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# Introduction to Phytoremediation

National Risk Management Research Laboratory
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# Notice

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# Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technicological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and ground water; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

# Abstract

Phytoremediation is the name given to a set of technologies that use different plants as a containment, destruction, or an extraction technique. Phytoremediation as a remediation technology that has been receiving attention lately as the results from field trials indicate a cost savings compared to conventional treatments.

The U.S. EPA has a dual role in which it seeks to protect human health and the environment associated with hazardous waste sites, while encouraging development of innovative technologies that might more efficiently clean up these sites.

This Introduction is intended to provide a tool for site regulators, owners, neighbors, and managers to evaluate the applicability of phytoremediation to a site. This document defines terms and provides a framework to understand phytoremediation applications. It is a compilation of research and remediation work that has been done to date. The format is intended to be accessible to EPA RPMs, state regulators, and others who need to choose between alternate technologies, as well for site owners, consultants, contractors, and students who are interested in basic information. It is not a design manual, and is not intended to provide enough information to choose, engineer, and install a phytoremediation application.

This work may also be used to help guide research, development, and regulation. Areas of needed research have been identified. By compiling the published and unpublished work, research repetition can be avoided, and areas of opportunity that need attention should be clear.

# Table of Contents

Foreword ..... iii
Acknowledgements ..... xi

Chapter 1 Introduction ..... 1

1.1 Objectives ..... 1
1.2 Approach ..... 1
1.3 Report Organization ..... 1

Chapter 2 Overview of Phytoremediation ..... 3

2.1 Background ..... 3
2.2 Technical Considerations ..... 7
2.3 Economic Considerations ..... 7
2.4 Regulatory Considerations ..... 9
2.5 Ecosystem Restoration ..... 10
2.6 Current Research ..... 12

Chapter 3 Evaluation of Phytoremediation Technologies ..... 14

3.1 Phytoextraction ..... 14
3.2 Rhizofiltration ..... 18
3.3 Phytostabilization ..... 21
3.4 Rhizodegradation ..... 23
3.5 Phytodegradation ..... 28
3.6 Phytovolatilization ..... 31
3.7 Hydraulic Control ..... 34
3.8 Vegetative Cover Systems ..... 35
3.9 Riparian Corridors/Buffer Strips ..... 39

Chapter 4 Phytoremediation System Selection and Design Considerations ..... 41

4.1 Contaminated Media Considerations ..... 42
4.2 Contaminant Considerations ..... 43
4.3 Plant Considerations ..... 44
4.4 Site Considerations ..... 48
4.5 Treatment Trains ..... 51
4.6 Additional Information Sources ..... 51

Chapter 5 Remedial Objectives, Treatability, and Evaluation ..... 52

5.1 Remedial Objectives ..... 52
5.2 Treatability Studies ..... 53
5.3 Monitoring for Performance Evaluation ..... 56

# **Contents** (continued)

Chapter 6 Case Studies ........................................ 58

6.1 Edgewood Area J-Field Toxic Pits Site Aberdeen Proving Grounds Edgewood, Maryland ........................................ 58
6.2 Carswell Site Fort Worth, Texas ........................................ 60
6.3 Edward Sears Properties Site New Gretna, New Jersey ........................................ 64
6.4 Bioengineering Management: U.S. Nuclear Regulatory Commission Beltsville, MD ........................................ 67
6.5 Lakeside Reclamation Landfill Beaverton, Oregon ........................................ 68
6.6 Alternative Landfill Cover Demonstration Sandia National Laboratories Albuquerque, NM ........................................ 70

Appendix A Glossary ........................................ A-1
Appendix B Phytoremediation Database ........................................ B-1
Appendix C References ........................................ C-1
Appendix D Common and Scientific Names of Referenced Plants ........................................ D-1

# Figures

Figure 2-1. Mechanisms for phytoremediation. .......... 4
Figure 2-2. Example root depths. .......... 6
Figure 3-1. Phytoextraction. .......... 16
Figure 3-2. Rhizodegradation. .......... 24
Figure 3-3. Phytodegradation. .......... 29
Figure 3-4. Phytovolatilization. .......... 32
Figure 3-5. Hydraulic control of contaminated plume. .......... 34
Figure 3-6. Illustration of an Evapotranspiration (ET) cover. .......... 36
Figure 3-7. Phytoremediation cover evolution. .......... 37
Figure 6-1. Experimental Design .......... 61
Figure 6-2. TCE Concentrations .......... 63
Figure 6-3. Site Map (Edward Sears Site) .......... 65
Figure 6-4. Sampling Grid (Edward Sears Site) .......... 66

# Tables

Table 2-1. Phytoremediation Applications ..... 5
Table 2-2. Root Depth for Selected Phytoremediation Plants ..... 6
Table 2-3. Phytoremediation at Superfund Sites ..... 8
Table 3-1. Phytoremediation Overview ..... 15
Table 4-1. Phytoremediation Technologies Applicable to Different Contaminant Types[1,2] ..... 43
Table 4-2. Plant Selection Process ..... 45
Table 5-1. Summary of Phytoremediation Technologies and Method of Contaminant Control 52
Table 5-2. Experimental Factors for Testing in Treatability Studies ..... 54
Table 5-3. Information Needed for a Pilot Treatability Study ..... 55
Table 5-4. Summary of Monitoring Parameters ..... 57
Table 6-1. Monitoring Approaches at the J-Field Site. ..... 59
Table 6-3. Estimated Cost of Phytoremediation at the Carswell Site. ..... 63
Table 6-2. Average Concentrations of TCE, cis-DCE, and trans-DCE at Carswell Site. ..... 63
Table 6-4. Design Type and Completion Dates for the Experimental Covers. ..... 67
Table 6-5. Summary of Run-off, Evapotranspiration, and Deep Percolation From the Bioengineered Plots. ..... 68
Table 6-6. Summary of Percolation and Precipitation Rates From May 1997 Through March 1998 for the Six Cover Designs. ..... 72
Table 6.7 Construction Costs for the Final Landfill Covers ..... 72

# Acronyms

| | |
|---|---|
| AAP | Army Ammunition Plant |
| ACAP | Alternative Cover Assessment Program (U.S. EPA) |
| ALCD | Alternative Landfill Cover Demonstration |
| ANOVA | Analysis of Variance |
| APG | Aberdeen Proving Grounds |
| ARARs | Applicable or Relevant and Appropriate Requirements |
| ASTM | American Society for Testing and Materials |
| BTEX | Benzene, Toluene, Ethylbenzene, Xylenes |
| CERCLA | Comprehensive Environmental Response, Compensation, and Liability Act |
| $C_o$ | Original Concentration |
| DEPH | Diethylhexylphthalate |
| DNAPL | Dense Nonaqueous Phase Liquid |
| DOD | Department of Defense |
| DOE | Department of Energy |
| EPA | Environmental Protection Agency |
| ERT | U.S. EPA Emergency Response Team |
| FFDCA | Federal Food, Drug, and Cosmetic Act |
| FIFRA | Federal Insecticide, Fungicide, and Rodenticide Act |
| GC/MS | Gas Chromatography/Mass Spectroscopy |
| HCB | Hexachlorobenzene |
| $K_{ow}$ | octanol-water partition coefficient |
| LNAPL | Light Nonaqueous Phase Liquid |
| MCL | Maximum Contaminant Level |
| NPDES | National Pollutant Discharge Elimination System |
| NPL | National Priority List (Superfund) |
| NRMRL | National Risk Management Research Laboratory |
| OSC | On-Scene Coordinator |
| ORD | U.S. EPA Office of Research and Development |
| OSWER | U.S. EPA Office of Solid Waste and Emergency Response |
| PAH | Polynuclear Aromatic Hydrocarbons |
| PCB | Polychlorinated Biphenyls |
| PCE | Perchloroethylene, tetrachloroethene |
| PCP | Pentachlorophenol |
| PRP | Potentially Responsible Party |
| PVC | Polyvinyl Chloride |
| QA/QC | Quality Assurance/Quality Control |
| RCRA | Resource Conservation and Recovery Act |
| RD | Remedial Design |
| RPM | Remedial Project Manager |
| ROD | Record of Decision |
| RTDF | Remediation Technologies Development Forum |
| SITE | Superfund Innovative Technology Evaluation Program (EPA) |
| TCA | Tetrachloroethane |
| TCAA | Trichloroacetic acid |
| TCE | Trichloroethylene |
| TIO | U.S. EPA Technology Innovation Office |
| TNT | Trinitrotoluene |

# **Acronyms** (continued)

| | |
|---|---|
| TPH | Total Petroleum Hydrocarbons |
| TSCA | Toxic Substances Control Act |
| USDA | U.S. Department of Agriculture |
| UXO | Unexploded Ordinance |
| VOC | Volatile Organic Compounds |

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# Chapter 1
# Introduction

Phytoremediation is an emerging technology that uses various plants to degrade, extract, contain, or immobilize contaminants from soil and water. This technology has been receiving attention lately as an innovative, cost-effective alternative to the more established treatment methods used at hazardous waste sites.

The U.S. Environmental Protection Agency (EPA) seeks to protect human health and the environment from risks associated with hazardous waste sites, while encouraging development of innovative technologies such as phytoremediation to more efficiently clean up these sites.

This document reports the results of phytoremediation efforts as originally reported by researchers. No attempts were made to validate data obtained from the literature.

## 1.1 Objectives

The objectives of this report are as follows:

- Provide an educational tool for site regulators, owners, neighbors, and managers to evaluate the applicability of phytoremediation to a site. Phytoremediation projects have been proposed or applied to ecosystem restoration and soil, surface water, groundwater, and sediment remediation. This document identifies and defines phytoremediation technologies, and provides a guide to current research to aid in evaluation of proposed phytoremediation applications.

- Develop a format that is accessible to EPA and state regulators and others who need to evaluate alternate remedial technologies, as well as to site owners, project managers, consultants, contractors, and students who are interested in basic information.

- Evaluate the various phytoremediation processes (e.g., phytodegradation, rhizofiltration, hydraulic control).

- Present phytoremediation system characteristics that site managers and others might find useful in assessing the potential applicability of phytoremediation to a specific site.

- Present case studies illustrating field applications of phytoremediation.

- Provide a detailed bibliography of additional resources for those interested in learning more about phytoremediation.

- Provide access to general information on various resource applications. However, it should be noted that this document is not a design manual and is not intended to provide enough information to engineer and install any phytoremediation application.

- Provide a guide for research, development, and regulation, and identify areas of needed research. Through the compilation of published and unpublished work, research repetition can be avoided, and areas of opportunity that need attention should be clear.

## 1.2 Approach

The following approach was used to compile and summarize information on phytoremediation processes:

- Conduct a comprehensive literature search.

- Contact contractors and researchers to obtain information on phytoremediation applications and cost.

- Review and evaluate existing research and field applications of current phytoremediation projects.

- Assemble a compilation of research and remedial work that has been performed to date.

- Use the resources of the Internet to both gather and disseminate information. The creators of this document have written their sections so that they can be regularly updated to keep them relevant as the technology changes. This document may be accessed on the Internet “www.clu-in.org”.

## 1.3 Report Organization

This report has been designed to provide quick access to information on the various phytoremediation processes and associated information as follows:

- Chapter 2 provides an overview of phytoremediation including applications, limits, cost information, and regulatory concerns. Ecosystem restoration as it applies to phytoremediation processes is also discussed.

- Chapter 3 provides a literature review and evaluation of the major phytoremediation processes. This chapter is divided into subsections that present definitions, mechanisms, site characteristics, applicable media, contaminants amenable to each phytoremediation process, and the associated concentrations where available. The advantages, disadvantages, and current status of each process are also discussed. Finally, an annotated reference list is included at the end of the discussion of each phytoremediation process to provide more detailed, specific information. The purpose of this chapter is to provide site managers with an overview of the various phytoremediation processes as well as what can be expected from each process and its limitations.

- Chapter 4 discusses considerations involved in the selection, design, and implementation of phytoremediation systems. It presents information that will help a site manager to identify whether phytoremediation may be appropriate for a site and to select a particular phytoremediation technology, based on the conditions occurring at, or applicable to, a site. This chapter introduces issues and concepts that should be considered in the design and implementation of a phytoremediation system.

- Chapter 5 presents the remedial objectives for phytoremediation as well as associated monitoring needed to evaluate system performance. Information on conducting treatability studies is also included in this chapter.

- Chapter 6 presents six case studies where phytoremediation has been applied. The six case studies presented in this chapter illustrate specific field applications of phytoremediation. This chapter includes site descriptions, design considerations, monitoring recommendations, status, and costs of various phytoremediation processes.

- Included as appendices are a glossary of phytoremediation terms, references, common and scientific names of referenced plants, and part of the database that provides information on phytoremediation projects available on the Internet or through EPA.

Please note that because phytoremediation is an emerging technology, standard performance criteria for phytoremediation systems have not been developed. Data are being gathered and assessed to develop performance measures that can be used to predict the function and efficacy of an individual system.

# Chapter 2
# Overview of Phytoremediation

## 2.1 Background

Phytoremediation is the name given to a set of technologies that use plants to clean contaminated sites. Many techniques and applications have been called phytoremediation, possibly leading to confusion. This document uses the term phytoremediation to refer to a set of plant-contaminant interactions, and not to any specific application. Many of the phytoremediation techniques involve applying information that has been known for years in agriculture, silviculture, and horticulture to environmental problems.

The term phytoremediation (*phyto* = plant and *remediation* = correct evil) is relatively new, coined in 1991. Basic information for what is now called phytoremediation comes from a variety of research areas including constructed wetlands, oil spills, and agricultural plant accumulation of heavy metals. The term has been used widely since its inception, with a variety of specific meanings. In this document phytoremediation is used to mean the overall idea of using plant-based environmental technologies, not any specific application.

Research efforts into remediation can be roughly categorized into two sets: exploration of mechanisms and evaluation of claims. Mechanism work has centered on finding theoretical limits, and explanations for results observed in the field. Pilot-scale field work has both preceded and followed explanatory laboratory research, and early successes have piqued interest. Long-term, objective field evaluation is critical to understanding how well phytoremediation may work, what the real cost of application will be, and how to build models to predict the interaction between plants and contaminants. Most of the projects are ongoing and thus provide only preliminary data.

### *2.1.1 Applications*

Phytoremediation applications (as shown in Figure 2-1 and Table 2-1) can be classified based on the contaminant fate: degradation, extraction, containment, or a combination of these. Phytoremediation applications can also be classified based on the mechanisms involved. Such mechanisms include extraction of contaminants from soil or groundwater; concentration of contaminants in plant tissue; degradation of contaminants by various biotic or abiotic processes; volatilization or transpiration of volatile contaminants from plants to the air; immobilization of contaminants in the root zone; hydraulic control of contaminated groundwater (plume control); and control of runoff, erosion, and infiltration by vegetative covers. A brief explanation of these application categories follows, with more detailed explanations in following chapters.

#### 2.1.1.1 Degradation

Plants may enhance degradation in the rhizosphere (root zone of influence). Microbial counts in rhizosphere soils can be 1 or 2 orders of magnitude greater than in nonrhizosphere soils. It is not known whether this is due to microbial or fungal symbiosis with the plant, plant exudates including enzymes, or other physical/chemical effects in the root zone. There are, however, measurable effects on certain contaminants in the root zone of planted areas. Several projects examine the interaction between plants and such contaminants as trinitrotoluene (TNT), total petroleum hydrocarbons (TPH), pentachlorophenol (PCP), and polynuclear aromatic hydrocarbons (PAH).

Another possible mechanism for contaminant degradation is metabolism within the plant. Some plants may be able to take in toxic compounds and in the process of metabolizing the available nutrients, detoxify them. Trichloroethylene (TCE) is possibly degraded in poplar trees and the carbon used for tissue growth while the chloride is expelled through the roots. EPA has three projects underway in the field using *populus* species to remediate TCE. Tests at the University of Washington are being developed to verify this degradation mechanism under controlled conditions.

#### 2.1.1.2 Extraction

Phytoextraction, or phytomining, is the process of planting a crop of a species that is known to accumulate contaminants in the shoots and leaves of the plants, and then harvesting the crop and removing the contaminant from the site. Unlike the destructive degradation mechanisms, this technique yields a mass of plant and contaminant (typically metals) that must be transported for disposal or recycling. This is a concentration technology that leaves a much smaller mass to be disposed of when compared to excavation and landfilling. This technology is being evaluated in a Superfund Innovative Technology Evaluation (SITE) demonstration, and may also be a technology amenable to contaminant recovery and recycling.

Rhizofiltration is similar to phytoextraction in that it is also a concentration technology. It differs from phytoextraction

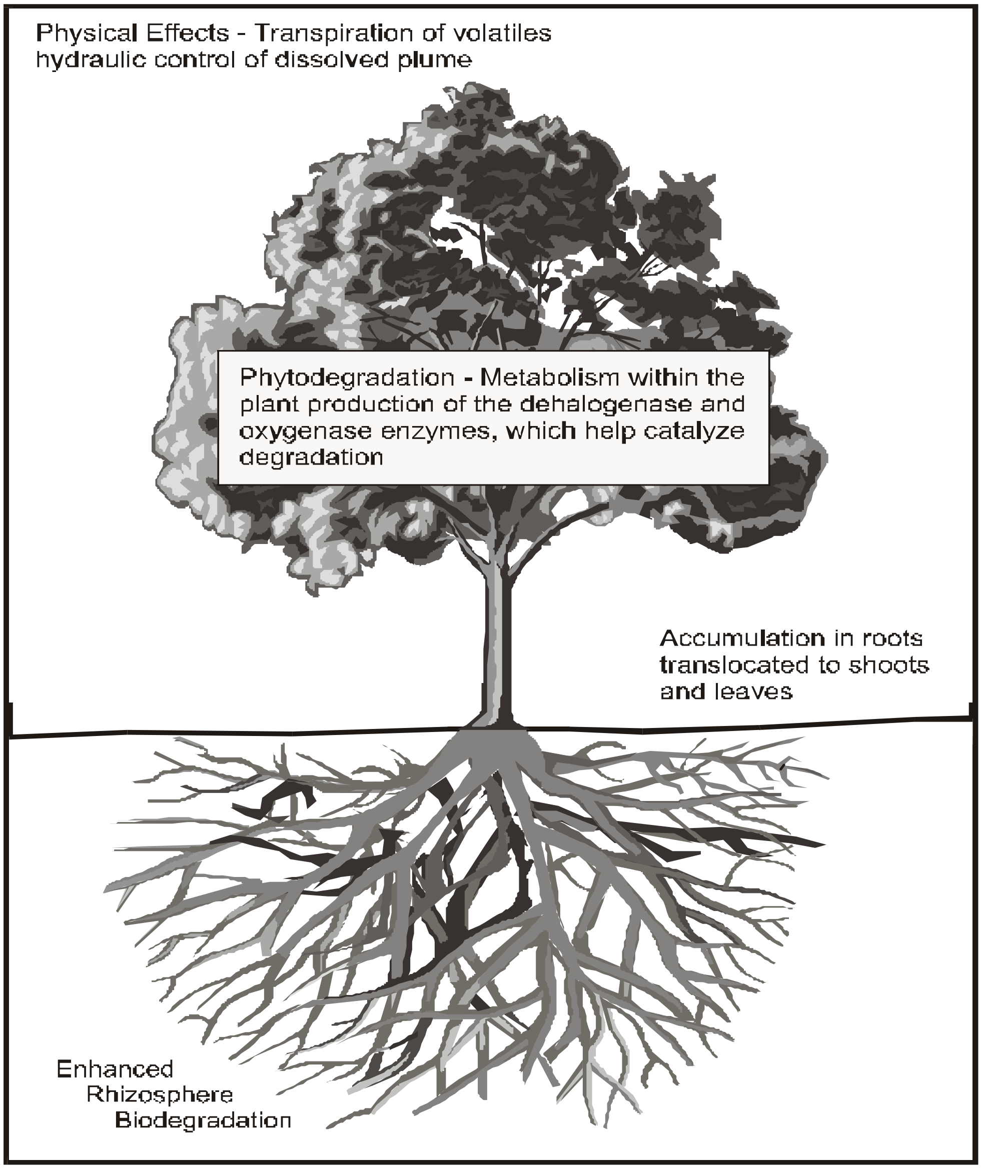


**Figure 2-1.** Mechanisms for phytoremediation.

in that the mechanism is root accumulation and harvest using hydroponic (soil-less) growing techniques. This is useful for separating metal contaminants from water. Rhizofiltration has been demonstrated on U.S. Department of Energy (DOE) sites for radionuclides.

