objective of the riparian system. If it is to address NPS runoff, then surface contouring along with plantings perpendicular to the flow may be able to reduce the rate of flow, minimize channeling, and increase the contact time between the vegetation and the surface flow, depending on the magnitude and frequency of the runoff flow. However, if the system is designed to address the riparian zone above a body of water subject to flow itself, the flow conditions should also be considered. Flowing conditions can be quiescent, intermittent, steadily continuous, or continuous but prone to surges. Depending on the location of the plantings along the grade, all or part of the plantings may need to be anchored to withstand the flow conditions. This measure is particularly important during establishment since the plants will not have grown sufficient root systems to anchor themselves. Installation methods include physically staking or securing the plants into place, using coconut or straw fiber "logs" that contain the plant or plug, or controlling the level of flow until the vegetation is established. If flow conditions can impact the riparian plantings in this type of system, the design should also accommodate by angling any rows of plantings with, instead of against, the flow.

2.5 Operation, Maintenance, and Monitoring

Phytotechnology systems are like any other operating remediation system in that they require maintenance and upkeep. While the activities needing to be performed for phytotechnology systems are generally quite different from conventional, mechanical treatment systems, the

optimum operation often translates into an optimum remedial performance. This usually means establishing and maintaining vigorous plant growth, development, and health by providing an optimum growth environment, reducing competition and predation, and performing seasonal activities that prepare the plantation for the next season. Growth conditions are monitored through techniques not commonly used for other technologies and resemble techniques more often used in agriculture or horticulture.

In general, it is more important to develop vigorous and deep root systems than a healthy canopy, although the two cannot be separated. Techniques to monitor how the plants interact with the contaminated site conditions (soil and water) also need to be conducted. In terms of the remedial performance of the system, the same criteria to monitor any other technology are used. However, supporting information may also need to be collected to address fate and transport issues and hydraulic influence and to confirm whether the suspected phytotechnology mechanisms (rhizodegradation, phytodegradation, etc.) are operating as designed.

> As a general reminder, the focus should always remain on the performance of the system as a remedial technology rather than just on the aesthetic quality of the surface appearance.

2.5.1 Standard Plant Care and Site Upkeep

Standard agricultural methods for fertilizing, irrigating, pest management, and weed control are used when caring for a phytotechnology plantation. The need to replant some portion of the system may arise either in response to inadequate growth conditions or events or as part of the remedial design itself. Similarly, the long-term nature of phytotechnologies implies annual maintenance activities at the end and beginning of each season.

2.5.1.1 Fertilizing and Irrigating

To maintain vigorous plant growth, development, and health, optimum soil nutrients need to be maintained and monitored periodically throughout the life of the remediation project. In some situations, the soil conditions may need to be monitored frequently (several times per year), while in other cases, soil agronomic samples may be needed only every few years. Typically, regular fertilizations can be done in early spring to help the new growth and in late fall to prepare the vegetation for winterization. Standard soil agronomy tests such as those performed at local agricultural extension services may be sufficient. Sample preparation should follow SW-846 methods 3050B or 3051A, EPA 200.2, or equivalent methods deemed appropriate by the regulatory authority. Table 2-12 lists standard methods for monitoring agronomic conditions (this list is not exhaustive). Additional information is available at www.epa.gov/epaoswer/hazwaste/test/main.htm and www.epa.gov/region1/info/testmethods/pdfs/testmeth.pdf. Many of these methods are also applicable to common inorganic COC(s).

Tables 2-9 and 2-10 offer guidance on soil amendments and target levels for various field conditions or optimal growth needs. Specialists such as botanists, horticulturist, and arborists may also be consulted to help optimize plant nutrition. These individuals are able to assess nutrient needs based on indicators obtained from the plants themselves, such as wilting, yellowing, leaf curling, etc. (see Section 2.5.2.1). These growth responses can often be traced to specific nutrient deficiencies and toxicities (Taiz and Zeiger 1991).

Table 2-12. Analytical methods for soil agronomic parameters

Parameter	Analytical method
pH	SW-846 9045D, ASTM D4972-01
Alkalinity	EPA 310.1
Conductivity	SW-846 9050A
Organic matter	ASTM D2974-07A
Cation exchange capacity	SW-846 9080, 9081
Inorganic nutrients (B, Ca, Cu, Fe, Mg, Mn, Mo, P, K, Na, Zn)	SW-846 6010C
Anions (Cl^-, NO_3^-, PO_4^{3-}, SO_4^{2-})	SW-846 9056A
Chloride (Cl)	SW-846 9212, 9250, 9251
Nitrogen (N) – nitrate (NO_3^-)	SW-846 9210A
Nitrogen (N) – ammonia (NH_3^+)	EPA 350.1, 350.2, 350.3
Nitrogen (N) – total Kjeldahl	EPA 351.1, 351.2, 351.3, 351.4
Ortho-phosphate[a]	EPA 300.0, 365.5, 365.6
Phosphorus (P), total	EPA 365.1, 365.2, 365.3, 365.4
Sulfate (SO_4^{2-})	SW-846 9035, 9036, 9038
Cations (Ca, Cu, Fe, Mg, Mn, Mo, K, Na, Zn)	SW-846 7000B
Cations (Ca, Cu, Fe, Mg, Mn, K, Na, Zn)	SW-846 6020A
Cations (Ca, Cu, Fe, Mn, Mo, K, Zn)	SW-846 6200
Cations (Cu, Fe, Mn, Mo, Zn)	SW-846 7010
Calcium (Ca)	SW-846 7140
Copper (Cu)	SW-846 7210, 7211
Iron (Fe)	SW-846 7380, 7381
Magnesium (Mg)	SW-846 7450
Manganese (Mn)	SW-846 7460, 7461
Molybdenum (Mo)	SW-846 7480, 7481
Potassium (K)	SW-846 7610
Sodium (Na)	SW-846 7770
Zinc (Zn)	SW-846 7950, 7951

[a]There are several different methods for determining available phosphorous in soil. Agricultural laboratories often use the Bray P-1 method (also known as "phosphorous soluble in dilute acid-fluoride"). For highly calcareous soils (>4% calcium carbonate), the Olsen P method (also known as "phosphorous soluble in sodium bicarbonate") is recommended. For additional information on test methods, see *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties*, American Society of Agronomy and Soil Science Society of America, 1982.

In addition to the soil nutrient content, water supply also needs to be at optimum conditions for vigorous plant growth, development, and health to be achieved. Under most conditions, plant stands should receive 1–2 inches of water per week as a general rule of thumb. However, the total amount of supplemental irrigation (see Section 2.4.2.1) may be greater or less than this, depending on many factors. First and foremost is the amount of natural rainfall that the site receives. This can be measured using rain gauges deployed at the site as either standalone devices (e.g., graduated cylinders, sight glass, weighing gauges) or connected to a larger meteorological

station (e.g., tipping bucket recorder). Second, species-specific water demands may need to be calculated using measurements of transpiration. These can be measured using sap flow sensors (see Section 2.5.3.1). Third, the water-holding capacity of the soil should also be considered and can be measured using soil moisture probes inserted into the root zone (see Section 2.5.3.2). These moisture probes can be used to control an automated irrigation system such that a specific soil moisture level is maintained.

2.5.1.2 Weed and Pest Control

Weeds should be controlled to reduce competition with the selected phytotechnology plants and prevent the spread of nuisance plants. Weed control may be necessary throughout the life of the project but is more important for the first few years before the desired canopy has fully formed and can shade any undesired growth from out-competing. Weed control can be accomplished by mechanical methods such as mowing, smothering, mulching, or manual removal or through the use of herbicides. When using herbicides, care should be taken to select an herbicide that is not detrimental to the desired plant, and the application time and methods should minimize spray drift.

Selected herbicides should be nonpersistent in the environment.

Similarly, all plant communities should be monitored for signs of stress or damage from insects so that the appropriate action can be taken. Certain pesticides containing *Bacillus thuringiensis*, also known as BT spray, are widely used due to their specificity for target insects and larvae such as caterpillars, moths, mosquitoes, flies, and beetles. Due to these specificities and their general nonpersistence, BT insecticides are often considered more environmentally friendly. Furthermore, many GMO plant species (see Section 2.3.1.5) have been developed that incorporate BT insect resistances.

Larger pests such as mice, rats, rabbits, moles, groundhogs, beavers, deer, snakes, migratory birds, and other vectors may also be attracted to phytotechnology systems. While ultimately these may be target end users of the site, they can also pose significant risks to the success of the phytotechnology system by damaging or consuming the vegetation. If these become a nuisance, a suitable control plan will be needed if not initially designed into the system or the design proves to be inadequate (see Section 2.4.2.2). Licensed trappers and hunters may be an option, depending on the setting of the site and surroundings and the method of control.

Monitoring the site for diseases should also be part of standard O&M activities. Diseases in a stand generally develop when some form of stress or damage to the vegetation creates weaknesses where the disease can take effect. These conditions or events include water damage from floods, chemical damage from road salt, and physical damage such as nicks or scrapes during mowing or other weed control activities or from wind, animals, or other infestations. Depending on the disease, different control and preventative measures can be employed, such as additional fertilizer, other biological agents that attack the disease rather than the host, or sprays containing plant antibiotics. Consultation with a botanist, horticulturist, or arborist is highly recommended should a disease take hold in the phytotechnology plantation. Additional plant disease control information is available at http://plant-disease.ippc.orst.edu.

In some cases, the contaminants that are to be addressed with the phytotechnology system may cause the stress leading to a disease infestation. However, this effect may be desirable since the secondary plant defense mechanisms used to combat the disease may also be the same physiological mechanisms that address the contamination. If this is the case and complete devastation results, the site will likely need to be replanted periodically.

2.5.1.3 Mowing, Pruning, Harvesting, Handling, and Removing Plant Waste

Mowing groundcovers (herbaceous species) and pruning/thinning tree (woody species) stands may also be needed to maintain a healthy stand, control weeds, strengthen plant structure, promote denser canopy, and minimize damage from storms. These activities are generally carried out using standard equipment such as mowers, clippers, shears, rotary trimmers (weed "whackers"), chainsaws, etc. as dictated by the type of vegetation. In addition, equipment selection may depend on the layout of the plantation, such as the width of a mower that can fit between adjacent rows of trees. Special care should be given when operating the equipment so as to not damage or destroy the desired species, such as damaging the bark when using rotary trimmers to cut weeds around trees.

Cutting down dead or dried grasses or plants should be done annually or as needed to maintain any safety requirements (see Table 2-7). Cutting in the spring should be done prior to the emergence of new leaf growth or before new seeds or annual plants are replanted at the site. Branches on trees and woody shrubs can be pruned during the late winter, spring, or summer months. Avoid pruning during the fall or early winter because, like fertilization, pruning in fall encourages tender new growth that may not be sufficiently hardened to resist the winter cold. Dead, damaged, or diseased branches can be removed as needed. Felling whole trees can also be done as needed and when it can be done safely. Woody species that are to be propagated from cuttings (see USDA PLANTS national database, http://plants.usda.gov) should be pruned in late winter/early spring before buds have broken, with the cuttings stored in refrigeration until ready to be planted. Similarly, coppicing trees that can regrow from a cut stump should be done while the trees are still able to actively grow and sufficiently harden prior to winter.

The plant material generated may need to be collected and treated as if it is a hazardous waste until appropriate testing for contaminant accumulation can be conducted. Even if the plant waste is not classified as a hazardous waste, it may be sufficiently contaminated to require special handling requirements according to some state rules. Test methods should be appropriate for the contaminants (see Section 2.5.3.3). In most cases, however, cut plant material can be left in place. It is recommended that testing be conducted beforehand to determine the need for collection. If collection is needed, it should be done when the material is cut. For groundcovers, threshers and bailers may be options to consider. If vegetation naturally produces plant litter (leaves/needles, seed/seed pods/fruit/pine cones, small branches/twigs, etc.), these may need to be tested and/or collected as well. Typically, the litter drop occurs at specific times throughout the growing season, and collection, if required, should be scheduled accordingly. To prevent the migration of plant litter prior to collection, fencing and netting may need to be considered (see Section 2.4.2.2). For litter drop produced through storm or weather damage, a specific assessment may need to be conducted, although historic information regarding the accumulation

of contaminants should be considered first. Furthermore, plant litter buildup may need to be removed simply to maintain storm water control systems.

Particular phytotechnology applications such as phytoextraction of metals or radionuclides may include these sampling, cutting, and collection activities as means to remove from the site the contaminants taken up into the aboveground tissues. When chelating agents or similar chemicals are used to mobilize contaminants to promote or enhance the phytoextraction, several factors must be considered beforehand, including method of application (usually through an irrigation system as part of the normal O&M, see Sections 2.4.2.1 and 2.1.1), weather conditions, stage of plant development, rate of application versus rate of water usage, and the potential to increase the risk of exposure. It is highly recommended to schedule the harvesting activity immediately or shortly after the application of the mobilizing chemical. If end targets have not yet been reached, the site will need to be replanted and will typically call for similar or identical procedures to the initial implementation (see Section 2.4).

In general, individual plants not specifically planted at the site as part of the designed phytotechnology plantation (i.e., weeds) do not need to be tested and/or collected. Furthermore, a weed control program should help minimize the growth of undesired and competitive species (see Section 2.5.1.2). However, should an unplanned species become prolific at a site, a species identification, growth assessment, and tissue sampling program (see Sections 2.5.2 and 2.5.3.3) may be needed to determine whether the species is contributing to the remediation, should be allowed to continue to grow or be managed, and constituents a hazardous waste if harvested. Specific information that might be worth documenting include the species; contaminant(s); impacted media; concentrations in the plant, in specific tissues (see Section 2.5.3.3), and in impacted media; growth; development; health results (see Sections 2.5.3.1 and 2.5.3.2); and information regarding the mechanism (see Section 1.2) of remediation or exclusion. This information can be added to the existing body of phytotechnology species information.

If contaminant concentrations in plant tissues do exceed regulatory limits, the cut plant material or litter will need to be treated as a hazardous waste. If disposal is necessary, a suitable waste disposal facility should be identified with proper handling and disposal procedures established beforehand including all safety precautions (see Table 2-7). In some cases, RCRA or state-specific hazardous waste regulations may also apply. Under certain circumstances, such as with inorganic contaminants, incineration or composting may be considered to help reduce the volume and mass of material that ultimately needs to be disposed.

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 (Bañuelos 2000 and personal communication with Jason Smesrud, CH2M Hill, Portland, Ore., 2007). Several options exist, including using the biomass as an energy source (direct-fired or as a biofuel feedstock), recovering inorganic constituents (e.g., precious metals) from the plant tissues, or supplementing animal feed supplies. Obviously, additional regulatory scrutiny, sampling, and analytical requirements may need to be performed to have these end uses approved. The economic feasibility of these options should be considered during the economic evaluation during the remedy selection phase (see Section 2.3.5).

2.5.2 Monitoring Growth Conditions

The growth, development, and health of the vegetation directly influence the ability of the system to perform the desired remediation. Most applications of phytotechnologies are most efficient when the plants are growing vigorously and rapidly. However, certain applications where chelating agents or acidic chemicals are added to promote the uptake of contaminants rely on the "last gasp" death response of vegetation for the remediation to occur (i.e., phytoextraction). When monitoring growth conditions, several areas should be considered, including the canopy, root system, and the community as a whole. Furthermore, monitoring should be conducted throughout the year including dormant months, although frequencies may be adjusted appropriately and reduced in frequency, particularly as the system matures.

One of the major factors affecting the growth of vegetation is the climate conditions, including temperature, barometric pressure, relative humidity, precipitation, wind speed and direction, and solar radiation. To monitor these conditions, local weather station data (e.g., from an airport or other recording station) or an on-site meteorological station can be set up. These units can be solar- and battery-powered for remote operation. Meteorological stations typically have continuous dataloggers that record the information at set intervals (every minute and/or averaged over the hour). The typical cost of a meteorological station is about $5,000. This information is used for various purposes, including setting irrigation schedules (see Section 2.5.1.1); estimating the maximum theoretical evapotranspiration, ET_0 (see Section 2.4.1.2, Allen et al. 1998); and comparing conditions to annual averages to gauge expected growth, rainfall, and groundwater levels.

2.5.2.1 Canopy Growth, Development, and Health

In general, the aboveground portion of a plant and the overall canopy are easier to monitor and measure for growth, development, and health than the subsurface root system. For tree systems, common measurements include the height, trunk girth (circumference) or diameter, and LAI. For herbaceous groundcover systems, common measurements include height and area coverage (or LAI). For riparian systems, a combination is often conducted. The community abundance, richness, and diversity are also often monitored to determine maturity and succession for each of these general types of systems.

Physical measurements of height, girth, and diameter are usually performed using standard measuring devices, including measuring tapes, poles, calipers, or dendrometers. A typical rule of thumb for hybrid poplars is to achieve 5–10 feet (2–3 m) of growth per year in the first few years. However, growth is highly dependent on the contaminant, climate, soil, and other environmental conditions. The rate generally tapers off when the tree becomes large enough that most resources are switched to maintaining the existing biomass rather than creating new matter. On the other hand, most herbaceous species attain the full growth characteristics each year, although some species such as clump grasses become broader each year as root runners are produced extending outward.

When measuring girth or diameter, one should consider the shrinking and swelling of a stem depending on amount of water and sap flowing through it during any given time of day. In

forestry, the convention is to measure at a fixed height above the ground, called "breast height." The height is 1.3 m (4 feet, 3 inches) in Europe, Australia, Canada, and some former members of the British Commonwealth. The convention in the United States and other countries is 1.4 m (4 feet, 6 inches) above ground. If these are not practical or abnormal growth occurs at that height, the actual height where the measurement is taken should be recorded. The trunk diameter can be converted into the basal trunk area (BA) by assuming the trunk approximates a circle ($BA = \pi D^2/4$). This approximation was used to generate the information in Table 2-8. BA is a common measure used when measuring sap flow (see Section 2.5.3.1); however, in this case, the measurement should be at the height where the sensor is installed.

LAI is a ratio of the total estimated one-sided leaf (or needle) area divided by the total ground area underneath the canopy. Area coverage is the percent of the total ground surface area covered (shaded) by a specific specimen or by an entire canopy growing directly above. Some species contain multiple layers of branching and leaves/needles and can therefore have LAIs greater than 1 even through their area coverage is less than 100%. This possibility is illustrated in Figure 2-8. A typical stand at 100% area coverage (closed canopy) has an average LAI of 3–4. Very dense canopies can have LAIs up to 6–7. Theoretically, when the area coverage approaches near 100% (complete shade), the stand also reaches maximum pumping capacity since all of the incident solar energy driving the process of transpiration is captured. Furthermore, the dense foliage creates a windbreak that prevents wind energy from driving additional transpiration through mechanical means except through the most exterior leaves/needles. For many phytotechnology designs, canopy closure can be attained in five or so years although many controllable factors influence this rate, including species selection, planting density, maintenance programs, etc.

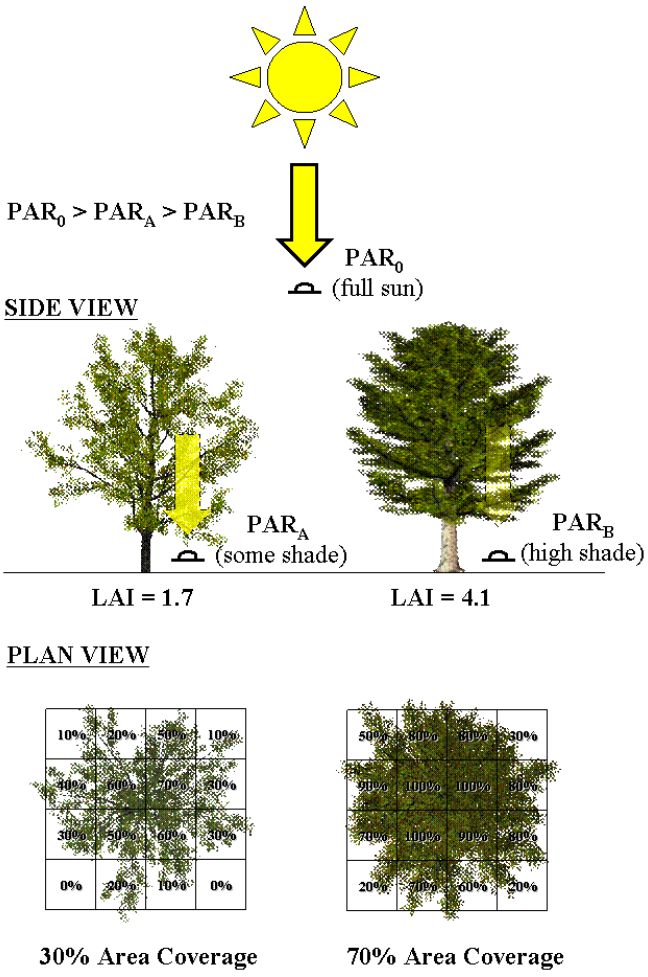


Figure 2-8. Example concepts and estimates of leaf area index and area coverage. PAR = photosynthetically active radiation, 400–700 nm.

LAI and area coverage can be measured in numerous ways, ranging from direct physical measurements to spectrographic techniques to indirect LAI measurement devices. Direct measurement includes using a sample grid of known area (ground area) placed in random locations throughout the planted area and estimating the area coverage within that area. Overhead

digital photographs are often useful in estimating both the area coverage of the canopy and individual specimens within the grid area (see Figure 2-8). For larger tree systems, area coverage can also be estimated from the shaded area within the grid. Individual specimens are then sacrificed by denuding the vegetation of the leaf or needle matter to estimate the LAI. Either total mass can be measured, or individual leaves or needles can be counted as they are removed. The actual technique depends on the size of the specimen. When using total mass, individual samples (subset of the whole) can then be weighed to give an average mass per leaf or needle that can then be used to estimate the overall number of leaves or needles. These individual samples are then electronically scanned (black and white image) and then overlaid with a grid to estimate the area of the sample. Alternatively, most scanning software can count the number of black and white pixels in the scanned image to provide an estimate from the total number of pixels in the scanned area. This area per leaf multiplied by the estimated number of leaves provides the total one-sided leaf area.

Alternatively, LAI meters that use a solar monitoring device specifically tuned to the photosynthetically active radiation (PAR) frequencies of light (400–700 nm) can be used to estimate the LAI and area coverage. These devices are placed (preferably on a cloudless day) in an unvegetated and unshaded area or above the canopy itself to gain a reference, full-sun reading. These devices are then either placed underneath the canopy to measure the shaded solar radiation through the canopy and compare to the reference reading or connected to another PAR light-measuring device placed outside or above the shaded area to obtain simultaneous measurements. Based on the PAR light emanating through the canopy, even under complete shading (i.e., 100% area coverage), the meter is able to estimate the LAI of the actual stand by comparing the readings to the number of leaf layers of a reference crop needed to decrease (filter) the amount that is passing through to the same level. This effect is also illustrated in Figure 2-8. These units cost $5,000 or more.

In addition to measuring the area coverage using the grid approach, ecological factors such as species richness (number of species, percentage of whole community), abundance (density, percent coverage, number of individuals per species), and diversity (distribution, phylogenetic relationships, and abundance relative to the community) can also be monitored. These usually entail counting and identifying individual species that make up the community as a whole and then entering the data into equations that generate various indices quantifying the overall plant community health. Several areas are generally evaluated by randomly placing the grid throughout the plantation. Another alternative includes the line-intersect method where straight lines (marked with rope) through the plantation are traversed and any plant intersecting the line is assessed and counted to generate the community characteristics. While these monitoring techniques are generally not needed for phytotechnology applications, they can be used to enumerate the competing growth of volunteer species. Some regulators may limit the percentage of volunteer growth that is allowable as a means to ensure optimal remedial performance, although primary lines of evidence (e.g., concentration reduction) should remain the primary success indicator. Furthermore, the succession of species over time may be relevant to other stakeholder decision factors in terms of the ultimate disposition of the site (see Section 2.3.4). In some cases, these community characteristics may also be used to compare to background areas to gauge site recovery.