Volatilization or transpiration through plants into the atmosphere is another possible mechanism for removing a contaminant from the soil or water of a site. It is often raised as a concern in response to a proposed phytoremediation project, but has not been shown to be an actual pathway for many contaminants. Mercury (Hg) has been shown to move through a plant and into the air in a plant that was genetically altered to allow it to do so. The thought behind this media switching is that elemental Hg in the air poses less risk than other Hg forms in the soil. However, the technology or the associated risk has not been evaluated.

#### 2.1.1.3 Containment and Immobilization

Containment using plants either binds the contaminants to the soil, renders them nonbioavailable, or immobilizes them by removing the means of transport.

Physical containment of contaminants by plants can take the form of binding the contaminants within a humic molecule (humification), physical sequestration of metals as occurs in some wetlands, or by root accumulation in nonharvestable plants. Certain trees sequester large concentrations of metals in their roots, and although harvesting and removal is difficult or impractical, the contaminants present a reduced human or environmental risk while they are bound in the roots.

Risk reduction may also be achieved by transforming the contaminant into a form that is not hazardous, or by render-

**Table 2-1.** Phytoremediation Applications

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

ing the contaminant nonbioavailable. EPA and the U.S. Department of Agriculture (USDA) have ongoing research in this area.

Hydraulic control is another form of containment. Groundwater contaminant plume control may be achieved by water consumption, using plants to increase the evaporation and transpiration from a site. Some species of plants use tremendous quantities of water, and can extend roots to draw from the saturated zone. EPA is pursuing research in this area at a number of sites, including the SITE demonstrations at Ogden, UT and Ft. Worth, TX, and the Emergency Response Team (ERT) lead projects at Aberdeen Proving Grounds (Edgewood, MD) and the Edward Sears Properties Site (New Gretna, NJ). Private companies have installed trees as a hydraulic control at many sites.

Vegetative cover (evapotranspiration or water-balance cover) systems are another remediation application utilizing the natural mechanisms of plants for minimizing infiltrating water. Originally proposed in arid and semi-arid regions, vegetative covers are currently being evaluated for all geographic regions. The effectiveness in all regions and climates needs to be assessed on a site-specific basis.

If there is potential for gas generation a vegetative cover may not be an option. For example, a municipal solid waste landfill can produce landfill gas that may be of concern to human health and the environment. Sites with requirements to collect and control landfill gas may not meet Federal requirements under the Clean Air Act if a vegetative cover is used.

Hydraulic control for groundwater plumes and water balance covers are two technologies that are being applied in the field prior to model development predicting their behavior. Under an EPA initiative called Alternative Cover Assessment Program (ACAP), several of these field installations will be monitored carefully and consistently to gather data to both evaluate performance and to build and verify models to predict the performance of other proposed installations. Data from a national network of sites that have similar measurement regimes will be a powerful tool for evaluating the appropriateness of a proposed installation, and help develop the tools for predicting the efficacy of similar cover systems.

### *2.1.2 Limits of Phytoremediation at Hazardous Waste Sites*

As a result of the early information provided by some research and reported by the media, site owners and citizen groups are interested in phytoremediation as possibly the cleanest and cheapest technology that may be employed in the remediation of selected hazardous sites. Although current research continues to explore and push the boundaries of phytoremediation applications, there are certain limitations to plant-based remediation systems.

#### 2.1.2.1 Root System

Root contact is a primary limitation on phytoremediation applicability. Remediation with plants requires that the contaminants be in contact with the root zone of the plants. Either the plants must be able to extend roots to the contaminants, or the contaminated media must be moved to within range of the plants. This movement can be accomplished with standard agricultural equipment and practices, such as deep plowing to bring soil from 2 or 3 feet deep to within 8 to 10 inches of the surface for shallow-rooted crops and grasses, or by irrigating trees and grasses with contaminated groundwater or wastewater. Because these activities can generate fugitive dust and volatile organic compound emissions, potential risks may need to be evaluated. As shown in Table 2-2 and illustrated in Figure 2-2, the effective root depth of plants varies by species and depends on soil and climate condition.

**Table 2-2.** Root Depth for Selected Phytoremediation Plants

| Plant | Maximum Root Depth | Target Contaminants |
|---|---|---|
| Indian mustard | To 12 inches | Metals |
| Grasses | To 48 inches | Organics |
| Poplar trees | To 15 feet | Metals, organics, chlorinated solvents |

### 2.1.2.2 Growth Rate

Phytoremediation is also limited by the growth rate of the plants. More time may be required to phytoremediate a site as compared with other more traditional cleanup technologies. Excavation and disposal or incineration takes weeks to months to accomplish, while phytoextraction or degradation may need several years. Therefore, for sites that pose acute risks for human and other ecological receptors, phytoremediation may not be the remediation technique of choice.

### 2.1.2.3 Contaminant Concentration

Sites with widespread, low to medium level contamination within the root zone are the best candidates for phytoremediative processes. High concentrations of contaminants may inhibit plant growth and thus may limit application on some sites or some parts of sites. This phytotoxicity could lead to a tiered remedial approach in which high concentration waste is handled with expensive ex situ techniques that quickly reduce acute risk, while in situ phytoremediation is used over a longer period of time to clean the high volumes of lower contaminant concentrations.

### 2.1.2.4 Impacts of Contaminated Vegetation

Some ecological exposure may occur whenever plants are used to interact with contaminants from the soil. The fate of the metals in the biomass is a concern. At one site, sunflower plants that extracted cesium (Cs) and strontium (Sr) from surface water were disposed of as radioactive waste (Adler 1996).

Although some forms of phytoremediation involve accumulation of metals and require handling of plant material embedded with metals, most plants do not accumulate significant levels of organic contaminants. While metal accumulating plants will need to be harvested and either recycled or disposed of in compliance with applicable regulations, most phytoremediative plants do not require further treatment or disposal.

Often overlooked, however, is the possibility that natural vegetation on the site is already creating very similar (but often unrecognized) food chain exposures. In addition, even on currently unvegetated sites, contaminants will be entering the food chain through soil organisms.

The remediation plan should identify and, if possible, quantify potential avenues of ecological exposure, and determine if and where any accumulation of toxics in the selected plants will occur. Accumulation in fruits, seeds, and

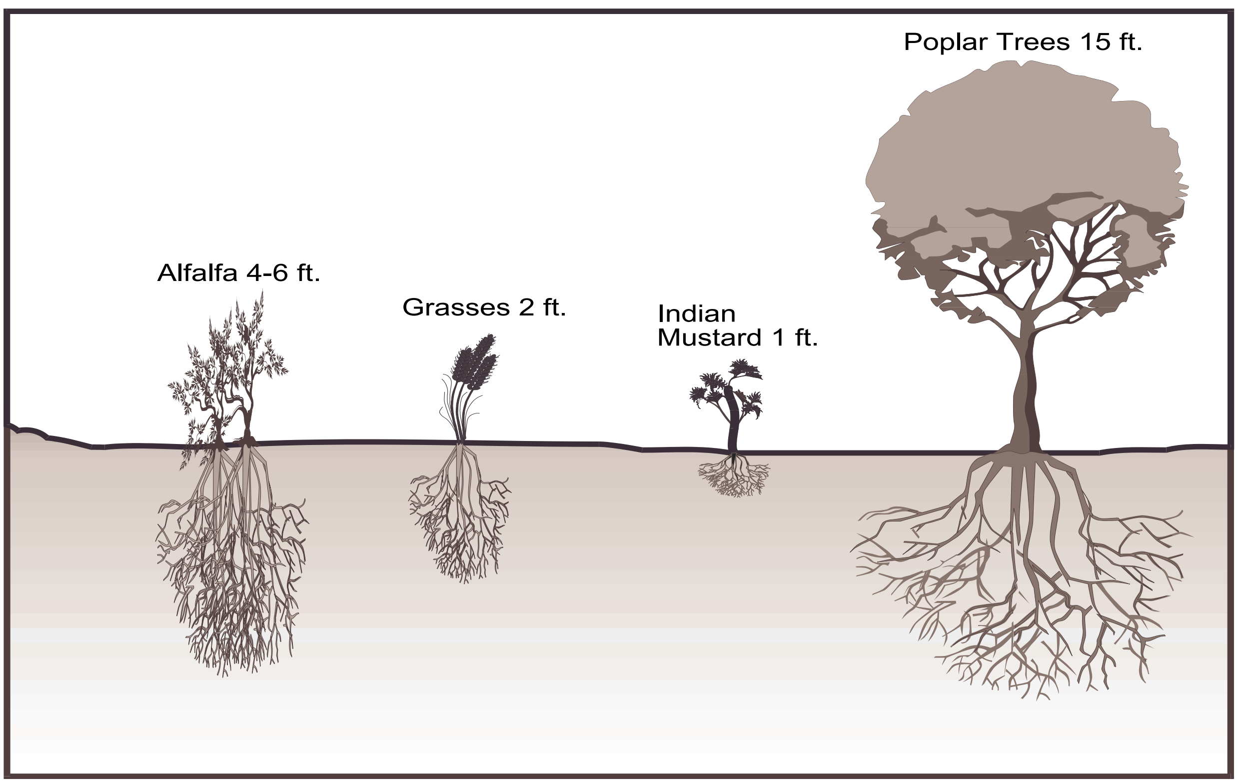


**Figure 2-2.** Example root depths.

leaves typically creates more exposure than accumulation in stems and roots. Most organic contaminants do not accumulate in significant amounts in plant tissue.

Some plant-eating animals have been shown to avoid eating plants with elevated metal levels (Pollard 1996). In addition, the increased habitat provided by the plants may in some cases offset any potential localized impacts.

If some organisms (e.g., caterpillars, rodents, deer, etc.) seem likely to ingest significant amounts of the vegetation, and if harmful bioconcentration up the food chain is a concern during the life of the remediation effort, appropriate exposure control measures should be implemented including perimeter fencing, overhead netting, and pre-flowering harvesting. Phytoextraction techniques aim to harvest metal-laden crops just as the plants translocate metals into shoots, thereby limiting availability of contaminants for consumption.

Transfer of the contaminants or metabolites to the atmosphere might be the greatest regulatory concern. Transpiration of TCE into the atmosphere has been measured (Newman et al. 1997a), but little information is available that would indicate any release of vinyl chloride.

Research being done on the bioavailability of contaminants and on human health and environmental risk assessment is directly related to phytoremediation. Studies are underway to determine if contaminants that are not available to plants for uptake or that are not vulnerable to plant remediation are less of a risk to human health and the environment.

## 2.2 Technical Considerations

Several key factors to consider when evaluating whether phytoremediation is a potential site remedy are described below.

1. Determine whether evidence of the potential effectiveness of phytoremediation is specific to the site matrix and contaminants. If laboratory studies on the plants and contaminants of interest are the primary evidence used to support the use of phytoremediation at the site, the studies should at least show that the plants to be used at the site are capable of remediating site contaminants.

2. Consider the protectiveness of the remedy during the time it takes the plants associated with phytoremediation to establish themselves at the site to a point where they are containing/degrading the contaminants of interest.

3. Consider whether phytoremediation is likely to clean up the site in an acceptable time frame.

4. An adequate backup or contingency technology should be identified in the event that phytoremediation is attempted and does not succeed.

Additionally, monitoring the efficacy of any innovative treatment may be more extensive than would be required for a more accepted technology. Monitoring needs to address both the decrease in the concentration of the contaminants in the media of concern, and examine the fate of the contaminants. The monitoring plan must be tailored to the site and plants.

### *2.2.1 Prior Applications of Phytoremediation*

One indication of acceptability of a technique is previous successful applications on similar sites. Because it is a relatively new technology, phytoremediation does not have a long history of completed cleanups. Table 2-3 lists 12 Superfund sites where phytoremediation has been accepted or is being field-tested for possible remediation of soil or groundwater contamination. Appendix B lists approximately 180 sites where the technology has been applied or is being field-tested. The peer-reviewed field data that are available on these projects are limited. More data should become available in the next few years through the efforts of programs such as the Superfund Innovative Technology Evaluation (SITE) program, the Remediation Technologies Development Forum (RTDF), and others.

Results of studies done in greenhouses and on field test plots can be used to show proof of concept, and some of that data may be directly applicable to site-specific consideration. If time and funding permit, soil or water from the site should be used in lab or greenhouse studies. Such treatability studies can confirm the effectiveness of the site-specific treatment. Chapter 5 provides more information on treatability studies.

## 2.3 Economic Considerations

Because phytoremediation is an emerging technology, standard cost information is not readily available. Subsequently, the ability to develop cost comparisons and to estimate project costs will need to be determined on a site-specific basis. Two considerations influence the economics of phytoremediation: the potential for application, and the cost comparison to conventional treatments. Care must be taken to compare whole system costs, which may include:

Design costs:
- Site characterization
- Work plan and report preparation
- Treatability and pilot testing

Installation costs
- Site preparation
  - Facilities removal
  - Debris removal
  - Utility line removal/relocation
- Soil preparation
  - Physical modification: tilling
  - Chelating agents
  - pH control
  - Drainage
- Infrastructure
  - Irrigation system
  - Fencing
- Planting
  - Seeds, plants
  - Labor
  - Protection

Operating costs:
- Maintenance
  - Irrigation water
  - Fertilizer
  - pH control
  - Chelating agent
  - Drainage water disposal
  - Pesticides
  - Fencing/pest control
  - Replanting
- Monitoring
  - Soil nutrients
  - Soil pH
  - Soil water
  - Plant nutrient status
  - Plant contaminant status roots, shoots, stems, leaves)
  - Tree sap flow monitoring
  - Air monitoring (leaves, branches, whole tree, area)
  - Weather monitoring

**Table 2-3.** Phytoremediation at Superfund Sites

| Site Name, State | Date Planted | Plant | Contaminant/Matrix |
|---|---|---|---|
| Carswell Site, TX | Spring 1996 | Eastern cottonwood tree | TCE/groundwater at 4-12 feet |
| Aberdeen Proving Grounds, MD | Spring 1996 | Hybrid poplar trees | TCE/groundwater |
| Edward Sears Site, NJ | Fall 1996 | Hybrid poplar trees | TCE/groundwater at 8 feet |
| Iowa Army Ammunition Depot, IA | Spring 1997 | Wetland and terrestrial plants | TNT/soil and pond water |
| Fort Wainwright, AK | Spring 1997 | Felt leaf willow | Pesticides/soil and groundwater |
| Kaufman & Minteer, NJ | Spring 1997 | Hybrid poplar trees | PCE/groundwater |
| Calhoun Park, SC | Fall 1998 | Local landscaping plants | PAH/groundwater at 1-4 feet |
| Solvent Recovery Systems of New England, CT | Spring 1998 | Hybrid poplar trees | Mixed solvents/groundwater |
| Twin Cities Army Ammunition Plant, MN | Spring 1998 | Corn, Indian mustard | Metals/soil |
| Bofors-Nobel, MI | Planting scheduled | Various trees and wetland plants | Residual sludge in waste lagoons |
| Del Monte, HI | Spring 1998 | Koa haole | Pesticides/soil and groundwater |
| INEEL, ID | Spring 1999 | Kochia, willow | Cesium, mercury in soil |

The national potential for phytoremediation could be estimated by first totaling the number of sites that contain organics and metals suitable for phytoremediation, i.e., those sites that contain contaminants in moderate concentrations in near-surface groundwater or in shallow soils. Currently, such specific information about hazardous waste sites in the United States is not available. Kidney (1997) has estimated the current domestic market for phytoremediation at only $2 to $3 million for organics removal from groundwater, and $1 to $2 million for removal of heavy metals from soils. The same study indicates that by the year 2005, however, the market for phytoremediation of organics in groundwater will be $20 to $45 million, of metals in soils will be $40 to $80 million, and of radionuclides will be $25 to $50 million.

David Glass (1998) and others have estimated that total system costs for some phytoremediation applications will be 50 to 80% lower than alternatives. Each application of plants will yield a separate performance evaluation including rate and extent of cleanup and cost. Three actual cost estimates of applications are compared to conventional treatments in Table 2-4.

For some of phytoremediation applications, hypothetical cost comparisons have been projected. These are estimates based on laboratory and pilot scale work and tend to reflect projected total project costs.

### *Phytoextraction Costs*

(A) The estimated 30-year costs (1998 dollars) for remediating a 12-acre lead site were $12,000,000 for excavation and disposal, $6,300,000 for soil washing, $600,000 for a soil cap, and $200,000 for phytoextraction (Cunningham 1996).

(B) Cost estimates made for remediation of a hypothetical case of a 20-in.-thick layer of sediments contaminated with Cd, Zn, and $^{137}Cs$ from a 1.2-acre chemical waste disposal pond indicated that phytoextraction would cost about one-third the amount of soil washing (Cornish et al. 1995).

(C) Costs were estimated to be $60,000 to $100,000 using phytoextraction for remediation of one acre of 20-in.-thick sandy loam compared to a minimum of $400,000 for just excavation and storage of this soil (Salt et al. 1995).

### *Rhizofiltration Costs*

The cost of removing radionuclides from water with sunflowers has been estimated to be $2 to $6 per thousand gallons of water (Dushenkov et al. 1997).

### *Phytostabilization Costs*

Cropping system costs have been estimated at $200 to $10,000 per hectare, equivalent to $0.02 to $1.00 per cubic meter of soil, assuming a 1-meter root depth (Cunningham et al. 1995b).

### *Hydraulic Control Costs*

Estimated costs for remediation of an unspecified contaminant in a 20-foot-deep aquifer at a 1-acre site were $660,00 for conventional pump-and-treat, and $250,000 for phytoremediation using trees (Gatliff 1994).

### *Vegetative Cover Costs*

Cost estimates indicate savings for an evapotranspiration cover compared to a traditional cover design to be 20

**Table 2-4.** Example Cost Comparisons

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

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

to 50%, depending on availability of suitable soil (RTDF 1998).

## 2.4 Regulatory Considerations

While Federal regulations specific to phytoremediation have not been developed, a range of existing Federal and state regulatory programs may pertain to site-specific decisions regarding the use of this technology. These programs include those established under the: Resource Conservation and Recovery Act (RCRA); Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) referred to as "Superfund"; Clean Air Act (CAA); Toxic Substances Control Act (TSCA); Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA); Federal Food, Drug, and Cosmetic Act (FFDCA); and statutes enforced by the U.S. Department of Agriculture. These programs are discussed in the following sections.

### *2.4.1 RCRA*

RCRA has nine sections (Subtitles) that deal with specific waste management activities. Two of these Subtitles are most likely to pertain to the use of phytoremediation: Subtitle C (Hazardous Waste Management), and Subtitle D (Solid Waste Management).

EPA issued closure requirements for Subtitles C and D treatment, storage, or disposal (TSD) units, which may be closed by removal or decontamination ("clean closure") or closed with waste in place ("landfill closure") (see 40 CFR Parts 257, 258, 264, and 265). The regulations include general closure requirements for all RCRA units and specific closure requirements for each type of TSD unit. The requirements are performance-based, and therefore do not stipulate any design standards. EPA delegates these regulatory programs to the states, which are responsible for their implementation. The Federal requirements are minimum requirements that must be incorporated into state regulatory programs; however, states may promulgate closure requirements that are more stringent than those of the Federal program. Site-specific evaluation of the use of alternative covers at TSDs that close as a landfill will need to include consideration of these requirements.

The Corrective Action Program, under RCRA, requires corrective action, as necessary, to protect human health and the environment for releases from solid waste management units at facilities seeking RCRA permits. This program is implemented primarily through a series of policy directives, and is similar in nature to the Superfund program's remedy selection process contained in the National Contingency Plan (NCP). EPA also delegates the Corrective Action Program to the states. Policy directives pertinent to the Corrective Action Program are available at *http://www.epa.gov/correctiveaction*.

### *2.4.2 CERLCA (Superfund)*

Remedial actions taken under the Superfund program must attain a general standard of cleanup that assures protection of human health and the environment, must be cost effective, and must use permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practicable. The regulatory framework for response actions under CERCLA is contained in 40 CFR Part 300, the National Oil and Hazardous Substances Pollution Contingency Plan, referred to as the NCP. The remedy selection process outlined in the NCP includes a Feasibility Study (FS), in which alternatives that represent viable approaches are assessed against nine criteria. With respect to phytoremediation, data collected from treatability studies or other means will provide the necessary scientific documentation to allow an objective evaluation (using the nine criteria) of whether phytoremediation is the most appropriate remedial option for a given site.