In addition to the physical structure of the canopy and community, the health and vigor of the plants are often used to determine the general physical state of the plantation. Other than complete mortality, other stress indicators can be used to determine the overall health of a specimen. Common symptoms include wilting, stunted growth, malformed growth (curling, crinkling, misshapen), chlorosis (leaf yellowing at the margins, tips, and/or between veins), interveinal chlorosis (yellowing of the leaf veins), necrosis (spots of dead tissue), and dryness/ brittleness. Often, these symptoms can be directly linked to specific nutrient issues and can be used to determine when additional fertilization is needed (see Section 2.5.1.1). Most plant physiology textbooks can provide additional guidance (e.g., Taiz and Zeiger 1991). Alternatively, samples can be collected and analyzed by a horticulturist, botanist, or arborist to determine appropriate care measures.

However, since these plants are growing on contaminated soil and/or water, the stress indicators may also be a sign of chemical toxicities associated with the contaminants. Other than spray irrigation of contaminated water onto the phytotechnology plantation, most contaminant-induced stresses as they are taken up through the root system show within the xylem vesicles of a trunk, stem, or branch and extend outwards to the surrounding tissues, while other noncontaminant-related stresses (nutrient deficiencies, diseases, etc.) are likely to be more systemic (affect all similar tissues simultaneously). Furthermore, the chemically induced stress indicators may appear towards the bottom of the plant first and extend upwards as the contaminant is translocated upwards through the xylem. If the plant is unable to sufficiently combat the stress conditions (e.g., through phytodegradation or phytosequestration of the contaminant), the stress indicator may become systemic. Since these are gross simplifications in assessing plant health, consultation with a plant specialist is highly recommended.

2.5.2.2 Root Growth, Development, and Health

While a healthy canopy generally indicates a healthy root system to support that canopy, another important factor to consider for phytotechnologies is the ability to either grow roots into the contaminated media or bring the contaminants into the root zone. Other than landfill covers, the remediation is generally not successful if the roots do not interact with the contamination (see decision trees, Figures 2-2, -3, -4, and -5). To assess root penetration, distribution, density, and physical characteristics, a combination of intrusive and nonintrusive methods can be employed. A highly destructive method (to the plant) is simply to excavate next to a tree or within the groundcover area to find, trace, and measure roots. If hand-digging or using a backhoe or trencher, an examination of the excavated material as well as the excavation walls can be done to identify root structures. This process is usually done in perpendicular transects starting at the base of a tree or in the groundcover area and then successively deeper within the previous transects to generate a three-dimensional distribution. In general, 70%–80% of the root structure is within the top 1–2 feet of surface (including tap-rooted species) with exploratory roots sent deeper and laterally. The major bulk of the root mass contains thicker roots, while exploratory roots are generally small and sometimes too fine to see after excavating. Therefore, initial lifts should be done closer together with successive lifts spaced deeper apart as one proceeds into the subsurface. If the contamination is stratified, roots also tend to proliferate in the clean zones while exploring the intermittent contaminated zones. Typically, these are advanced until root

structures can no longer be found, although practical limitations should be considered. If able to excavate directly into the original borehole or trench into which a tree was planted and backfilled with a medium conducive to root growth (see Section 2.4.3.2), typical penetrations can be 3–5 feet per year in the borehole or trench. However, most root systems for any species other than OBL species do not penetrate significantly into a saturated zone. Note that all sloping/shoring, confined space requirements, and other safety factors should also be included in the health and safety plan and followed as the excavation is advanced.

A slightly less destructive alternative is to use a hollow-core drill rig or Geoprobe® to advance a boring at the base of a tree or within the groundcover area. For trees, multiple borings can be done, moving away from the initial boring to approximate the distribution, assuming the rig can safely access the entire area and properly raise its mast. Once the core is produced, it can be brought to the surface and examined for root structures noting the depth, density, and diameters.

In many cases, the actual depth of penetration is less important than an indication that the plant system has reached the zone of impact or, more likely, is interacting with the contaminant. Several methods to monitor this interaction include sampling and analyzing tissues. A definitive tracking compound is the contaminant itself or a known breakdown product. Since contaminant uptake is a factor considered when selecting phytotechnologies as a potential remedy as well as a technical factor for specific applications (see Section 2.3 and Figures 2-2 through 2-5), then whether a compound can be found should be relatively known at this phase. Furthermore, sampling tissues for the compound will likely be a requirement to monitor and/or confirm the fate and transport in the plant system (see Section 2.5.3.3). However, the contaminant or breakdown product would have to be able to enter into the plant (see Section 1.2.4) and be fairly persistent (slow to rhizo- or phytodegrade). Certainly if the contaminants are known to persist in aboveground tissues or transpire from them, they should be targeted in the sampling program. Examples are MTBE and TBA, the breakdown product of MTBE, which have been found transpiring from aboveground tissues of pine trees growing over a plume (Arnold, Parfitt, and Kaltreider 2007). However, many other organic contaminants that are likely to enter into a plant (i.e., with a log K_{ow} between 1 and 3.5) are also fairly degradable in the rhizosphere and within the plant. Therefore, using these compounds to determine whether interaction is occurring can have limited, if any, success, particularly when sampling aboveground tissues.

Similarly, many inorganic contaminants are also able to enter into certain plants (see databases referenced in Section 2.3.1). Since these do not degrade (although a few elements such as mercury can volatilize under certain conditions), specific inorganic contaminants found in tissues are also direct evidence of interaction of the root system with the impacted zone. For example, tritium was found in sap of hybrid poplars grown into an impacted aquifer, indicating direct influence on the groundwater (Negri et al. 2003). However, many inorganic contaminants are essential plant nutrients, such as Cu, Zn, Mn, etc. (see Section 1.1.1), which means they are found in above- and belowground tissues. Thus, the low levels present in uncontaminated soil that are sufficient to sustain vegetation confound attempts to use this as a means to determine interaction of a root system with a contaminated zone. Furthermore, the basis of phytosequestration is that the root system acts as a protection system to the plant (see Section 1.2.1). This barrier may prevent inorganic contaminants from translocating into the leaves and

stems. Therefore, it is recommended that, at a minimum, root tissues be sampled over leaves and stems as a means of determining whether the plants have impacted a contaminated zone if the contaminant can be used as a tracking compound.

Alternatively, other tracers known to be present in the contaminated media but not in the clean zones in which a plant must grow may be used instead of the contaminant itself. Bromide is a common conservative tracer used in hydrogeology. Recent studies have investigated whether this can be taken up and found in plants (Kolhatkar et al. 2006). Specifically, bromide concentrations in poplar leaves were found to correlate with the increasing levels supplied with the irrigation. However, there was no significant correlation exhibited in eucalyptus leaves. Although these initial results were highly variable, the technique warrants further investigation as a nonintrusive means of determining whether plants systems are accessing groundwater.

Similarly, water containing stable oxygen isotope (^{18}O) or deuterated hydrogen (^{2}H, or D), also known as "heavy water" or D_2O, naturally occurs in low quantities in regular water (H_2O). The molar ratio of isotopic water to regular water can vary depending on the source water (Ehleringer and Dawson 1992). For deuterated hydrogen, the ratio of D_2O to H_2O is denoted as δD. Therefore, groundwater (δD_{GW}) can contain a different ratio than what would be found in rainwater or more generally, in the vadose zone (δD_{VZ}). Furthermore, sampling the xylem sap using trunk coring techniques (see Section 2.5.3.3) and analyzing for deuterated hydrogen can also reveal a different ratio (δD_{xylem}) than either source. Since water is the only source of hydrogen available to a plant system, then conceptually, the fluid in the xylem should be a combination of the two sources; therefore, δD_{xylem} should be between δD_{VZ} and δD_{GW}.

Furthermore, this comparison of δD values can be used to determine the relative percentage of the total water taken up from groundwater versus what is taken up from surface-available water. In a field study, eucalypts were shown to strictly use vadose zone water in the initial year after planting, but up to 35% groundwater in the following year (Ferro et al. 2002). Although these percentage values are site specific, they can be used in groundwater modeling and should be considered in the design of a phytotechnology application (see Section 2.4.1.2). However, the isotopic composition of water can vary with depth. Therefore, discrete samples by depth may also be used to indicate when a specific depth has been reached by creating a vertical profile and comparing the xylem isotopic signature to the profile. However, the overall technique requires further development. A similar method also under development is the use of soil moisture sensors installed at various depths beneath a tree planted into a borehole (see Section 2.4.3.2). Using these sensors, poplars and willows were shown to use water from the saturated zone located 20 feet below (Ferro et al. 2006). Furthermore, the successively deeper sensors were monitored over time to control the depth at which a multilevel drip irrigation system (see Section 2.4.2.1) would provide supplemental water to the trees.

2.5.3 Monitoring Remediation Performance

As with any other remedial approach, monitoring the performance of phytotechnology systems should rely on standard soil and water analytical results as the primary line of evidence. Supplemental information such as the growth conditions (see Section 2.5.2) provides an

indication whether the plantation is effectively influencing or interacting with the contamination at the site. If that influence or interaction cannot be demonstrated, then the apparent remedial performance may simply be due to natural attenuation rather than the phytotechnology. Additional information may also be required to address hydrologic effects, soil changes, and/or fate and transport issues associated with a phytotechnology system. These may be needed to confirm or refine modeling results, develop site specific attenuation rates, optimize the system performance, or assure regulators and stakeholders that the system is not presenting unforeseen health and ecological impacts. Furthermore, these secondary lines of evidence may be able to differentiate the effects of the phytotechnology from those of natural attenuation.

The frequency, duration, and types of tests and protocols; sampling locations (including plant specimens); and reporting requirements are site specific. Typically, secondary lines of evidence are monitored more frequently (e.g., quarterly) immediately after the installation of the system and may be done less frequently (e.g., annually) as the plantation matures and the remedial effectiveness can be demonstrated. However, the monitoring period should also take into account seasonal variations. While sampling for primary lines of evidence may be conducted immediately after planting, even before plants have emerged, sampling for secondary lines of evidence likely needs to commence only after sufficient biomass has been produced. However, some secondary lines of evidence require a baseline uninfluenced by the vegetation for comparisons.

2.5.3.1 Influence on Hydrology

Creating a plant canopy, by definition, results in rain being intercepted onto the surfaces of the canopy. Table 1-2 presents example water interception capacities for various species. While water interception capacities depend on the duration and intensity of each individual rain event, information on the relative percentage of precipitation captured and prevented from infiltrating into the subsurface can be used in modeling (see Section 2.4.1) and ongoing monitoring of the effects of the phytotechnology system on the site hydrology. However, rain interception is normally not the primary line of evidence for the success of a phytotechnology application while soil moisture at specific depths below the contaminated zone may be (see also Section 2.5.3.2), particularly for phytostabilization and alternative landfill covers. To calculate the rain interception capacity, rain gauges (see Section 2.5.1.1) can be used to measure the amount of precipitation outside (or above) and underneath a particular canopy structure. Similarly, this setup can be used to estimate the amount of spray irrigation that soaks into the root zone compared to the amount supplied as measured through a meter (see Section 2.4.2.1).

Typically, systems designed to address groundwater plumes should include monitoring wells or piezometers located upgradient, downgradient, and within the plantation. While compliance monitoring remains the primary performance requirement, supplemental criteria for these types of systems often include reducing the overall groundwater levels across the planted area (aquifers with low hydraulic conductivities) or creating a cone of depression towards the boundary of the plantation (aquifers with high hydraulic conductivities). These are measured using standard groundwater elevation measurements. Obtaining an adequate resolution (spacing between monitoring points) depends on many factors but can be enhanced by gauging water table depths within breather tubes installed into individual tree boreholes (see Section 2.4.3.2). For groundwater reductions beneath an entire plantation, the apparent drop in elevations may simply

be due to the surface water (precipitation and irrigation) being intercepted and prevented from recharging groundwater rather than from any direct uptake of groundwater. Therefore, performance measurements that track groundwater elevation changes should consider the interception capacity of the canopy. Furthermore, root growth and development measurements, including tracking compounds (see Section 2.5.2.2), can be used to determine whether roots have penetrated to depths sufficient to access the target groundwater and can thus attribute water table reductions accordingly.

For boundary situations, the lateral recharge rate may overshadow the rate of extraction, preventing significant groundwater depressions from being measured through standard well gauging. Therefore, the upgradient flow velocity may also need to be periodically measured using standard hydrogeology techniques to determine whether the lateral recharge into the zone where the depression is expected to form is increased due to water being extracted by the phytotechnology system. Likewise, the downgradient velocity should decrease as a result of the influence of the plantation on the hydrology. Because this changes each season as the stand matures, these measurements should be done annually at least until canopy closure. Furthermore, groundwater fluctuations vary seasonally and daily where the depression may be significant only for portions within those periods. Therefore, monitoring schedules should be planned appropriately. Similarly, these should also be supported by monitoring root penetration into the target aquifer (see Section 2.5.2.2) to confirm groundwater is being accessed.

In addition to gauging water table elevations, the rate of transpiration occurring through the stand should be used to supplement the groundwater depression results and develop a site-wide water balance. Again, estimates of the ratios of surface water and/or groundwater use to the total water uptake should be included (see Section 2.5.2.2). To estimate transpiration, representative plants can be instrumented with either sap flow sensors or be planted above underground lysimeters. Sap flow sensors operate using the rate of thermal dissipation created from a heating source attached to the sensor. Two forms of sap flow sensors (shown in Figure 2-9, also known as "thermal dissipation probes" or "heat-balance gauges"), are available: collar type and needle type. Each is equipped with a series of thermocouples that measure the temperature both with and without sap flowing past the heating source. The basic concept of these thermal dissipation probes is that as the transpiration stream moves through the stem or trunk in which these instruments are attached, the heat is dissipated at a rate proportional to the rate of convective flow. The volumetric rate (or mass rate converted using the density of water) of transpiration is calculated using the energy balance, also shown in Figure 2-9.

The collar type sensors come in various sizes and are limited in applicability to a small range of stem diameters. Another disadvantage is that the collars can restrict stem growth if used for extended periods of time. Their advantage is that they encompass the complete circumference of the stem, thus providing a complete measure of the sap flow, whereas the needle type probes measure the sap flowing only in a discrete section of the stem. Another disadvantage of the needle type sensors is that their insertion into the plant through a drilled hole is invasive and can lead to potential damage and disease (see Section 2.5.1.2), whereas the collar type sensors are noninvasive. However, if left on too long, the collar type sensors can also cause moisture to build up around the trunk, leading to tissue rotting. On the other hand, the needle probes are not as

restricted in terms of the stem diameter and multiple probes can be instrumented on a single specimen of sufficient diameter. In addition, the needle probes also come in various lengths to accommodate larger specimens. When instrumenting large diameter trees, probes should be placed on both the north-south and east-west coordinates at a minimum to estimate an average

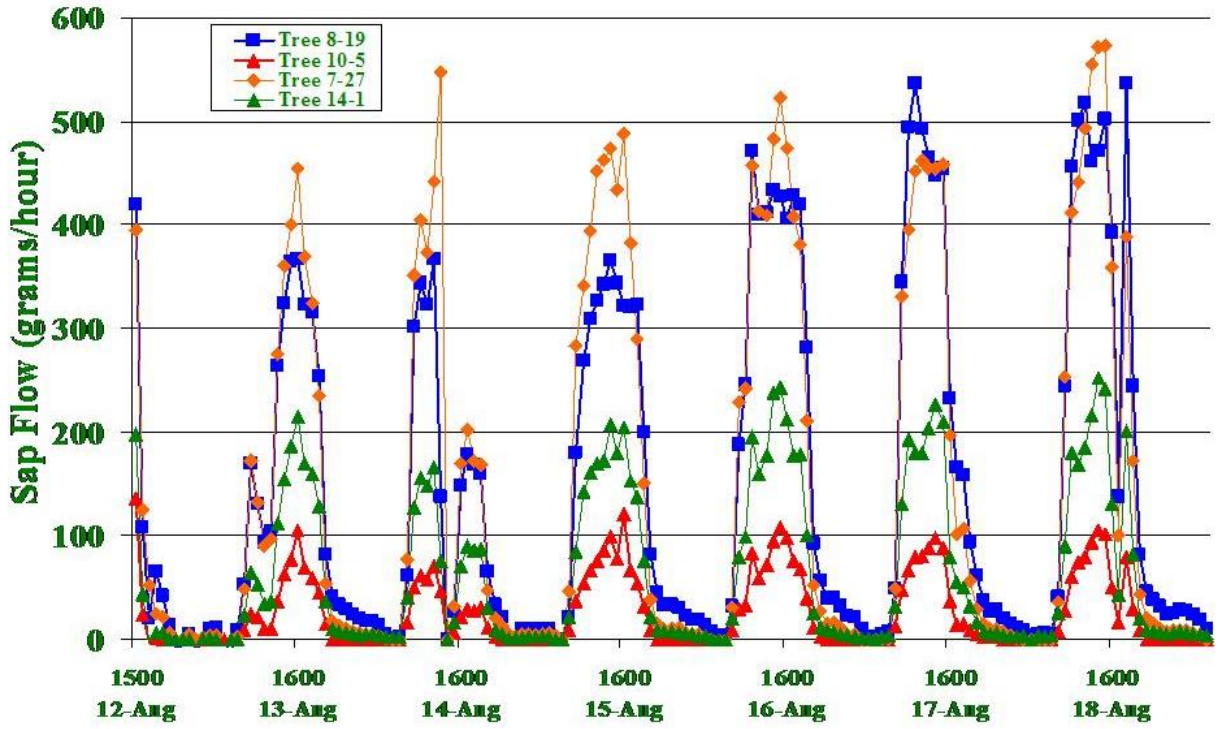
Energy Balance Equations:

Energy Balance:	$P_{in} = Q_{radial} + Q_{vertical} + Q_{flow}$	[W]	(1)
Ohm's Law:	$P_{in} = V^2 / R$	[W, fixed]	
where	V = voltage	[mV]	
	R = resistance	[ohm]	
Vertical Conductivity	$Q_{vertical} = Q_{up} + Q_{down}$		(2)
	$Q_{up} = K_{ST} A dT / dx$		
	$Q_{down} = K_{ST} A dT / dx$		
where	K_{ST} = stem thermal conductivity	[W/m°K]	
	A = stem area	[m^2]	
	dT / dx = temperature gradient	[°K/m]	
	dx = thermocouple junction spacing	[m]	
Radial Conductivity:	$Q_{radial} = C_H \times K_{sh}$		(3)
where	C_H = radial heat thermopile voltage	[mV]	
	K_{sh} = sheath conductance	[W/mV]	
	K_{sh} is determined by solving Eqn. (1) with $Q_{flow} = 0$		
	$K_{sh} = (P_{in} - Q_{vertical}) / C_H$		(4)
Sap Flow Rate:	$F = (P_{in} - Q_{vertical} - Q_{radial}) / C_p \times dT$	[g/s]	(5)
where	C_p = specific heat of water	[J/g°C]	
	$dT = (T_A + T_B) / 2$ = average temperature increase of sap	[°C]	
	T_A, T_B = thermocouple temperatures	[°C]	

sap flow rate through the trunk. It is interesting to note that the sun-facing side of the specimen generally has a higher rate of sap flow.

Figure 2-9. Types of thermal dissipation probes used to measure transpiration rates.
Left, collar type, courtesy Dynamax, Inc.; right, needle type.

Furthermore, each of these sensors can be connected to a continuous data logger to monitor the transpiration over a series of day-night cycles and at different times throughout the growing season. These units can be solar- and battery-powered for remote operation and can be programmed to collect readings throughout each day. Figure 2-10 shows typical output, with the total daily transpiration calculated by integration. To standardize the rate across an entire plantation, the basal area of the instrumented trunk or stem is measured (see Section 2.5.2.1) to



generate a volumetric rate per unit basal trunk area. The basal trunk area can likewise be measured and summed up for every tree to estimate the total transpiration from the stand.

Figure 2-10. Typical results from thermal dissipation probes measuring transpiration over several days.

As a supplemental measurement of canopy development, the individual rates of sap flow can be approximated as the total ET. This value can then be compared to the theoretical maximum rate, ET_0, calculated using the FAO Penman-Monteith equation (see Section 2.4.1.2). However, ET_0 is based on a theoretical reference grass crop of specified height and uniformity accessing water within the top 2 feet of soil. Therefore, crop-specific coefficients, K_c, are often calculated as the ratio of ET/ET_0 and change as the canopy matures and fully develops. Since deeply planted trees are able to access additional water deeper than the reference crop assumption of 2 feet, ET values for phytotechnology applications can often be greater than the calculated ET_0. Note that the theoretical calculations also depend on measuring LAI (see Section 2.5.2.1).

The alternative method to measure the total plant water usage is through the use of weighing lysimeters placed directly below the vegetation to be monitored. These instruments simply measure the total change in weight of the vegetation, soil above the unit, and water within a

known area. The basic assumption for a weighing lysimeter is that the amount (weight) of precipitation and/or irrigation falling onto the area is known and the change in weight of the biomass is negligible in the time frame when the measurement is taken. Therefore, the measured weight change is compared to the weight change expected if no precipitation or irrigation water were removed. By difference, the weight of water lost through evapotranspiration can be calculated. The advantage of weighing lysimeters is they are generally more accurate and less prone to interferences or power issues than sap flow sensors. However, they do require forethought for installation before the site is planted, are fixed at the location once installed, and can be more expensive, depending on the size. For groundcovers, the area coverage may need to be taken into account, as well as the mix of species growing in the sampled area (see Section 2.5.2.1). Weighing lysimeters may not be practical for trees in true field situations, particularly as they grow beyond the bounds of the lysimeter. Installing lysimeters with a large area needs to be balanced with the practicality, and again, requires forethought.

On the other hand, for experimental purposes, whole specimens may be planted in a weighing lysimeter (i.e., in an aboveground soil tank). In this situation, lysimeters dedicated to an individual plant are extremely accurate and have even been used to show the accuracy of sap flow sensors. Specifically, using lysimeters, the error from thermal dissipation probes was estimated to be ±10% at high sap-flow rates and ±20% at medium rates (Rose and Rose 1998). Furthermore, lysimeters have been used to develop correction factors that compensate for the change in sap flow due to the wounding caused during insertion of the needles. These correction factors account for the 50% or more underestimation directly measured by these probes (Green, Clothier, and Jardine 2003).

Other types of lysimeters are also available and can be used for other monitoring purposes. The common feature of these other types is that they contain a vessel or cup in which liquid can be captured. Pan lysimeters are simply gravity fed, while suction lysimeters use a vacuum to draw liquid into a porous ceramic or stainless steel cup. These lysimeters can be instrumented with a sampling port to allow collection of liquid captured in the cup. If placed below the root zone, they can also be used to gauge the amount of irrigation applied to the site (see Section 2.5.1.1). Similarly, they can be used to monitor whether contaminants are migrating below the capture zone of the vegetation. In some applications, this information may be for compliance monitoring. In general however, these would not replace standard monitoring wells and are more applicable if the phytotechnology system calls for building the system from ground level upwards (i.e. landfill cover) rather than into the ground (i.e., below a deeply planted tree hydraulic barrier).

2.5.3.2 Influence on Soil Conditions

In some phytotechnology applications such as phytostabilization, riparian buffers, and alternative landfill covers, soil moisture may be a primary line of evidence demonstrating system performance since these often rely on controlling moisture at specific depths within the soil. In other applications, such as phytoremediation of soil/sediments, hydraulic groundwater control, phytoremediation of groundwater, or constructed treatment wetlands, soil moisture may be only a secondary line of evidence since primary performance is contaminant concentration reduction or migration control. Regardless, permanent in-ground soil moisture monitoring systems can be connected to an irrigation system to control the amount of supplemental water that is applied to

these plantations (see Sections 2.4.2.1 and 2.5.1.1). Therefore, soil moisture is generally a parameter to be monitored for most phytotechnology applications, regardless of whether it is used to monitor remedial performance.