An important component in Superfund response actions is the requirement that for any material remaining on-site, EPA will attain or exceed any Federal or state limitation, standard, or criteria that is considered to be applicable or relevant and appropriate (ARAR) given the circumstances of the site (for off-site actions, all applicable requirements must be met). Further, on-site remedial actions must attain promulgated state ARARs that are more stringent than Federal ARARs. A requirement is applicable if the specific terms of the law or regulations directly address the circumstances at the site. If not applicable, a requirement may nevertheless be relevant and appropriate if circumstances at the site are sufficiently similar to the problems regulated by the requirement. The Maximum Contaminant Levels (MCLs) under the Safe Drinking Water Act are an example of relevant and appropriate requirements.

In order for phytoremediation to be selected as a remedy at a CERLCA site, it will be necessary to meet or waive the ARARs identified for the site. ARARs can be waived under six specific circumstances described in the NCP.

### *2.4.3 CAA*

Sections 111 and 112 of the Clean Air Act (CAA) contain the statutory basis for regulation of criteria and hazardous air pollutant emissions from source categories. The New Source Performance Standards and Emission Guidelines for Municipal Solid Waste Landfills, 40 CFR Part 60 Subparts WWW and Cc, are statutorily based on section 111 of the CAA. These standards were promulgated in March 1996 and regulate air emissions of non-methane organic compounds (NMOCs) from municipal solid waste landfills. Specifically, these standards require municipal solid waste landfills with a waste capacity of at least 2.5 million megagrams and with the potentially to emit at least 50 megagrams of NMOC to collect and control landfill gas. A second standard, 40 CFR Part 63 Subpart AAAA, statutorily based on section 112 of the CAA is currently under development. This regulation will regulate hazardous air pollutant emissions from municipal solid waste landfills. These regulations set performance based standards that allow owners and operators a number of options to achieve compliance. EPA delegates the implementation of these regulations to Federal, State and local governments. These Federal standards establish minimum requirements that must be implemented. However, State and local governments may choose to increase the stringency of these requirements. Any site contemplating the use of Phytoremediation needs to consider the requirements established by Federal, State and local government programs to regulate air emissions from municipal solid waste landfills.

### *2.4.4 TSCA*

Although the EPA does not currently regulate plants intended for commercial bioremediation, EPA believes the Toxic Substances Control Act (TSCA) gives it authority to do so if such action is necessary to prevent unreasonable risk to human health or the environment. TSCA gives EPA authority to regulate "chemical substances." TSCA defines chemical substances broadly to mean all chemicals and mixtures of chemical substances. Living organisms such as plants are mixtures of chemical substances and thus are subject to TSCA. Although TSCA could potentially be applied to plants used in bioremediation, EPA has not yet made a determination of whether such action is necessary to protect the environment and human health. EPA to date has only issued regulations for microorganisms under Section 5 of TSCA (EPA, 1997). Further information on TSCA and biotechnology products can be found at *http://www.epa.gov/opptintr/biotech/*.

### *2.4.5 FIFRA/FFDCA*

Certain plants engineered to contain sequences that afford the plant resistance to pests to enhance the remediation efficacy of the plant could be subject to review by EPA under its authority to regulate pesticides. EPA regulates pesticides under two statutes: the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), and the Federal Food, Drug, and Cosmetic Act (FFDCA). Substances that plants produce to protect themselves against pests and disease are pesticides under the definition of FIFRA Section 2 (i.e., if they are "...intended for preventing, destroying, repelling, mitigating any pest....") regardless of whether the pesticidal capabilities evolved in the plants or were introduced by breeding or through the techniques of modern biotechnology. These substances, along with the genetic material necessary to produce them, are designated "plant-pesticides"(EPA, 1994). Additional details about EPA plant pesticide regulations can be found at *http://www.epa.gov/fedrstr/EPA-PEST/1994/November/Day-23/*. The U.S. Food and Drug Administration has responsibility for food safety under the FFDCA. It is unlikely FDA would be involved in the review of phytoremediation plants since use of phytoremediation plants as food or as components of food is an unlikely scenario.

### *2.4.6 Department of Agriculture Statutes*

Plants used for phytoremediation could be potentially regulated under several U.S. statutes. The U.S. Department of Agriculture (USDA) administers several statutes that could be used to regulate such plants: e.g., the Federal Plant Pest Act (7 U.S.C. 150aa et seq.), the Plant Quarantine Act (7 U.S.C. 151 et seq.), and the Federal Noxious Weed Act (7 U.S.C. 2801 et seq.). Pertinent regulations are found at 7 CFR Parts 319, 321, 330, 340, and 360, respectively. Under USDA authority, one type of plant (transgenic or naturally-occurring) potentially subject to review would be a plant considered to be a plant pest. For additional guidance on USDA regulations pertaining to plants, refer to *http://www.aphis.usda.gov/bbep/bp/*.

## 2.5 Ecosystem Restoration

Vegetation is not only an aid to ecosystem restoration, it is a key indicator. Plant species that are present on a site, as well as their quantities and condition, describe a watershed's health and resilience. Loss of vegetation through clearing, building, and human land use has severe ecosystem effects. After a human disturbance such as mining, dumping, industrial, agricultural, or residential use, revegetation may occur slowly. Recolonization of contaminated or disturbed ground by plants typically starts at the edges of an impacted area. Natural revegetation may take decades or hundreds of years because it is dependent on animal and windborne seeding. If replanting is designed and carried out in a way that includes the perspectives of engineers, botanists, ecologists, landscape architects, and others, the environmental systems can begin to be restored in a few years. In some cases phytoremediation can help restore wild species diversity through habitat growth in addition to aiding in remediation of soil and water.

Despite the general ecological advantages of phytoremediation, adverse ecological effects are possible to both on- and off-site biological communities. In evaluating such concerns, it is important to compare the relative ecological risks posed by phytoremediation to those risks already occurring on site or those risks posed by alternative cleanup methods. Actions needed to protect ecosystems should be clearly specified in the site cleanup plan.

Overall ecological risks associated with remediation of a site are often overlooked, even by interested parties who may be familiar with the human health and ecological risks associated with current site conditions or with the general risks posed by feasible alternative cleanup methods. These overall ecological concerns may be expressed in a limited context that does not help in the selection of an alternative. Often, however, a site visit will broaden the understanding of interested parties and thus enable them to better assist in identifying options with the greatest overall ecological benefits.

Listed below are issues that typically arise in such discussions. Also included are frequently overlooked factors that should be considered in identifying the relative risks.

### 2.5.1 Introduction of Non-Native Plants

History is rife with disastrous examples of newly introduced plant species spreading quickly to damage native ecosystems (e.g., kudzu, Eurasian watermilfoil, etc.). Plants that work best in remediating a particular contaminant may or may not be native to a particular area. Although native plants are most desirable, non-native species may be acceptable under the following circumstances:

- The plants have been previously introduced, and are now so common that their proposed use would not create a new ecological risk.
- The plants are unable to propagate effectively in the wild (e.g., sterility, dependence on human cultivation, etc.).
- Genetically altered plants have been introduced. Mankind has been using selective breeding to obtain desired plant characteristics for at least 10,000 years. Now, researchers in many fields are using new genetic engineering techniques to replace selective breeding, allowing them to achieve their desired results more quickly and selectively. Decisions on the desirability of using genetically engineered plants must be site specific.

### 2.5.2 Integration of Phytoremediation Into the Site's Long-Term Landscaping Objectives

Long-term phytoremediation-based treatment can be designed into future site landscaping plans, e.g., tree borders used for shading and visual screening can also provide ongoing groundwater remediation, etc. Such vegetation can often create valuable ecological niches, particularly in urban industrial areas.

#### *Public Uses*

A number of contaminated sites are being converted to parks and other low-intensity public uses. These sites, particularly with their greater flexibility in the timing and design of cleanup, frequently offer significant ecological opportunities. Trees and shrubs do not have to be planted in straight rows to be effective in remediation.

#### *Commercial Uses*

Businesses traditionally landscape for aesthetic reasons and storm run-off control. These functions may be combined with phytoremediation to offer significant opportunities. Properly designed and located, such landscaping could also provide long-term treatment and enhanced ecological habitats. A site owner may be willing to significantly expand the land committed to phytoremediative landscaping if that commitment would reduce overall cleanup costs and allow quicker site redevelopment. A phased approach, with intensive short-term treatment by one plant species followed by permanent plantings with more beneficial vegetation, may maximize ecosystem benefits.

#### *Wood Lot Uses*

Short-rotation woody crops for pulp, fuel, or timber may be grown on land with nonaccumulating organic contaminants. The trees could be grown and harvested while recalcitrant compounds slowly degrade.

### 2.5.3 Phytoremediation as an Interim Solution

Phytoremediation is most suitable for remediating sites or portions of sites with widespread, low-mid level contaminants that are often too expensive to remediate by traditional means. Absent a cost-effective remediation method, contaminants are often left in place, and contact with the waste attempted to be minimized by fences, institutional controls and deed restrictions. Too often no one is required or able to cleanup the site, and many sites have been abandoned with no clean up or controls. Occasionally a phytoremediation system may be inexpensive enough that it could be installed during considerations and debate regarding a permanent solution, and removed once a final remedy is implemented. The interim ecosystem benefits, coupled with improved aesthetics, and some containment and/or degradation may combine to make even temporary revegetation worthwhile.

Although phytoremediation may not be the selected final technique, the benefits of a well-designed, properly installed, and capably managed phytoremediation system may be preferable to the risks posed by leaving a waste site completely untreated during delays in implementing a final remedy.

### 2.5.4 Ecosystem Restoration at Phytoremediation Sites

Many sites with contamination support complex ecosystems, primarily due to the low level of human activity on the site. Plants and animals recolonize some areas where decreased human traffic allows vegetation to take root. Phytoremediation could aid the natural revegetation underway on such site. Phytoremediation can make use of various types of plants, and it is possible to consider local or native plants as part of a remediation system.

In order to consider using native plants, the remediation potential of plants already growing on the site must be carefully assessed. It must be determined whether these plants are just tolerating the contaminant or whether they are already actively remediating it. A field or greenhouse study may be needed to make this determination.

If non-native plants must be utilized, appropriate control techniques (e.g., sterile plants) should be used to ensure that genetic contamination or invasive spread does not occur.

Phytoremediative plants with desirable ecological values could provide diversified habitat where appropriate. A combination of trees, understory shrubs, and grasses may provide shelter and food for numerous species. Nonphytoremediative plants can be added to supplement ecological values such as soil stabilization or to provide a food source.

Evaluating the ecological recovery of a site is important, but such an evaluation does not have to be expensive or complex. Neighborhood environmental and school groups could "adopt" a brownfield or similar distressed site and provide data of mutual interest (e.g., the local Audubon Society could assess bird habitat utilization; a biology class could track plant species survival and growth, etc.). Properly done, such collaborative monitoring can build community understanding and support, while also providing data that would be otherwise unaffordable, and is seldom collected during remediation. Many sites will not allow access by untrained personnel. Personal protection must always be a foremost concern in any such collaboration.

As noted earlier, phytoremediation offers significant ecological promise, but it is not a perfect solution. Ecological benefits in one area may create ecological impacts in others. Negative impacts must be avoided. Some stakeholders may disagree with this definition of ecosystem restoration because it does not attempt to recreate a pristine ecosystem. Although it may not be possible or feasible to return a site to its condition before human impact, phytoremediation may provide realistic opportunities to improve the overall ecological health of a site.

## 2.6 Current Research

To assess the appropriateness of any phytoremediation application, media- and contaminant-specific field data must be obtained that can show the rate and extent of degradation or extraction. The existing knowledge base is limited, and specific data are needed on more plants, contaminants, and climate conditions.

In addition, monitoring systems need to be standardized. Currently there is no industry or research consensus on which parameters are crucial to measure, and very few projects can afford to sample, analyze, or monitor very many parameters over the years needed for most phytoremediation projects.

The EPA's Office of Research and Development (ORD) and the Office of Solid Waste and Emergency Response (OSWER) have several programs that investigate the efficacy, risk, and cost of phytoremediation. These EPA activities include EPA in-house laboratory research efforts, support given to universities that are centers for phytoremediation research, and joint EPA-private cooperative efforts to field-test phytoremediation.

EPA's Office of Research and Development manages various in-house research projects, and several EPA laboratories have work underway to determine the fate of contaminants in phytoremediation applications. Steve McCutcheon and Lee Wolfe at the EPA National Exposure Research Laboratory (NERL) in Athens, GA, have explored the degradation of TNT by wetland plants, and continue to investigate plant enzyme and contaminant interactions. Albert Venosa at the EPA National Risk Management Research Laboratory (NRMRL) in Cincinnati, OH, is researching the effect of plants on oil spills in salt and fresh water wetlands. James Ryan, who is also at EPA-NRMRL, is working with Rufus Chaney of USDA on using plants to immobilize metals in soil. Richard Brenner, also at EPA-NRMRL, is leading a team comparing the use of land farming and phytoremediation on the site of a former manufactured gas facility. Harry Compton and George Prince of the ERT are monitoring poplar tree plantings at Superfund sites in MD and NJ (see Table 2-3). Larry Erickson's EPA-supported Hazardous Substance Research Center at Kansas State University has for many years sponsored research and symposia on the interaction of plants and contaminants. Tom Wilson at EPA Region 10 continues to explore and encourage innovative applications and interactions between phytoremediation and ecosystem restoration.

The Superfund Innovative Technology Evaluation Program (SITE) demonstrates field-ready technologies that are initiated and installed by the developer of the technology. SITE began evaluating phytoremediation projects in 1994. Currently four full demonstrations (including two at Superfund sites), and one Emerging Program project have been done or are underway using phytoremediation, coordinated by Steve Rock at EPA-NRMRL in Cincinnati, OH. Reports detailing the performance of the demonstrations will be published at the conclusion of the field work. Information on the SITE program or individual projects can be found at h*ttp://www.epa.gov/ORD/SITE*.

EPA's Office of Research and Development and the Office of Solid Waste and Emergency Response (OSWER) jointly support the Remediation Technologies Development Forum (RTDF). The RTDF was established in 1992 by the EPA to foster collaboration between the public and private sectors in developing innovative solutions to mutual hazardous waste problems. The RTDF has grown to include partners from industry, several government agencies, and academia who share the common goal of developing more effective, less-costly hazardous waste characterization and treatment technologies. There are currently seven RTDF Action Teams, including the "Phytoremediation of Organics Action Team." This Action Team was formed in early 1997, and is currently comprised of three working groups that are concerned with phytoremediation of three separate pollution/matrix situations: petroleum compounds in shallow soils, chlorinated solvents in near-surface groundwater, and the use of vegetation with high transpiration rates as an alternative cap for hydraulic containment and/or degradation of various pollutants. The Action Team has held several meetings, and has regular conference calls to select and implement field testing projects. Current co-chairs in the subcommittees include representatives from Chevron, Exxon, the Air Force, and Union Carbide.

To access meeting and teleconference minutes, bibliographic information on phytoremediation, and other information, refer to *http://www.rtdf.org*. The Technology Innovation Office (TIO) within OSWER supports RTDF activities, as well as other efforts aimed at bringing innovative site characterization and treatment technologies to commercialization. Further information on the Technology Innovation Office and resources generated by TIO can be found at *http://www.clu-in.org*.

In addition to EPA efforts, other Federal agencies, universities, consultants, and remediation contractors have research underway in phytoremediation. All these projects expand the knowledge base of what plants can be expected to do consistently, and make the application of innovative technologies more acceptable to regulators and consumers.

Continuing research and policy discussions in the related areas of determining possible risk-based alternative endpoints for cleanups, and measuring the intrinsic remediative capacity of a site (natural attenuation) will impact the applicability of many biological-based technologies, including plant-based systems.

Enhancements to the various phytoremediation processes are continuing. Some applied research is directed at selecting and breeding plants that have more of an attractive quality such as hyperaccumulation of metal, production of certain enzymes, and affinity or tolerance for contaminants. Research continues in genetic engineering of plants to combine positive traits, alter enzyme systems, or increase a plant's natural range.

An engineering approach could be pursued by using existing plant traits as only a part of a remediation system of combined planted systems and mechanical, thermal, or chemical systems in treatment trains. Suggested combinations include electrokinetics, bioventing, and surfactant addition.

# Chapter 3
# Evaluation of Phytoremediation Technologies

This chapter presents a literature review and evaluation of the major phytoremediation processes or technologies. The technologies presented represent the major, significant, or widely studied forms of phytoremediation.

This chapter is divided into subsections that present definitions, mechanisms, site characteristics, applicable media, contaminants amenable to each process, and the associated concentrations where available. The advantages, disadvantages, and current status of each process are also discussed. Finally, an annotated reference list is included at the end of the discussion of each process to provide more detailed, specific information.

The purpose of this chapter is to provide site managers with an overview of the various phytoremediation processes as well as what can be expected from the process and its limitations. Therefore, information on applicable contaminants/concentrations is included even though the information may not be complete. Table 3-1 presents a summary of the various phytoremediation processes.

## 3.1 Phytoextraction

### *3.1.1 Definition/Mechanism*

Phytoextraction is the uptake of contaminants by plant roots and translocation within the plants. Contaminants are generally removed by harvesting the plants. This concentration technology leaves a much smaller mass to be disposed of than does excavation of the soil or other media. This technology is most often applied to metal-contaminated soil as shown in Figure 3-1.

### *3.1.2 Media*

Phytoextraction is primarily used in the treatment of soil, sediments, and sludges. It can be used to a lesser extent for treatment of contaminated water.

### *3.1.3 Advantages*

The plant biomass containing the extracted contaminant can be a resource. For example, biomass that contains selenium (Se), an essential nutrient, has been transported to areas that are deficient in Se and used for animal feed (Bañuelos 1997a).

### *3.1.4 Disadvantages*

Phytoextraction has the following disadvantages:

- Metal hyperaccumulators are generally slow-growing with a small biomass and shallow root systems.
- Plant biomass must be harvested and removed, followed by metal reclamation or proper disposal of the biomass. Hyperaccumulators may accumulate significant metal concentrations — e.g., *Thlaspi rotundifolium* grown in a lead-zinc mine area contained 8,200 g/g Pb (0.82%) and 17,300 g/g zinc (Zn) (1.73%), and *Armeria maritima* var. *halleri* contained 1,300 g/g Pb, dry weight basis (Reeves and Brooks 1983).
- Metals may have a phytotoxic effect (Nanda Kumar et al. 1995).
- Phytoextraction studies conducted using hydroponically-grown plants, with the contaminant added in solution, may not reflect actual conditions and results occurring in soil. Phytoextraction coefficients measured under field conditions are likely to be less than those determined in the laboratory (Nanda Kumar et al. 1995).

### 3.1.5 Applicable Contaminants/Concentrations

#### 3.1.5.1 Applicable Contaminants

Constituents amenable to phytoextraction include:

- Metals: Ag, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Zn

  The relative degree of uptake of different metals will vary. Experimentally-determined phytoextraction coefficients [ratio of g metal/g dry weight (DW) of shoot to g metal/g DW of soil] for *B. juncea* (Nanda Kumar et al. 1995) indicate, for example, that lead was much more difficult to take up than cadmium:

| Metal | Phytoextraction Coefficient |
|---|---|
| $Cr^{6+}$ | 58 |
| $Cd^{2+}$ | 52 |
| $Ni^{2+}$ | 31 |
| $Cu^{2+}$ | 7 |
| $Pb^{2+}$ | 1.7 |
| $Cr^{3+}$ | 0.1 |
| $Zn^{2+}$ | 17 |

- Metalloids: As, Se

**Table 3-1.** Phytoremediation Overview

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

- Radionuclides: $^{90}Sr$, $^{137}Cs$, $^{239}Pu$, $^{238}U$, $^{234}U$
- Nonmetals: B
- Organics: The accumulation of organics and subsequent removal of biomass generally has not been examined as a remedial strategy.

#### 3.1.5.2 Contaminant Concentrations

Contaminated soil concentrations used in research studies or found in field investigations are given below. These are total metal concentrations; the mobile or available concentrations would be less.

- 1,250 mg/kg As (Pierzynski et al. 1994).
- 9.4 mg/kg Cd (Pierzynski et al. 1994).
- 11 mg/kg Cd (Pierzynski and Schwab 1992).
- 13.6 mg/kg Cd (*Thlaspi caerulescens*) (Baker et al. 1995).
- 2000 mg/kg Cd was used in studies of Cd uptake in vegetables (Azadpour and Matthews, 1996).
- 110 mg/kg Pb (Pierzynski and Schwab 1992).
- 625 mg/kg Pb (Nanda Kumar et al. 1995).
- 40 mg/kg Se (Bañuelos et al. 1997b).
- 444 mg/kg Zn (*Thlaspi caerulescens*) (Baker et al. 1995).
- 1,165 mg/kg Zn was suspected to have phytotoxic effects (Pierzynski and Schwab 1992).