In addition to lysimeters, soil moisture can be monitored through other devices such as electrical resistance blocks, tensiometers, capacitance probes, neutron probes, and time domain reflectometry. These are fairly standard techniques and field instruments. Each has its advantages and disadvantages, such as effective soil moisture ranges, accuracy, direct or indirect measurement, in-ground components, portability, durability, and costs ranging from $200 to over $10,000 in equipment to monitor an entire plantation. Selecting the appropriate technology depends on the significance of the data to monitor system performance or control irrigation.

Plants also have a profound influence on the microbial characteristics within the soil. While concentration reductions remain the primary line of evidence for system performance, microbial characteristics and community structure can provide supplemental information showing efficacy. Simple microbial counts of the number of colony-forming units of heterotrophic bacteria within and outside of the vegetated soil can be monitored. In general, vegetation should significantly enhance these microbial counts, providing an indication that the plants are impacting the overall microbial activity (and thus, rates of remediation). These can be monitored over time to demonstrate the proliferation of the community within the rhizosphere compared to the bulk, nonvegetated soil. Once confirmed, these may not be needed in future monitoring events. These generally cost around $100 per sample. Care should be given to ensure that the soil sample is not contaminated with airborne microbes when collected and transported to the laboratory.

Additional characterization using contaminant-specific culturing techniques can also reveal whether specific microbes such as alkane degraders (e.g., *Acinetobacter* sp.), toluene degraders (e.g., *Pseudomonas* sp.), naphthalene degraders (e.g., *Burkholderia* sp.), dehalogenators (e.g., *Dehalococoides* sp.), etc. are present in the microbial community and also the levels at which they are present. Several of these microbes are broad-spectrum degraders (address many contaminant compounds) while others are more specific (only address individual compounds). In most cases, these levels of detail are sufficient to demonstrate as supporting information to concentration reduction data, that the microbial-level "machinery" is present to conduct the desired remediation.

However, should those techniques not be able to demonstrate presence, additional detailed characterization techniques are also available to consider the majority of microbes that are not culturable using standard plate counting methods. Phospholipid fatty acid (PLFA) analysis provides a GC/MS "fingerprint" of the PLFA membrane composition of the microbial community. PLFA fingerprints differ between organisms and are influenced by nutritional status and other stress factors (e.g., pollution) affecting the community. PLFA structural groups (i.e., degree of saturation and branching of the phospholipids) are unique to different classes of bacteria. Therefore, the community structure with and without vegetation can be compared. Monitoring shifts in PLFA from a stressed to an unstressed condition over time may be used to confirm contaminant reduction. However, wide variability and biogenic interferences can significantly confound results. PLFA analyses typically cost around $350 per sample and entail a multistep solvent extraction of the lipids from a soil sample.

Similarly, denaturing gradient gel electrophoresis separation of gene sequences generated using polymerase chain reactions provides a "fingerprint" of the genetic sequences unique to individual

organisms. Specifically, all organisms from bacteria to higher organisms contain 16S rRNA genes. These gene sequences can be compared to those in extensive databases such as GenBank (www.ncbi.nlm.nih.gov/Genbank) to identify specific organisms or phylogenetic relationships. These genetic tools can be used to determine whether specific genetic-level "machinery" is present to conduct the desired remediation even if the specific microbes are not known or culturable. Therefore, these may simply be done to provide confirmation rather than an ongoing monitoring requirement. However, these genetic techniques may not confirm whether the vegetation is enhancing the performance over natural attenuation/biodegradation. Whether these additional levels of detail are warranted depends on the significance or conclusiveness of the primary line of evidence of concentration reduction. Polymerase chain reaction generation and denaturing gradient gel electrophoresis separation of genetic sequences typically costs around $1,000 per sample and entails extracting the genetic material from a soil sample by incubation with detergent, freeze thawing, homogenization in a bead mill, and other steps.

In addition to changes in the microbial characteristics, soil conditions such as redox potential, temperature, oxygen and CO_2 soil gases, and presence of daughter products provide additional information that can help demonstrate degradation. However, these too are not specific to phytotechnologies and may simply confirm biodegradation. Therefore, these are conducted using conventional techniques not described here. Furthermore, many of the cultivation techniques used to establish a phytotechnology plantation are also means of stimulating microbial activity, including nutrient and water addition, tilling and manipulating soil, installing passive oxygen diffusion tubes (breather tubes), etc. In many cases, confirming the beneficial enhancements provided by the vegetation over the microbial activity alone requires comparative studies and sampling inside and outside a vegetated area. However, these are more likely done during the feasibility or treatability stages of the project rather than in a full-scale implementation (see Section 2.3.3).

2.5.3.3 Fate and Transport in the Plant

Procedures for sampling and analyzing plant tissues for contaminant, by-products, and/or inorganic nutrients depend on the tissue to be sampled. Most tissue samples need to be weighed; however, wet weight measurements usually underestimate the true conditions, as desiccation occurs almost immediately after the sample is excised from the main plant. Therefore dry weights are more reliable. For inorganic constituents, reporting concentrations on a dry weight basis is less of an issue. For organic contaminants, the constituents may rapidly volatilize as the tissues begin drying out. Therefore, dry weight measurements may have to be taken on separate samples from those tissues analyzed for constituents. Furthermore, cellular breakdown of the tissues also begins almost immediately and can generate organic compounds that can interfere with these analyses. Mowing lawns or cutting crops is known to produce distinct odors that generally can be traced back to C2 to C6 compounds being released (de Gouw et al. 2000). Samples to analyze for inorganic nutrients are best taken and considered more representative when the tree is dormant. However, when analyzing for organic constituents, sampling is usually best done when the tree is actively transpiring.

Once at the laboratory, subsequent preparation of the tissues for analysis entails grinding the sample in a bead mill, grinding to pass different sized mesh sieves (typically 0.25–2 mm),

digestion in a mild acid (nitric or hydrochloric), and/or extraction with a solvent. In some cases, freezing in liquid nitrogen facilitates grinding tissues. These additional preparation steps simply create a liquid sample from the plant tissues so that the constituents can be analyzed using standard analytical methodologies. The specific protocols may depend on the sample preparation requirements called for by the analysis (see text and Internet links in Section 2.5.1.1).

The easiest tissues to sample are the leaves/needles, stems, branches, and fruits/seeds/nuts. These are collected simply by pulling or cutting sufficient material from the plant and storing them in sealed plastic bags. For most analyses, samples of 20 g dry weight (10–15 average leaves) should be sufficient. To estimate the wet to dry weight ratio for field sample collection, as general rules of thumb, green stems typically contain 95% water weight, leaves 90%, fruits 85%, hardwood stems 50%, and nuts and seeds 5%. Once collected, the tissues should be stored on ice for transport to the laboratory.

Fine-root samples can be collected by excavating into soils containing the roots, excising the roots from the bulk soil, and then washing off the rhizosphere soil using water and/or a mild detergent. In some instances, it may be sufficient to collectively sample the roots together with the rhizosphere soil that clings onto the roots simply because the even finer, microscopic root hairs facilitate the binding of the soil onto the roots. However, one should recognize that the significant disturbance created when isolating the root/rhizosphere soil sample likely alters the activity of the microbial community (see Section 2.5.3.2), plus significant desiccation limits how representative the sample is compared to original undisturbed conditions. Once collected, the root samples are usually stored in plastic bags, stored on ice, and transported to the laboratory. In some cases, depending on the parameter to be analyzed, the wash water also needs to be collected and sampled. Once at the laboratory, a headspace sample from the bag should also be collected if analyzing for organic constituents.

Sampling hard-wood roots and tree trunks can generally be done by taking a core of the tissues (Vroblesky 2008). This is a common method in forestry that has been successful at detecting TCE (Vroblesky, Nietch, and Morris 1999; Ma and Burken 2002), BTEX, and MTBE (Landmeyer, Vroblesky, and Bradley 2000) in trees. Furthermore, the technique has been considered for rapidly mapping contaminant plumes using existing trees, as a prelude to placing permanent monitoring wells (Fiorenza et al. 2005). This is achieved using an increment corer such as one shown in Figure 2-11. For roots, shallow excavation can be done to expose the subsurface root structure prior to sampling. For trunk tissues, samples should be taken closer to ground surface since concentration of contaminants have been found to decline exponentially with height on the trunk (Ma and Burken 2002). Once excised, the core material (typically ¼-inch diameter by 1–2 inches long) is generally placed immediately into a volatile organic analysis vial and stored on ice for transport to the laboratory. Once there, a headspace sample should be collected and analyzed as the tissues in the vial immediately begin to degas. Some protocols call for the sample to degas for 24–48 hours prior to sampling for equilibrium to be reached. Refinements to the analytical procedure have shown that

Figure 2-11. Increment corer used to collect hardwood tissue samples.

a heated purge of the headspace sample improves reproducibility and recoverability from the sample (Fiorenza et al. 2005).

Since coring is an invasive procedure, care may need to be provided to the sampled specimen if it is not to be completely sacrificed. Historically, plant care professionals suggested using a tree wound dressing (typically petroleum asphalt based) or paint to protect the wound from infections. However, studies have shown that it is generally better to promote and allow the natural callusing to occur as the best means of care (Shigo and Shortle 1983). Regardless, the practice of wound dressing still continues.

Alternatively, recent work has investigated using replaceable sorbent inserts that can be used to collect and sample sap from the core hole (Fiorenza et al. 2005). Specifically, Gore™ modules were inserted into existing core holes, left in place for several days, and then replaced with another module while the original one was analyzed. Initial results indicated that the hydrophobic sorbent modules were able to accumulate organic contaminants used in the dosing experiment and increased the overall method sensitivity. However, as the tree creates a callus around the wound, the sap flow conditions will alter and likely not be representative over time. Sampling sap in this manner of course requires the tree to be actively transpiring.

In addition to sampling tissues and plant sap, some phytotechnology applications may require transpiration gases emanating from the plants to be sampled as well. Again, these are confirmatory samples that demonstrate the overall fate and transport of volatile contaminants through the plant system rather than primary lines of evidence of remedial performance. To capture transpiration gases, Tedlar® bags or similar airtight plastic chambers have been used with some success (Compton et al. 1998; Newman et al. 1999b; Arnold, Parfitt, and Kaltreider 2007). Specifically, this enclosed chamber method was used to confirm the transpiration of MTBE at field sites. TCE could be detected only in laboratory studies, not in the field (Newman et al. 1997a). One of the main issues with capturing transpiration gases with this method is that the process ceases once humidity within the collection vessel reaches 100%, which generally occurs rapidly as the plant continues to transpire water through the branches that are contained. Therefore, very low sample volumes are created.

To address this issue, the volume of the vessel can be made large enough to capture a sufficient amount of transpirate to be condensed for a liquid sample. However, one needs to account for the equilibrium partitioning between vapor and liquid phases. For some compounds, such as MTBE, 96% ± 2.9% of the concentration was found to remain in the vapor phase, with the remaining condensing at 24–33°C (Arnold, Parfitt, and Kaltreider 2007). Alternatively, Tedlar sleeves can be used with a constant airflow passing through to remove the humidity; however, the airflow sweeps the volatile contaminant out as well. To sample the air stream, online gas samplers or Summa canisters have been connected in series to the outlet, allowing for transpiration gases to be captured and subsequently analyzed (Kolhatkar et al. 2007). One advantage of this technique over the enclosed system is that the air used to maintain humidity can be conditioned (i.e., warmed and dried) to promote higher rates of transpiration from the specific branch than would be produced through ambient air conditions.

2.5.4 Contingency Planning

A contingency plan should define the actions to be taken if the phytotechnology system does not meet remedial objectives within a specified timeline or milestones. These conditions should be clearly spelled out in the contingency plan and rely heavily on the monitoring and performance plan for the system. Options may include implementing an entirely different remedial solution, supplementing the phytotechnology system with another alternative, expanding/altering the scope of the phytotechnology (e.g., additional plantings, change O&M procedures to increase/ decrease water usage or growth, etc.), or changing the timeline or milestones that need to be met. In some cases, the expected performance of the system may have been altered due to unforeseen or uncontrolled events such as floods, hurricanes, extended droughts, wildfires, etc. In many of these situations, any remedial technology would have failed; thus, the phytotechnology remedy may remain the best option even if the remedial objectives were not met according to the original timeline.

Similarly, a contingency plan should be developed and may be implemented if there is permanent large-scale failure of the plants (predation, disease, flood, drought, vandalism, etc.). In such cases it is necessary to dispose of the destroyed plants and plant litter (see Section 2.5.1.3) as well as implement necessary steps to replace the destroyed plants. Operational considerations that applied to the initial implementation will also likely apply to any replanting activities (see Section 2.4). However, the plan should also consider the resiliency of the phytotechnology system since it is a living system. A detrimental event may result in only temporary loss of the plant system. The time frame of the loss may be only a few days, the remainder of the season, or a season or two after the event. The contingency plan should clearly define the conditions that are acceptable and unacceptable for the site risks.

Furthermore, an event may impact only part of the system, such as one of several species planted at the site or a small area of the larger plantation. Similarly, in the absence of a triggering event, areas of the plantation that do not survive may be an indication of adverse subsurface conditions specific to that location that were not identified during the initial site assessment (see Section 2.2). In this case, additional characterization may be warranted prior to implementing an abbreviated or modified version of the original plan (see Section 2.4). In most cases, however, individual specimens here and there throughout the plantation do not survive. These losses may occur due to shading or other nutrient competition, localized soil issues, compaction, or fill material, or simply weak stock. In these situations, it may be acceptable to not replace that particular plant since over time the adjacent vegetation will likely fill in the canopy in that area anyway.

When initially planting a site with whole plant stock (see Section 2.4.3), it is also common for some mortality to occur. A standard landscaping rule of thumb is that 10% of recently planted trees do not survive the first year, simply due to the transplantation shock that a plant specimen undergoes when removed, transported, and then replanted at a foreign site. Landscape companies typically provide warrantees to replace these. However, most warrantees will not be honored for phytotechnology applications, given the adverse site conditions and unconventional planting techniques employed. Therefore, replanting should be included in the initial cost estimates for the

phytotechnology application. As a general rule of thumb, 10%–15% of the initial capital costs should be added as a contingency for replanting (see Section 2.4 and Tables 2-5a and 2-5b).

2.6 Closure

Upon achieving the remedial objectives for the site and meeting all other closure requirements, a final report can be prepared summarizing the information gained during the life of the entire project. Reporting may include contributing to the growing database of phytotechnology information. Two general options remains for the phytotechnology system itself. If during the remedy selection phase (see Section 2.3) it was decided that the site is to be maintained as a greenspace as the final disposition, then system decommissioning activities are relatively simple. These include removal of monitoring equipment, plugging and abandoning wells, and securing a long-term steward for the site to carry on plant upkeep and maintenance (see Section 2.5.1). This relative simplicity is one of the main advantages in selecting phytotechnologies over other alternatives in that restoration is accomplished or highly advanced towards a final state while the remediation is occurring, leaving less to do at the conclusion of the project.

The other general option is if during the remedy selection phase it was decided that the site is to be converted into a different end use where the vegetation will have to be removed. In this less likely case, decommissioning activities also require plant removal and possibly the removal of some infrastructure items such as the irrigation system, breather tubes, borehole casings, fencing/netting, etc. If these are to be removed at the conclusion of the project, this process should be considered in the design of the system (see Section 2.4), particularly for in-ground components. Furthermore, when removing vegetation, sampling may be necessary to determine plant disposal requirements or financial opportunities (see Sections 2.5.1.3 and 2.5.3.3). Other activities such as stump removal, clearing and grubbing, and soil stockpiling will likely be identical to any other construction project.

3. CHALLENGES

Challenge 1. 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 EPA has granted an exemption to allow "treated" groundwater to be reinjected, it should be clarified for a site 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 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.

Challenge 2. In addition, if a project requires excavation or removal of contaminated soil from one area to another, it is considered land disposal (pursuant to Title 40 Code of Federal Regulations [CFR], Part 268), and a RCRA permit is required. However, RCRA 3000(k) does not consider movement of contaminated media within a defined area of contamination as land disposal. Pursuant to 40 CFR 264 Subpart S, this exemption was extended to corrective action

management units. It is not clear whether soil moved from one area to another within the disposal site during a phytotechnology project is exempt from this requirement. However, ITRC 2003a offers an example of a similar situation for soils berms at small arms firing ranges: "It is USEPA's position that ranges that reclaim and recycle lead bullets or lead shot may place the soil that is generated during the reclamation process back onto an active range on the same property or facility or a property adjacent to and under the same ownership as the property where the soils originated, without testing the soil for hazardous waste characteristics."

Challenge 3. 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 and hazardous waste landfills. RCRA regulations require that the final cover have permeability no greater than 1×10^{-5} cm/sec. This permeability requirement applies for both municipal solid waste and hazardous waste landfills (RCRA Subtitle D and C, respectively). However, at several points in 40 CFR Subchapter I, Parts 260–279 the regulations indicate "alternative regulatory requirements may be used to supplant the more prescriptive regulations" (ITRC 2003c, Section 2.2.1). See ITRC 2003c for the proper application of ET covers.

Challenge 4. During the implementation/growth stage of a remediation project using phytotechnologies, the project should clearly focus on managing potential exposure.

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Appendix A

Internet Resources for Phytoremediation

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INTERNET RESOURCES FOR PHYTOREMEDIATION

1. Interstate Technology & Regulatory Council: www.itrcweb.org
   - Phytotechnologies Team Public Page: http://www.itrcweb.org/Team/Public?teamID=40

2. Remediation Technologies Development Forum:
   - Phytoremediation of Organics Action Team: www.rtdf.org/public/phyto/phylinks.htm#Resources
   - Field study protocol for the phytoremediation of petroleum hydrocarbons in soil put together by the Phytoremediation Action Team (1999): www.rtdf.org/PUBLIC/phyto/protocol/protocol99.htm
   - *Evaluation of Phytoremediation for Management of Chlorinated Solvents in Soil and Groundwater*: www.rtdf.org/public/phyto/chlor_solv_management.pdf

3. Federal Remediation Technologies—Roundtable Remediation Technologies Screening Matrix and Reference Guide Version 4.0:
   - www.frtr.gov/matrix2/top_page.html
   - www.frtr.gov/matrix2/section4/4-3.html
   - www.frtr.gov/matrix2/section4/4-33.html

4. *International Journal of Phytoremediation*: www.aehs.com/journals/phytoremediation

5. Great Plains/Rocky Mountain Hazardous Substance Research Center, a 14-institution consortium led by Kansas State University—see list-serv and additional links: www.engg.ksu.edu/HSRC/phytorem/home.html

6. "Phytopet," a database of plants that play a role in the phytoremediation of petroleum hydrocarbons from the University of Saskatchewan: www.phytopet.usask.ca/mainpg.php

7. Order a copy of "Phytorem," the searchable database of plants that that remediate metals, created by Environment Canada: www.ec.gc.ca/publications/index.cfm?screen=PubDetail&PubID=546&CategoryID=0&showimage=False&order_by=pubyear&search=phytorem&lang=e&start=1

8. International resources:
   - International Phytotechnology Society, host of International Conference on Phytotechnologies: www.phytosociety.org/index.htm
   - PHYTONET Phytoremediation Electronic Newsgroup Network: www.dsa.unipr.it/phytonet
   - Cost 859, a network of 29 European countries' coordinated research projects: http://w3.gre.ac.uk/cost859
   - Phytolink Australia: www.phytolink.com.au

9. USDA Natural Resource Conservation Service:
   - USDA PLANTS National Database: http://www.plants.usda.gov
   - Plant Materials Program: http://plant-materials.nrcs.usda.gov

10. U.S. EPA Hazardous Waste Clean-Up Information: www.clu-in.org
   - Phytotechnology Project Profiles Searchable Database: www.cluin.org/products/phyto
   - Phytoremediation Technology Focus: www.cluin.org/techfocus/default.focus/sec/Phytoremediation/cat/Overview
   - "Citizen's Guide to Phytoremediation": http://clu-in.org/s.focus/c/pub/i/67
   - "Status Report on Use of Field-Scale Phytotechnology for Chlorinated Solvents, Metals, Explosives and Propellants, and Pesticides": www.cluin.org/download/remed/542-r-05-002.pdf

Appendix B

Database of Contaminant Remediation by Plants

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DATABASE OF CONTAMINANT REMEDIATION BY PLANTS

Key to phytomechanism abbreviations:

CW = constructed wetland
NW = natural wetlands
PD = phytodegradation
PE = phytoextraction
PS = phytosequestration
PV = phytovolatilization
RD = rhizodegradation
RF = rhizofiltration

1. ORGANIC REMEDIATION BY PLANTS

Table B-1. Plants remediating petroleum constituents

Petroleum hydrocarbon	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Acenaphthene	Perennial ryegrass (*Lolium perenne)*	RD	Decreased concentrations from 33.0 to 1.8 mg/kg in 258 days	Ferro, Kennedy, and Knight 1997
Acenaphthene	Mixed plant/tree community (51 species identified)	RD	Natural regrowth in sludge basin; 38 and 566 mg/kg within and below the rhizosphere, respectively	Wong 1998
Acenaphthylene	Mixed plant/tree community (51 species identified)	RD	Natural regrowth in sludge basin; 202 and 1,722 mg/kg within and below the rhizosphere, respectively	Wong 1998
Aliphatics (total)	Mixed grass community (5–7 species)	RD	Decreased total aliphatic (C8–C21+) soil concentrations from 14,500 to 2,500 mg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Aliphatics (total)	Mixed grass community (5–6 species)	RD	Decreased total aliphatic (C8–C21+) soil concentrations from 6,300 to 1,400 mg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Aniline	Carolina hybrid poplar (*Populus deltoides* x *nigra* DN34)	(PE, PV)	15% of 50 ppm hydroponic feed volatilized, 10% accumulated in upper stem, 10% in leaves, and 65% in roots in 3–6 days	Burken and Schnoor 1997a
Anthracene	Fescue (*Festuca arundinacea*)	RD	Decreased soil concentrations from 100 to 0.76 mg/kg in 24 weeks	Reilley, Banks, and Schwab 1993; Schwab and Banks, 1994
Anthracene	Alfalfa (*Medicago sativa*)	RD	Decreased soil concentrations from 100 to 0.60 mg/kg in 24 weeks	Reilley, Banks, and Schwab 1993; Schwab and Banks 1994
Anthracene	Switchgrass (*Panicum virgatum*)	RD	Decreased soil concentrations from 100 to 0.79 mg/kg in 24 weeks	Reilley, Banks, and Schwab 1993; Schwab and Banks 1994
Anthracene	Sudangrass (*Sorghum vulgare*)	RD	Decreased soil concentrations from 100 to 0.74 mg/kg in 24 weeks	Reilley, Banks, and Schwab 1993; Schwab and Banks 1994