Nanda Kumar et al. (1995) reported that the following concentrations were not phytotoxic to *Brassica juncea* when added to soil mixtures:

2 mg/L $Cd^{2+}$
50 mg/L $Cr^{3+}$
3.5 mg/L $Cr^{6+}$
10 mg/L $Cu^{2+}$
100 mg/L $Ni^{2+}$
500 mg/L $Pb^{2+}$
100 mg/L $Zn^{2+}$

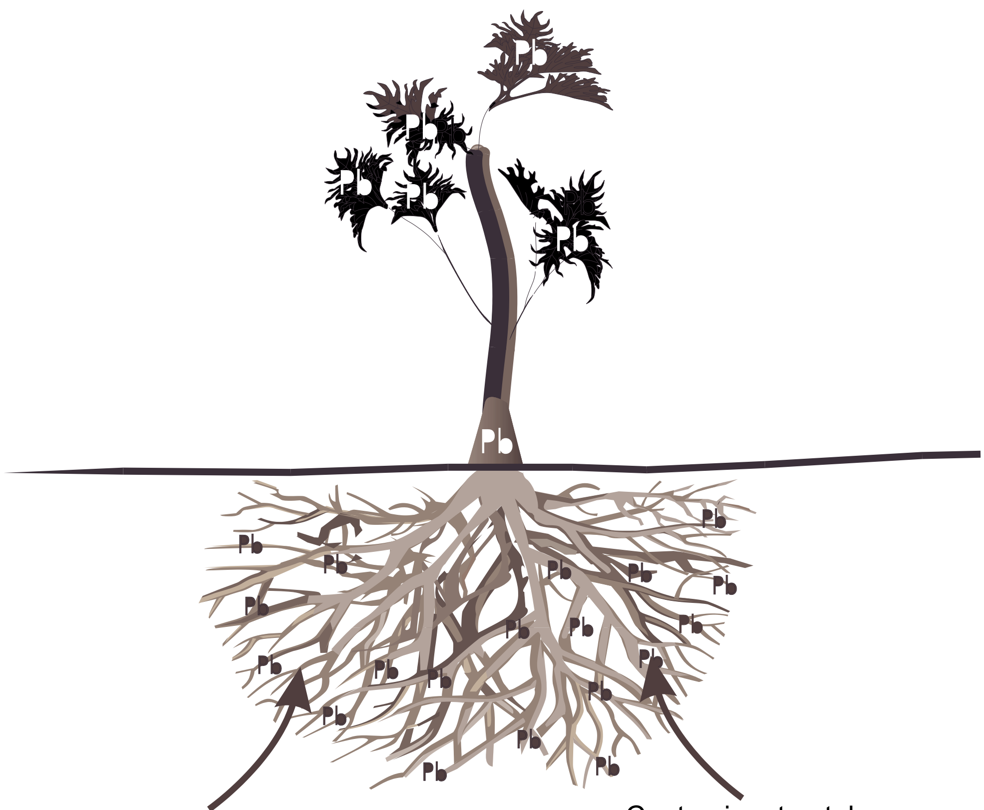


**Figure 3-1.** Phytoextraction.

The following solution concentrations were reported in studies of phytoextraction that used hydroponically-grown plants:

- Cd: *Thlaspi caerulescens* survived 63.2 M Cd without evidence of chlorosis at 21 days in hydroponic solution, but was severely affected at 200 M (22 mg/L) (Brown et al. 1995).
- Pb: 6, 22, 47, 98, 188 mg/L. Root uptake of Pb became saturated at Pb solution concentrations above 188 mg/L (Nanda Kumar et al. 1995).
- Zn: *Thlaspi caerulescens* survived 3,160 M Zn without evidence of chlorosis at 21 days in hydroponic solution, but was severely affected at 10,000 M (650 mg/L) (Brown et al. 1995).

### *3.1.6 Root Depth*

Phytoextraction is generally limited to the immediate zone of influence of the roots; thus, root depth determines the depth of effective phytoextraction. The root zones of most metal accumulators are limited to the top foot of soil.

### *3.1.7 Plants*

Hyperaccumulator plants are found in the Brassicaceae, Euphorbiaceae, Asteraceae, Lamiaceae, or Scrophulariaceae plant families (Baker 1995). Examples include:

- *Brassica juncea* (Indian mustard) - a high-biomass plant that can accumulate Pb, Cr (VI), Cd, Cu, Ni, Zn, $^{90}$Sr, B, and Se (Nanda Kumar et al. 1995; Salt et al. 1995; Raskin et al. 1994). It has over 20 times the biomass of *Thlaspi caerulescens* (Salt et al. 1995). Brassicas can also accumulate metals. Of the different plant species screened, *B. juncea* had the best ability to transport lead to the shoots, accumulating >1.8% lead in the shoots (dry weight). The plant species screened had 0.82 to 10.9% Pb in roots (with *Brassica* spp. having the highest), with the shoots having less Pb. Except for sunflower (*Helianthus annuus*) and tobacco (*Nicotiana tabacum*), other non-*Brassica* plants had phytoextraction coefficients less than one. 106 *B. juncea* cultivars varied widely in their ability to accumulate Pb, with different cultivars ranging from 0.04% to 3.5% Pb accumulation in the shoots and 7 to 19% in the roots (Nanda Kumar et al. 1995).

- *Thlaspi caerulescens* (Alpine pennycress) for Ni and Zn (Brown et al. 1994).

- *Thlaspi rotundifolium* ssp. *cepaeifolium,* a noncrop Brassica and one of the few Pb accumulators mentioned in the literature (Nanda Kumar et al. 1995).

- *Alyssum wulfenianum* for Ni (Reeves and Brooks 1983).

- Baker (1995) found 80 species of nickel-accumulating plants in the Buxaceae (including boxwood) and Euphoribiaceae (including cactus-like succulents) families. Some euphorbs can accumulate up to 5% of their dry weight in nickel.

- Indian mustard (*Brassica juncea*) and canola (*Brassica napus*) have been shown to accumulate Se and B. Kenaf (*Hibiscus cannabinus* L. cv. Indian) and tall fescue (*Festuca arundinacea* Schreb cv. Alta) also take up Se, but to a lesser degree than canola (Bañuelos et al. 1997b).

- Hybrid poplar trees were used in a field study in mine-tailing wastes contaminated with As and Cd (Pierzynski et al. 1994).

- Lambsquarter leaves had relatively higher As concentrations (14 mg/kg As) than other native plant or poplar leaves (8 mg/kg) in mine-tailing wastes (Pierzynski et al. 1994).

- Sunflowers took up Cs and Sr, with Cs remaining in the roots and Sr moving into the shoots (Adler 1996).

- Metal accumulator plants such as the crop plants corn, sorghum, and alfalfa may be more effective than hyperaccumulators and remove a greater mass of metals due to their faster growth rate and larger biomass. Additional study is needed to quantify contaminant removal.

The number of taxonomic groups (taxa) of hyperaccumulators varies according to which metal is hyperaccumulated:

| Metal | Number of Taxonomic Groups of Hyperaccumulators |
|---|---|
| Ni | >300 |
| Co | 26 |
| Cu | 24 |
| Zn | 18 |
| Mn | 8 |
| Pb | 5 |
| Cd | 1 |

### *3.1.8 Site Considerations*

Because potentially toxic levels of metals can accumulate in the aboveground portion of the plant, access to the plants must be controlled and plant debris must be monitored more closely than with other phytoremediation technologies. Thus, care must be taken to restrict access of browsing animals, and harvested plant material must be properly disposed of.

#### 3.1.8.1 Soil Conditions

Soil conditions must be appropriate for plant growth and contaminant migration to the plant, yet not allow leaching of the metals. The pH of the soil may need to be adjusted and/or chelating agents may need to be added to increase plant bioavailability and uptake of metals.

#### 3.1.8.2 Ground and Surface Water

The primary considerations for phytoremediation in groundwater are depth to groundwater and depth to contamination zone. Groundwater phytoremediation is essentially limited to unconfined aquifers in which the water table depths are within reach of plant roots.

#### 3.1.8.3 Climatic Conditions

Hyperaccumulators are often found in specific geographic locations and might not grow under other climatic conditions.

### *3.1.9 Current Status*

Both laboratory and field experiments have been conducted. The first controlled field trial of *Thlaspi caerulescens* in the UK was in 1994 (Moffat 1995). In this study, *Thlaspi caerulescens* accumulated Zn and Cd to several percent dry weight. A commercial operation, Phytotech, Inc., also conducted field tests and small-scale field applications (including the “Magic Marker” site in Trenton, NJ) with some degree of success using Indian mustard (*Brassica juncea*) to remove lead from soil.

Plant selection, breeding, and genetic engineering for fast-growing, high-biomass hyperaccumulators are active areas of research. Information on uptake and translocation of metals has been assessed by Nellessen and Fletcher (1993a).

### *3.1.10 System Cost*

The estimated 30-year costs (1998 dollars) for remediating a 12-acre lead site are $12,000,000 for excavation and disposal, $6,300,000 for soil washing, $600,000 for a soil cap, and $200,000 for phytoextraction (Cunningham 1996).

In a hypothetical study involving the remediation of a 20-in.-thick layer of sediments contaminated with Cd, Zn, and $^{137}$Cs from a 1.2-acre chemical waste disposal pond, phytoextraction cost was estimated to be about one-third the cost of soil washing (Cornish et al. 1995).

Phytoextraction costs were estimated to be $60,000 to $100,000 for remediation of one acre of 20-in.-thick sandy loam, compared to a minimum of $400,000 for just excavation and storage of this soil (Salt et al. 1995).

### *3.1.11 Selected References*

Azadpour, A., and J. E. Matthews. 1996. Remediation of Metal-Contaminated Sites Using Plants. Remed. Summer. 6(3):1-19.

In this literature review of research conducted on the uptake of metals by plants, factors that affect metals uptake are provided along with examples of plants examined for phytoextraction.

Chaney, R. L. 1983. Plant Uptake of Inorganic Waste Constituents. pp. 50-76. In J. F. Parr, P. B. Marsh, and J. M. Kla (eds.), Land Treatment of Hazardous Waste. Noyes Data Corporation, Park Ridge, NJ.

This literature review of factors affecting metals uptake by plants, metals tolerance, and metals impacts on plant growth is written from the viewpoint of the impact of land-applied waste on plants. It is also an early proposal for the use of plants to remediate contaminated sites.

Cornish, J. E., W. C. Goldberg, R. S. Levine, and J. R. Benemann. 1995. Phytoremediation of Soils Contaminated with Toxic Elements and Radionuclides. pp. 55-63. In R. E. Hinchee, J. L. Means, and D. R. Burris (eds.), Bioremediation of Inorganics. Battelle Press, Columbus, OH.

This review focuses on the application of plants for remediating U.S. Department of Energy sites contaminated with metals and radionuclides. It lists the contaminant ranges found at these sites, the phytotoxicity threshold for the contaminants, and the number of hyperaccumulating species for the contaminants. It develops a hypothetical example to show the potential cost savings of phytoextraction.

Nanda Kumar, P. B. A., V. Dushenkov, H. Motto, and I. Raskin. 1995. Phytoextraction: The Use of Plants to Remove Heavy Metals from Soils. Environ. Sci. Technol. 29(5):1232-1238.

Experimental studies are described examining metals uptake by a variety of plant species and different *Brassica juncea* cultivars. The experiments focused on lead but also included other metals.

## 3.2 Rhizofiltration

### *3.2.1 Definition/Mechanism*

Rhizofiltration is the adsorption or precipitation onto plant roots, or absorption into the roots of contaminants that are in solution surrounding the root zone, due to biotic or abiotic processes. Plant uptake, concentration, and translocation might occur, depending on the contaminant. Exudates from the plant roots might cause precipitation of some metals. Rhizofiltration first results in contaminant containment, in which the contaminants are immobilized or accumulated on or within the plant. Contaminants are then removed by physically removing the plant.

### *3.2.2 Media*

Extracted groundwater, surface water, and waste water can be treated using this technology. Rhizofiltration is generally applicable to low-concentration, high-water-content conditions. This technology does not work well with soil, sediments, or sludges because the contaminant needs to be in solution in order to be sorbed to the plant system.

### *3.2.3 Advantages*

Rhizofiltration has the following advantages:

- Either terrestrial or aquatic plants can be used. Although terrestrial plants require support, such as a floating platform, they generally remove more contaminants than aquatic plants.
- This system can be either in situ (floating rafts on ponds) or ex situ (an engineered tank system).
- An ex situ system can be placed anywhere because the treatment does not have to be at the original location of contamination.

### *3.2.4 Disadvantages*

Rhizofiltration has the following disadvantages:

- The pH of the influent solution may have to be continually adjusted to obtain optimum metals uptake.
- The chemical speciation and interaction of all species in the influent have to be understood and accounted for.
- A well-engineered system is required to control influent concentration and flow rate.
- The plants (especially terrestrial plants) may have to be grown in a greenhouse or nursery and then placed in the rhizofiltration system.
- Periodic harvesting and plant disposal are required.
- Metal immobilization and uptake results from laboratory and greenhouse studies might not be achievable in the field.

### *3.2.5 Applicable Contaminants/ Concentrations*

Constituents amenable to phytoremediation include:

- Metals:
  - Lead
    - (i) $Pb^{2+}$ at a solution concentration of 2 mg/L, was accumulated in Indian mustard roots with a bioaccumulation coefficient of 563 after 24 hours. $Pb^{2+}$ (at solution concentrations of 35, 70, 150, 300, and 500 mg/L) was accumulated in Indian mustard roots, although root adsorption of Pb saturated at 92 to 114 mg Pb/g DW root. Pb disappeared from the 300- and 500-mg/L solutions due to precipitation of lead phosphate. Pb absorption by roots was found to be rapid, although the amount of time required to remove 50% of the Pb from solution increased as the Pb concentration increased (Dushenkov et al. 1995).

(ii) Pb was accumulated in the roots of Indian mustard (*Brassica juncea*) in water concentrations of approximately 20 to 2,000 g/L, with bioaccumulation coefficients of 500 to 2,000 (Salt et al. 1997).

(iii) Pb at concentrations of 1 to 16 mg/L was accumulated by water milfoil (*Myriophyllum spicatum*) with a minimum residual concentration below 0.004 mg/L (Wang et al. 1996).

- Cadmium

$Cd^{2+}$ (2 mg/L) was accumulated in Indian mustard roots with a bioaccumulation coefficient of 134 after 24 hours (Dushenkov et al. 1995). Cd was accumulated by the roots of Indian mustard (*Brassica juncea*) in water concentrations of about 20 to 2,000 g/L, with bioaccumulation coefficients of 500 to 2,000. The seedlings removed 40 to 50% of the Cd within 24 hours at a biomass loading of 0.8 g dry weight/L solution. The Cd went from 20 g/L to 9 g/L within 24 hours. After 45 hours, the Cd reached 1.4% in the roots and 0.45% in the shoots. Cd saturation was reached in the roots in 12 hours and in the shoots in 45 hours. Removal of competing ions in the solution increased the uptake 47-fold (Salt et al. 1997). Cd at concentrations of 1 to 16 mg/L was accumulated by water milfoil (*Myriophyllum spicatum*) with a minimum residual concentration of approximately 0.01 mg/L (Wang et al. 1996).

- Copper

$Cu^{2+}$ (6 mg/L) was accumulated in Indian mustard roots with a bioaccumulation coefficient of 490 after 24 hours (Dushenkov et al. 1995). Cu at concentrations of 1 to 16 mg/L was accumulated by water milfoil (*Myriophyllum spicatum*) with a minimum residual concentration of approximately 0.01 mg/L (Wang et al. 1996).

- Nickel

$Ni^{2+}$ (10 mg/L) was accumulated in Indian mustard roots with a bioaccumulation coefficient of 208 after 24 hours (Dushenkov et al. 1995). Ni was accumulated by the roots of Indian mustard (*Brassica juncea*) in water concentrations of about 20 to 2,000 g/L, with bioaccumulation coefficients of 500 to 2,000 (Salt et al. 1997). Ni at concentrations of 1 to 16 mg/L was accumulated by water milfoil (*Myriophyllum spicatum*) with a minimum residual concentration of approximately 0.01 mg/L (Wang et al. 1996).

- Zinc

$Zn^{2+}$ (100 mg/L) was accumulated in Indian mustard roots with a bioaccumulation coefficient of 131 after 24 hours (Dushenkov et al. 1995). Zn at concentrations of 1 to 16 mg/L was accumulated by water milfoil (*Myriophyllum spicatum*) with a minimum residual concentration of approximately 0.1 mg/L (Wang et al. 1996).

- Chromium

(i) $Cr^{6+}$ (4 mg/L) was accumulated in Indian mustard roots with a bioaccumulation coefficient of 179 after 24 hours. The roots contained $Cr^{3+}$, indicating reduction of $Cr^{6+}$ (Dushenkov et al. 1995).

(ii) Cr (VI) was accumulated by the roots of Indian mustard (*Brassica juncea*) in water concentrations of about 20 to 2000 g/L, with bioaccumulation coefficients of 100 to 250 (Salt et al. 1997).

• Radionuclides:

- Uranium

U was studied using sunflowers in bench-scale and pilot-scale engineered systems (Dushenkov et al. 1997).

$C_o$ = 56 g/L, reduced by >95% in 24 hours.

$C_o$ = 600 g/L, to 63 g/L in 1 hour, then down to 10 g/L after 48 hours.

$C_o$ = 10, 30, 90, 810, or 2430 g/L with no signs of phytotoxicity, and doubled their biomass.

$C_o$ = several hundred g/L, went to below regulatory goal of 20 g/L.

$C_o$ = >1,000 g/L, could not reach 20 g/L goal; went down to 40 to 70 g/L.

Average $C_o$ = 207 g/L, went to <20 g/L.

Influent concentrations at the field site were 21 to 874 g/L.

- Cesium

(i) Cs was used with sunflowers in bench-scale and pilot-scale engineered systems (Dushenkov et al. 1997). $C_o$ = 200 g/L, decreased noticeably after 6 hours, then went below 3 g/L after 24 hours.

(ii) Cs was accumulated in the roots of Indian mustard (*Brassica juncea*) in water concentrations of approximately 20 to 2,000 g/L, with bioaccumulation coefficients of 100 to 250 (Salt et al. 1997).

- Strontium

(i) Sr was used with sunflowers (Dushenkov et al. 1997). $C_o$ = 200 g/L, went to 35 g/L within 48 hours, then down to 1 g/L by 96 hours.

(ii) Sr was accumulated in the roots of Indian mustard (*Brassica juncea*) in water concentrations of approximately 20 to 2,000 g/L (Salt et al. 1997).

Rhizofiltration has not been evaluated for use with nutrients or organics.

### 3.2.6 Root Depth

Rhizofiltration occurs within the root zone in water. For rhizofiltration to occur, the water must come into contact with the roots. Engineered systems can be designed to maximize this contact zone by matching the depth of the unit to the depth of the roots. Groundwater may be extracted from any depth and piped to an engineered hydroponic system for ex-situ treatment. The depth of treatable groundwater is a function of the extraction system, not the rhizofiltration treatment system.

For in situ technologies, such as natural water bodies, the depth of the roots might not be the same as the depth of the water body. The water must be adequately circulated in such cases to ensure complete treatment, which is likely to become more difficult as the depth of the water increases.

### 3.2.7 Plants

The following are examples of plants used in rhizofiltration systems:

- Terrestrial plants can be grown and used hydroponically in rhizofiltration systems. These plants generally have a greater biomass and longer, faster-growing root systems than aquatic plants (Dushenkov et al. 1995). Seedlings have been proposed for use instead of mature plants because seedings do not require light or nutrients for germination and growth for up to 2 weeks (Salt et al. 1997).

- Under hydroponic conditions, 5 dicots (broadleaf crops), 3 monocots (cereals), 11 cool season grasses, and 6 warm season grasses were each effective in accumulating Pb in their roots after three days of exposure to 300 mg/L Pb. The maximum lead concentration on a dry weight basis was 17% in a cool season grass (colonial bentgrass), and the minimum was 6% in a warm season grass (Japanese lawngrass). The dicot Indian mustard (*Brassica juncea*) was also effective in taking up other metals (Dushenkov et al. 1995).

- Sunflowers (*Helianthus annuus* L.) removed concentrated $Cr^{6+}$, Mn, Cd, Ni, Cu, U, Pb, Zn, and Sr in laboratory greenhouse studies (Salt et al. 1995). Sunflowers also were more effective than Indian mustard (*Brassica juncea*) and bean (*Phaseolus coccineus*) in removing uranium. Bioaccumulation coefficients for uranium in the sunflowers were much higher for the roots than for the shoots (Dushenkov et al. 1997).