Petroleum hydrocarbon	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Anthracene	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 493 to 9 µg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Anthracene	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 108 µg/kg to nondetect (ND) in 34 weeks	Remediation Technologies, Inc. 1997
Anthracene	Mixed plant/tree community (51 species identified)	RD	Natural regrowth in sludge basin, 66 and 856 mg/kg within and below the rhizosphere, respectively	Wong 1998
Aromatics (total)	Mixed grass community (5–7 species)	RD	Decreased total aromatics (C8–C35+) soil concentrations from 5,900 to 2,300 mg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Aromatics (total)	Mixed grass community (5–6 species)	RD	Decreased total aromatics (C8–C35+) soil concentrations from 5,700 to 2,900 mg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Benzene	Alfalfa (*Medicago sativa* Mesa var. Cimarron VR*)*	RD, PD	2% of ^{14}C-label recovered in foliage, 2%–8% in rhizosphere soil/roots (probably biodegraded in soil then taken up)	Ferro et al. 1997
Benzene	Common reed (*Phragmites communis)*	(RD)	Increased removal rates in vegetated wetland filters compared to unvegetated filters	See original reference in Anderson, Guthrie, and Walton 1993
Benzene	Carolina hybrid poplar (*Populus deltoides* x *nigra* DN34)	(PE, PV)	90% of 50 ppm hydroponic feed volatilized, 10% accumulated in stems in 3–6 days	Burken and Schnoor 1997a
Benzo(a)anthracene	Perennial ryegrass (*Lolium perenne)*	RD	Decreased concentrations from 4.1 to 0.9 mg/kg in 258 days	Ferro, Kennedy, and Knight 1997
Benzo(a)anthracene	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 375 to 36 µg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Benzo(a)anthracene	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 114 to 39 µg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Benzo(a)anthracene	Various prairie grasses (8 species)	RD	Decreased soil concentrations by 97%	Aprill and Sims 1990
Benzo(a)anthracene	Mixed plant/tree community (51 species identified)	RD	Natural regrowth in sludge basin, 39 and 558 mg/kg within and below the rhizosphere, respectively	Wong 1998
Benzo(a)pyrene	Perennial ryegrass (*Lolium perenne)*	RD	Decreased concentrations from 13.1 to 7.1 mg/kg in 258 days	Ferro, Kennedy, and Knight 1997
Benzo(a)pyrene	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 115 to 57 µg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Benzo(a)pyrene	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 46 to 36 µg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Benzo(a)pyrene	Various prairie grasses (8 species)	RD	Decreased soil concentrations by 93%	Aprill and Sims 1990
Benzo(a)pyrene	Mixed plant/tree community (51 species identified)	RD	Natural regrowth in sludge basin, 15 and 174 mg/kg within and below the rhizosphere, respectively	Wong 1998
Benzo(b)fluoranthene	Perennial ryegrass (*Lolium perenne)*	RD	Decreased concentrations from 17.6 to 8.4 mg/kg in 258 days	Ferro, Kennedy, and Knight 1997

Petroleum hydrocarbon	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Benzo(b)fluoranthene	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 180 to 57 µg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Benzo(b)fluoranthene	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 91 to 61 µg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Benzo(b)fluoranthene	Mixed plant/tree community (51 species identified)	RD	Natural regrowth in sludge basin, 8 and 73 mg/kg within and below the rhizosphere, respectively	Wong 1998
Benzo(e)pyrene	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 238 to 150 µg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Benzo(ghi)perylene	Perennial ryegrass (*Lolium perenne)*	RD	Decreased concentrations from 12.0 to 2.6 mg/kg in 258 days	Ferro, Kennedy, and Knight 1997
Benzo(ghi)perylene	Mixed plant/tree community (51 species identified)	RD	Natural regrowth in sludge basin, 3 and 166 mg/kg within and below the rhizosphere, respectively	Wong 1998
Benzo(k)fluoranthene	Perennial ryegrass (*Lolium perenne)*	RD	Decreased concentrations from 8.8 to 2.7 mg/kg in 258 days	Ferro, Kennedy, and Knight 1997
Benzo(k)fluoranthene	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 29 to 16 µg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Benzo(k)fluoranthene	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 16 to 10 µg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Biphenyl	Common reed (*Phragmites communis)*	RD	Increased removal rates in vegetated wetland filters compared to unvegetated filters	See original reference in Anderson, Guthrie, and Walton 1993
Biphenyl	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 3,675 to 6 µg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Biphenyl	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 160 to 4 µg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Biological oxygen demand	Bulrush and cattail(*Scirpus* and *Typha* spp.)		25 mg/L influent reduced to 3 mg/L at effluent	Kadlec and Knight 1996
Biological oxygen demand	Multiple wetland species (numbers of types not reported)		Average reduction from 25.9 to 7.4 mg/L sustained for 2 years	Kadlec and Knight 1996
Chemical oxygen demand	Bulrush and cattail (*Scirpus* and *Typha* spp.)		175 mg/L influent reduced to 37 mg/L at effluent	Kadlec and Knight 1996
Chrysene	Perennial ryegrass (*Lolium perenne)*	RD	Decreased concentrations from 19.6 to 3.0 mg/kg in 258 days	Ferro, Kennedy, and Knight 1997
Chrysene	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 793 to 88 µg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Chrysene	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 220 to 133 µg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Chrysene	Various prairie grasses (8 species)	RD	Decreased soil concentrations by 94%	Aprill and Sims 1990
Chrysene	Mixed plant/tree community (51 species identified)	RD	Natural regrowth in sludge basin, 27 and 370 mg/kg within and below the rhizosphere, respectively	Wong 1998

Petroleum hydrocarbon	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Dibenzo(ah)anthracene	Perennial ryegrass (*Lolium perenne)*	RD	Decreased concentrations from 2.1 to 1.6 mg/kg in 258 days	Ferro, Kennedy, and Knight 1997
Dibenzo(ah)anthracene	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 45 to 28 µg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Dibenzo(ah)anthracene	Various prairie grasses (8 species)	RD	Decreased soil concentrations by 43%	Aprill and Sims 1990
Dibenzothiophene	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 1,700 to 7 µg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Dibenzothiophene	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 5,450 to 120 µg/kg in 34 weeks	Remediation Technologies, Inc. 1997
DROs	Cattail (*Typha* spp.)	CW	Decreased sediment concentrations from 100 to 1 mg/L in 20 hours hydraulic residence time	Kadlec and Knight 1998
DROs	Willows (*Salix* spp.)	RD	Decreased soil concentrations up to 5,000 mg/kg by 40%–90% in 24 weeks	Carman, Crossman, and Gatliff 1997, 1998
DROs	Willows and hybrid poplars (*Salix* and *Populus* spp.)	RD	Decreased soil concentrations from 225 to 25 mg/kg in 2 years	Applied Natural Sciences, Inc. 1997
Ethylbenzene	Common reed (*Phragmites communis)*	(RD)	Increased removal rates in vegetated wetland filters compared to unvegetated filters	See original reference in Anderson, Guthrie, and Walton 1993
Ethylbenzene	Carolina hybrid poplar (*Populus deltoides* x *nigra* DN34)	(PE, PV)	50% of 50 ppm hydroponic feed volatilized, 5% accumulated in upper stems, 35% in lower stems, 5% in leaves, and 5% in roots in 3–6 days	Burken and Schnoor 1997a
Ethylene glycol	Tall fescue (*Festuca arundinacea*)	RD	41% reduction in soil concentrations after 28 days	Rice, Anderson, and Coats 1996a
Ethylene glycol	Alfalfa (*Medicago sativa*)	RD	40% reduction in soil concentrations after 28 days	Rice, Anderson, and Coats 1996a
Fluoranthene	Bermuda grass (*Cynodon dactylon*)	RD, PE	Approximately 35% degradation in soil achieved in 23 months, 10 µg/kg measured in plant shoots	Banks and Schwab 1998
Fluoranthene	Tall fescue (*Festuca arundinacea*)	RD, PE	Approximately 55% degradation in soil achieved in 23 months, 10 µg/kg measured in plant shoots	Banks and Schwab 1998
Fluoranthene	Perennial ryegrass (*Lolium perenne)*	RD	Decreased concentrations from 63.7 to 3.6 mg/kg in 258 days	Ferro, Kennedy, and Knight 1997
Fluoranthene	Perennial ryegrass (*Lolium perenne)*	RD	Decreased concentrations from 63.7 to 2.8 mg/kg in 11 months	Ferro et al. 1999
Fluoranthene	White clover (*Trifolium repens*)	RD	Approximately 35% degradation in soil achieved in 23 months	Banks and Schwab 1998
Fluoranthene	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 293 to 78 µg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Fluoranthene	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 102 to 45 µg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Fluoranthene	Mixed plant/tree community (51 species identified)	RD	Natural regrowth in sludge basin, 80 and 940 mg/kg within and below the rhizosphere, respectively	Wong 1998

Petroleum hydrocarbon	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Fluorene	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 2,800 to 10 µg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Fluorene	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 248 to 8 µg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Fluorene	Mixed plant/tree community (51 species identified)	RD	Natural regrowth in sludge basin, 82 and 1,487 mg/kg within and below the rhizosphere, respectively	Wong 1998
GROs	Mixed grass community (5–7 species)	RD	Decreased soil aliphatic concentrations from 45 to 2 mg/kg in 44 weeks	Remediation Technologies, Inc. 1997
GROs	Mixed grass community (5–7 species)	RD	Decreased soil aromatics concentrations from 6 mg/kg to ND in 44 weeks	Remediation Technologies, Inc. 1997
GROs	Mixed grass community (5–6 species)	RD	Decreased soil aliphatic concentrations from 11 mg/kg to ND in 34 weeks	Remediation Technologies, Inc. 1997
n-Heptadecane	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 72 to 0.38 mg/kg in 44 weeks	Remediation Technologies, Inc. 1997
n-Heptadecane	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 57 to 0.27 mg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Indeno(123cd)pyrene	Perennial ryegrass (*Lolium perenne)*	RD	Decreased concentrations from 6.4 to 4.4 mg/kg in 258 days	Ferro, Kennedy, and Knight 1997
Indeno(123cd)pyrene	Mixed plant/tree community (51 species identified)	RD	Natural regrowth in sludge basin, 1 and 18 mg/kg within and below the rhizosphere, respectively	Wong 1998
MTBE	Alfalfa (*Medicago sativa*)	PE, PV	Preliminary results indicating 0.844 mM feed in groundwater is significantly reduced	Zhang, Davis, and Erickson 1998
MTBE	Hybrid poplars (*Populus* spp.)	PE, PD, PV	Preliminary laboratory results indicate 0.03% mineralized to CO_2, 0.37% fixed in tissues, and 5.1% transpired	L. A. Newman, personal communication, 1998
Naphthalene	Perennial ryegrass (*Lolium perenne)*	RD	Decreased concentrations from 23.6 to 0.0 mg/kg in 258 days	Ferro, Kennedy, and Knight 1997
Naphthalene	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 4,725 to 16 µg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Naphthalene	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 1,030 to 11 µg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Naphthalene	Mixed plant/tree community (51 species identified)	RD	Natural regrowth in sludge basin, 38 and 6,813 mg/kg within and below the rhizosphere, respectively	Wong 1998
Naphthalene	Wetland species (species not identified)	RD	Reduced sediment concentrations by 64%–82% in 140 days	Mills et al. 1997
n-Octadecane	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 63 to 0.19 mg/kg in 44 weeks	Remediation Technologies, Inc. 1997
n-Octadecane	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 52 to 0.16 mg/kg in 34 weeks	Remediation Technologies, Inc. 1997
n-Octadecane	Wetland species (species not identified)	RD	Reduced sediment concentrations by 93%–99% in 140 days	Mills et al. 1997

Petroleum hydrocarbon	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Oil and gasoline	Bulrush and cattail (*Scirpus* and *Typha* spp.)	CW	2,100 µg/L influent reduced to 130 µg/L at effluent	Kadlec and Knight 1996
Perylene	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 135 to 77 µg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Phenanthrene	Bermuda grass (*Cynodon dactylon*)	RD, PE	Between 50%–55% degradation in soil achieved in 23 months, 30 µg/kg measured in plant shoots	Banks and Schwab 1998
Phenanthrene	Tall fescue (*Festuca arundinacea*)	RD, PE	Approximately 60% degradation in soil achieved in 23 months, 20 µg/kg measured in plant shoots	Banks and Schwab 1998
Phenanthrene	White clover (*Trifolium repens*)	RD	60%–70% degradation in soil achieved in 23 months	Banks and Schwab 1998
Phenanthrene	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 6,050 to 58 µg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Phenanthrene	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 1,038 to 52 µg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Phenanthrene	Mixed plant/tree community (51 species identified)	RD	Natural regrowth in sludge basin, 219 and 3,678 mg/kg within and below the rhizosphere, respectively	Wong 1998
Phenanthrene	Wetland species (species not identified)	RD	Reduced sediment concentrations by 87%–92% in 140 days	Mills et al. 1997
Phenol	Alfalfa (*Medicago sativa*)	RD	500 ppm solution at inlet decreased 85%–100% at outlet at flow rates of 0.6–1.4 L/day	Muralidharan, Davis, and Erickson 1993; Davis et al. 1994
Phenol	Bulrush (*Schoenoplectus lacustris*)	CW	Decreased concentrations from 105 to 0 mg/L in 6 days (microcosm study)	Kadlec and Knight 1996
Phenol	Bulrush and cattail (*Scirpus* and *Typha* spp.)	CW	80 µg/L influent reduced to 5 µg/L at effluent	Kadlec and Knight 1996
Phenol	Cattail (*Typha* spp.)	CW	Decreased concentrations from 87 to 0 mg/L in 340 hours (microcosm study)	Kadlec and Knight 1996
Phenol	Cattail (*Typha* spp.)	CW	Decreased concentrations from 400 to 40 mg/L in 12.5 m through the wetland	Kadlec and Knight 1996
Phenol	Carolina hybrid poplar (*Populus deltoides* x *nigra* DN34)	(PE, PV)	5% of 50 ppm hydroponic feed volatilized, 10% accumulated in upper stem, 5% in leaves, 80% in roots in 3–6 days	Burken and Schnoor 1997a
Phytane	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 120 to 1.70 mg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Phytane	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 54 to 1.73 mg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Phytane	Wetland species (species not identified)	RD	Reduced sediment concentrations by 88%–97% in 140 days	Mills et al. 1997
PAH (total priority)	Alfalfa (*Medicago sativa*)	RD	Decreased soil concentrations from 49.4 to 35.4 mg/kg in 6 months	Pradhan et al. 1998
PAH (total priority)	Switchgrass (*Panicum virgatum*)	RD	Decreased soil concentrations from 49.4 to 34.7 mg/kg in 6 months	Pradhan et al. 1998

Petroleum hydrocarbon	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
PAH (total priority)	Little bluestem (*Schizachyrium scoparium*)	RD	Decreased soil concentrations from 49.4 to 45.0 mg/kg in 6 months	Pradhan et al. 1998
PAH (total priority)	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 16,943 to 696 µg/kg in 44 weeks	Remediation Technologies, Inc. 1997
PAH (total priority)	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 3,230 to 584 µg/kg in 34 weeks	Remediation Technologies, Inc. 1997
PAH (total priority)	Mixed plant/tree community (51 species identified)	RD	Natural regrowth in sludge basin, 986 and 19,382 mg/kg within and below the rhizosphere, respectively	Wong 1998
PAH (total)	Alfalfa (*Medicago sativa*)	RD	Decreased soil concentrations from 184.5 to 80.2 mg/kg in 6 months	Pradhan et al. 1998
PAH (total)	Switchgrass (*Panicum virgatum*)	RD	Decreased soil concentrations from 184.5 to 79.5 mg/kg in 6 months	Pradhan et al. 1998
PAH (total)	Little bluestem (*Schizachyrium scoparium*)	RD	Decreased soil concentrations from 184.5 to 97.1 mg/kg in 6 months	Pradhan et al. 1998
PAH (total)	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 335 to 7 mg/kg in 44 weeks	Remediation Technologies, Inc. 1997
PAH (total)	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 239 to 29 mg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Pristane	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 148 to 1.70 mg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Pristane	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 27 to 0.78 mg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Pyrene	Bermuda grass (*Cynodon dactylon*)	RD, PE	Approximately 45% degradation in soil achieved in 23 months, 40 µg/kg measured in plant shoots	Banks and Schwab 1998
Pyrene	Tall fescue (*Festuca arundinacea*)	RD	Decreased soil concentrations from 100 to 1.49 mg/kg in 24 weeks	Reilley, Banks, and Schwab 1993; Schwab and Banks 1994
Pyrene	Tall fescue (*Festuca arundinacea*)	RD, PE	Approximately 70% degradation in soil achieved in 23 months, <10 µg/kg measured in plant shoots	Banks and Schwab 1998
Pyrene	Perennial ryegrass (*Lolium perenne)*	RD	Decreased concentrations from 85.1 to 4.9 mg/kg in 11 months	Ferro et al. 1999
Pyrene	Alfalfa (*Medicago sativa*)	RD	Decreased soil concentrations from 100 to 1.66 mg/kg in 24 weeks	Reilley, Banks, and Schwab 1993; Schwab and Banks 1994
Pyrene	Switchgrass (*Panicum virgatum*)	RD	Decreased soil concentrations from 100 to 1.32 mg/kg in 24 weeks	Reilley, Banks, and Schwab 1993; Schwab and Banks 1994
Pyrene	Winter rye (*Secale cereale*)	RD	Decreased soil concentrations by 46% from an initial concentration of 700 mg/kg in 26 weeks	Reynolds et al. 1998
Pyrene	Sudangrass (*Sorghum vulgare*)	RD	Decreased soil concentrations from 100 to 1.49 mg/kg in 24 weeks	Reilley, Banks, and Schwab 1993; Schwab and Banks 1994

Petroleum hydrocarbon	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Pyrene	White clover (*Trifolium repens*)	RD	Approximately 55% degradation in soil achieved in 23 months	Banks and Schwab 1998
Pyrene	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 910 to 88 µg/kg in 44 weeks	Remediation Technologies, Inc. 1997
Pyrene	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 145 to 79 µg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Pyrene	Mixed plant/tree community (51 species identified)	RD	Natural regrowth in sludge basin, 167 and 1,955 mg/kg within and below the rhizosphere, respectively	Wong 1998
Toluene	Alfalfa (*Medicago sativa*)	RD	Solution saturated with toluene at 26°C at inlet decreased 50%–70% at outlet at flow rates of 1.0–3.5 L/day	Muralidharan, Davis, and Erickson 1993; Davis et al. 1994
Toluene	Common reed (*Phragmites communis)*	RD	Increased removal rates in vegetated wetland filters compared to unvegetated filters	See original reference in Anderson, Guthrie, and Walton 1993
Toluene	Carolina hybrid poplar (*Populus deltoides* x *nigra* DN34)	(PE, PV)	50% of 50 ppm hydroponic feed volatilized, 10% accumulated in upper stem, 40% in lower stem in 3–6 days	Burken and Schnoor 1997a
TPH	Bermuda grass (*Cynodon dactylon*)	RD	Decreased soil concentrations ranging from 2,500 to 3,000 ppm by 41% in 26 months	Banks and Schwab 1998, Flathman and Lanza 1998
TPH	Tall fescue (*Festuca arundinacea*)	RD	Decreased soil concentrations ranging from 2,500 to 3,000 ppm by 45% in 26 months	Banks and Schwab 1998, Flathman and Lanza 1998
TPH	Annual rye (*Lolium multiflorum*)	RD	Decreased soil concentrations ranging from 2,000 to 20,000 ppm by 50% in 9 months	Flathman and Lanza 1998
TPH	Alfalfa (*Medicago sativa*)	RD	Decreased soil diesel concentrations from 7,300 to 2,000 mg/kg in 6 weeks	Komisar and Park 1997
TPH	Alfalfa (*Medicago sativa*)	RD	Decreased soil diesel concentrations from 12,400 to <1,000 mg/kg in 10 weeks	Komisar and Park 1997
TPH	Winter rye (*Secale cereale*)	RD	Decreased soil concentrations from 5,000 to 4,000 mg/kg in 26 weeks	Reynolds et al. 1998
TPH	Sorghum (*Sorghum bicolor*)	RD	Decreased soil concentrations ranging 2,000–20,000 ppm by 34% in 9 months	Flathman and Lanza 1998
TPH	St. Augustine grass (*Stenotaphrum secundatum*)	RD	Decreased soil concentrations ranging 2,000–20,000 ppm by 50% in 9 months	Flathman and Lanza 1998
TPH	White clover (*Trifolium repens*)	RD	Decreased soil concentrations ranging 2,500–3,000 ppm by 50% in 26 months	Banks and Schwab 1998, Flathman and Lanza 1998
TPH	Mixed grass community (5–7 species)	RD	Decreased soil concentrations from 27,000 to 10,500 mg/kg in 44 weeks	Remediation Technologies, Inc. 1997
TPH	Mixed grass community (5–6 species)	RD	Decreased soil concentrations from 19,000 to 13,500 mg/kg in 34 weeks	Remediation Technologies, Inc. 1997
Total suspended solids	Bulrush and cattail (*Scirpus* and *Typha* spp.)	CW	35 mg/L influent reduced to 5 mg/L at effluent	Kadlec and Knight 1996

Petroleum hydrocarbon	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Total suspended solids	Multiple wetland species (numbers of types not reported)	CW	Average reduction from 40.4 to 14.1 mg/L for 2 years	Kadlec and Knight 1996
m-Xylene	Carolina hybrid poplar (*Populus deltoides* x *nigra* DN34)	(PE, PV)	40% of 50 ppm hydroponic feed volatilized, 10% accumulated in upper stems, 40% in lower stems, 10% in roots in 3–6 days	Burken and Schnoor 1997a
p-Xylene	Common reed (*Phragmites communis)*	RD	Increased removal rates in vegetated wetland filters compared to unvegetated filters	See original reference in Anderson, Guthrie, and Walton 1993

Table B-2. Plants remediating halogenated compounds and surfactants

Chlorinated hydrocarbon	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Bromoform	Common reed (*Phragmites communis)*	RD	Increased removal rates in vegetated wetland filters compared to unvegetated filters	See original reference in Anderson, Guthrie, and Walton 1993
Carbon tetrachloride	Hybrid poplar (*Populus trichocarpa* x*P.deltoides* H11-11)	PE, PD	Removed 95% from 50 ppm continuous feed stream, negligible phytovolatilization measured	Newman et al. 1997a
Chlorobenzene	Common reed (*Phragmites communis)*	RD	Increased removal rates in vegetated wetland filters compared to unvegetated filters	See original reference in Anderson, Guthrie, and Walton 1993
Chloroform	Common reed (*Phragmites communis)*	RD	Increased removal rates in vegetated wetland filters compared to unvegetated filters	See original reference in Anderson, Guthrie, and Walton 1993
Dichloroethane	Common reed (*Phragmites communis)*	RD	Increased removal rates in vegetated wetland filters compared to unvegetated filters	See original reference in Anderson, Guthrie, and Walton 1993
Dodecyl linear alcohol ethoxylate	Soybean (*Glycine max)*	RD	Initial mineralization rates in rhizosphere soils increased by 1.1x to 1.9x compared to unvegetated soils	See original reference in Anderson, Guthrie, and Walton 1993
Dodecyl linear alcohol ethoxylate	Cattail (*Typha* spp.*)*	RD	Increased mineralization rates in vegetated sediments compared to root-free sediments	See original reference in Anderson, Guthrie, and Walton 1993
Dodecyl linear alcohol ethoxylate	Corn (*Zea mays)*	RD	Initial mineralization rates in rhizosphere soils increased by 1.1x to 1.9x compared to unvegetated soils	See original reference in Anderson, Guthrie, and Walton 1993
Dodecyl linear alkylbenzene sulfonate	Soybean (*Glycine max)*	RD	Initial mineralization rates in rhizosphere soils increased by 1.1x to 1.9x compared to unvegetated soils	See original reference in Anderson, Guthrie, and Walton 1993
Dodecyl linear alkylbenzene sulfonate	Cattail (*Typha* spp.*)*	RD	Increased mineralization rates in vegetated sediments compared to root-free sediments	See original reference in Anderson, Guthrie, and Walton 1993
Dodecyl linear alkylbenzene sulfonate	Corn (*Zea mays)*	RD	Initial mineralization rates in rhizosphere soils increased by 1.1x to 1.9x compared to unvegetated soils	See original reference in Anderson, Guthrie, and Walton 1993
Dodecyltrimethyl ammonium chloride	Soybean (*Glycine max)*	RD	Initial mineralization rates in rhizosphere soils increased by 1.1x to 1.9x compared to unvegetated soils	See original reference in Anderson, Guthrie, and Walton 1993
Dodecyltrimethyl ammonium chloride	Cattail (*Typha* spp.*)*	RD	Increased mineralization rates in vegetated sediments compared to root-free sediments	See original reference in Anderson, Guthrie, and Walton 1993