- At a field site in Chernobyl, Ukraine, sunflowers were grown for 4 to 8 weeks in a floating raft on a pond. Bioaccumulation results indicated that sunflowers could remove $^{137}Cs$ and $^{90}Sr$ from the pond.

- Aquatic plants have been used in water treatment, but they are smaller and have smaller, slower-growing root systems than terrestrial plants (Dushenkov et al. 1995). Floating aquatic plants include water hyacinth (*Eichhornia crassipes*), pennyworth (*Hydrocotyle umbellata*), duckweed (*Lemna minor*), and water velvet (*Azolla pinnata*) (Salt et al. 1995).

- The floating aquatic plant water milfoil (*Myriophyllum spicatum*), at a biomass density of 0.02 kg/L, rapidly accumulated Ni, Cd, Cu, Zn, and Pb. The plant accumulated up to 0.5% Ni, 0.8% Cd, 1.3% Cu, 1.3% Zn, and 5.5% Pb by weight (Wang et al. 1996).

- Wetland plants can be used in engineered or constructed beds to take up or degrade contaminants. Hydroponically-grown plants concentrated Pb, Cr(VI), Cd, Ni, Zn, and Cu onto their roots from wastewater. Lead had the highest bioaccumulation coefficient, and zinc the lowest (Raskin et al. 1994).

### 3.2.8 Site Considerations

In situ applications in water bodies are not likely to represent a disturbance or limitation to the use of a site because site activities generally do not occur in water.

#### 3.2.8.1 Soil Conditions

Because this technology involves the hydroponic or aquatic use of plants, soil use may be limited to raising plants prior to installation. A layer of soil may be required on a floating platform.

#### 3.2.8.2 Ground and Surface Water

An ex-situ engineered system using rhizofiltration needs to accommodate the predicted volume and discharge rate of groundwater or surface water. Groundwater and surface-water chemistry must be assessed to determine the interactions of the constituents in the water.

Groundwater must be extracted prior to rhizofiltration. Ex situ rhizofiltration of groundwater or surface water in an engineered system might also require pretreatment of the influent. Pretreatment could include pH adjustment, removal or settling out of particulate matter, or other modification of the water chemistry to improve the efficiency of rhizofiltration. In situ applications such as the treatment of water bodies might also require pretreatment, although this is likely to be more difficult than with an engineered system due to the potentially larger water volume and more complex configuration.

#### 3.2.8.3 Climatic Conditions

The amount of precipitation is not important in this technology because the plants are grown in water and often in greenhouses. The treated media (water) supplies the water requirements of the plants.

### 3.2.9 Current Status

Rhizofiltration applications are currently at the pilot-scale stage.

Scientists from Rutgers University and Phytotech, Inc., have conducted laboratory, greenhouse, and field pilot-scale rhizofiltration studies. Phytotech tested a pilot-scale rhizofiltration system in a greenhouse at a DOE uranium-processing facility in Ashtabula, Ohio (Dushenkov et al. 1997). This engineered ex situ system used sunflowers to remove uranium from contaminated groundwater and/or process water. Phytotech also conducted a small-scale field test of rhizofiltration to remove radionuclides from a small pond near the Chernobyl reactor, Ukraine, using sunflowers floating on a raft.

The use of constructed wetlands for wastewater treatment and/or acid mine drainage is a related technology that has a significant history of research and application. Ex situ rhizofiltration in engineered systems might be the phytoremediation technology that most often uses traditional engineering methods.

### *3.2.10 System Cost*

The cost of removing radionuclides from water by using sunflowers has been estimated to be $2 to $6 per thousand gallons of water.

### *3.2.11 Selected References*

Dushenkov, V., P. B. A. Nanda Kumar, H. Motto, and I. Raskin. 1995. Rhizofiltration: The Use of Plants to Remove Heavy Metals from Aqueous Streams. Environ. Sci. Technol. 29:1239-1245.

This study examined metals removal by roots of a variety of plant species. It provides bioaccumulation coefficents and discusses the mechanisms of uptake. The study focuses on lead, but also provides information on other metals.

Dushenkov, S., D. Vasudev, Y. Kapulnik, D. Gleba, D. Fleisher, K. C. Ting, and B. Ensley. 1997. Removal of Uranium from Water Using Terrestrial Plants. Environ. Sci. Technol. 31(12):3468-3474.

This research included growth chamber, greenhouse, and field-scale studies for remediation of uranium-contaminated water. Continuous operation and optimization of an ex-situ system were examined.

## 3.3 Phytostabilization

### *3.3.1 Definition/Mechanism*

Phytostabilization is defined as (1) immobilization of a contaminant in soil through absorption and accumulation by roots, adsorption onto roots, or precipitation within the root zone of plants, and (2) the use of plants and plant roots to prevent contaminant migration via wind and water erosion, leaching, and soil dispersion.

Phytostabilization occurs through root-zone microbiology and chemistry, and/or alteration of the soil environment or contaminant chemistry. Soil pH may be changed by plant root exudates or through the production of $CO_2$. Phytostabilization can change metal solubility and mobility or impact the dissociation of organic compounds. The plant-affected soil environment can convert metals from a soluble to an insoluble oxidation state (Salt et al. 1995). Phytostabilization can occur through sorption, precipitation, complexation, or metal valence reduction (EPA 1997a). Plants can also be used to reduce the erosion of metal-contaminated soil.

The term phytolignification has been used to refer to a form of phytostabilization in which organic compounds are incorporated into plant lignin (Cunningham et al. 1995b). Compounds can also be incorporated into humic material in soils in a process likely related to phytostabilization in its use of plant material.

### *3.3.2 Media*

Phytostabilization is used in the treatment of soil, sediments, and sludges.

### *3.3.3 Advantages*

Phytostabilization has the following advantages:

- Soil removal is unnecessary.
- It has a lower cost and is less disruptive than other more-vigorous soil remedial technologies.
- Revegetation enhances ecosystem restoration.
- Disposal of hazardous materials or biomass is not required.

### *3.3.4 Disadvantages*

Phytostabilization has the following disadvantages:

- The contaminants remain in place. The vegetation and soil may require long-term maintenance to prevent rerelease of the contaminants and future leaching.
- Vegetation may require extensive fertilization or soil modification using amendments.
- Plant uptake of metals and translocation to the aboveground portion must be avoided.
- The root zone, root exudates, contaminants, and soil amendments must be monitored to prevent an increase in metal solubility and leaching.
- Phytostabilization might be considered to only be an interim measure.
- Contaminant stabilization might be due primarily to the effects of soil amendments, with plants only contributing to stabilization by decreasing the amount of water moving through the soil and by physically stabilizing the soil against erosion.

### 3.3.5 Applicable Contaminants/ Concentrations

Phytostabilization has not generally been examined in terms of organic contaminants. The following is a discussion of metals and metal concentrations, with implications for phytostabilization:

- Arsenic: As (as arsenate) might be taken up by plants because it is similar to the plant nutrient phosphate, although poplar leaves in a field study did not accumulate significant amounts of As (Pierzynski et al. 1994). Poplars were grown in soil containing an average of 1250 mg/kg As (Pierzynski et al. 1994).

- Cadmium: Cd might be taken up by plants because it is similar to the plant nutrients Ca, Zn, although poplar leaves in a field study did not accumulate significant amounts of Cd (Pierzynski et al. 1994). Poplars were grown in soil containing an average of 9.4 mg/kg Cd. Plants were grown in mine waste containing up to 160 mg/kg Cd (Pierzynski et al. 1994).

- Chromium: Indian mustard (*Brassica juncea*) might be able to reduce $Cr^{6+}$ to $Cr^{3+}$.

- Copper: Mine wastes containing copper were stabilized by grasses (Salt et al. 1995).

- Mercury: Mercury might be one of the leading candidates for the phytostabilization of metals, although additional study is required (EPA 1997b).

- Lead: Pb in leachate was 22 g/mL in soil containing Indian mustard (*Brassica juncea*) compared to 740 µg/mL in soil without plants (Salt et al. 1995). Mine wastes containing lead were stabilized by grasses (Salt et al. 1995). 625 µg/g Pb was used in a sand-Perlite mixture that supported Indian mustard (*Brassica juncea*) (Salt et al. 1995). Soil with 1660 mg/kg Pb had less than 50% plant cover. Plants in soil with 323 mg/kg Pb exhibited heavy chlorosis. Plants were grown in mine waste containing up to 4500 mg/kg (Pierzynski et al. 1994).

- Zinc: Mine wastes containing zinc were stabilized by grasses (Salt et al. 1995). Soil with 4230 mg/kg Zn had less than 50% plant cover. Plants in soil with 676 mg/kg Zn exhibited heavy chlorosis. Plants were grown in mine waste containing up to 43,750 mg/kg Zn (Pierzynski et al. 1994).

### *3.3.6 Root Depth*

The root zone is the primary area affecting chemically-moderated immobilization or root precipitation. Plants can be selected for their root depth; for example, poplars can be used for remediation of soil to a depth of 5 to 10 feet. The impact of the roots may extend deeper into the soil, depending on the transport of root exudates to lower soil depths.

### *3.3.7 Plants*

Metal-tolerant plants are required for heavy-metal-contaminated soils. *Brassica juncea* has been shown to reduce leaching of metals from soil by over 98% (Raskin et al. 1994).

The following grasses have been used to reduce metals leaching (Salt et al. 1995):

- Colonial bentgrass (*Agrostis tenuis* cv Goginan) for acid lead and zinc mine wastes.

- Colonial bentgrass (*Agrostis tenuis* cv Parys) for copper mine wastes.

- Red fescue (*Festuca rubra* cv Merlin) for calcareous lead and zinc mine wastes.

Native and tame grasses and leguminous forbs including big bluestem (*Andropogon gerardi* Vit.), tall fescue (*Festuca arundinacea* Schreb.), and soybean [*Glycine max* (L.) Merr.] were studied to determine their effectiveness in remediating mine wastes (Pierzynski et al. 1994). In addition, hybrid poplars were evaluated in a field study at a Superfund site to determine their metal tolerance (Pierzynski et al. 1994).

### *3.3.8 Site Considerations*

Plants used will require long-term maintenance if site-specific constraints prohibit reversal of the stabilization process.

#### 3.3.8.1 Soil Conditions

Phytostabilization might be most appropriate for heavy-textured soils and soils with high organic matter content (Cunningham et al. 1995a). Phytostabilization can be performed after more active soil treatment technologies have been tried. “Hot spots” of higher contaminant concentrations can be excavated and treated using other technologies, or landfilled. Soil amendments can also be used to stabilize metals in soils. Amendments should be selected that will maximize the growth of vegetation, which then also helps to phytostabilize the soil (Berti and Cunningham, 1997).

#### 3.3.8.2 Ground and Surface Water

Soil water content, which can affect redox conditions in the soil, must be appropriate for plant growth.

#### 3.3.8.3 Climatic Conditions

As discussed in Chapter 4, plans for remedial activities must take into account the fact that phytoremediation systems can be severely impacted by weather conditions.

### *3.3.9 Current Status*

The following are examples of typical phytostabilization studies:

- Land affected by mining activities has been revegetated with potentially useful plants. For example, a stabilizing cover of vegetation was successfully established on metalliferous mine wastes in the United Kingdom (Salt et al. 1995).

- Phytostabilization using metal-tolerant grasses is being investigated for large areas of Cd- and Zn-contaminated soils at a Superfund site in Palmerton, PA. Experimental plots of poplars have been studied at the

Whitewood Creek Superfund site, SD, and vegetative remediation has been proposed as part of the remediation at the Galena Superfund site in southeastern KS (Pierzynski et al. 1994).

- The IINERT (In-Place Inactivation and Natural Ecological Restoration Technologies) Soil-Metals Action team coordinated by EPA's Jim Ryan and Dupont's Bill Berti under the RTDF program has used plants to physically stabilize metal-contaminated soil in order to decrease the off-site movement of contaminants.

- Researchers at Kansas State University and Montana State University, among others, are actively examining the use of vegetation in reclaiming sites contaminated by mining wastes.

### *3.3.10 System Cost*

Cropping system costs have been estimated at $200 to $10,000 per hectare, equivalent to $0.02 to $1.00 per cubic meter of soil, based on a 1-meter root depth (Cunningham et al. 1995b).

### *3.3.11 Selected References*

Azadpour, A., and J. E. Matthews. 1996. Remediation of Metal-Contaminated Sites Using Plants. Remed. Summer. 6(3):1-19.

This is a literature review of factors that affect metals uptake by plants. It discusses plant tolerance to heavy metals and summarizes work done on the use of plants in soils that contain high levels of metal.

Cunningham, S. D., W. R. Berti, and J. W. Huang. 1995b. Remediation of Contaminated Soils and Sludges by Green Plants. pp. 33-54. In R.E. Hinchee, J. L. Means, and D. R. Burris (eds.), Bioremediation of Inorganics. Battelle Press, Columbus, OH.

The chemistry of metals is discussed in this paper, with a focus on lead. The article examines the stabilization and bioavailability of lead using sequential extractions. Phytoextraction of metals and phytoremediation of organic contaminants are also discussed.

Pierzynski, G. M., J. L. Schnoor, M. K. Banks, J. C. Tracy, L. A. Licht, and L. E. Erickson. 1994. Vegetative Remediation at Superfund Sites. Mining and Its Environ. Impact (Royal Soc. Chem. Issues in Environ. Sci. Technol. 1). pp. 49-69.

This paper discusses in detail the chemical and microbiological aspects of metal-contaminated soils. Two case studies of the phytoremediation of mine waste sites are presented along with a modeling discussion of the fate of heavy metal in vegetated soils.

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

This article is an introduction to the use of phytoremediation technologies for reducing metals contamination. Field research is presented on the use of plants to immobilize metals in soils. Bioavailability issues and mechanisms of plant accumulation are discussed in detail.

## 3.4 Rhizodegradation

### *3.4.1 Definition/Mechanism*

Rhizodegradation is the breakdown of an organic contaminant in soil through microbial activity that is enhanced by the presence of the root zone (Figure 3-2). Rhizodegradation is also known as plant-assisted degradation, plant-assisted bioremediation, plant-aided in situ biodegradation, and enhanced rhizosphere biodegradation.

Root-zone biodegradation is the mechanism for implementing rhizodegradation. Root exudates are compounds produced by plants and released from plant roots. They include sugars, amino acids, organic acids, fatty acids, sterols, growth factors, nucleotides, flavanones, enzymes, and other compounds (Shimp et al. 1993; Schnoor et al. 1995a). The microbial populations and activity in the rhizosphere can be increased due to the presence of these exudates, and can result in increased organic contaminant biodegradation in the soil. Additionally, the rhizosphere substantially increases the surface area where active microbial degradation can be stimulated. Degradation of the exudates can lead to cometabolism of contaminants in the rhizosphere.

Plant roots can affect soil conditions by increasing soil aeration and moderating soil moisture content, thereby creating conditions more favorable for biodegradation by indigenous microorganisms. Thus, increased biodegradation could occur even in the absence of root exudates. One study raised the possibility that transpiration due to alfalfa plants drew methane from a saturated methanogenic zone up into the vadose zone where the methane was used by methanotrophs that cometabolically degraded TCE (Narayanan et al. 1995).

The chemical and physical effects of the exudates and any associated increase in microbial populations might change the soil pH or affect the contaminants in other ways.

### *3.4.2 Media*

### *3.4.3 Advantages*

Rhizodegradation has the following advantages:

- Contaminant destruction occurs in situ.

- Translocation of the compound to the plant or atmosphere is less likely than with other phytoremediation technologies since degradation occurs at the source of the contamination.

- Mineralization of the contaminant can occur.

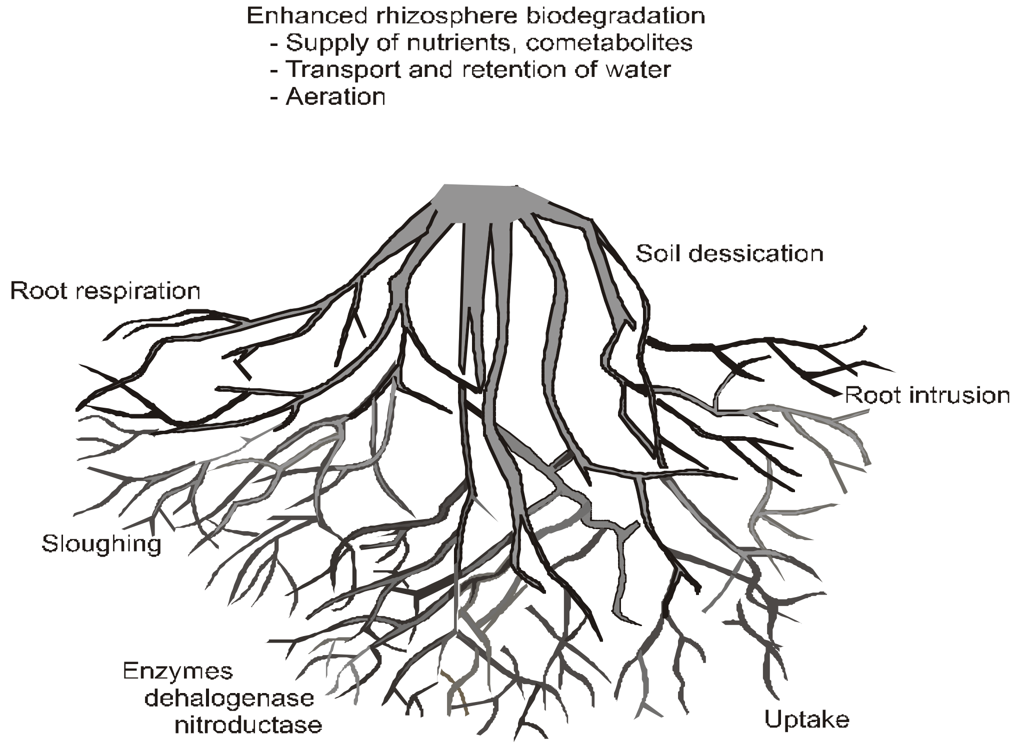


**Figure 3-2.** Rhizodegradation.

- Low installation and maintenance cost as compared to other remedial options.

### 3.4.4 Disadvantages

Rhizodegradation has the following disadvantages:

- Development of an extensive root zone is likely to require substantial time.
- Root depth can be limited due to the physical structure or moisture conditions of the soil.
- The rhizosphere might effect an increase in the initial rate of degradation compared to a nonrhizosphere soil, but the final extent or degree of degradation might be similar in both rhizosphere and nonrhizosphere soil.
- Plant uptake can occur for many of the contaminants that have been studied. Laboratory and field studies need to account for other loss and phytoremediation mechanisms that might complicate the interpretation of rhizodegradation. For example, if plant uptake occurs, phytodegradation or phytovolatilization could occur in addition to rhizodegradation.
- The plants need additional fertilization because of microbial competition for nutrients.
- The exudates might stimulate microorganisms that are not degraders, at the expense of degraders.
- Organic matter from the plants may be used as a carbon source instead of the contaminant, which could decrease the amount of contaminant biodegradation. In laboratory sediment columns, debris from the salt marsh plant *Spartina alterniflora* decreased the amount of oil biodegradation. This could have been due to competition for limited oxygen and nutrients between the indigenous oil-degrading microorganisms and the microorganisms degrading plant organic matter (Molina et al. 1995).

### 3.4.5 Applicable Contaminants/ Concentrations

The following contaminants are amenable to rhizodegradation:

- TPH (total petroleum hydrocarbons)
  - Several field sites contaminated with crude oil, diesel, a heavier oil, and other petroleum products were studied for phytoremediation by examining TPH disappearance. Rhizodegradation and humification were the most important disappearance mechanisms, with little plant uptake occurring. Phytoremediation was able to bring TPH levels to below the plateau level found with normal (non-plant-influenced) bioremediation (Schwab 1998).
  - High initial petroleum hydrocarbon contents (2,000 to 40,000 mg/kg TPH) were studied at several field

sites. Plant growth varied by species, but the presence of some species led to significantly greater TPH disappearance than with other species or in unvegetated soil (Schwab 1998).

- PAHs (polycyclic aromatic hydrocarbons)
  - Chrysene, benzo(a)anthracene, benzo(a)pyrene, and dibenzo(a,h)anthracene had greater disappearance in vegetated soil than in nonvegetated soil (Aprill and Sims 1990).
  - Anthracene and pyrene had greater disappearance in vegetated soils than in unvegetated soil (Reilley et al. 1996).
  - Pyrene was mineralized at a greater rate in a planted system than in an unplanted system (Ferro et al. 1994a).
  - Pyrene at 150 mg/kg was used in an experiment with crested wheatgrass (Ferro et al. 1994b).
  - Anthracene and pyrene at 100 mg/kg were used in a study with grasses and a legume (Reilley et al. 1996).
  - 10 mg/kg PAH (chrysene, benzo(a)anthracene, benzo(a)pyrene, dibenzo(a,h)anthracene) had greater disappearance in vegetated soil than in nonvegetated soil (Aprill and Sims 1990).
  - PAHs at 1,450 to 16,700 mg/kg (in soil also contaminated with PCP) strongly inhibited germination and growth of eight species of grasses (Pivetz et al. 1997).
- BTEX (Benzene, toluene, ethylbenzene, and xylenes)
  - Soil from the rhizosphere of poplar trees had higher populations of benzene-, toluene-, and o-xylene-de grading bacteria than did nonrhizosphere soil. Root exudates contained readily biodegradable organic macromolecules (Jordahl et al. 1997).
- Pesticides
  - Atrazine, metolachlor, and trifluralin herbicides: Soil from the rhizosphere had increased degradation rates compared to nonrhizosphere soil. The experiments were conducted in the absence of plants to minimize effects of root uptake (Anderson et al. 1994).
  - Parathion and diazinon organophosphate insecticides: Mineralization rates of the radiolabeled compounds were higher in rhizosphere soil (soil with roots) than in nonrhizosphere soil (soil without roots). Diazinon mineralization in soil without roots did not increase when an exudate solution was added, but parathion mineralization did increase (Hsu and Bartha 1979).
  - Propanil herbicide: An increased number of gram-negative bacteria were found in rhizosphere soil. It was hypothesized that the best propanil degraders would benefit from the proximity to plant roots and exudates (Hoagland et al. 1994).
  - 2,4-D herbicide: Microorganisms capable of degrading 2,4-D occurred in elevated numbers in the rhizo sphere of sugar cane, compared to nonrhizosphere soil (Sandmann and Loos 1984). The rate constants for 2,4-D biodegradation were higher in rhizosphere soil than in nonrhizosphere soil (Boyle and Shann 1995).
  - 2,4,5-T herbicide: The rate constants for 2,4,5-T biodegradation were higher in rhizosphere soil than in nonrhizosphere soil (Boyle and Shann 1995).
  - Increased degradation of 0.3 g/g trifluralin, 0.5 g/g atrazine, and 9.6 g/g metolachlor occurred in rhizosphere soil compared to nonrhizosphere soil (Anderson et al. 1994).
  - Parathion and diazinon at 5 g/g had greater mineralization in rhizosphere soil than in nonrhizosphere soil (Hsu and Bartha 1979).
  - Rhizosphere soil with 3 g/g propanil had increased numbers of gram-negative bacteria that could rapidly transform propanil (Hoagland et al. 1994).
- Chlorinated solvents
  - Greater TCE mineralization was measured in vegetated soil as compared to nonvegetated soil (Anderson and Walton 1995).
  - TCE and TCA dissipation was possibly aided by rhizosphere biodegradation enhanced by the plant roots (Narayanan et al. 1995).
  - TCE at 100 and 200 g/L in groundwater was used in a soil and groundwater system (Narayanan et al. 1995).
  - TCA at 50 and 100 g/L in groundwater was used in a soil and groundwater system (Narayanan et al. 1995).
- PCP (pentachlorophenol)
  - PCP was mineralized at a greater rate in a planted system than in an unplanted system (Ferro et al. 1994b).
  - 100 mg PCP/kg soil was used in an experiment with hycrest crested wheatgrass [*Agropyron desertorum* (Fisher ex Link) Schultes] (Ferro et al. 1994b).
  - Proso millet (*Panicum miliaceum* L.) seeds treated with a PCP-degrading bacterium germinated and grew well in soil containing 175 mg/L PCP, compared to untreated seeds (Pfender 1996).

- PCP at 400 to 4100 mg/kg (in soil also contaminated with PAHs) strongly inhibited germination and growth of eight species of grasses (Pivetz et al. 1997).

• PCBs (polychlorinated biphenyls)

- Compounds (such as flavonoids and coumarins) found in leachate from roots of specific plants stimulated the growth of PCB-degrading bacteria (Donnelly et al. 1994; Gilbert and Crowley 1997).

• Surfactants

- Linear alkylbenzene sulfonate (LAS) and linear alcohol ethoxylate (LAE) had greater mineralization rates in the presence of root microorganisms than in nonrhizosphere sediments (Federle and Schwab 1989).

- LAS and LAE at 1 mg/L had greater mineralization rates in the presence of root microorganisms than in nonrhizosphere sediments (Federle and Schwab 1989).

### *3.4.6 Root Depth*

Because the rhizosphere extends only about 1 mm from the root and initially the volume of soil occupied by roots is a small fraction of the total soil volume, the soil volume initially affected by the rhizosphere is limited. With time, however, new roots will penetrate more of the soil volume and other roots will decompose, resulting in additional exudates to the rhizosphere. Thus, the extent of rhizodegradation will increase with time and with additional root growth. The effect of rhizodegradation might extend slightly deeper than the root zone. If the exudates are water soluble, not strongly sorbed, and not quickly degraded, they may move deeper into the soil. Contaminated groundwater can be affected if it is within the influence of roots.

### *3.4.7 Plants*

Plants that produce exudates that have been shown to stimulate growth of degrading microorganisms or stimulate cometabolism will be of more benefit than plants without such directly useful exudates. The type, amount, and effectiveness of exudates and enzymes produced by a plant's roots will vary between species and even within subspecies or varieties of one species.

The following are examples of plants capable of rhizodegradation:

• Red mulberry (*Morus rubra* L.), crabapple [*Malus fusca* (Raf.) Schneid], and osage orange [*Maclura pomifera* (Raf.) Schneid] produced exudates containing relatively high levels of phenolic compounds, at concentrations capable of stimulating growth of PCB-degrading bacteria (Fletcher and Hegde 1995).

• Spearmint (*Mentha spicata*) extracts contained a compound that induced cometabolism of a PCB (Gilbert and Crowley 1997).

• Alfalfa (*Medicago sativa*) appears to have contributed to the dissipation of TCE and TCA through exudates on soil bacteria (Narayanan et al. 1995).

• A legume [*Lespedeza cuneata* (Dumont)], Loblolly pine [*Pinus taeda* (L.)], and soybean [*Glycine max* (L.) Merr., cv Davis] increased TCE mineralization compared to nonvegetated soil (Anderson and Walton 1995).

• At a Gulf Coast field site, the use of annual rye and St. Augustine grass led to greater TPH disappearance after 21 months than that experienced with the use of sorghum or an unvegetated plot (Schwab 1998).

• At one field site, although white clover did not survive the second winter, concentrations of TPH were reduced more than with tall fescue or bermudagrass with annual rye, or bare field (Schwab 1998).

• PAH degradation occurred through the use of the following mix of prairie grasses: big bluestem (*Andropogon gerardi*), little bluestem (*Schizachyrium scoparius*), Indiangrass (*Sorghastrum nutans*), switchgrass (*Panicum virgatum*), Canada wild rye (*Elymus canadensis*), western wheatgrass (*Agropyron smithii*), side oats grama (*Bouteloua curtipendula*), and blue grama (*Bouteloua gracilis*) (Aprill and Sims 1990).

• Fescue (*Festuca arundinacea* Schreb), a cool-season grass; sudangrass (*Sorghum vulgare* L.) and switchgrass (*Panicum virgatum* L.), warm-season grasses; and alfalfa (*Medicago sativa* L.), a legume, were used to study PAH disappearance; greater disappearance was seen in the vegetated soils than in unvegetated soils (Reilley et al. 1996).

• Hycrest crested wheatgrass [*Agropyron desertorum* (Fischer ex Link) Schultes] increased mineralization rates of PCP and pyrene relative to unplanted controls (Ferro et al. 1994a, 1994b).

• In PAH- and PCP-contaminated soil, a mix of fescues [hard fescue (*Festuca ovina* var. *duriuscula*), tall fescue (*Festuca arundinacea*), and red fescue (*Festuca rubra*)] had higher germination rates and greater biomass relative to controls than did a mix of wheatgrasses [western wheatgrass (*Agropyron smithii*) and slender wheatgrass (*Agropyron trachycaulum*)] and a mix of little bluestem (*Andropogon scoparius*), Indiangrass (*Sorghastrum nutans*), and switchgrass (*Panicum virgatum*) (Pivetz et al. 1997).

• Bush bean (*Phaseolus vulgaris* cv. "Tender Green") rhizosphere soil had higher parathion and diazinon mineralization rates than nonrhizosphere soil (Hsu and Bartha 1979).

• Rice (*Oryza sativa* L.) rhizosphere soil had increased numbers of gram-negative bacteria, which were able to rapidly transform propanil (Hoagland et al. 1994).

• *Kochia* sp. rhizosphere soil increased the degradation of herbicides relative to nonrhizosphere soil (Anderson et al. 1994).

- Cattail (*Typha latifolia*) root microorganisms produced greater mineralization rates of LAS and LAE than did nonrhizosphere sediments (Federle and Schwab 1989).

- Hybrid poplar tree (*Populus deltoides* X *nigra* DN-34, Imperial Carolina) rhizosphere soil contained significantly higher populations of total heterotrophs, denitrifiers, pseudomonads, BTX degraders, and atrazine degraders than did nonrhizosphere soil (Jordahl et al. 1997).

## *3.4.8 Site Considerations*

### 3.4.8.1 Soil Conditions

The physical and chemical soil conditions must allow for significant root penetration and growth.

### 3.4.8.2 Ground and Surface Water

Although rhizodegradation is primarily soil-based, groundwater movement can be induced by the transpiration of plants bringing contaminants from the groundwater into the root zone.

### 3.4.8.3 Climatic Conditions

Field studies that include rhizodegradation as a component have been conducted under in a wide variety of climates including the humid south, arid west, and the cold north.

## *3.4.9 Current Status*

The following list provides information on the status or application of rhizodegradation studies:

- Rhizodegradation was first extensively studied in relation to the biodegradation of pesticides in agricultural soils.

- Numerous laboratory and greenhouse studies and several field studies have been conducted, including a field study conducted at the McCormick & Baxter Superfund Site.

- "Hot spots" of higher contaminant concentrations can be excavated and treated using other technologies, or landfilled. Rhizodegradation could be applied as a polishing or final step after active land treatment bioremediation has ended.

- A TPH/PAH subgroup has been established as part of the RTDF Phytoremediation of Organics Action Team to examine rhizodegradation. The Petroleum Environmental Research Forum is also examining rhizodegradation in the phytoremediation of petroleum hydrocarbons.

## *3.4.10 System Cost*

Cost information for rhizodegradation is incomplete at this time.

## *3.4.11 Selected References*


Anderson, T.A., and J. R. Coats (eds.). 1994. Bioremediation Through Rhizosphere Technology, ACS Symposium Series, Volume 563. American Chemical Society, Washington, DC. 249 pp.

This is a collection of 17 articles examining rhizodegradation. The papers introduce the concepts involved in rhizodegradation; discuss interactions between microorganisms, plants, and chemicals; and provide examples of rhizodegradation of industrial chemicals and pesticides.

Anderson, T. A., E. A. Guthrie, and B. T. Walton. 1993. Bioremediation in the Rhizosphere. Environ. Sci. Technol. 27:2630-2636.

This literature review summarizes research work conducted on a variety of contaminants (pesticides, chlorinated solvents, petroleum products, and surfactants).

Anderson, T. A., and B. T. Walton. 1995. Comparative Fate of [$^{14}$c]trichloroethylene in the Root Zone of Plants from a Former Solvent Disposal Site. Environ. Toxicol. Chem. 14:2041-2047.

Exposure chambers within an environmental chamber were used with a variety of plant types and with radiolabeled TCE. Mineralization rates were greater in vegetated soils than in unvegetated soils.

Aprill, W., and R. C. Sims. 1990. Evaluation of the Use of Prairie Grasses for Stimulating Polycyclic Aromatic Hydrocarbon Treatment in Soil. Chemosphere. 20:253-265.

Eight prairie grasses were examined using chambers constructed of 25-cm-diameter PVC pipe. PAH-spiked soil at 10 mg PAH/kg soil was added to the chambers prior to seeding. Soil, leachate, and plant tissue samples were collected during the study. PAH disappearance was greater in planted chambers compared to unplanted chambers.

Ferro, A. M., R. C. Sims, and B. Bugbee. 1994a. Hycrest Crested Wheatgrass Accelerates the Degradation of Pentachlorophenol in Soil. J. Environ. Qual. 23:272-279.

A growth-chamber study conducted using radiolabeled pentachlorophenol indicated that mineralization was greater in planted systems than in unplanted systems.

Fletcher, J. S., and R. S. Hegde. 1995. Release of Phenols by Perennial Plant Roots and their Potential Importance in Bioremediation. Chemosphere. 31:3009-3016.

Greenhouse studies identified chemical and microbiological evidence for the occurrence of rhizodegradation. The potential for biodegradation within the root zone was determined to be dependent on the particular plant species and exudates produced by the plant.

Schnoor, J. L., L. A. Licht, S. C. McCutcheon, N. L. Wolfe, and L. H. Carreira. 1995a. Phytoremediation of Organic and Nutrient Contaminants. Environ. Sci. Technol. 29:318A-323A.

This paper introduces the important concepts for rhizodegradation and phytodegradation, including the role of plant enzymes. Laboratory and field research for TNT, pesticides, and nutrient contaminants is summarized. Applications and limitations of phytoremediation are discussed, and field applications of phytoremediation are tabulated.

Schwab, A. P. 1998. Phytoremediation of Soils Contaminated with PAHs and Other Petroleum Compounds. Presented at: Beneficial Effects of Vegetation in Contaminated Soils Workshop, Kansas State University, Manhattan, KS, January 7-9, 1998. Sponsored by Great Plains/Rocky Mountain Hazardous Substance Research Center.

This presentation summarizes the methods and results of field test plots at a variety of geographic and climatic regions. Dissipation of TPH was greater in planted plots than in unplanted plots, and differences were seen in the growth and effectiveness of different plant species.

## 3.5 Phytodegradation

### *3.5.1 Definition/Mechanism*

Phytodegradation (also known as phytotransformation) is the breakdown of contaminants taken up by plants through metabolic processes within the plant, or the breakdown of contaminants external to the plant through the effect of compounds (such as enzymes) produced by the plants. As shown in Figure 3-3, the main mechanism is plant uptake and metabolism. Additionally, degradation may occur outside the plant, due to the release of compounds that cause transformation. Any degradation caused by microorganisms associated with or affected by the plant root is considered rhizodegradation.

#### 3.5.1.1 Uptake

For phytodegradation to occur within the plant, the compounds must be taken up by the plant. One study identified more than 70 organic chemicals representing many classes of compounds that were taken up and accumulated by 88 species of plants and trees (Paterson et al. 1990). A database has been established to review the classes of chemicals and types of plants that have been investigated in regard to their uptake of organic compounds (Nellessen and Fletcher 1993b).

Uptake is dependent on hydrophobicity, solubility, and polarity. Moderately hydrophobic organic compounds (with log $k_{ow}$ between 0.5 and 3.0) are most readily taken up by and translocated within plants. Very soluble compounds (with low sorption) will not be sorbed onto roots or translocated within the plant (Schnoor et al. 1995a). Hydrophobic (lipophilic) compounds can be bound to root surfaces or partitioned into roots, but cannot be further translocated within the plant (Schnoor et al. 1995a; Cunningham et al. 1997). Nonpolar molecules with molecular weights <500 will sorb to the root surfaces, whereas polar molecules will enter the root and be translocated (Bell 1992).

Plant uptake of organic compounds can also depend on type of plant, age of contaminant, and many other physical and chemical characteristics of the soil. Definitive conclusions cannot always be made about a particular chemical. For example, when PCP was spiked into soil, 21% was found in roots and 15% in shoots after 155 days in the presence of grass (Qiu et al. 1994); in another study, several plants showed minimal uptake of PCP (Bellin and O'Connor 1990).

#### 3.5.1.2 Metabolism

Metabolism within plants has been identified for a diverse group of organic compounds, including the herbicide atrazine (Burken and Schnoor 1997), the chlorinated solvent TCE (Newman et al. 1997a), and the munition TNT (Thompson et al. 1998). Other metabolized compounds include the insecticide DDT, the fungicide hexachlorobenzene (HCB), PCP, the plasticizer diethylhexylphthalate (DEHP), and PCBs in plant cell cultures (Komossa et al. 1995).

#### 3.5.1.3 Plant-Formed Enzymes

Plant-formed enzymes have been identified for their potential use in degrading contaminants such as munitions, herbicides, and chlorinated solvents. Immunoassay tests have been used to identify plants that produce these enzymes (McCutcheon 1996).

### *3.5.2 Media*

Phytodegradation is used in the treatment of soil, sediments, sludges, and groundwater. Surface water can also be remediated using phytodegradation.

### *3.5.3 Advantages*

Contaminant degradation due to enzymes produced by a plant can occur in an environment free of microorganisms (for example, an environment in which the microorganisms have been killed by high contaminant levels). Plants are able to grow in sterile soil and also in soil that has concentration levels that are toxic to microorganisms. Thus, phytodegradation potentially could occur in soils where biodegradation cannot.

### *3.5.4 Disadvantages*

Phytodegradation has the following disadvantages:

- Toxic intermediates or degradation products may form. In a study unrelated to phytoremediation research, PCP was metabolized to the potential mutagen tetrachlorocatechol in wheat plants and cell cultures (Komossa et al. 1995).
- The presence or identity of metabolites within a plant might be difficult to determine; thus contaminant destruction could be difficult to confirm.

### *3.5.5 Applicable Contaminants/ Concentrations*

Organic compounds are the main category of contaminants subject to phytodegradation. In general,

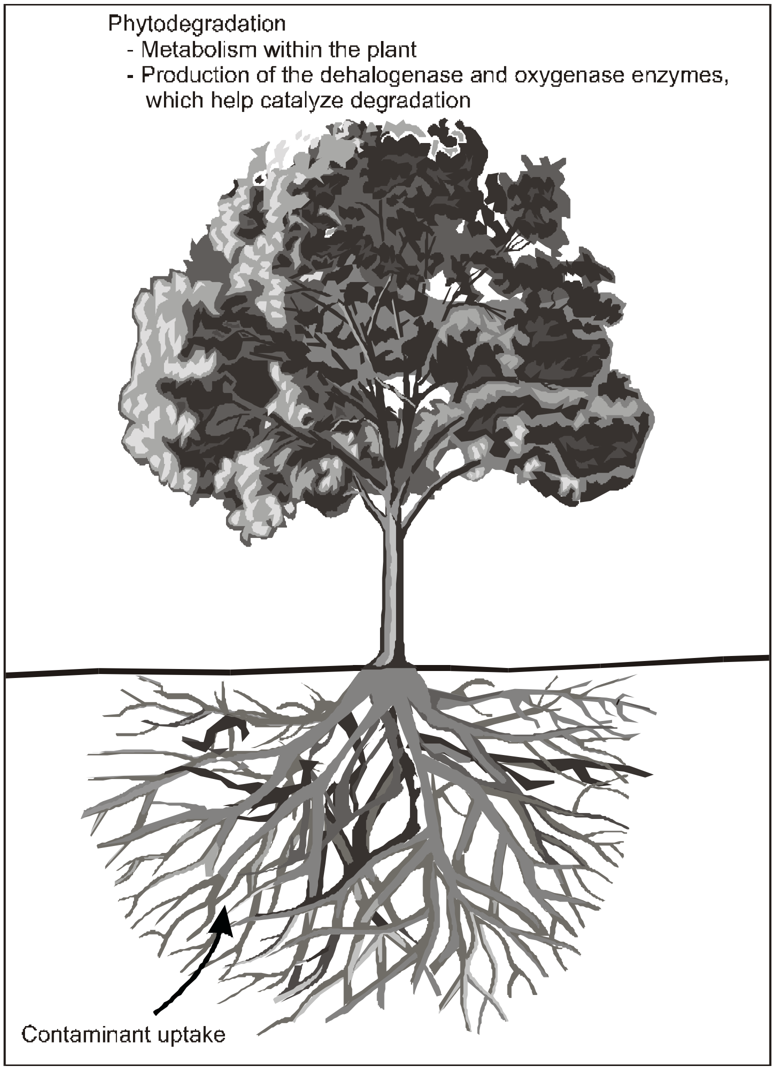


**Figure 3-3.** Phytodegradation.

organic compounds with a log $k_{ow}$ between 0.5 and 3.0 can be subject to phytodegradation within the plant. Inorganic nutrients are also remediated through plant uptake and metabolism. Phytodegradation outside the plant does not depend on log $k_{ow}$ and plant uptake.