Chlorinated hydrocarbon	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Dodecyltrimethyl ammonium chloride	Corn (*Zea mays)*	RD	Initial mineralization rates in rhizosphere soils increased by 1.1x to 1.9x compared to unvegetated soils	See original reference in Anderson, Guthrie, and Walton 1993
PCE	Common reed (*Phragmites communis)*	RD	Increased removal rates in vegetated wetland filters compared to unvegetated filters	See original reference in Anderson, Guthrie, and Walton 1993
PCE	Goldenrod (*Solidago* spp.)	RD	Soil concentrations decreased from 0.27 to 0.0 mg/g in 2 days; TCE concurrently increased from 0.0 to 0.27 mg/g	Anderson and Walton 1992
PCE	Cottonwood (*Populus deltoides*)	RD	Decreased groundwater concentrations by 700 ppb in 3 months	Harvey 1998
Pentachlorophenol	Crested wheatgrass (*Agropyron desertorum* cv. Hycrest)	RD, PE, PD	15% of ^{14}C-label recovered in shoots, 21% in rhizosphere soil/roots (probably biodegraded in soil then taken up)	Ferro, Simms, and Bugbee 1994
Pentachlorophenol	Perennial ryegrass (*Lolium perenne)*	RD	Decreased concentrations from 162 to 40 mg/kg in 11 months	Ferro, Kennedy, and Knight 1997
Pentachlorophenol	Carolina hybrid poplar (*Populus deltoides* x *nigra* DN34)	E	95% of 14 ppm hydroponic feed bound to roots, trace amounts in upper and lower stems in 3–6 days	Burken and Schnoor 1997a
1,2,4-Trichlorobenzene	Hybrid poplar (*Populus deltoides* x *nigra* DN34)	E	100% of 30 ppm hydroponic feed bound to roots or lower stem in 3–6 days	Burken and Schnoor 1997a
Trichloroethane	Common reed (*Phragmites communis)*	RD	Increased removal rates in vegetated wetland filters compared to unvegetated filters	See original reference in Anderson, Guthrie, and Walton 1993
TCE	Soybean (*Glycine max)*	RD, PD, PE, PV	27% of ^{14}C-TCE mineralized to $^{14}CO_2$ in 18 days in soil, measured 21.2% of total ^{14}C in plant tissues, 9.8% in air	Anderson and Walton 1991, 1992
TCE	Bush clover (*Lespedeza cuneata*)	RD, PD, PE, PV	30% of ^{14}C-TCE mineralized to $^{14}CO_2$ in 32 days in soil, measured 1.3% of total ^{14}C in plant tissues, 0.2% in air	Anderson and Walton 1991, 1992
TCE	Bahia grass (*Paspalum notatum*)	RD, PD, PE, PV	17% of ^{14}C-TCE mineralized to $^{14}CO_2$ in 16 days in soil, measured 6.6% of total ^{14}C in plant tissues	Anderson and Walton 1992
TCE	Castor bean (*Ricinus communis*)	PE, PD	TCE and metabolites (trichloroethanol [TCEt], trichloroacetic acid [TCAA], dichloroacetic acid [DCAA]) detected up to 1.1 mg/kg in tissues from 0.4 to 91 mg/kg in groundwater	Hayhurst et al. 1998
TCE	Goldenrod (*Solidago* spp.)	RD, PD, PE, PV	20% of ^{14}C-TCE mineralized to $^{14}CO_2$ in 18 days in soil, measured 14.8% of total ^{14}C in plant tissues, 4.3% in air	Anderson and Walton 1991, 1992
TCE	Loblolly pine (*Pinus taeda*)	RD, PD, PE, PV	29% of ^{14}C-TCE mineralized to $^{14}CO_2$ in 17 days in soil; measured 14.6% of total ^{14}C in plant tissues, 10.1% in air	Anderson and Walton 1991, 1992
TCE	Hybrid poplar (*Populus* spp.)	RD, PE	Decreased groundwater concentrations from 610 to 550 µg/L in 7 months, DCE increased from 134 to 174 µg/L	Applied Natural Sciences, Inc. 1997
TCE	Cottonwood (*Populus deltoides*)	RD	Decreased groundwater concentrations from 1300 to 50 ppb in 1 year	Applied Natural Sciences, Inc. 1997
TCE	Carolina hybrid poplar (*Populus deltoides* x *nigra* DN34)	RD, PE, PD	5, 1.5, and 53 mg/kg ^{14}C-TCE and/or metabolites in leaves, stems, roots from 0.8 mg/L feed, RD 20–40x plant uptake	Orchard et al. 1998

Chlorinated hydrocarbon	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
TCE	Carolina hybrid poplar (*Populus deltoides* x *nigra* DN34)	RF (PE, PV)	70% of 50 ppm hydroponic feed volatilized, 5% accumulated in upper stems, 20% in lower stems, and 5% bound to roots in 3–6 days	Burken and Schnoor 1997a
TCE	Hybrid poplar (*Populus trichocarpa* x*P.deltoides* 50-189)	PE, PD, PV	From 50 ppm TCE in feed, up to 49 and 1,900 mg/kg TCE found in leaves and stems, up to 7,200 and 170 mg/kg metabolites (TCEt, TCAA, DCAA) in leaves and stems, up to 0.81 µg TCE transpired in 0.5 hours	Newman et al. 1997b, Gordon et al. 1997
TCE	Hybrid poplar (*Populus trichocarpa* x*P.deltoides* H11-11)	PE, PD, PV	From 50 ppm TCE in feed, up to 13, 770, and 640 mg/kg TCE found in leaves, stems, roots, up to 1,100, 140, and 320 mg/kg metabolites (TCEt, TCAA, DCAA) in leaves, stems, roots, up to 0.54 µg TCE transpired in 0.5 hours	Newman et al. 1997b, Gordon et al. 1997
TCE	Hybrid poplar (*Populus trichocarpa* x*P.maximowiczii* 289-19)	PV	Up to 0.22 µg TCE transpired in 0.5 hours	Newman et al. 1997b
TCE	Live oak (*Quercus virginiana*)	PE, PD, PV	9 µg/L measured in transpiration, TCE and metabolites detected up to 1.1 mg/kg in tissues from 0.4 to 91 mg/kg in groundwater	Hayhurst et al. 1998
TCE	Saw palmetto (*Serenoa repens*)	PE, PD	TCE and metabolites (TCEt, TCAA, DCAA) detected up to 1.1 mg/kg in tissues from 0.4 to 91 mg/kg in groundwater	Hayhurst et al. 1998

Table B-3. Plants remediating pesticides

Pesticide	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
2,4-D	Flax (*Linum* spp.)	RD	Specific bacterial populations increased in the rhizosphere by 1–2 orders of magnitude	See original reference in Anderson, Guthrie, and Walton 1993
2,4-D	Sugarcane/African clover (*Saccharum* spp./*Trifolium* spp.)	RD	Population of degrading microbes higher in sugarcane rhizosphere compared to sensitive African clover	See original reference in Anderson, Guthrie, and Walton 1993
2,4-D	Wheat (*Triticum aestevum*)	RD	Mixed rhizosphere consortia shown to use as carbon source	See original reference in Anderson, Guthrie, and Walton 1993
Alachlor	Corn (*Zea mays*)	RD, PE	74.6% of 1.35 kg/ha biotransformed in the soil, 12.5% taken up into plant	Paterson and Schnoor 1992
Alachlor	Hybrid poplars (*Populus* spp.)	RD	Decreased groundwater concentrations from 1,900 to 100 ppb in 4 years	Applied Natural Sciences, Inc. 1997
Alachlor	Hybrid poplars (*Populus* spp.)	RD	Decreased soil concentrations from 175 to 10 ppm in 3 years	Applied Natural Sciences, Inc. 1997
Atrazine	*Kochia* spp.	RD	Decreased soil concentrations from an initial of 0.5 ppm by 43% in 14 days	Anderson, Kruger, and Coats 1994

Pesticide	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Atrazine	Cattail (*Typha* spp.)	(PS)	95% removals achieved	Kadlec and Knight 1996
Atrazine	Corn (*Zea mays*)	RD, PE	82.0% of 0.78 kg/ha biotransformed in the soil, 5.5% taken up into plant	Paterson and Schnoor 1992
Atrazine	Hybrid poplar (*Populus* spp.)	RD	Decreased groundwater concentrations from 1,600 to 50 ppb in 4 years	Applied Natural Sciences, Inc. 1997
Atrazine	Hybrid poplar (*Populus* spp.)	RD	Decreased soil concentrations from 900 to 10 ppm in 3 years	Applied Natural Sciences, Inc. 1997
Atrazine	Hybrid poplar (*Populus* spp.)	RD, PD	Concentrations reduced by 10%–20% in soil and 100% in sand	Black 1995
Atrazine	Hybrid poplar (*Populus* spp.)	RD, PE	82.6% of 1.34 kg/ha biotransformed in the soil, 3.6% taken up into plant	Paterson and Schnoor 1992
Atrazine	Hybrid poplar (*Populus* spp. cv. Imperial Carolina)	RD, PE, PD	370 mg/kg ^{14}C-atrazine applied to soil, 10.4, 1.4, and 2.8 mg/kg ^{14}C found in tissue, majority degraded in soil	Nair et al. 1992
Atrazine	Carolina hybrid poplar (*Populus deltoides x nigra* DN34)	RD, PE, PD	Metabolic products of ^{14}C-atrazine found in soil, roots, stems, and leaves at various percentages of total label	Burken and Schnoor 1997b
Atrazine	Carolina hybrid poplar (*Populus deltoides x nigra* DN34)	(PE, PV)	60% of 260 ppb hydroponic feed volatilized, 5% accumulated in upper stem, 5% in leaves in 3–6 days	Burken and Schnoor 1997a
Benthiocarb	Rice (*Oryza sativa*)	RD	8x increase in heterotrophic bacteria in rhizospheric soils compared to unvegetated soils	See original reference in Anderson, Guthrie, and Walton 1993
Demeton-8-methyl	Duckweed (*Lemna minor*)	PE, PD	Approximately 10% total transformation (PE and PD) measured in 48 hours	Gao et al. 1998
Demeton-8-methyl	Parrot feather (*Myriophyllum aquaticum*)	PE, PD	Approximately 14% total degradation measured (10% found in plant) in 48 hours	Gao et al. 1998
Diazinon	Bush bean (*Phaseolus vulgaris*)	RD	Decreased soil concentrations by 18%, mineralization to $^{14}CO_2$ measured	Hsu and Bartha 1979
Diazinon	Peas (*Pisum sativum*)	RD	Rhizosphere microbes increased by 2 orders of magnitude compared to unvegetated soils	See original reference in Anderson, Guthrie, and Walton 1993
Diazinon	Wheat (*Triticum aestevum*)	RD	Rhizosphere microbes increased by 2 orders of magnitude compared to unvegetated soils	See original reference in Anderson, Guthrie, and Walton 1993
Diazinon	Corn (*Zea mays*)	RD	Rhizosphere microbes increased by 2 orders of magnitude compared to unvegetated soils	See original reference in Anderson, Guthrie, and Walton 1993
Dioxane	Hybrid poplar (*Populus* spp.)	RD, PE, PD	Decreased soil microcosm concentrations from 95 to 0 mg/L in 40 days	Schnoor et al. 1997, Schnoor 1997
MCPA	Wheat (*Triticum aestevum*)	RD	Mixed rhizosphere consortia shown to use as carbon source	See original reference in Anderson, Guthrie, and Walton 1993

Pesticide	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Malathion	Duckweed (*Lemna minor*)	PE, PD	Approximately 25% total transformation (PE and PD) measured in 24 hours	Gao et al. 1998
Malathion	Parrot feather (*Myriophyllum aquaticum*)	PE, PD	Approximately 55% total degradation measured (25% found in plant) in 48 hours	Gao et al. 1998
Mecoprop	Wheat (*Triticum aestevum*)	RD	Mixed rhizosphere consortia shown to use as carbon source	See original reference in Anderson, Guthrie, and Walton 1993
Metolachor	Coontail (*Ceratophyllum demersum*)	PE	1.5% remaining in the water after 16 days	Rice, Anderson, and Coats 1996b
Metolachlor	*Kochia* spp.	RD	Decreased soil concentrations from an initial of 9.6 ppm by 49% in 14 days	Anderson, Kruger, and Coats 1994
Metolachor	Duckweed (*Lemna minor*)	PE	25% remaining in the water after 16 days	Rice, Anderson, and Coats 1996b
Metolachlor	Hybrid poplar (*Populus* spp.)	RD	Decreased groundwater concentrations from 1,900 to 350 ppb in 4 years	Applied Natural Sciences, Inc. 1997
Metolachlor	Hybrid poplar (*Populus* spp.)	RD	Decreased soil concentrations from 300 to 10 ppm in 3 years	Applied Natural Sciences, Inc. 1997
Metribuzin	Hybrid poplar (*Populus* spp.)	RD	Decreased groundwater concentrations from 400 to 25 ppb in 4 years	Applied Natural Sciences, Inc. 1997
Parathion	Rice (*Oryza sativa*)	RD	Decreased soil concentrations by 25%, mineralization to $^{14}CO_2$ measured	Reddy and Sethunathan 1983
Parathion	Rice (*Oryza sativa*)	RD	Increased mineralization in rhizospheric soils compared to unvegetated soils	See original reference in Anderson, Guthrie, and Walton 1993
Parathion	Bush bean (*Phaseolus vulgaris*)	RD	Decreased soil concentrations by 18%, mineralization to $^{14}CO_2$ measured	Hsu and Bartha 1979
Propanil	Rice (*Oryza sativa*)	RD	Decreased soil concentrations from an initial of 3 mg/kg by >90% in 48 hours	Hoagland, Zablotowicz, and Locke 1994
Ruelene	Parrot feather (*Myriophyllum aquaticum*)	PE, PD	Approximately 17% total degradation measured (11% found in plant) in 48 hours	Gao et al. 1998
Temik	Cotton (*Gossypium* spp.*)*	RD	Higher microbial counts in rhizosphere soils compared to unvegetated soils	See original reference in Anderson, Guthrie, and Walton 1993
Temik	Beans (*Phaseolus* spp.*)*	RD	Higher microbial counts in rhizosphere soils compared to unvegetated soils	See original reference in Anderson, Guthrie, and Walton 1993
Temik	Corn (*Zea mays)*	RD	Higher microbial counts in rhizosphere soils compared to unvegetated soils	See original reference in Anderson, Guthrie, and Walton 1993
Trifluralin	*Kochia* spp.	RD	Decreased soil concentrations from an initial of 0.3 ppm by 69% in 14 days	Anderson, Kruger, and Coats 1994

2. INORGANIC REMEDIATION BY PLANTS

Table B-4. Plants accumulating significant concentrations of essential plant elements

Inorganic	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
B	Beetroot (*Beta vulgaris*)	PE, PS	36 mg/kg in soil concentrated to 800 mg/kg in beetroot leaves and 73 mg/kg in beetroot	Speir, August, and Feltham 1992
B	Day flower (*Commelinae* spp.)	PE	Accumulated up to 43.5 mg/kg in plant tissue	Keiffer and Ungar 1996
B	Morning glory (*Ipomoea* spp.)	PE	Accumulated up to 35.0 mg/kg in plant tissue	Keiffer and Ungar 1996
B	Clover (*Trifolium repens* cv. Huia)	PE, PS	36 mg/kg in soil concentrated to 570 mg/kg in leaves and 89 mg/kg in roots	Speir, August, and Feltham 1992
Ca	*Atriplex prostrata*	PE	Accumulated up to 6,460 mg/kg in shoots	Keiffer 1996
Ca	Day flower (*Commelinae* spp.)	PE	Accumulated up to 13,690 mg/kg in plant tissue	Keiffer and Ungar 1996
Ca	Bermuda grass (*Cynodon dactylon*)	PE	Accumulated up to 6,180 mg/kg in plant tissue	Keiffer and Ungar 1996
Ca	*Cyperus* spp.	PE	Accumulated up to 11,200 mg/kg in plant tissue	Keiffer and Ungar 1996
Ca	Wild rye (*Elymus* spp.)	PE, PS	410 ppm in soil concentrated to 7,000 ppm in plants	Cipollini and Pickering 1986
Ca	Squirrel tail grass (*Hordeum jubatum*)	PE	Accumulated up to 4,130 mg/kg in shoots	Keiffer 1996
Ca	Barley (*Hordeum vulgare*)	PE, PS	4,700 ppm in soil concentrated to 35,000 ppm in plants	Cipollini and Pickering 1986
Ca	Barley (*Hordeum vulgare* cv. Atlas 57)	PE	Accumulated up to 4.43% (dry wt.) in shoots	Chaudhry, Wallace, and Mueller 1977
Ca	Morning glory (*Ipomoea* spp.)	PE	Accumulated up to 13,200 mg/kg in plant tissue	Keiffer and Ungar 1996
Ca	Tomato (*Lycopersicon esculentum* cv. Marmande)	PE, PS	160.4 mg/L in soil water concentrated up to 21,000, 19,000, and 50,000 mg/kg in roots, stems, and leaves	Moral et al. 1995
Ca	Beans (*Phaseolus vulgaris*)	PE, PS	3,500 ppm in soil concentrated to 30,000 ppm in plants	Cipollini and Pickering 1986
Ca	Bush beans (*Phaseolus vulgaris* cv. Improved Tendergreen)	PE	Accumulated up to 4.3% (dry wt.) in leaves	Chaudhry, Wallace, and Mueller 1977
Ca	Slender or jointed glasswort (*Salicornia europaea*)	PE	Accumulated up to 4,650 mg/kg in shoots	Keiffer 1996
Ca	Spurries (*Spergularia marina*)	PE	Accumulated up to 3,050 mg/kg in shoots	Keiffer 1996
Ca	Type of sea blight (*Suaeda calceoliformis*)	PE	Accumulated up to 5,050 mg/kg in shoots	Keiffer 1996
Cu	Beetroot (*Beta vulgaris*)	PE, PS	64 mg/kg in soil concentrated to 200 mg/kg in beetroot	Speir, August, and Feltham 1992
Cu	Indian mustard (*Brassica juncea*)		Decreased solution concentration from 6.0 to 1.2 mg/L in 8 hours	Phytotech, Inc. 1997
Cu	Indian mustard (*Brassica juncea* cv. 182921)	PE	10 mg/kg in soil concentrated to 70 mg/kg in shoots	Kumar et al. 1995
Cu	Indian Mustard (*Brassica juncea* cv. 426308)	PE	200 mg/kg in soil (+chelate) concentrated to 1,000 mg/kg in shoots, simultaneous with other metals	Blaylock et al. 1997

Inorganic	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Cu	Sunflower (*Helianthus annuus*)		Decreased solution concentration from 9,000 to 1,000 µg/L in 24 hours	Salt et al. 1995
Cu	Lettuce (*Lactuca sativa* cv. cos)	PE, PS	64 mg/kg in soil concentrated to 80 mg/kg in roots	Speir, August, and Feltham 1992
Cu	Ryegrass (*Lolium perenne*)	PE, PS	Accumulated up to 50 mg/kg in shoots and 94 mg/kg in roots	Otabbong 1990
Cu	Alfalfa (*Medicago sativa*)	PE, PS	Bound 3.4 mg/g tissue from groundwater	Tiemann et al. 1998
Cu	Reed (*Phragmites* spp.)		Accumulated up to 38 mg/kg in plant tissue	Kadlec and Knight 1996
Cu	Alpine pennycress (*Thlaspi caerulescens*)	PE, PS	1 mg/L in solution concentrated to 623 mg/kg in shoots and 61,000 mg/kg in roots	Salt et al. 1995
Cu	Clover (*Trifolium repens* cv. Huia)	PE, PS	64 mg/kg in soil concentrated to 85 mg/kg in roots	Speir, August, and Feltham 1992
Cu	Cattail (*Typha* spp.)		Accumulated up to 45 mg/kg in plant tissue	Kadlec and Knight 1996
Fe	Day flower (*Commelinae* spp.)	PE	Accumulated up to 102.2 mg/kg in plant tissue	Keiffer and Ungar 1996
Fe	*Cyperus* spp.	PE	Accumulated up to 125.6 mg/kg in plant tissue	Keiffer and Ungar 1996
Fe	Morning glory (*Ipomoea* spp.)	PE	Accumulated up to 248.4 mg/kg in plant tissue	Keiffer and Ungar 1996
Fe	Ryegrass (*Lolium perenne*)	PE, PS	25 mg/kg in soil concentrated up to 1,210 mg/kg in shoots and 4,910 mg/kg in roots	Otabbong 1990
Fe	Bush beans (*Phaseolus vulgaris* cv. Contender)	PE	0.56 mg/kg concentrated up to 102.5 mg/kg in roots, 59.7 mg/kg in stems, and 130.3 mg/kg in leaves	Bonet, Poschenreider, and Barcelo 1991
Fe	Common reed (*Phragmites australis*)		Accumulated 65.8 mg/kg in shoots, 3,709 mg/kg in roots	Kadlec and Knight 1996
Fe	Ground cherry (*Physalis* spp.)	PE	Accumulated up to 350.9 mg/kg in plant tissue	Keiffer and Ungar 1996
Mg	*Atriplex prostrata*	PE	Accumulated up to 6,200 mg/kg in shoots	Keiffer 1996
Mg	Day flower (*Commelinae* spp.)	PE	Accumulated up to 8,260 mg/kg in plant tissue	Keiffer and Ungar 1996
Mg	Type of grass (*Echinochloa* spp.)	PE	Accumulated up to 4,330 mg/kg in plant tissue	Keiffer and Ungar 1996
Mg	Wild rye (*Elymus* spp.)	PE, PS	60 ppm in soil concentrated to 1,200 ppm in plants	Cipollini and Pickering 1986
Mg	Squirrel tail grass (*Hordeum jubatum*)	PE	Accumulated up to 3,330 mg/kg in shoots	Keiffer 1996
Mg	Barley (*Hordeum vulgare*)	PE, PS	570 ppm in soil concentrated to 9,100 ppm in plants	Cipollini and Pickering 1986
Mg	Barley (*Hordeum vulgare* cv. Altas 57)	PE	Accumulated up to 0.55% (dry wt.) in shoots	Chaudhry, Wallace, and Mueller 1977
Mg	Morning glory (*Ipomoea* spp.)	PE	Accumulated up to 6,650 mg/kg in plant tissue	Keiffer and Ungar 1996
Mg	Tomato (*Lycopersicon esculentum* cv.Marmand)	PE, PS	31.6 mg/L in soil water concentrated up to 10,000, 11,000, and 9,500 mg/kg in roots, stems, and leaves	Moral et al. 1995
Mg	Beans (*Phaseolus vulgaris*)	PE, PS	390 ppm in soil concentrated to 7,200 ppm in plants	Cipollini and Pickering 1986
Mg	Bush beans (*Phaseolus vulgaris* cv. Improved Tendergreen)	PE	Accumulated up to 0.61% (dry wt.) in leaves	Chaudhry, Wallace, and Mueller 1977
Mg	Slender or jointed glasswort (*Salicornia europaea*)	PE	Accumulated up to 5,690 mg/kg in shoots	Keiffer 1996