#### 3.5.5.1 Organics

- Chlorinated solvents
  - The plant-formed enzyme dehalogenase, which can dechlorinate chlorinated compounds, has been discovered in sediments (McCutcheon 1996).
  - TCE was metabolized to trichloroethanol, trichloroacetic acid, and dichloroacetic acid within hybrid poplar trees (Newman et al. 1997a). In a similar study, hybrid poplar trees were exposed to water containing about 50 ppm TCE and metabolized the TCE within the tree (Newman et al. 1997a).
  - Minced horseradish roots successfully treated wastewater containing up to 850 ppm of 2,4-dichlorophenol (Dec and Bollag 1994).
- Herbicides
  - Atrazine in soil was taken up by trees and then hydrolyzed and dealkylated within the roots, stems, and leaves. Metabolites were identified within the plant tissue, and a review of atrazine metabolite toxicity studies indicated that the metabolites were less toxic than atrazine (Burken and Schnoor 1997).
  - The plant-formed enzyme nitrilase, which can degrade herbicides, has been discovered in sediments (Carreira 1996).

- A qualitative study indicated that the herbicide bentazon was degraded within black willow trees, as indicated by bentazon loss during a nurs ery study and by identification of metabolites within the tree. Bentazon was phytotoxic to six tree species at concentrations of 1000 and 2000 mg/L. At 150 mg/kg, bentazon metabolites were detected within tree trunk and canopy tissue samples (Conger and Portier 1997).

- Atrazine at 60.4 g/kg (equivalent to about 3 times field application rates) was used to study phytodegradation in hybrid poplars (Burken and Schnoor 1997).

- The herbicide bentazon was phytotoxic at concentrations of 1,000 to 2,000 mg/L, but allowed growth at 150 mg/L (Conger and Portier 1997).

• Insecticides

- The isolation from plants of the enzyme phosphatase, which can degrade organophosphate insecticides,may have phyotodegradation applications (McCutcheon 1996).

• Munitions

- The plant-formed enzyme nitroreductase, which can degrade munitions, has been discovered in sediments; this enzyme, from parrot feather, degraded TNT (McCutcheon 1996).

- Hybrid poplar trees metabolized TNT to 4-amino-2,6-dinitrotoluene (4-ADNT), 2-amino-4,6-dinitrotoluene (2-ADNT), and other unidentified compounds (Thompson et al. 1998).

- TNT concentrations in flooded soil decreased from 128 to 10 ppm with parrot feather (Schnoor et al. 1995b).

• Phenols

- Chlorinated phenolic concentrations in wastewater decreased in the presence of oxidoreductase enzymes in minced horseradish roots (Dec and Bollag 1994).

#### 3.5.5.2 Inorganics

• Nutrients

- Nitrate will be taken up by plants and transformed to proteins and nitrogen gas (Licht and Schnoor 1993).

### *3.5.6 Root Depth*

Phytodegradation is generally limited to the root zone, and possibly below the root zone if root exudates are soluble, nonsorbed, and transported below the root zone. The degree to which this occurs is uncertain.

### *3.5.7 Plants*

The aquatic plant parrot feather (*Myriophyllum aquaticum*) and the algae stonewort (*Nitella*) have been used for the degradation of TNT. The nitroreductase enzyme has also been identified in other algae, ferns, monocots, dicots, and trees (McCutcheon 1996).

Degradation of TCE has been detected in hybrid poplars and in poplar cell cultures, resulting in production of metabolites and in complete mineralization of a small portion of the applied TCE (Gordon et al. 1997; Newman et al. 1997a). Atrazine degradation has also been confirmed in hybrid poplars (*Populus deltoides x nigra* DN34, Imperial Carolina) (Burken and Schnoor 1997). Poplars have also been used to remove nutrients from groundwater (Licht and Schnoor 1993).

Black willow (*Salix nigra*), yellow poplar (*Liriodendron tulipifera*), bald cypress (*Taxodium distichum*), river birch (*Betula nigra*), cherry bark oak (*Quercus falcata*), and live oak (*Quercus viginiana*) were able to support some degradation of the herbicide bentazon (Conger and Portier 1997).

### *3.5.8 Site Considerations*

#### 3.5.8.1 Soil Conditions

Phytodegradation is most appropriate for large areas of soil having shallow contamination.

#### 3.5.8.2 Ground and Surface Water

Groundwater that can be extracted by tree roots or that is pumped to the surface may be treated by this system. Phytodegradation can also occur in surface water, if the water is able to support the growth of appropriate plants.

#### *3.5.8.3 Climatic Conditions*

Phytoremediation studies involving phytodegradation have been conducted under a wide variety of climatic conditions.

### *3.5.9 Current Status*

Research and pilot-scale studies have been conducted primarily at Army Ammunition Plants (AAPs). These demonstrations include field studies at the Iowa AAP, Volunteer AAP, and Milan AAP (McCutcheon 1996).

### *3.5.10 System Costs*

Cost information has not been reported.

### *3.5.11 Selected References*

Bell, R. M. 1992. Higher Plant Accumulation of Organic Pollutants from Soils. Risk Reduction Engineering Laboratory, Cincinnati, OH. EPA/600/R-92/138.

This paper includes an extensive literature review of the behavior of organic contaminants in plant-soil systems and the uptake of contaminants by plant. A wide variety of plant species and contaminant types are covered in

the paper. Tables and graphs in the reviewed literature provide quantitative information on plant uptake. Experiments conducted on plant uptake of hexachlorobenzene, phenol, toluene, and TCE are described in depth.

Burken, J. G., and J. L. Schnoor. 1997. Uptake and Metabolism of Atrazine by Poplar Trees. Environ. Sci. Technol. 31:1399-1406.

This presentation describes poplar trees grown in soil or sand that took up, hydrolyzed, and dealkylated radiolabeled atrazine to less-toxic compounds. Metabolism was found to occur in roots, stems, and leaves, and the amount of metabolism increased with increased time in plant tissue. In leaves, the atrazine parent compound was found to be 21% of the radiolabel at 50 days, and 10% at 80 days. In the sand planting, uptake of the radiolabel was 27.8% at 52 days and 29.2% at 80 days. Less than 20% of radiolabel remained as bound residue in plant tissue. Atrazine degradation in unplanted soil was similar to degradation in planted soil. A model for atrazine metabolism was also presented.

McCutcheon, S. 1996. Phytoremediation of Organic Compounds: Science Validation and Field Testing. In W. W. Kovalick and R. Olexsey (eds.), Workshop on Phytoremediation of Organic Wastes, December 17-19, 1996, Ft. Worth, TX. An EPA unpublished meeting summary.

An overview of the uses, advantages, and disadvantages of phytoremediation are presented along with the identification and use of plant-derived enzymes for photodegradation. Field demonstrations at several Army Ammunition Plants are also discussed.

Newman, L. A., S. E. Strand, N. Choe, J. Duffy, G. Ekuan, M. Ruszaj, B. B. Shurtleff, J. Wilmoth, P. Heilman, and M. P. Gordon. 1997a. Uptake and Biotransformation of Trichloroethylene by Hybrid Poplars. Environ. Sci. Technol. 31:1062-1067.

Discussions are presented of axenic poplar tumor cell cultures dosed with TCE and samples that were analyzed for degradation products and $^{14}CO_2$. The cells studied metabolized TCE to trichloroethanol and di- and trichloracetic acid. The cell cultures oxidized 1 to 2% of the TCE to $CO_2$ in 4 days. Whole trees were exposed to 50 ppm TCE. Leaves were bagged and the entrapped air sampled for TCE. Plant parts were harvested and analyzed for TCE and metabolites. TCE-exposed trees had significant TCE in stems but minimal amounts in leaves. Equal concentrations of trichloroethanol and TCE were found in leaves, but a smaller concentration of trichloroethanol than TCE was found in stems. Trichloroacetic acid appeared in stems and leaves. Roots contained TCE, trichloroacetic acid, dichloroacetic acid, and trichloroethanol. TCE was transpired from the trees.

Paterson, S., D. Mackay, D. Tam, and W. Y. Shiu. 1990. Uptake of Organic Chemicals by Plants: A Review of Processes, Correlations and Models. Chemosphere. 21:297-331.

The routes of entry (root uptake and foliar uptake) of organic compounds into plants are discussed. Equations are presented that correlate the concentration in various parts of a plant to the octanol-water partition coefficient, molecular weight, or Henry's Law constant. A review of plant uptake models is also included. Crossed-referenced tables are included that identify the literature citations for plant uptake research conducted on different plant species and on different chemical compounds.

Thompson, P. L., L. A. Ramer, and J. L. Schnoor. 1998. Uptake and Transformation of TNT by Hybrid Poplar Trees. Environ. Sci. Technol. 32:975-980.

In these laboratory experiments, hybrid poplars and radiolabeled TNT were used in hydroponic and soil systems. Much of the TNT was bound in the roots, with relative little (<10%) translocation within the tree. Metabolites of TNT were found within the plant tissue.

## 3.6 Phytovolatilization

### *3.6.1 Definition/Mechanism*

Phytovolatilization (Figure 3-4) is the uptake and transpiration of a contaminant by a plant, with release of the contaminant or a modified form of the contaminant to the atmosphere from the plant through contaminant uptake, plant metabolism, and plant transpiration. Phytodegradation is a related phytoremediation process that can occur along with phytovolatilization.

### *3.6.2 Media*

Phytovolatilization has mainly been applied to groundwater, but it can be applied to soil, sediments, and sludges.

### *3.6.3 Advantages*

Phytovolatilization has the following advantages:

- Contaminants could be transformed to less-toxic forms, such as elemental mercury and dimethyl selenite gas.
- Contaminants or metabolites released to the atmosphere might be subject to more effective or rapid natural degradation processes such as photodegradation.

### *3.6.4 Disadvantages*

Phytovolatilization has the following disadvantages:

- The contaminant or a hazardous metabolite (such as vinyl chloride formed from TCE) might be released into the atmosphere. One study indicated TCE transpiration, but other studies found no transpiration.
- The contaminant or a hazardous metabolite might accumulate in vegetation and be passed on in later products such as fruit or lumber. Low levels of metabolites have been found in plant tissue (Newman et al. 1997a).

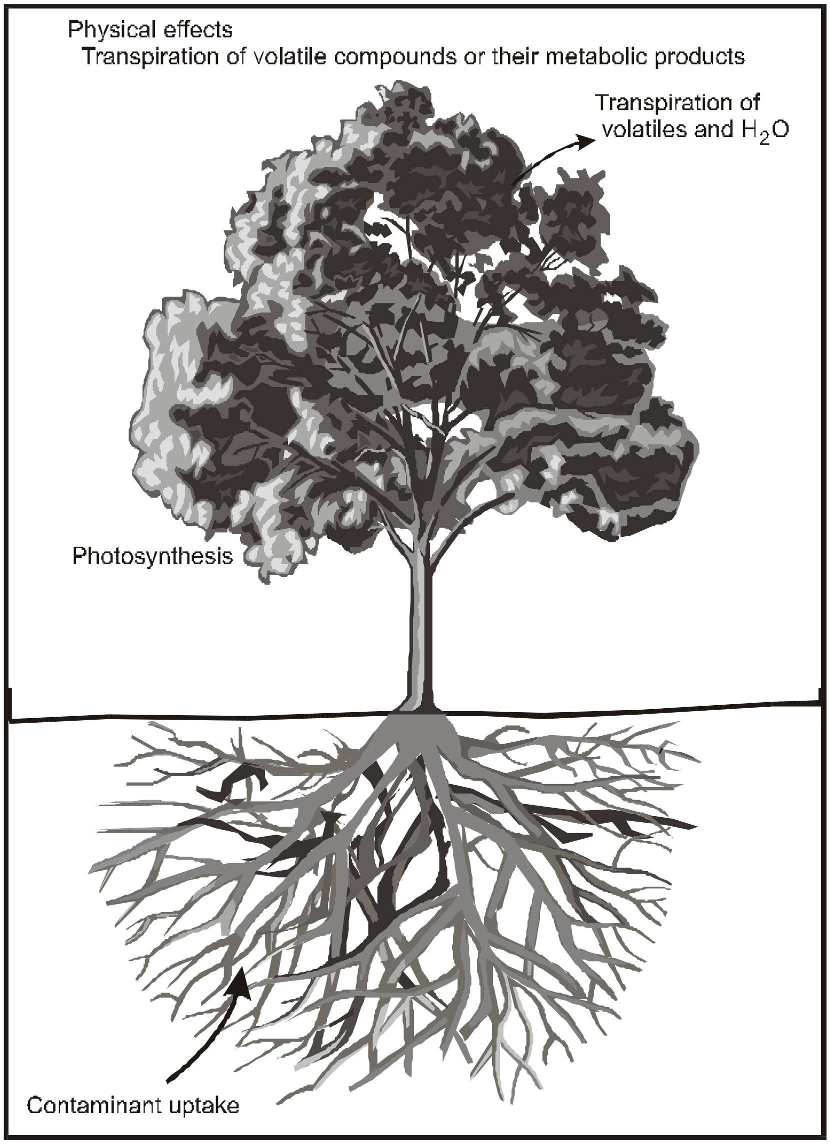


**Figure 3-4.** Phytovolatilization.

### *3.6.5 Applicable Contaminants/ Concentrations*

#### 3.6.5.1 Organics

Chlorinated solvents include TCE, 1,1,1-trichloroethane (TCA) and carbon tetrachloride (Newman et al. 1997a, 1997b; Narayanan et al. 1995). In two years, hybrid poplars removed >97% of the 50-ppm TCE from the water (Newman et al. 1997b). 100 and 200 µg/L TCE in groundwater was studied using alfalfa (Narayanan et al. 1995). 50 and 100 µg/L TCE in groundwater were studied using alfalfa (Narayanan et al. 1995). In one year, 95% of 50-ppm carbon tetrachloride was removed by hybrid poplars (Newman et al. 1997b).

#### 3.6.5.2 Inorganics

The inorganic contaminants Se and Hg, along with As, can form volatile methylated species (Pierzynski et al. 1994). Selenium has been taken up and transpired at groundwater concentrations of 100 to 500 µg/L (Bañuelos et al. 1997a) and at soil concentrations of 40 mg/L (Bañuelos et al. 1997b). Genetically engineered plants were able to germinate and grow in 20-ppm $Hg^{++}$ and then volatilize the Hg; 5 to 20 ppm $Hg^{++}$ was phytotoxic to unaltered plants (Meagher and Rugh 1996).

### *3.6.6 Root Depth*

The contaminant has to be within the influence of the root of the plant. Since groundwater is the target media, contaminated groundwater upgradient of the plants may flow into the area of influence of the plants. Contaminated water may also be pumped and watered on plants.

### 3.6.7 Plants

Plants used for phytovolatilization include:

- University of Washington researchers have extensively studied the use of poplars in the phytoremediation of chlorinated solvents. In these studies, transformation of TCE was found to occur within the trees (Newman et al. 1997a).

- Alfalfa (*Medicago sativa*) has been studied by Kansas State University researchers for its role in the phytovolatilization of TCE.

- Black locust species were studied for use in remediating TCE in groundwater (Newman et al. 1997b).

- Indian mustard (*Brassica juncea*) and canola (*Brassica napus*) have been used in the phytovolatilization of Se. Selenium (as selenate) was converted to less-toxic dimethyl selenite gas and released to the atmosphere (Adler 1996). Kenaf (*Hibiscus cannabinus* L. cv. Indian) and tall fescue (*Festuca arundinacea* Schreb cv. Alta) have also been used to take up Se, but to a lesser degree than canola (Bañuelos et al. 1997b).

- A weed from the mustard family (*Arabidopsis thaliana*) genetically modified to include a gene for mercuric reductase converted mercuric salts to metallic mercury and released it to the atmosphere (Meagher and Rugh 1996).

### 3.6.8 Site Considerations

Because phytovolatilization involves the transfer of contaminants to the atmosphere, the impact of this contaminant transfer on the ecosystem and on human health needs to be addressed.

#### 3.6.8.1 Soil Conditions

For significant transpiration to occur, the soil must be able to transmit sufficient water to the plant.

#### 3.6.8.2 Ground and Surface Water

Groundwater must be within the influence of the plant (usually a tree) roots.

#### 3.6.8.3 Climatic Conditions

Climatic factors such as temperature, precipitation, humidity, insolation, and wind velocity can affect transpiration rates.

### 3.6.9 Current Status

Several research groups are performing active laboratory and field studies of TCE phytovolatilization and other chlorinated solvents. A SITE demonstration project has been started at the Carswell Site, Fort Worth, TX using poplars to phytoremediate TCE-contaminated groundwater and to examine the possible fate of the TCE, including volatilization.

A significant amount of research, including field testing and application, has been conducted on selenium volatilization.

### 3.6.10 System Costs

Cost information is being collected as part of the SITE demonstration project at the Carswell Site.

### 3.6.11 Selected References

Bañuelos, G. S., H. A. Ajwa, N. Terry, and S. Downey. 1997a. Abstract: Phytoremediation of Selenium-Laden Effluent. Fourth International In Situ and On-Site Bioremediation Symposium, April 28 - May 1, 1997, New Orleans, LA. 3:303.

This abstract summarizes the methods used in field investigations of the use of *Brassica napus* (canola) to remediate water contaminated with selenium. These field studies included an investigation of the volatilization of selenium by the plants.

Bañuelos, G. S., H. A. Ajwa, B. Mackey, L. L. Wu, C. Cook, S. Akohoue, and S. Zambrzuski. 1997b. Evaluation of Different Plant Species Used for Phytoremediation of High Soil Selenium. J. Environ. Qual. 26:639-646.

This evaluation discusses three plant species (canola, kenaf, and tall fescue) grown in seleniferous soil under greenhouse conditions. Total soil selenium was significantly reduced by each species. A partial mass balance indicated that some selenium was lost by a mechanism that was not measured. Selenium volatilization was hypothesized as the cause of the decrease in soil concentration.

Meagher, R. B., and C. Rugh. 1996. Abstract: Phytoremediation of Mercury Pollution Using a Modified Bacterial Mercuric Ion Reductase Gene. International Phytoremediation Conference, May 8-10, 1996, Arlington, VA. International Business Communications, Southborough, MA.

This abstract describes transgenic plants developed to reduce mercuric ion to metallic mercury, which was then volatilized, and additional plants developed to process methyl mercury to metallic mercury.

Newman, L. A., S. E. Strand, N. Choe, J. Duffy, G. Ekuan, M. Ruszaj, B. B. Shurtleff, J. Wilmoth, P. Heilman, and M. P. Gordon. 1997a. Uptake and Biotransformation of Trichloroethylene by Hybrid Poplars. Environ. Sci. Technol. 31:1062-1067.

Whole trees were exposed to 50 ppm TCE and bags were placed around leaves. Analysis of the entrapped air indicated that TCE was transpired from the trees.

### 3.7.5 *Applicable Contaminants/ Concentrations*

Water-soluble leachable organics and inorganics are used at concentrations that are not phytotoxic. Poplar trees were used to form a barrier to groundwater movement at a site contaminated with gasoline and diesel (Nelson 1996).

### 3.7.6 *Root Depth*

Hydraulic control by plants occurs within the root zone or within a depth influenced by roots, for example:

- The effective rooting depth of most crops is 1 to 4 feet. Trees and other vegetation can be used to remediate groundwater in water table depths of 30 feet or less (Gatliff 1994).
- Plant roots above the water table can influence contaminants in the groundwater by interfacing through the capillary fringe. Fe, Tc, U, and P diffused upward from the water table and were absorbed by barley roots that were 10 cm (3.9 in) above the water table interface (Sheppard and Evenden 1985).
- The placement depth of roots during planting can be varied. Root depth, early tree growth, and nitrogen accumulation were enhanced by placing poplar tree root balls closer to shallow groundwater during planting (Gatliff 1994).

### 3.7.7 *Plants*

The following plants are used in hydraulic control:

- Cottonwood and hybrid poplar trees were used at seven sites in the East and Midwest to contain and treat shallow groundwater contaminated with heavy metals, nutrients, or pesticides (Gatliff 1994). Poplars were used at a site in Utah to contain groundwater contaminated with gasoline and diesel (Nelson 1996). Passive gradient control was studied at the French Limited Superfund site using a variety of phreatophyte trees; native nondeciduous trees were found to perform the best (Sloan and Woodward 1996).

### 3.7.8 *Site Considerations*

The establishment of trees or other vegetation is likely to require a larger area than would be required for the installation of a pumping well.