Inorganic	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Mg	Spurries (*Spergularia marina*)	PE	Accumulated up to 3,450 mg/kg in shoots	Keiffer 1996
Mg	Type of sea blight (*Suaeda calceoliformis*)	PE	Accumulated up to 5,250 mg/kg in shoots	Keiffer 1996
Mg	Corn (*Zea mays*)	PE, PS	60 ppm in soil concentrated to 1,800 ppm in plants	Cipollini and Pickering 1986
Mn	Beaked sedge (*Carex rostrata*)	PE	Accumulated up to 616 mg/kg in plant tissues	Kadlec and Knight 1996
Mn	Bermuda grass (*Cynodon dactylon*)	PE	Accumulated up to 114.1 mg/kg in plant tissue	Keiffer and Ungar 1996
Mn	*Cyperus* spp.	PE	Accumulated up to 136.5 mg/kg in plant tissue	Keiffer and Ungar 1996
Mn	Sunflower (*Helianthus annuus*)		Decreased solution concentration from 5,000 to 0 µg/L in 24 hours	Salt et al. 1995
Mn	Morning glory (*Ipomoea* spp.)	PE	Accumulated up to 149.5 mg/kg in plant tissue	Keiffer and Ungar 1996
Mn	Common reed (*Phragmites australis*)		Accumulated 68.9 mg/kg in shoots, 289 mg/kg in roots	Kadlec and Knight 1996
Mn	Bulrush and cattail (*Scirpus* and *Typha* spp.)		Accumulated up to 1,200 mg/kg in plant tissues	Kadlec and Knight, 1996
NH_4	Meadow rush and salt grass (*Juncus* spp. and *Distichlis spicata*)		Decreased concentrations from 14.1 to 0.1 mg/L (near natural background)	Kadlec and Knight 1996
NH_4	Hybrid poplars (*Populus* spp.)	PE, PS	Decreased groundwater concentrations from 140 to 20 mg/kg in 1 year	Applied Natural Sciences, Inc. 1997
NO_3	Meadow rush and salt grass (*Juncus* spp. and *Distichlis spicata*)		Decreased concentrations from 41 to 0.6 mg/L (below natural background)	Kadlec and Knight 1996
NO_3	Tomato (*Lycopersicon esculentum* cv.Marmand)	PE, PS	700 mg/L in soil water concentrated up to 21,000, 27,000, and 47,000 mg/kg in roots, stems, and leaves	Moral et al. 1995
NO_3	Hybrid poplars (*Populus* spp.)	PE, PS	Decreased groundwater concentrations by over 100 mg/kg compared to unvegetated areas	Applied Natural Sciences, Inc. 1997
Total P	Day flower (*Commelinae* spp.)	PE	Accumulated up to 3,990 mg/kg in plant tissue	Keiffer and Ungar 1996
Total P	Bermuda grass (*Cynodon dactylon*)	PE	Accumulated up to 3,000 mg/kg in plant tissue	Keiffer and Ungar 1996
Total P	*Cyperus* spp.	PE	Accumulated up to 6,010 mg/kg in plant tissue	Keiffer and Ungar 1996
Total P	Type of grass (*Echinochloa* spp.)	PE	Accumulated up to 5,430 mg/kg in plant tissue	Keiffer and Ungar 1996
Total P	Morning glory (*Ipomoea* spp.)	PE	Accumulated up to 4,060 mg/kg in plant tissue	Keiffer and Ungar 1996
Total P	Type of grass (*Leptochola* spp.)	PE	Accumulated up to 3,090 mg/kg in plant tissue	Keiffer and Ungar 1996
Total P	Ryegrass (*Lolium perenne*)	PE, PS	Accumulated up to 4,110 mg/kg in shoots and 3,010 mg/kg in roots	Otabbong 1990

Inorganic	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Total P	Meadow rush and salt grass (*Juncus* spp. and *Distichlis spicata*)		Decreased concentrations from 24 to 0.7 mg/L (below natural background)	Kadlec and Knight 1996
Total P	*Sesbania* spp.	PE	Accumulated up to 4,010 mg/kg in plant tissue	Keiffer and Ungar 1996
PO_4	Tomato (*Lycopersicon esculentum* cv.Marmand)	PE, PS	142.5 mg/L in soil water concentrated up to 2,500, 2,600, and 5,500 mg/kg in roots, stems, and leaves	Moral et al. 1995
K	*Atriplex prostrata*	PE	Accumulated up to 20,300 mg/kg in shoots	Keiffer 1996
K	Day flower (*Commelinae* spp.)	PE	Accumulated up to 24,400 mg/kg in plant tissue	Keiffer and Ungar 1996
K	Bermuda grass (*Cynodon dactylon*)	PE	Accumulated up to 19,700 mg/kg in plant tissue	Keiffer and Ungar 1996
K	*Cyperus* spp.	PE	Accumulated up to 51,000 mg/kg in plant tissue	Keiffer and Ungar 1996
K	Type of grass (*Echinochloa* spp.)	PE	Accumulated up to 26,100 mg/kg in plant tissue	Keiffer and Ungar 1996
K	Wild rye (*Elymus* spp.)	PE, PS	110 ppm in soil concentrated to 25,000 ppm in plants (concentration factors up to 257x reported)	Cipollini and Pickering 1986
K	Squirrel tail grass (*Hordeum jubatum*)	PE	Accumulated up to 29,300 mg/kg in shoots	Keiffer 1996
K	Barley (*Hordeum vulgare*)	PE, PS	200 ppm in soil concentrated to 20,000 ppm in plants (concentration factors up to 2,900x reported)	Cipollini and Pickering 1986
K	Barley (*Hordeum vulgare* cv. Altas 57)	PE	Accumulated up to 6.15% (dry wt.) in shoots	Chaudhry, Wallace, and Mueller 1977
K	Morning glory (*Ipomoea* spp.)	PE	Accumulated up to 34,300 mg/kg in plant tissue	Keiffer and Ungar 1996
K	Tomato (*Lycopersicon esculentum* cv. Marmande)	PE, PS	215.1 mg/L in soil water concentrated up to 23,000, 51,000, and 34,000 mg/kg in roots, stems, and leaves	Moral et al. 1995
K	Beans (*Phaseolus vulgaris*)	PE, PS	140 ppm in soil concentrated to 21,000 ppm in plants (concentration factors up to 1,200x reported)	Cipollini and Pickering, 1986
K	Bush beans (*Phaseolus vulgaris* cv. Improved Tendergreen)	PE	Accumulated up to 3.06% (dry wt.) in leaves	Chaudhry, Wallace, and Mueller 1977
K	Slender or jointed glasswort (*Salicornia europaea*)	PE	Accumulated up to 38,800 mg/kg in shoots	Keiffer 1996
K	Spurries (*Spergularia marina*)	PE	Accumulated up to 41,200 mg/kg in shoots	Keiffer 1996
K	Type of sea blight (*Suaeda calceoliformis*)	PE	Accumulated up to 15,900 mg/kg in shoots	Keiffer 1996
K	Corn (*Zea mays*)	PE, PS	60 ppm in soil concentrated to 13,000 ppm in plants	Cipollini and Pickering 1986
Zn	Indian mustard (*Brassica juncea*)	RF	Decreased solution concentration from 95 to 15 mg/L in 8 hrs	Phytotech, Inc. 1997
Zn	Indian mustard (*Brassica juncea* cv. 182921)	PE	100 mg/kg in soil concentrated to 1,723 mg/kg in shoots	Kumar et al. 1995
Zn	Indian mustard (*Brassica juncea* cv. 426308)	PE	300 mg/kg in soil (+chelate) concentrated to 1,100 mg/kg in shoots, simultaneous with other metals	Blaylock et al. 1997

Inorganic	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Zn	Alfalfa (*Medicago sativa*)	PE, PS	Bound 1.3 mg/g tissue from groundwater	Tiemann et al. 1998
Zn	Alpine pennycress (*Thlaspi caerulescens*)	PE, PS	3 mg/L in solution concentrated to 2,300 mg/kg in shoots and 9,000 mg/kg in roots	Salt et al. 1995
Zn	Alpine pennycress (*Thlaspi caerulescens*)	PE, PS	Accumulated up to 25,000 mg/kg in plant	Rouhi 1997
Zn	Eastern gamagrass (*Tripsacum dactyloides)*	PE, PS	Accumulated 1,000 ppm in leaves, 10,000 ppm in roots	Hinchman, Negri, and Gatliff 1997
Zn	Hybrid poplar (*Populus* spp.)	PE, PS	Accumulated 4,200 ppm in leaves, 38,000 ppm in roots	Hinchman, Negri, and Gatliff 1997
Zn	Hybrid poplar (*Populus* spp.)		Decreased solution concentrations from 800 to 0 ppm in 4 hours	Hinchman, Negri, and Gatliff 1997

Table B-5. Plants accumulating significant concentrations of salts, heavy metals, and trace elements

Inorganic	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Salinity	*Atriplex prostrata*	PE	Accumulated up to 0.85% Na and up to 1.17% Cl in shoots when grown in soil containing 2.5% NaCl (plant density dependent)	Keiffer 1996
Salinity	Squirrel tail grass (*Hordeum jubatum*)	PE	Accumulated up to 0.62% Na and up to 0.75% Cl in shoots when grown in soil containing 2.5% NaCl (plant density dependent)	Keiffer 1996
Salinity	Slender or jointed glasswort (*Salicornia europaea*)	PE	Accumulated up to 0.97% Na and up to 1.56% Cl in shoots when grown in soil containing 2.5% NaCl (plant density dependent)	Keiffer 1996
Salinity	Great bulrush/saltwater cordgrass (*Scirpus validus/ Spartina alterniflora*)	RF	Reduced processed water volume (and subsequent disposal costs) by 75% by evapotranspiration, increased salinity from 1.5% to 6%	Negri, Hinchman, and Johnson 1998
Salinity	Spurries (*Spergularia marina*)	PE	Accumulated up to 0.80% Na and up to 1.13% Cl in shoots when grown in soil containing 2.5% NaCl (plant density dependent)	Keiffer 1996
Salinity	Type of sea blight (*Suaeda calceoliformis*)	PE	Accumulated up to 0.97% Na and up to 1.49% Cl in shoots when grown in soil containing 2.5% NaCl (plant density dependent)	Keiffer 1996
Al	Day flower (*Commelinae* spp.)	PE	Accumulated up to 198.6 mg/kg in plant tissue	Keiffer and Ungar 1996
Al	*Cyperus* spp.	PE	Accumulated up to 202.1 mg/kg in plant tissue	Keiffer and Ungar 1996
Al	Morning glory (*Ipomoea* spp.)	PE	Accumulated up to 475.7 mg/kg in plant tissue	Keiffer and Ungar 1996
Al	Ryegrass (*Lolium perenne*)	PE, PS	Accumulated up to 1,690 mg/kg in shoots and 6,220 mg/kg in roots	Otabbong 1990
Al	Ground cherry (*Physalis* spp.)	PE	Accumulated up to 823.0 mg/kg in plant tissue	Keiffer and Ungar 1996
As	Beetroot (*Beta vulgaris*)	PE, PS	66 mg/kg in soil concentrated to 375 mg/kg in beetroot	Speir, August, and Feltham 1992
As	Lettuce (*Lactuca sativa* cv. cos)	PE, PS	66 mg/kg in soil concentrated to 165 mg/kg in root	Speir, August, and Feltham 1992
As	Beans (*Phaseolus vulgaris* cv. Buenos Aires)	PE, PS	5 mg/L in solution concentrated to 43.1, 44.3, 27.2 mg/kg in roots, stems, and leaves	Carbonell-Barrachina, Burlo-Carbonell, and Mataix-Beneyto 1997

Inorganic	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
As	Clover (*Trifolium repens* cv. Huia)	PE, PS	66 mg/kg in soil concentrated to 130 mg/kg in root	Speir, August, and Feltham 1992
As	Hybrid willow (*Salix* spp.)	PE, PS	40 ppm sequestered mainly in the roots in 1 month from 100 ppm irrigation	Hinchman, Negri, and Gatliff 1997
Ba	Barley (*Hordeum vulgare* cv. Altas 57)	PE	2,000 mg/kg in soil concentrated to 9,770 mg/kg in shoots	Chaudhry, Wallace, and Mueller 1977
Ba	Bush beans (*Phaseolus vulgaris* cv. Imp. Tendergreen)	PE	2,000 mg/kg in soil concentrated to 22,200 mg/kg in leaves, 12,600 in stems	Chaudhry, Wallace, and Mueller 1977
Cd	Indian mustard (*Brassica juncea*)		Decreased solution concentration from 1.7 to 0.2 mg/L in 8 hours	Phytotech, Inc. 1997
Cd	Indian mustard (*Brassica juncea* cv. 182921)	PE	2.0 mg/kg in soil concentrated to 104 mg/kg in shoots	Kumar et al. 1995
Cd	Indian mustard (*Brassica juncea* cv. 426308)	PE	100 mg/kg in soil (+chelate) concentrated to 2,800 mg/kg in shoots, simultaneous with other metals	Blaylock et al. 1997
Cd	Chicory (*Chicorium intybus* var. *foliosum*)	PE	1.9 mg/kg in soil concentrated to 44.8, 23.6, and 18.0 mg/kg in leaves, stems, and roots	Martin et al. 1996
Cd	Canada fleabane (*Erigeron canadensis*)	PE	1.9 mg/kg in soil concentrated to 47.4 mg/kg in leaves and 38.2 mg/kg in stems	Martin et al. 1996
Cd	Dogfennel (*Eupatorium capillifolium*)	PE	1.9 mg/kg in soil concentrated to 12.3 mg/kg in leaves and 16.4 mg/kg in stems	Martin et al. 1996
Cd	Sunflower (*Helianthus annuus*)	RF	Decreased solution concentration from 900 to 220 µg/L in 24 hours	Salt et al. 1995
Cd	Alfalfa (*Medicago sativa*)	PE, PS	Bound 1.5 mg/g tissue from groundwater	Tiemann et al. 1998
Cd	Tobacco (*Nicotiana tabacum*)	(PE)	Accumulated 550 mg/kg in aboveground tissues from 3.4 mg/L hydroponic solution	Yancey et al. 1998
Cd	Purple nightshade (*Solanum elaegnofolium*)	PE, PS	Accumulated up to 745, 65, 370 mg/kg in roots, stems, and leaves, respectively	Gardea-Torresdey et al. 1998a
Cd	Alpine pennycress (*Thlaspi caerulescens*)	PE, PS	5 mg/L in solution concentrated to 295 mg/kg in shoots and 21,000 mg/kg in roots	Salt et al. 1995
Cd	Alpine pennycress (*Thlaspi caerulescens*)	PE, PS	Accumulated up to 5,000 mg/kg in plant	Rouhi 1997
Cr(III)	Chicory (*Chicorium intybus* var. *foliosum*)	PE	0.06 mg/kg in soil concentrated to 9.2, 3.4, and 5.1 mg/kg in leaves, stems, and roots	Martin et al. 1996
Cr(III)	Canada fleabane (*Erigeron canadensis*)	PE	0.06 mg/kg in soil concentrated to 7.6 mg/kg in leaves and 6.4 mg/kg in stems	Martin et al. 1996
Cr(III)	Dogfennel (*Eupatorium capillifolium*)	PE	0.06 mg/kg in soil concentrated to 9.4 mg/kg in leaves and 8.1 mg/kg in stems	Martin et al. 1996
Cr(III)	Tomato (*Lycopersicon esculentum* cv. Marmande)	PE, PS	100 mg/L in soil water concentrated to 2354 mg/kg in roots	Moral et al. 1995
Cr(III)	Alfalfa (*Medicago sativa*)	PE, PS	Bound 8.2 mg/g tissue from groundwater	Tiemann et al. 1998

Inorganic	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Cr(III)	Bush beans (*Phaseolus vulgaris* cv. Contender)	PE	52 µg/kg concentrated up to 155.4 mg/kg in roots, 3.8 mg/kg in stems, and 12.5 mg/kg in leaves	Bonet, Poschenrieder, and Barcelo 1991
Cr(VI)	Beetroot (*Beta vulgaris*)	PE, PS	179 mg/kg in soil concentrated to 320 mg/kg in beetroot	Speir, August, and Feltham 1992
Cr(VI)	Indian mustard (*Brassica juncea*)	RF	Decreased solution concentration from 4.7 to 1.2 mg/L in 8 hours	Phytotech, Inc. 1997
Cr(VI)	Indian mustard (*Brassica juncea* cv. 182921)	PE	3.5 mg/kg in soil concentrated to 202 mg/kg in shoots	Kumar et al. 1995
Cr(VI)	Sunflower (*Helianthus annuus*)	RF	Decreased solution concentration from 1,100 to 0 µg/L in 24 hours	Salt et al. 1995
Cr(VI)	Lettuce (*Lactuca sativa* cv. cos)	PE, PS	179 mg/kg in soil concentrated to 200 mg/kg in root	Speir, August, and Feltham 1992
Cr(VI)	Duckweed (*Lemna* spp.)	PE	Accumulated up to 38 mg/kg in plant tissues	Kadlec and Knight 1996
Cr(VI)	Alpine pennycress (*Thlaspi caerulescens*)	PE, PS	0.4 mg/L in solution concentrated to 35.6 mg/kg in shoots and 3,400 mg/kg in roots	Salt et al. 1995
Cr(VI)	Cattail and bulrush (*Typha* and *Scirpus* spp.)	PE	16.0 µg/L influent reduced to 3.6 µg/L at effluent	Kadlec and Knight 1996
Au	Alfalfa (*Medicago sativa*)	PE	Bound 40.9 mg/g in shoots and 18.7 mg/g in roots, gold reduced in tissues from Au(III) to Au(0)	Gardea-Torresdey et al. 1998b
Pb	Spleen amaranth (pilewort) (*Amaranthus hybridus*)	PE, PS	625 mg/kg in solution concentrated to 0.3 g/kg in shoots and 8.7 g/kg in roots	Kumar et al. 1995
Pb	Amaranth (*Amaranthus paniculata*)	PE, PS	625 mg/kg in solution concentrated to 0.4 g/kg in shoots and 8.9 g/kg in roots	Kumar et al. 1995
Pb	Turnip (*Brassica campestris*)	PE, PS	625 mg/kg in solution concentrated to 7.2 g/kg in shoots and 103.4 g/kg in roots	Kumar et al. 1995
Pb	Brassica (*Brassica carinata*)	PE, PS	625 mg/kg in solution concentrated to 4.6 g/kg in shoots and 108.9 g/kg in roots	Kumar et al. 1995
Pb	Indian mustard (*Brassica juncea*)	PE, PS	625 mg/kg in solution concentrated to 10.3 g/kg in shoots and 103.5 g/kg in roots	Kumar et al. 1995
Pb	Indian mustard (*Brassica juncea*)	PE	Decreased solution concentration from 0.8 to 0.2 mg/L in 8 hours	Phytotech, Inc. 1997
Pb	Indian mustard (*Brassica juncea* cv. 182921)	PE	500 mg/kg in soil concentrated to 844 mg/kg in shoots	Kumar et al. 1995
Pb	Indian mustard (*Brassica juncea* cv. 426308)	PE	600 mg/kg in soil (+chelate) concentrated to 16,500 mg/kg in shoots, simultaneous with other metals	Blaylock et al. 1997
Pb	Canola (*Brassica Napus*)	PE, PS	625 mg/kg in solution concentrated to 3.4 g/kg in shoots and 61.2 g/kg in roots	Kumar et al. 1995
Pb	Black mustard (*Brassica nigra*)	PE, PS	625 mg/kg in solution concentrated to 9.4 g/kg in shoots and 106.6 g/kg in roots	Kumar et al. 1995
Pb	Wild cabbage (*Brassica oleracea*)	PE, PS	625 mg/kg in solution concentrated to 0.6 g/kg in shoots and 52.7 g/kg in roots	Kumar et al. 1995
Pb	Sedge (*Carex microptera*)	PE	Accumulated up to 1,000 mg/kg in aboveground tissues from soils at 3,000–15,000 mg/kg	Klassen et al. 1998

Inorganic	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Pb	Sunflower (*Helianthus annuus*)	PE, PS	625 mg/kg in solution concentrated to 5.6 g/kg in shoots and 61.6 g/kg in roots	Kumar et al. 1995
Pb	Duckweed (*Lemna minor*)	PE	Accumulated up to 200 mg/kg in tissues	Kadlec and Knight 1996
Pb	Alfalfa (*Medicago sativa*)	PE, PS	Bound 43.3 mg/g tissue from groundwater	Tiemann et al. 1998
Pb	Tobacco (*Nicotiana tabacum*)	PE, PS	625 mg/kg in solution concentrated to 0.8 g/kg in shoots and 24.9 g/kg in roots	Kumar et al. 1995
Pb	Purple nightshade (*Solanum elaegnofolium*)	PE, PS	Accumulated up to 1,875, 97, and 380 mg/kg in roots, stems, and leaves, respectively	Gardea-Torresdey et al. 1998a
Pb	Sorghum (*Sorghum bicolor*)	PE, PS	625 mg/kg in solution concentrated to 0.3 g/kg in shoots and 8.2 g/kg in roots	Kumar et al. 1995
Pb	Alpine pennycress (*Thlaspi caerulescens*)	PE, PS	5 mg/L in solution concentrated to 145 mg/kg in shoots and 35,000 mg/kg in roots	Salt et al. 1995
Pb	Cattail and reed (*Typha* and *Phragmites* spp.)	PE	Accumulated up to 444 mg/kg in tissues	Kadlec and Knight 1996
Pb	Corn (*Zea mays*)	PE, PS	625 mg/kg in solution concentrated to 0.2 g/kg in shoots and 14.7 g/kg in roots	Kumar et al. 1995
Pb	5 Dicotyledonous (broadleaf) crops	PE, PS	300 mg/L in solution concentrated to 95–140 g/kg in roots	Dushenkov et al. 1995
Pb	3 Monocotyledonous (cereal) crops	PE, PS	300 mg/L in solution concentrated to 75–104 g/kg in roots	Dushenkov et al. 1995
Pb	11 Cool-season grass species	PE, PS	300 mg/L in solution concentrated to 60–169 g/kg in roots	Dushenkov et al. 1995
Pb	6 Warm-season grass species	PE, PS	300 mg/L in solution concentrated to 56–124 g/kg in roots	Dushenkov et al. 1995
Pb	Alder (*Alnus tenuifolia*)	PE	Accumulated up to 1,000 mg/kg in aboveground tissues from soils at 3,000–15,000 mg/kg	Klassen et al. 1998
Pb	Birch (*Betula occidentalis*)	PE, PS	Accumulated up to 1,000 mg/kg in aboveground tissues from soils at 3,000–15,000 mg/kg, increased total concentrations in root zone but maintained concentrations of exchangeable form	Klassen et al. 1998
Pb	Hybrid willow (*Salix* spp.)	PE, PS	4 ppm sequestered mainly in the roots in 1 month from 10 ppm irrigation	Hinchman, Negri, and Gatliff 1997
Hg(II)	Mustard weed (*Arabidopsis thaliana - merA* transgenic)	(PV)	Bound 1 ppm Hg(II) to roots in 24 hours, reduced to Hg(0) and volatilized 70% in 7 days	Heaton et al. 1998
Hg(II)	Tobacco (*Nicotiana tabacum - merA* transgenic)	PE, (PV)	Accumulated 17–76 ppm Hg(II) in shoots from 500 ppm soil, reduced to Hg(0) and volatilized an (undisclosed) amount	Heaton et al. 1998
Ni	Indian mustard (*Brassica juncea*	PE	Decreased solution concentration from 12.0 to 2.0 mg/L in 8 hours	Phytotech, Inc. 1997
Ni	Indian mustard (*Brassica juncea* cv. 182921)	PE	100 mg/kg in soil concentrated to 3,086 mg/kg in shoots	Kumar et al. 1995
Ni	Indian mustard (*Brassica juncea* cv. 426308)	PE	300 mg/kg in soil (+chelate) concentrated to 300 mg/kg in shoots, simultaneous with other metals	Blaylock et al. 1997
Ni	Chicory (*Chicorium intybus* var. *foliosum*)	PE	0.16 mg/kg in soil concentrated to 5.7, 6.9, and 4.1 mg/kg in leaves, stems, and roots	Martin et al. 1996

Inorganic	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
Ni	Canada fleabane (*Erigeron canadensis*)	PE	0.16 mg/kg in soil concentrated to 4.2 mg/kg in leaves and 3.8 mg/kg in stems	Martin et al. 1996
Ni	Dogfennel (*Eupatorium capillifolium*)	PE	0.16 mg/kg in soil concentrated to 4.6 mg/kg in leaves and 2.3 mg/kg in stems	Martin et al. 1996
Ni	Sunflower (*Helianthus annuus*)	PE	Decreased solution concentration from 2,000 to 300 µg/L in 24 hours	Salt et al. 1995
Ni	Alfalfa (*Medicago sativa*)	PE, PS	Bound 0.5 mg/g tissue from groundwater	Tiemann et al. 1998
Ni	Alpine pennycress (*Thlaspi caerulescens*)	PE, PS	1 mg/L in solution concentrated to 2,739 mg/kg in shoots and 8,425 mg/kg in roots	Salt et al. 1995
Ni	Alpine pennycress (*Thlaspi caerulescens*)	PE, PS	Accumulated up to 16,200 mg/kg in plant	Rouhi 1997
Ni	Latex rubber tree (*Sebertia acuminata*)	PE	Accumulated up to 25% (dry wt.) in tissues	Cunningham and Berti 1993
Se	Canola (*Brassica Napus*)	PE, PS	Accumulated up to 700 mg/kg in plant, also volatilized Se as dimethyl selenide	Rouhi 1997
Se	Canola (*Brassica Napus* cv. Westar)	PE, PS	In greenhouse: 104 mg/kg in 0–30 cm deep soil (0.39 mg/L extractable) concentrated to 182, 27, and 25 mg/kg in leaves, stems, roots, 8 mg/kg in 60–90 cm deep soil (0.99 mg/L ext.) concentrated to 19, 8, and 11 mg/kg in leaves, stems, roots	Bañuelos et al. 1998
Se	Canola (*Brassica Napus* cv. Westar)	PE, PS	In field: 21.6 mg/kg in 0–30 cm deep soil (<0.01 mg/L ext.) and 1.6 mg/kg in 60–90 cm deep soil (<0.01 mg/L ext.) concentrated to 44.5, 8.3, and 12.1 mg/kg in leaves, stems, roots	Bañuelos et al. 1998
Se	Cattails and bulrushes (*Typha* and *Scirpus* spp.)	PE	70%–75% reduction in concentrations from 10,000,000 L/day feed	Adler 1996
Na	*Atriplex* spp.	PE	Soil concentrations reduced by an average of 65%	Keiffer and Ungar 1996
Na	Day flower (*Commelinae* spp.)	PE	Accumulated up to 60,500 mg/kg in plant tissue	Keiffer and Ungar 1996
Na	Wild rye (*Elymus* spp.)	PE, PS	140 ppm in soil concentrated to 1,300 ppm in plants (concentration factors up to 32x reported)	Cipollini and Pickering 1986
Na	Barley (*Hordeum vulgare*)	PE, PS	8,200 ppm in soil concentrated to 73,000 ppm in plants	Cipollini and Pickering 1986
Na	Morning glory (*Ipomoea* spp.)	PE	Accumulated up to 7,100 mg/kg in plant tissue	Keiffer and Ungar 1996
Na	Type of grass (*Leptochola* spp.)	PE	Accumulated up to 6,600 mg/kg in plant tissue	Keiffer and Ungar 1996
Na	Tomato (*Lycopersicon esculentum* cv. Marmande)	PE, PS	3.7 mg/L in soil water concentrated up to 10,000, 1,900, and 2,100 mg/kg in roots, stems, and leaves	Moral et al. 1995
Na	Beans (*Phaseolus vulgaris*)	PE, PS	5,000 ppm in soil concentrated to 48,000 ppm in plants	Cipollini and Pickering 1986
Na	Ground cherry (*Physalis* spp.)	PE	Accumulated up to 12,500 mg/kg in plant tissue	Keiffer and Ungar 1996
Na	Sea blight (*Suaeda* spp.)	PE	Soil concentrations reduced by an average of 65%	Keiffer and Ungar 1996
Na	Type of sea slight (*Suaeda salsa*)	PE	Up to 3,860 kg/ha of Na removed by 15 plants/m^2 in one season	Zhao 1991
Na	Corn (*Zea mays*)	PE, PS	600 ppm in soil concentrated to 820 ppm in plants (concentration factors up to 15x reported)	Cipollini and Pickering 1986

Inorganic	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
V	Chicory (*Chicorium intybus* var. *foliosum*)	PE	0.08 mg/kg in soil concentrated to 2.9, 1.2, and 6.5 mg/kg in leaves, stems, and roots	Martin et al. 1996
V	Canada fleabane (*Erigeron canadensis*)	PE	0.08 mg/kg in soil concentrated to 2.0 mg/kg in leaves and 1.4 mg/kg in stems	Martin et al. 1996
V	Dogfennel (*Eupatorium capillifolium*)	PE	0.08 mg/kg in soil concentrated to 1.9 mg/kg in leaves and 1.2 mg/kg in stems	Martin et al. 1996

Table B-6. Plants accumulating significant concentrations of radionuclides

(1 Becquerel [Bq] = 1 disintegration/second; 3.7×10^{10} Bq = 1 Curie [Ci])

Inorganic	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
^{144}Ce	Peas (*Pisum sativum*)	PE, PS	2.0×10^4 Bq/kg in leaves, simultaneous with other radionuclides spiked into soil	Bell, Minski, and Grogan 1988
^{144}Ce	Wheat (*Triticum aestevum*)	PE, PS	3.0×10^3 Bq/kg in straw, simultaneous with other radionuclides spiked into soil	Bell, Minski, and Grogan 1988
^{134}Cs	Chickweed (*Cerastium fontanum*)	PE	Accumulated up to 1.04×10^6 Bq/kg in shoots in 4 weeks	Salt, Mayes, and Elston 1992
^{134}Cs	Red fescue (*Festuca rubra*)	PE	Accumulated up to 1.60×10^5 Bq/kg in shoots in 4 weeks	Salt, Mayes, and Elston 1992
^{134}Cs	Wild millet (*Holcus mollis*)	PE	Accumulated up to 1.75×10^5 Bq/kg in shoots in 4 weeks	Salt, Mayes, and Elston 1992
^{134}Cs	Perennial ryegrass (*Lolium perenne*)	PE	Accumulated up to 1.14×10^5 Bq/kg in shoots in 4 weeks	Salt, Mayes, and Elston 1992
^{134}Cs	Common meadow grasses (*Poa* spp.)	PE	Accumulated up to 1.99×10^5 Bq/kg in shoots in 4 weeks	Salt, Mayes, and Elston 1992
^{134}Cs	White clover (*Trifolium repens*)	PE	Accumulated up to 2.55×10^5 Bq/kg shoots in 4 weeks	Salt, Mayes, and Elston 1992
^{134}Cs	7 (Dominant) pasture species community	PE	74 Bq/kg in soil concentrated to 2,080 Bq/kg in vegetation, 950 Bq/kg in roots	Coughtery, Kirton, and Mitchell 1989
^{134}Cs	5 (Dominant) pasture species community	PE	94 Bq/kg in soil concentrated to 1,670 Bq/kg in vegetation, 990 Bq/kg in roots	Coughtery, Kirton, and Mitchell 1989
^{137}Cs	Meadow foxtail grass (*Alopecurus pratensis*)	PE	2.2×10^5 Bq/kg in shoots, 2.3×10^5 Bq/kg in roots	Coughtery, Kirton, and Mitchell 1989
^{137}Cs	Indian mustard (*Brassica juncea*)	PE	1.6×10^4 Bq/kg in shoots	Vasudev et al. 1996
^{137}Cs	Turnip (*Brassica Rapa*)	PE, PS	6.3×10^3 Bq/kg in outer leaves, simultaneous with other radionuclides spiked into soil	Bell, Minski, and Grogan 1988
^{137}Cs	Common heather (*Calluna vulgaris*)	PE, PS	Concentration factors (plant to soil Bq/kg levels) of 28.7 leaves, 35.3 flowers, 10.0 stems, 13.3 roots	Bunzl and Kracke 1984
^{137}Cs	Black sedge (*Carex nigra*)	PE, PS	Accumulated 1,300 Bq/kg in dry tissue weight	Olsen 1994
^{137}Cs	Tall cottongrass (*Eriophorum augustifolium*)	PE, PS	Accumulated 2,500 Bq/kg in dry tissue weight	Olsen 1994
^{137}Cs	Tall fescue (*Festuca arundinacea*)	PE	Accumulated 4.2×10^6 Bq/m^2 in 8 months	Dalhman, Auerbach, and Dunaway 1969

Inorganic	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
^{137}Cs	Sunflower (*Helianthus annuus* cv. SF-187)	PE	Decreased solution concentration from 200 to 3 µg/L in 24 hours, accumulated 1.6×10^5 Bq/kg of dry matter	Dushenkov et al. 1997a,b
^{137}Cs	Cow wheat (*Melampyrum sylvaticum*)	PE, PS	Accumulated 1,600 Bq/kg in dry tissue weight	Olsen 1994
^{137}Cs	Buckbean (*Menyanthes trifoliata*)	PE, PS	Accumulated 1,600 Bq/kg in dry tissue weight	Olsen 1994
^{137}Cs	Switchgrass (*Panicum virginatum*)	PE	36.2% of total ^{137}Cs in sand medium removed after 5 monthly cuttings	Entry et al. 1996
^{137}Cs	Common timothy grass (*Phleum pratense*)	PE	4.5×10^4 Bq/kg in shoots; 8.0×10^4 Bq/kg in roots	Vasudev et al. 1996
^{137}Cs	Peas (*Pisum sativum*)	PE	3.1×10^4 Bq/kg in shoots, 7.1×10^4 Bq/kg in roots	Vasudev et al. 1996
^{137}Cs	Peas (*Pisum sativum*)	PE, PS	9.2×10^4 Bq/kg in leaves, simultaneous with other radionuclides spiked into soil	Bell, Minski, and Grogan 1988
^{137}Cs	Common sorrel (*Rumex acetosa*)	PE, PS	Accumulated 5,500 Bq/kg in dry tissue weight	Olsen 1994
^{137}Cs	Potato (*Solanum tuberosum*)	PE, PS	1.4×10^4 Bq/kg in tubers, simultaneous with other radionuclides spiked into soil	Bell, Minski, and Grogan 1988
^{137}Cs	Wheat (*Triticum aestevum*)	PE, PS	1.1×10^4 Bq/kg in straw, simultaneous with other radionuclides spiked into soil	Bell, Minski, and Grogan 1988
^{137}Cs	Bilberry (*Vaccinium myrtillus*)	PE, PS	Concentration factors (plant to soil Bq/kg levels) of 15.3 leaves, 9.3 stems	Bunzl and Kracke 1984
^{137}Cs	7 (Dominant) pasture species community	PE	280 Bq/kg in soil concentrated to 4,690 Bq/kg in vegetation, 2,340 Bq/kg in roots	Coughtery, Kirton, and Mitchell 1989
^{137}Cs	5 (Dominant) pasture species community	PE	490 Bq/kg in soil concentrated to 3,750 Bq/kg in vegetation, 2,370 Bq/kg in roots	Coughtery, Kirton, and Mitchell 1989
^{137}Cs	Eucalyptus (*Eucalyptus tereticornis*)	PE	31.0% of total ^{137}Cs in sphagnum peat removed after 1 month	Entry and Emmingham 1995
^{137}Cs	Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws)	PE	Accumulated 5.28×10^5 Bq/kg in roots, 2.86×10^5 Bq/kg in shoots (removed from site with needle litter removal) in 4 weeks	Entry, Rygiewicz, and Emmingham 1993
^{137}Cs	Monterey pine (*Pinus radiata* D Don)	PE	Accumulated 6.28×10^5 Bq/kg in roots, 1.72×10^5 Bq/kg in shoots (removed from site with needle litter removal) in 4 weeks	Entry, Rygiewicz, and Emmingham 1993
^{58}Co	Ryegrass (*Lolium perenne* cv. Premo)	PE, PS	0.06 mg/kg in solution concentrated to 58.9 mg/kg in plant	Macklon and Sim 1990
^{224}Ra	Tassel flower (*Emilia baldwinii*)	PE, PS	Concentration factors (plant to soil Bq/kg levels) of 3.36 in shoots and 2.86 in roots	Hewamanna, Samarakoon, and Karunaratne 1988
^{226}Ra	Cattail (*Typha latifolia*)	PE, PS	Accumulated 275.9 Bq/kg in leaves, 248.2 Bq/kg in stems, and 1,135 Bq/kg in roots	Mirka et al. 1996
^{226}Ra	Red maple, sweet gum, tulip (*Acer rubrum*, *Liquidamber stryaciflua*, *Liriodendron tulipifera*)	PE	Concentration factors (plant to soil Bq/kg levels) of 2.0 in leaves (composite of each species)	Pinder et al. 1984
^{226}Ra	Trembling aspen (*Populus tremuloides*)	PE	Accumulated 41.8 Bq/kg in leaves, 68.9 Bq/kg in stems	Clulow et al. 1992

Inorganic	Plant species	Phyto-mechanism	Comments on phytoremedial effectiveness	Reference
^{226}Ra	Largetooth aspen (*Populus grandidentata*)	PE	Accumulated 52.7 Bq/kg in leaves, 98.7 Bq/kg in stems	Clulow et al. 1992
^{106}Ru	Peas (*Pisum sativum*)	PE, PS	7.9×10^4 Bq/kg in leaves, simultaneous with other radionuclides spiked into soil	Bell, Minski, and Grogan 1988
^{106}Ru	Potato (*Solanum tuberosum*)	PE, PS	4.9×10^3 Bq/kg in tuber peels, simultaneous with other radionuclides spiked into soil	Bell, Minski, and Grogan 1988
^{106}Ru	Wheat (*Triticum aestevum*)	PE, PS	7.3×10^3 Bq/kg in straw, simultaneous with other radionuclides spiked into soil	Bell, Minski, and Grogan 1988
^{90}Sr	Meadow foxtail grass (*Alopecurus pratensis*)	PE	1.1×10^6 Bq/kg in shoots	Vasudev et al. 1996
^{90}Sr	Sunflower (*Helianthus annuus* cv. SF-187)	PE	Decreased solution concentration from 200 to 1 µg/L in 75 hours, accumulated 2.5×10^6 Bq/kg of dry matter	Dushenkov et al. 1997a,b
^{90}Sr	Switchgrass (*Panicum virginatum*)	PE	43.6% of total ^{90}Sr in sand medium removed after 5 monthly cuttings	Entry et al. 1996
^{90}Sr	Common timothy grass (*Phleum pratense*)	PE	1.4×10^5 Bq/kg in roots	Vasudev et al. 1996
^{90}Sr	Eucalyptus (*Eucalyptus tereticornis*)	PE	11.3% of total ^{90}Sr in sphagnum peat removed after 1 month	Entry and Emmingham 1995
^{90}Sr	Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws)	PE	Accumulated 2.63×10^6 Bq/kg in roots, 1.66×10^6 Bq/kg in shoots (removed from site with needle litter removal) in 4 weeks	Entry, Rygiewicz, and Emmingham 1993
^{90}Sr	Monterey pine (*Pinus radiata* D Don)	PE	Accumulated 2.62×10^6 Bq/kg in roots, 2.47×10^6 Bq/kg in shoots (removed from site with needle litter removal) in 4 weeks	Entry, Rygiewicz, and Emmingham 1993
^{99}Tc	Turnip (*Brassica Rapa*)	PE, PS	1.1×10^6 Bq/kg in outer leaves, simultaneous with other radionuclides spiked into soil	Bell, Minski, and Grogan 1988
^{99}Tc	Peas (*Pisum sativum*)	PE, PS	9.2×10^6 Bq/kg in leaves, simultaneous with other radionuclides spiked into soil	Bell, Minski, and Grogan 1988
^{99}Tc	Wheat *Triticum aestevum*)	PE, PS	9.9×10^5 Bq/kg in straw, simultaneous with other radionuclides spiked into soil	Bell, Minski, and Grogan 1988
^{238}U	Indian mustard (*Brassica juncea* cv. 426308)	PE	Decreased solution concentration from 56 to 42 µg/L in 72 hours	Dushenkov et al. 1997b
^{238}U	Sunflower (*Helianthus annuus* cv. Mammoth)	PE	Decreased solution concentration from 56 to 2 µg/L in 24 hours	Dushenkov et al. 1997b
^{238}U	Sunflower (*Helianthus annuus* cv. SF-187)	PE	Decreased solution concentration from 600 to 10 µg/L in 48 hours; 90-day operation at average inlet concentration of 207 µg/L to below 20 µg/L outlet	Dushenkov et al. 1997a,b
^{238}U	Beans (*Phaseolus coccineus* cv Half White Runner)	PE	Decreased solution concentration from 56 to 23 µg/L in 72 hours	Dushenkov et al. 1997b

3. PLANT HYDRAULIC CHARACTERISTICS AND RAIN INTERCEPTION CAPACITIES

Table B-7. Plant hydraulic characteristics

Species	Transpiration	Comments	Reference
Brachiari mutica	3.9 mm/day	From potential evapotranspiration (PET) calculations and lysimeter data taken during 12 peak months in Zaire	Allen et al. 1989
Soybeans (*Glycine max*)	475 gal/day/acre	Estimated from 200,000 plants/acre × 9 mL/plant/day for young plants (Anderson and Walton 1991)	Tsao 1997
Perennial ryegrass (*Lolium perenne*)	6.9 mm/day	From PET calculations and lysimeter data taken during 12 peak months in California	Allen et al. 1989
Perennial ryegrass (*Lolium perenne*)	4.1 mm/day	From PET calculations and lysimeter data taken during 12 peak months in California	Allen et al. 1989
Perennial ryegrass (*Lolium perenne*)	5.4 mm/day	From PET calculations and lysimeter data taken during 12 peak months in New Jersey	Allen et al. 1989
Alfalfa (*Medicago sativa*)	8,300 gal/acre	Estimated daily average	Gatliff 1994
Alfalfa (*Medicago sativa*)	10.5 mm/day	From PET calculations and lysimeter data taken during 8 peak months in California	Allen et al. 1989
Alfalfa (*Medicago sativa*)	7.9 mm/day	From PET calculations and lysimeter data taken during 7 peak months in Idaho	Allen et al. 1989
Alfalfa (*Medicago sativa*)	10.1 mm/day	From PET calculations and lysimeter data taken during 4 peak months in Nebraska	Allen et al. 1989
Great bulrush (*Scirpus validus*)	21.9 L/m^2day	16,655 L evapotranspired in 7.6 days from one 100 m^2 aboveground compartment (modeled from laboratory results)	Negri, Hinchman, and Johnson 1998
Saltwater cordgrass (*Spartina* spp.)	8,500 gal/acre	Estimated daily average	Hinchman, Negri, and Gatliff 1997
Saltwater cordgrass (*Spartina alterniflora*)	21.9 L/m^2day	33,310 L evapotranspired in 7.6 days from two 100 m^2 aboveground compartments (modeled from laboratory results)	Negri, Hinchman, and Johnson 1998
Clover/perennial ryegrass (*Trifolium* spp./*Lolium perenne*)	7.7 mm/day	From PET calculations and lysimeter data taken during 12 peak months in Australia	Allen et al. 1989
Clover/grass mix (unspecified)	3.0 mm/day	From PET calculations and lysimeter data taken during 8 peak months in Denmark	Allen et al. 1989
Grass species (unspecified)	46.18 inches/year	From PET calculations and lysimeter data taken during over a 1 year in Ohio, ranged from 1.5 (February) to 7.0 (July) inches/month	Potter 1998
Grass/legume mix (unspecified)	4.1 mm/day	From PET calculations and lysimeter data taken during 9 peak months in Ohio	Allen et al. 1989
Native meadow (unspecified)	4.1 mm/day	From PET calculations and lysimeter data taken during the 4 peak months in Colorado	Allen et al. 1989
Alders (*Alnus* spp.)	200–800 gal/day/tree	1 of 12 species identified that would use desired range of water	Woodward 1996
River birch (*Betula nigra*)	200–800 gal/day/tree	1 of 12 species identified that would use desired range of water	Woodward 1996
Eucalyptus (*Eucalyptus* spp.)	200–800 gal/day/tree	1 of 12 species identified that would use desired range of water	Woodward 1996
Ash (*Fraxinus* spp.)	200–800 gal/day/tree	1 of 12 species identified that would use desired range of water	Woodward 1996
Hybrid poplar (*Populus* spp.)	20–40 gal/day/tree	Average transpirations for 5-year-old trees, dependent on local climate	Phytokinetics, Inc. 1998
Hybrid poplar (*Populus* spp.)	200–800 gal/day/tree	For 5-year-old trees	Newman et al. 1997b

Species	Transpiration	Comments	Reference
Hybrid poplar (*Populus* spp.)	100 L/day/tree	For a 5-year-old tree under optimal conditions	Stomp et al. 1994
Hybrid poplar (*Populus* spp.)	13 gal/day/tree	Calculated based on trees acting as low-flow pumping wells	Nelson 1996
Hybrid poplar (*Populus* spp.)	1.6–10 gal/day/tree	Sap flow measurements of young trees in Maryland	Chappell 1997
Hybrid poplar (*Populus* spp.)	2,300,000 gal/acre	Stand of 5-year-old trees at a density of 2170 trees/acre	Chappell 1997
Hybrid poplar (*Populus* spp.)	55.62 inches/year	From PET calculations and lysimeter data taken during over 1 year in Ohio, ranged from 1.5 (February) to 9.5 (July) inches/month	Potter 1998
Poplar (*Populus* spp.)	200–800 gal/day/tree	1 of 12 species identified that would use desired range of water	Woodward 1996
Cottonwood (*Populus deltoides*)	50–350 gal/day	40-foot-tall trees in Ohio, 0.5–1 foot decrease in water level from April to November	Gatliff 1994
Cottonwood (*Populus deltoides*)	3.75–350 gal/day	Pumped 3.75 gpd per tree after only 1.5 years and 350 gpd by a 19-year-old tree in Ft. Worth., Texas	Harvey 1998
Cottonwood (*Populus deltoides*)	10–11 kg/gal/day	Observed in early summer for 1–2-year-old trees in Texas	Chappell 1997
Cottonwood (*Populus deltoides*)	200–800 gal/day/tree	1 of 12 species identified that would use desired range of water	Woodward 1996
Hybrid poplar (*Populus deltoides* x *nigra* DN34)	100 mL/day	Very young trees in an experimental plant growth chamber	Chard et al. 1998
Aspen (*Populus tremuloides*)	200–800 gal/day/tree	1 of 12 species identified that would use desired range of water	Woodward 1996
Mesquite (*Prosopis glandulosa*)	200–800 gal/day/tree	1 of 12 species identified that would use desired range of water	Woodward 1996
Hybrid willow (*Salix* spp.)	5,000 gal in 1 day	Maximum value measured on a single, hot summer day	Hinchman, Negri, and Gatliff 1997
Willow (*Salix* spp.)	200–800 gal/day/tree	1 of 12 species identified that would use desired range of water	Woodward 1996
Salt cedar (*Tamarisk gallica*)	200–800 gal/day/tree	1 of 12 species identified that would use desired range of water	Woodward 1996
Bald cypress (*Taxodium distichum*)	200–800 gal/day/tree	1 of 12 species identified that would use desired range of water	Woodward 1996
Greasewood (*Sarcobatus vermiculatus*)	200–800 gal/day/tree	1 of 12 species identified that would use desired range of water	Woodward 1996

Table B-8. Plant rain interception capacities

Source: Viessman, Lewis, and Knapp 1989

Species	Interception capacity (%)	Comments
Big bluestem (*Andropogon furcatus*)	5	Water applied at a rate of 1/2 inch in 30 minutes
Oats (*Avena* spp.)	7	
Buffalo grass (*Bulbilis dactyloides*)	31	Water applied at a rate of 1/2 inch in 30 minutes
Bindweed (*Convovulus* spp.)	17	Water applied at a rate of 1/2 inch in 30 minutes
Soybeans (*Glycine max*)	1	
Alfalfa (*Medicago sativa*)	36	
Tall panicgrass (*Panicum* spp.)	57	Water applied at a rate of 1/2 inch in 30 minutes
Bluegrass (*Poa* spp.)	17	
Little bluestem (*Schizachyrium scoparium*)	50–60	Water applied at a rate of 1/2 inch in 30 minutes
Corn (*Zea mays*)	16	
Mixed species (unspecified)	26	
Natural grass pasture (unspecified)	14–19	
Birch (*Betula* spp.)	10	Average over 5-month span in a forest cover
Ash (*Fraxinus* spp.)	24	0.36 inches intercepted from a 1.5-inch rain event
Spruce and fir (*Picea* and *Abies* spp.)	30	Average over 5-month span in a forest cover
Ponderosa pine (*Pinus ponderosa*)	12	
Loblolly pine (*Pinus taeda*)	14	10-year old plantation in southern United States
Douglas fir (*Pseudotsuga douglasii*)	24	Dense, closed canopy forest in western United States
Oak (*Quercus* spp.)	24	0.36 inches intercepted from a 1.5-inch rain event

Appendix C

Case Study Information Collected during the International Phytoremediation Conference 2007 in Denver Colorado

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CASE STUDY INFORMATION COLLECTED DURING THE INTERNATIONAL PHYTOREMEDIATION CONFERENCE 2007 IN DENVER COLORADO

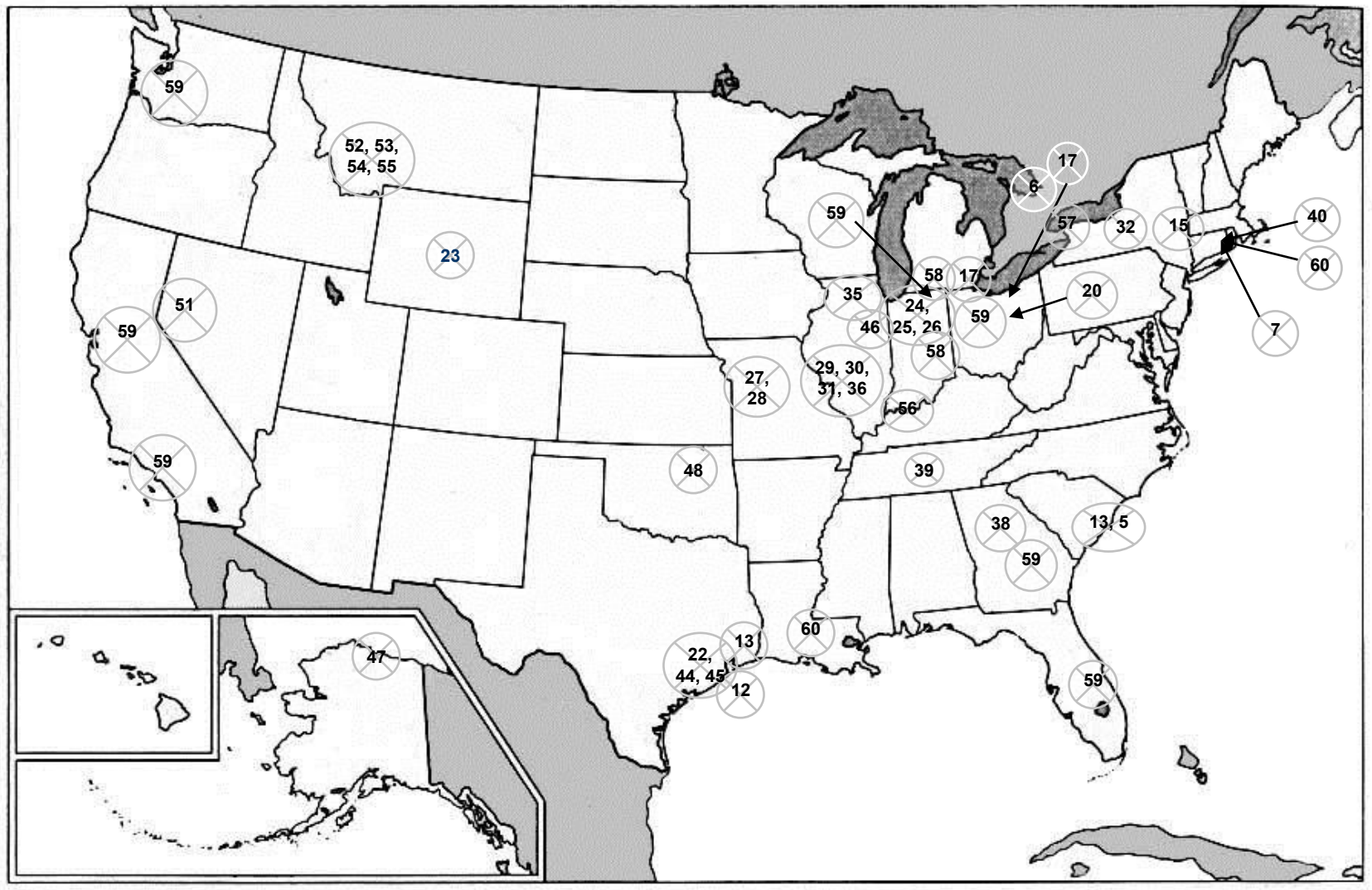

Figure C-1. Case study locations.

Figure C-2. Case study locations.

Table C-1. Phytoremediation inventory, October 2007

No.	Application	Contaminants	Treatment period	Project scale	Success?	Follow-up contact
1	Vegetative covers	BTEX, PAH, PCB, metals –2°, groundwater –1°	30+ years	Pilot 1999–2005, 10 acres, full scale 2006–2009, 60+ acres	Record of decision issued 2005, call me in 30–300 years?	D McMillan dmcmillan@natresco.com
2	Phytobarrier, riparian treatment system	TCE/PCE	5 to >30 years, installed 2002	Full scale, 1.63 acre	Yes to date	D McMillan dmcmillan@natresco.com
3	Phytoextraction	Heavy metals, Cd, Cu, As, Zn	5 years, started 2002	Demonstration, 1.5 hectares	Yes to date	YM Luo (China) ymluo@issas.ac.ca
4	Phytovolatilization extraction degradation	TCE/PCE, heavy metals	30 years	Full scale (three sites in Wisconsin)	Yes to date	J Isebrand efcllc@athenet.net
5	Chinese brake fern	Arsenic (lead)	2 years	Small field, 100 feet square	Yes	RE Carlton carlton.roger@epa.gov
6	Phytoextraction, Lindsey, Ontario	PCBs (Aroclor 1248)		12 × 10 m Field plot and greenhouse work	Maybe	jennifer.low@rmc.ca
7	Phytoextraction and phytostabilization	PCBs, TPH, Pb, An, Cd, Cu	2001–2002	Lab microcosms, wetland using field sediments	Partially	glanza@role.umass.edu
8	ET cap rhizodegradation	PCE, TCE, DCE, VC		Field	Yes	lorentz@ukzn.ac.za
9	Hydraulic control, VOC soil remediation, chemical process and production	Volatile organic compounds (VOCs)	10 years	Full scale	?	F Thomas, KMA Environmental, 409-599-3384
10	Hydraulic control, HS sequestration, Crystal Superfund site	As	10 years	Full scale	?	F Thomas, KMA Environmental, 409-599-3384
11	Hydraulic control, VOC groundwater remediation, oxyvinyls, Deer Park, Tex.	VOCs	30 years	Full scale	?	F Thomas, KMA Environmental, 409-599-3384
12	Evapotranspiration phytostabilization, Grouse Creek, S.C.	F, CN, Mn, Ni, Zn	30 years	Pilot	Yes	A Ludlow, Roux Associates, 631-232-2600
13	Hydraulic control rhizodegration, Rensselear, N.Y.	Metals, VOCs	30 years	Full scale TBD		A Ludlow, Roux Associates, 631-232-2600
14	Hydraulic control rhizodegration, East Providence, R.I.	VOCs, semivolatile organic compounds (SVOCs)	30 years	Pilot	Yes	A Ludlow, Roux Associates, 631-232-2600

No.	Application	Contaminants	Treatment period	Project scale	Success?	Follow-up contact
15	Hydraulic control, Riverview, Mich.	Metals	30 years	Full scale	Yes	A Ludlow, Roux Associates, 631-232-2600
16	Evapotranspiration, Iceland	Metals, F	30 years	Full scale	TBD	W Eifert, Roux Associates, 304-274-0156
17	Hydraulic control, Williamsburg, Va.	Metals	30 years	Full scale	Yes	W Eifert, Roux Associates, 304-274-0156
18	Vegetative cover (dermal barrier)/hydraulic control	Benzene, acetone, MIBK primarily (waste oil, weathered)	30 years	Full scale	So far (2 years)	J Stathyelich, ERM, Indianapolis, IN, 317-706-2014
19	Phytovolatilization, phytocontainment, Minnesota	Landfill mix, As, solvents	30+ years	Full scale	Yes	J Isebrands efcllc@athenet.net
20	Phytoremediation groundcover, active refinery land farm	TPH, organics	2001–2006	Full scale, 25 acres	Yes	tsaodt@bp.com
21	Constructed treatment wetland, former refinery	Various petroleum products	99 years as part of the redevelopment	Full scale, 3.5 acres	Yes	tsaodt@bp.com
22	Constructed treatment wetland, active refinery outfall	Phenol, alkalinity	Operating since 2003, active facility	Full scale, 1 acre	Yes	tsaodt@bp.com
23	Phytoremediation groundcover, active refinery warehouse	Xylene	Operating since 2003, active facility	Full scale, 1 acre	v	tsaodt@bp.com
24	Phytoremediation groundcover, active refinery off-site area	TPH	5 years	Full scale, 2 acre total (of phytoscapes)	Yes	tsaodt@bp.com
25	Riparian buffer, former refinery tank farm	BTEX, MTBE	Installed in 2001	Full scale, <1 acre	Yes	tsaodt@bp.com
26	Phytoremediation tree stand, former refinery off-site area	BTEX	Installed in 2005	Full scale, 1 acre	Yes ?	tsaodt@bp.com
27	Phytoremediation groundcover, former refinery fire training area	TPH	2001–2004	Full scale, 1 acre	N	tsaodt@bp.com
28	Phytoremediation groundcover, former refinery process area	TPH	Installed in 2001, until redevelopment	Full scale, 30 acres	Yes	tsaodt@bp.com

No.	Application	Contaminants	Treatment period	Project scale	Success?	Follow-up contact
29	Phytostabilization cover, former refinery disposal facility	Leachate	7 years pilot, full scale approved for installation in 2008	Field demonstration, full scale, 8–10 acres	Yes	tsaodt@bp.com
30	Constructed treatment wetland, former refinery	TPH, benzene	2008–2009	Full scale	?	tsaodt@bp.com
31	Phytoremediation groundcover, active refinery land farm	TPH	2000–2005	Full scale, 5 acres	Yes and no	tsaodt@bp.com
32	Constructed treatment wetland, active refinery tertiary wastewater treatment	BTEX	Active facility	Full scale	Yes	tsaodt@bp.com
33	Phytoremediation tree stand, active terminal	BTEX, MTBE	5 years, installed in 2002	Full scale, 1 acre	Yes, trees; no, groundcover	tsaodt@bp.com
34	Phytoremediation groundcover, active terminal	BTEX	5 years, installed in 2003	Full scale, 1 acre	Yes?	tsaodt@bp.com
35	Phytoremediation tree stand, active terminal	BTEX, MTBE	1999–2006	Full scale, <1 acre	Yes	tsaodt@bp.com
36	Riparian ruffer, active terminal	BTEX	Installed in 1999, active facility	Full scale, <1 acre	Yes	tsaodt@bp.com
37	Tree hydraulic barrier, active terminal	BTEX	Installed in 2001, active facility	Full scale, <1 acre	?	tsaodt@bp.com
38	Phytoremediation groundcover, former terminal	TPH	2001–2004	Full scale, 1 acre	N	tsaodt@bp.com
39	Phytoremediation tree stand, active terminal	Naphthalene, TPH	30 years in 2000, new strategy implemented in 2008	Full scale, 40 acres	Yes and no	tsaodt@bp.com
40	Phytoremediation tree stand, two active adjacent retail sites	BTEX, MTBE	Installed in 2003, active facility	Full scale, <1 acre	Yes	tsaodt@bp.com
41	Constructed treatment wetland, active retail site	BTEX, gray water	Active in 2000	Full scale, 1 acre	Yes	tsaodt@bp.com
42	Phytoremediation tree stand, unused chemical plant property impacted by adjacent Superfund site	Cu, Cd, Pb, salinity	2000–2005	Field demonstration, <1 acre	Yes	tsaodt@bp.com

No.	Application	Contaminants	Treatment period	Project scale	Success?	Follow-up contact
43	Phytoremediation tree stand, unused chemical plant property	TPH	Divested	Full scale, 1 acre	?	tsaodt@bp.com
44	Constructed treatment wetland, chemical plant remediation streams	Organic acids	2003–2004	Field demonstration, <1 acre	Yes	tsaodt@bp.com
45	Riparian buffer, former exploration and production site	DRO	30 years	Field demonstration, <1 acre	?	tsaodt@bp.com
46	Phytostabilization cover, exploration and production brine release site	Salinity, sodium (sodic soils)	2000–2005	Field demonstration, <1 acre	Yes	tsaodt@bp.com
47	Phytostabilization cover, former exploration and production disposal pits	TPH	20 years	Full scale, 4 acres	Yes	tsaodt@bp.com
48	Constructed treatment wetland	Crude	Active pipeline	Full scale	Backup containment system, never used	tsaodt@bp.com
49	Tree hydraulic barrier, former mine site	Metals, acid pH	1 year	Field demonstration, <1 acre	Yes?	tsaodt@bp.com
50	Phytostabilization cover, former smelter	Metals tailings	In perpetuity	Full scale	Yes	tsaodt@bp.com
51	Phytostabilization cover, former tailings impoundment	Metals tailings	In perpetuity	Full scale	Yes	tsaodt@bp.com
52	Constructed treatment wetland, former tailings impoundment	Acid, arsenic	In perpetuity	Full scale	Yes	tsaodt@bp.com
53	Constructed treatment wetland, city storm water system	Acid pH, metals	In perpetuity	Full scale, 1–2 acres	Yes	tsaodt@bp.com
54	Constructed treatment wetland, former aluminum processing landfill	Cyanide, fluoride	To be installed in 2008	Full scale	Yes, pilot	tsaodt@bp.com
55	Phytoremediation tree stand, former manufacturing facility	Toluene	2007	Full scale, <1 acre	?	tsaodt@bp.com

No.	Application	Contaminants	Treatment period	Project scale	Success?	Follow-up contact
56	Constructed treatment wetland, former solvent recycling facility	TCE	Installed in 1997, still operating	Full scale, 2 acres	Yes	tsaodt@bp.com
57	Phytostabilization cover, former waste disposal	Acid tar	?	Full scale, 2.5 acres	Yes and no	tsaodt@bp.com
58	Phytoremediation tree stand, Superfund site	EDC, TDA	30 years (5-year review)	Full scale	Yes?	tsaodt@bp.com
59	Phytoscapes prevention in various retail markets	Gasoline, BTEX, oxygenates	Prevention	Full scale	Yes	tsaodt@bp.com
60	Vegetative covers for infiltration control	Zinc		Full scale, 1000 acres	Yes	rbelani@state.pa.us

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Appendix D

Phytotechnologies Update Team Contacts

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Appendix E

Glossary

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GLOSSARY

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

adsorption The physical process occurring when liquids, gases, or suspended matter adhere to the surfaces of, or in the pores of, an adsorbent material. Adsorption is a physical process which occurs without chemical reaction.

aerobe An organism that can grow in the presence of air or free oxygen.

aerobic An environment that has a partial pressure of oxygen similar to normal atmospheric conditions.

anaerobe An organism that grows in the absence of oxygen or air.

anaerobic An environment without oxygen or air.

anoxic An atmosphere greatly deficient in oxygen.

bacteria A group of diverse and ubiquitous prokaryotic single-celled microorganisms.

bioaccumulation Intracellular accumulation of environmental pollutants such as heavy metals by living organisms.

biodegradation The breakdown of organic substances by microorganisms.

bioremediation The process by which living organisms are used to degrade or transform hazardous organic contaminants.

bound residue Chemical contaminant that is not extractable from plant tissues by conventional methods (covalent bonding, polymerization, or lignification within the plant).

brownfield An abandoned, idled, or underused industrial or commercial facility where expansion or redevelopment is complicated by a real or perceived environmental contamination.

capillary fringe The porous material just above the water table which may hold water by capillarity (a property of surface tension that draws water upward) in the smaller soil void spaces.

chelate The type of coordination compound in which a central metallic ion (CO^2+, Ni^2+, or Zn^2+) is attached by covalent bonds to two or more nonmetallic atoms in the same molecule, called "ligands." Chelating agents are used to remove ions from solutions and soil.

creosote An antifungal wood preservative used frequently to treat telephone poles and railroad ties. Creosote consists of coal tar distillation products, including phenols and PAHs.

enhanced rhizosphere biodegradation Enhanced biodegradation of contaminants near plant roots where compounds exuded by the roots increase microbial biodegradation activity. Other plant processes such as water uptake by the plant roots can enhance biodegradation by drawing contaminants to the root zone.

enzyme Protein that acts as a biological catalyst. These chemicals produced by living organisms bring about the digestion (breakdown) of organic molecules into smaller units that can be used by living cell tissues.

evapotranspiration Water lost to the atmosphere from the ground surface, evaporation from the capillary fringe of the groundwater table, and the transpiration of groundwater by plants whose roots tap the capillary fringe of the groundwater table.

ex situ Out of the original position (excavated).

exudate Soluble organic matter released from the roots of plants to enhance availability of nutrients or as a by-product of fine root degradation.

greenhouse study Study conducted to evaluate the ability of green plants to grow in toxic soil or water environments. Greenhouse studies are normally conducted during treatability studies.

groundwater Water found beneath the surface of the ground. Groundwater is primarily water which has seeped down from the surface by migrating through the interstitial spaces in soils and geologic formations.

hydrophobic Repelling, tending not to combine with, or incapable of dissolving in water.

in situ In place, without excavation.

lignification Covalent bonding of the chemical or its by-products into the lignin of a plant.

log K_{ow} The octanol-water partition coefficient, a dimensionless constant which provides a measure of how an organic compound will partition between an organic phase and water. A low log K_{ow} indicates that a chemical readily partitions into a water phase; a high log K_{ow} indicates that the chemical prefers to stay in the organic phase. It provides an indication of the quantity of the chemical that will be taken up by the plants.

microorganism Includes bacteria, algae, fungi, and viruses.

mineralization The breakdown of organic matter to inorganic materials (such as carbon dioxide and water) by bacteria and fungi.

nutrients Elements or compounds essential as raw materials for organism growth and development. Nitrogen, phosphorous, potassium, and numerous other mineral elements are essential plant nutrients.

organic pump Uptake of large quantities of water by plant (trees) roots and translocation into the atmosphere to reduce a flow of water. Used to keep contaminated groundwater from reaching a body of water or to keep surface water from seeping into a capped landfill and forming leachate.

part per billion (ppb) A measure of proportion by weight which is equivalent to one unit weight of solute (dissolved substance) per billion unit weights of the solution. One liter of water weighs 1 billion micrograms, and 1 ppb is the equivalent of 1 microgram per liter (µg/L) when used for water analysis.

part per million (ppm) A measure of proportion by weight which is equivalent to one unit weight of solute (dissolved substance) per million unit weights of the solution. One liter of water weighs 1 million milligrams, and 1 ppm is equal to 1 milligram per liter (mg/L) when used for water analysis.

phenol Carbolic acid (C_6H_5OH). Phenols and substituted phenols are used as antimicrobial agents in high concentrations.

phytoaccumulation See "phytoextraction."

phytodegradation The process where plant-produced enzymes break down dissolved organic contaminants that are in the plant through the uptake of water.

phytoextraction The uptake and accumulation of inorganic elements into the plant tissues.

phytoremediation Use of plants to remediate contaminated soil, sediments, surface water, or groundwater.

phytosequestration The ability of plant to sequester certain inorganic elements in the plant and the root zone.

phytostabilization Commonly referred to as "phytosequestration."

phytotoxic Harmful to plants.

phytovolatilization The uptake and subsequent transpiration of volatile contaminants through the plant leaves.

polynuclear aromatic hydrocarbon (PAH) A hydrocarbon compound with multiple benzene rings. PAHs are typical components of asphalts, fuels, oils, and greases.

rhizodegradation Biodegradation of organics by the soil organisms. Exuded plant products through phytosequestration can lead to enhanced biodegradation in the rhizosphere

rhizofiltration Uptake of contaminants by the roots of plants immersed in water. When the roots are saturated with contaminants, they are harvested. This is not synonymous with "hydroponics."

rhizosphere Soil in the area surrounding plant roots that is influenced by the plant root. Typically a few millimeters or at most centimeters from the plant root. Important because this area is higher in nutrients and thus has a higher and more active microbial population.

root turnover The release and decay of fine roots in the soil profile.

Toxicity Characteristic Leaching Procedure (TCLP) An EPA-developed test to determine the toxicity of a chemical.

toxic substances Chemical elements and compounds such as lead, benzene, dioxin, and others that have toxic (poisonous) properties when exposure by ingestion, inhalation, or absorption into the organism occurs. There is a large variation in the degree of toxicity among toxic substances and in the exposure levels that induce toxicity.

translocation Cellular transport through the plant vascular system (xylem) from roots to other plant tissues.

transpiration The plant-based process involving the uptake, transport, and eventual vaporization of water through the plant body.

vadose zone Unsaturated zone of soil above the groundwater, extending from the bottom of the capillary fringe all the way to the soil surface.

volatile organic compound Synthetic organic chemical capable of becoming vapor at relatively low temperatures.

water table The level at the top of the zone of groundwater saturation.

water table depression A drop in water table level caused by mechanical or natural groundwater pumping.

zone of saturation The layer in the ground in which all available interstitial voids (cracks, crevices, and holes) are filled with water. The level of the top of this zone is the water table.

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Appendix F

Acronyms

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ACRONYMS

ARAR	applicable or relevant and appropriate requirement
ASTM	American Society for Testing and Materials
B&B	balled and burlapped
BA	basal trunk area
bgs	below ground surface
BT	*Bacillus thuringiensis*
BTEX	benzene, toluene, ethylbenzene, and (o-, m-, p-) xylenes
CADD	computer-aided design and drafting
CEC	cation exchange capacity
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
COC	contaminant of concern
DCE	dichloroethene
DRO	diesel-range organic
EC	electrical conductivity
ECOS	Environmental Council of the States
EDC	ethylene dichloride
EDTA	ethylene diamine tetra-acetic acid
EPA	U.S. Environmental Protection Agency
EPIC	Erosion/Productivity Impact Calculator
ERIS	Environmental Research Institute of the States
ET	evapotranspiration
FAC	facultative
FACU	facultative upland
FACW	facultative wetland
GAC	granulated activated carbon
GC/MS	gas chromatography/mass spectrometry
GMO	genetically modified organism
gpd	gallons per day
GRO	gasoline-range organic
ITRC	Interstate Technology & Regulatory Council
HELP	hydrologic evaluation of landfill performance
HMX	1,3,5,7-tetranitro-1,3,5,7-tetrazocane
HRT	hydraulic retention time

LAI	leaf area index
MIBK	methyl isobutyl ketone
MTBE	methyl tertiary-butyl ether
ND	nondetect
NESHAPS	National Emissions Standards for Hazardous Air Pollutants
NGO	nongovernmental organization
NPDES	National Pollutant Discharge and Elimination System
NPS	nonpoint source
O&M	operation and maintenance
OBL	obligate wetland
OM&M	operation, maintenance, and monitoring
PAH	polycyclic aromatic hydrocarbon
PAR	photosynthetically active radiation
PCB	polychlorinated biphenyl
PCE	perchloroethene
PET	potential evapotranspiration
PLFA	phospholipid fatty acid
PPE	personal protective equipment
PSI	photosystem I
PSII	photosystem II
PVC	polyvinyl chloride
RCF	root concentration factor
RCRA	Resource Conservation and Recovery Act
RDX	1,3,5-trinitroperhydro-1,3,5-triazine
RO	reverse osmosis
SAR	sodium adsorption ratio
SVOC	semivolatile organic compound
TBA	tertiary butyl alcohol
TCE	trichloroethene
TDA	toluenediamine
TDS	total dissolved solids
TNT	trinitrotoluene
TPH	total petroleum hydrocarbons
TSCA	Toxic Substances Control Act
TSCF	transpiration stream concentration factor
UPL	upland
U.S.C.	U.S. Code

USDA	U.S. Department of Agriculture
VC	vinyl chloride
VOC	volatile organic compound