#### 3.7.8.1 Soil Conditions

The primary considerations for selecting hydraulic control as the method of choice are the depth and concentration of contaminants that affect plant growth. Soil texture and degree of saturation are influential factors. Planting technique and materials can extend the influence of plants through non-saturated zones to water-bearing layers.

#### 3.7.8.2 Ground and Surface Water

The amount of water transpired by a tree depends on many factors, especially the size of the tree. Some estimates of the rate of water withdrawal by plants are given below.

- Poplar trees on a landfill in Oregon transpired 70 acre-inches of water per acre of trees (Wright and Roe 1996).
- Two 40-foot-tall cottonwood trees in southwestern Ohio pumped 50 to 350 gallons per day (gpd) per tree, based on calculations using observed water-table drawdown (Gatliff 1994).
- A 5-year-old poplar tree can transpire between 100 and 200 L water per day (Newman et al. 1997a).
- Young poplars were estimated to transpire about 8 gpd per tree, based on the observed water table drawdown (Nelson 1996).
- Mature phreatophyte trees were estimated to use 200 to 400 gpd (Sloan and Woodward 1996).

#### 3.7.8.3 Climatic Conditions

The amount of precipitation, temperature, and wind may affect the transpiration rate of vegetation.

### 3.7.9 *Current Status*

Several U.S. companies have installed phytoremediation systems that have successfully incorporated hydraulic control.

### 3.7.10 *System Cost*

Estimated costs for remediating an unspecified contaminant in a 20-foot-deep aquifer at a 1-acre site were $660,00 for conventional pump-and-treat, and $250,000 for phytoremediation using trees (Gatliff 1994).

### 3.7.11 *Selected References*

Gatliff, E. G. 1994. Vegetative Remediation Process Offers Advantages Over Traditional Pump-and-Treat Technologies. Remed. Summer. 4(3):343-352.

A summary is presented of the impact of poplar or cottonwood trees to influence a shallow water table at sites along the East Coast and in the Midwest that were contaminated with pesticides, nutrients, or heavy metals. The contribution of the trees to water table drawdown was measured at some sites. Information is presented on the decrease in contaminant concentrations at some of the sites.

Wright, A. G., and A. Roe. 1996. It's Back to Nature for Waste Cleanup. ENR. July 15. pp. 28-29.

A poplar tree system for landfill leachate collection and treatment is described. The trees use up to 70 inches of water per acre per year. A proposed project at another landfill is presented.

## 3.8 Vegetative Cover Systems

### *3.8.1 Definition/Mechanism*

A vegetative cover is a long-term, self-sustaining system of plants growing in and/or over materials that pose environmental risk; a vegetative cover may reduce that risk to an acceptable level and, generally, requires minimal maintenance. There are two types of vegetative covers: the Evapotranspiration (ET) Cover and the Phytoremediation Cover.

- Evapotranspiration Cover: A cover composed of soil and plants engineered to maximize the available storage capacity of soil, evaporation rates, and transpiration processes of plants to minimize water infiltration. The evapotranspiration cap is a form of hydraulic control by plants. Risk reduction relies on the isolation of contaminants to prevent human or wildlife exposure and the reduction of leachate formation or movement. Fundamentally, an ET cover is a layer of monolithic soil with adequate soil thickness to retain infiltrated water until it is removed by evaporation and transpiration mechanisms. Mechanisms include the uptake and storage of water in soil and vegetation. An ET cover is one type of a water-balance cover, illustrated in Figure 3-6.

- Phytoremediation Cover: A cover consisting of soil and plants to minimize infiltration of water and to aid in the degradation of underlying waste. Risk reduction relies on the degradation of contaminants, the isolation of contaminants to prevent human or wildlife exposure, and the reduction of leachate formation or movement. Mechanisms include water uptake, root-zone microbiology, and plant metabolism. The phytoremediation cover incorporates certain aspects of hydraulic control, phytodegradation, rhizodegradation, phytovolatilization, and perhaps phytoextraction. Figure 3-7 presents the evolution of a phytoremediation cover as it moves from a remediation function to a water exclusion function.

In limited cases, vegetative covers may be used as an alternative to traditional covers that employ a resistive barrier (i.e., a multilayered cover with a relatively impermeable component). Vegetative covers may be appropriate to address contaminated surface soil or sludge, certain waste disposal units, waste piles, and surface impoundments.

In general, the application of any cover system should provide the following functions:

- isolate underlying waste from direct human or wildlife exposure (e.g., prevent burrowing animals from reaching the contaminants);

- minimize the percolation of water into the underlying waste;

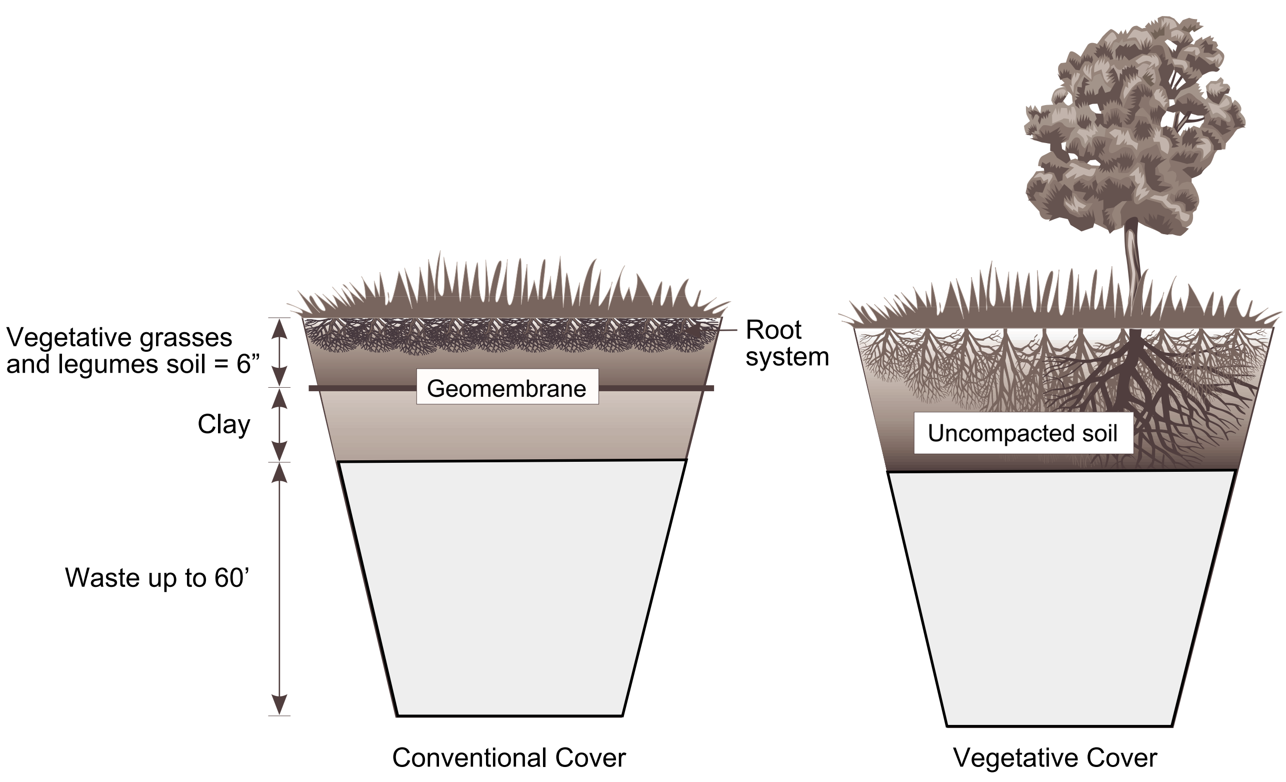


**Figure 3-6.** Illustration of an Evapotranspiration (ET) cover.

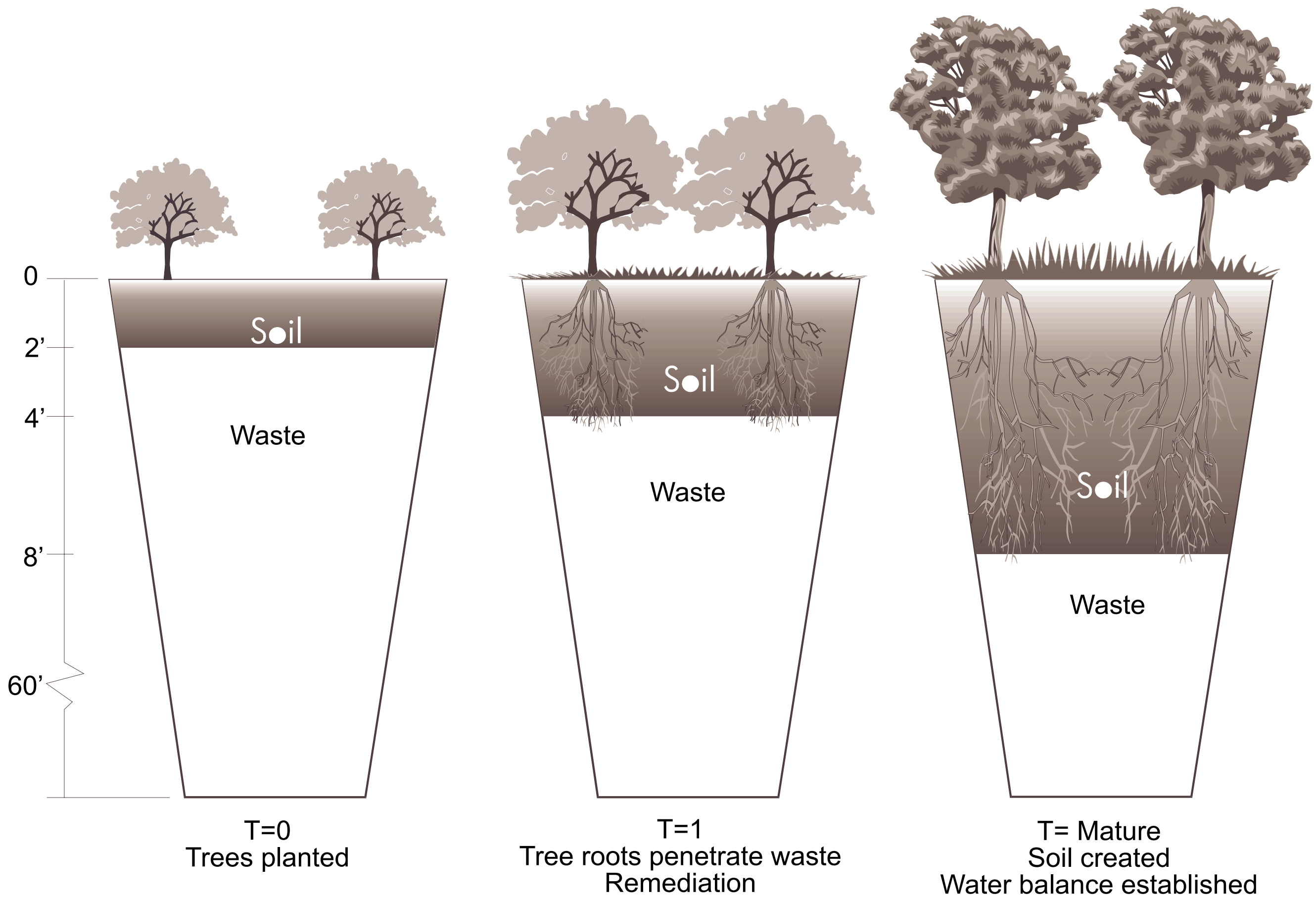


**Figure 3-7.**

- achieve long-term performance and minimize maintenance needs (e.g., control surface water runoff and reduce soil erosion); and
- prevent the migration or release of significant quantities of gas produced.

The acceptability of vegetative covers as a final cover for certain waste disposal units, such as landfill cells, is dependent on applicable regulatory requirements (e.g., RCRA). EPA's minimum technical requirements for landfill cover systems have evolved within a framework referred to as the "liquids management strategy." The two primary objectives of the strategy are: (1) to minimize leachate formation by keeping liquids out of the landfill (or source area); and (2) to detect, collect, and remove the leachate that is generated (EPA, 1987, 1991). A vegetative cover must demonstrate equivalent performance with generic cover designs specified in EPA guidance [i.e., Design and Construction of RCRA/CERCLA Final Covers (EPA/625/4-91/025); Design, Operation, and Closure of Municipal Solid Waste Landfills (EPA/625/R-94/008); and Technical Guidance For RCRA/CERCLA Final Covers (EPA/OSWER Draft)].

Vegetative covers are not appropriate for certain landfill units, such as municipal solid waste (MSW) landfills, that generate gas in chronic, large, or uncontrolled amounts. As reported by Flower et al. (1981), landfill gases can be toxic to plants and therefore must be considered. To date, vegetative cover systems have not been shown to prevent the diffusion of gases from landfills. Gas emissions from MSW landfills are governed by two sets of regulations.

- 40 CFR §258.23, under RCRA Subtitle D, addresses the personal and fire/explosion safety aspects of landfill gas.
- New Source Performance Standards (NSPS) and Emissions Guidelines (EG) promulgated under the Clean Air Act (CAA), 40 CFR Part 60 Subparts Cc and WWW,, regulate emissions of non-methane organic compounds (NMOCs) as a surrogate to total landfill gas emissions.

### *3.8.2 Media*

ET and phytoremediation covers are used in the uptake of infiltrating surface water. A phytoremediation cover can also be used in the treatment of soil, sludge, and sediments.

### 3.8.3 Advantages

A vegetative cover may have the following advantages:

- May reduce maintenance needs and requirements, such as minimizing surface erosion by establishing a self-sustainable ecosystem.
- The use of vegetative covers is generally considered cost-effective, as evaluated in the Alternative Landfill Cover Demonstration (Dwyer, 1997a) for an ET cover.
- Vegetation has been shown to be an effective final layer for hazardous waste site covers (EPA 1983; McAneny et al. 1985).
- Vegetation may encourage aerobic microbial activity in the root zone; such activity could discourage formation of anaerobic landfill gases or degrade them.
- Phytoremediation covers have the potential to enhance the biodegradation of contaminants in soils, sludges, and sediments.

### 3.8.4 Disadvantages

A vegetative cover may have any or all of the following disadvantages:

- Proper long-term inspection and maintenance may be required to ensure appropriate plant cover. Natural succession of plants may lead to a predominance by plant species other than those originally planted as part of the cover.
- Surface water may have a tendency to follow macropores opened by decaying roots and consequently flow downward to underlying waste or groundwater.
- For a phytoremediation cover, contaminants may be taken up by plants intended or used for human, domestic animal, or wild animal consumption, and potential adverse effects on the food chain could occur.
- Most plant based cover designs will be effective only in a specific climate. Universally applicable designs may not be possible.
- If trees planted as part of a vegetative cover are toppled by wind, buried waste may be exposed.
- Most alternative cover designs do not contain and collect landfill gas.

### 3.8.5 Applicable Contaminants/ Concentrations

#### 3.8.5.1 Organics and Inorganics

- Evapotranspiration Cover: The concentration of the contaminants in the underlying material is not a concern, as long as the plants are not in contact with materials having phytotoxic concentrations.
- Phytoremediation Cover: Contaminants in the waste materials should not be at phytotoxic levels because for degradation to occur, the plant roots need to be in contact with the contaminated waste.

### 3.8.6 Root Depth

For an evapotranspiration cover, the depth of the underlying waste is generally not a factor because the mechanisms (i.e, water evaporation, transpiration, and storage) occur above the waste.

The effective depth of contaminant degradation for the phytoremediation cover is the root depth of the plants.

### 3.8.7 Plants

Poplar trees and grasses have been used commercially to construct vegetative covers. Ideally, the vegetation selected for the system should be a mixture of native plants and consist of warm- and cool-season species.

### 3.8.8 Site Considerations

Several factors should be evaluated when considering the use of a vegetative cover such as soil physical properties, plant community activities, the potential for gas production from the biodegradation of waste, and climatic variables (e.g., precipitation quantity, type, intensity, and seasonality, temperature, humidity).

#### 3.8.8.1 Soil Conditions

Soils most suitable for a vegetative cover should have a high water storage capacity. The soil should be a high mixture of clays and silts (e.g., fine-grain soils). Soils with rapid drainage are to be avoided, although a carefully designed and maintained cover may include a coarser-grained material.

#### 3.8.8.2 Ground and Surface Water

Water tables that are relatively high may result in soils with less available water storage capacity, if evaporation and transpiration processes are not sufficient. However, with an appropriate thickness of soil to provide a sufficient water storage capacity, the water table may not be a factor in the performance of the cover.

#### 3.8.8.3 Climatic Conditions

Areas with high precipitation rates require more water to be transpired or stored in the soil. In humid regions (i.e., more than 20 inches of annual precipitation), inadequate evapotranspiration may occur seasonally, and soil layers will need to be thicker than in arid and semi-arid regions to provide adequate water storage capacity.

### 3.8.9 Current Status

Vegetative covers have been constructed, including numerous testing facilities as described in the Alternative Covers Assessment Project's "Phase I Report." There are no performance evaluations at present; each installation must be approved on a site by site basis.

### *3.8.10 System Costs*

In general, vegetative covers are considered cost-effective remedies. Cost estimates indicate notable savings for an evapotranspiration cover compared to a traditional cover design (RTDF 1998).

### 3.8.11 Selected References


Dobson, M. C., and A. J. Moffat, 1993. The Potential for Woodland Establishment on Landfill Sites. HMSO Press.

The information presented in this report focuses primarily on the effects of the landfill environment on tree growth, the typical rooting pattern of trees, the likelihood of windthrow, and the possible effects of trees on landfill hydrology.

Flower, F. B., E. F. Gilman, and I.A. Leone. 1981. Landfill Gas, What It Does to Trees and How Its Injurious Effects may be Prevented. J. of Arboriculture. 7(2):February 1981.

Methods are suggested for preventing the entry of landfill gases into the root zones of the trees and in accommodating other tree growth problems found to be associated with former refuse dumping areas. These methods include gas venting and blocking, irrigation, planting adaptable species, using small sized specimens in preference to large, and providing adequate maintenance.

Environmental Science and Research Foundation Conference Proceedings. 1997. Landfill Capping in the Semi-Arid West: Problems, Perspectives, and Solutions. May 21-27, 1997. Grand Teton National Park.

These conference proceedings address the following:

- Regulatory performance and monitoring requirements for landfills and caps
- Perspectives and problems with landfill closure
- What landfill covers do and how they do it
- Different approaches to landfill caps
- Perspective and alternative cap designs
- Economic issues

RTDF. 1998. Summary of the Remediation Technologies Development Forum Alternative Covers Assessment Program Workshop. February 17-18, 1998, Las Vegas, NV. *http://www.rtdf.org*.

The meeting minutes of these workshops on alternative covers include a discussion of the technical and regulatory issues relating to the use of vegetative covers. Regulatory and industry participants present their views on the use of alternative covers for a variety of geographic regions and on the research needs required to validate this technology. Models used to assess landfill covers are included in the discussion.

EPA. 1991. Design and Construction of RCRA/CERCLA Final Covers. (Seminar Publication, EPA 625-4-91-025).

This seminar publication provides regulatory and design personnel with an overview of design, construction, and evaluation requirements for cover systems for RCRA/ CERCLA waste management facilities.

EPA. 1994. Design, Operation, and Closure of Municipal Solid Waste Landfills. (Seminar Publication, EPA 625-R-94-008).

This seminar publication provides a documented summary of technical information presented at a series of 2-day seminars. The goal of the seminars were to present state-of-the-art information on the proper design, construction, operation, and closure of Municipal Solid Waste Landfills.

EPA. Draft December 1998. Technical Guidance For RCRA/CERCLA Final Covers.

The purpose of this guidance document is to provide information to facility owners/operators, engineers, and regulators regarding the regulatory standards, performance monitoring, and maintenance of final cover systems for municipal solid waste and hazardous waste landfills regulated under RCRA, and sites being remediated under CERCLA. When released (approximately December 1999), it will be an update to the 1991 EPA document entitled, Design and Construction of RCRA/CERCLA Final Covers (EPA-625-4-91-025).


## 3.9 Riparian Corridors/Buffer Strips

### *3.9.1 Definition/Mechanism*

Riparian corridors/buffer strips are generally applied along streams and river banks to control and remediate surface runoff and groundwater contamination moving into the river. These systems can also be installed to prevent downgradient migration of a contaminated groundwater plume and to degrade contaminants in the plume. Mechanisms for remediation include water uptake, contaminant uptake, and plant metabolism. Riparian corridors are similar in conception to physical and chemical permeable barriers such as trenches filled with iron filings, in that they treat groundwater without extraction containment. Riparian corridors and buffer strips may incorporate certain aspects of hydraulic control, phytodegradation, rhizodegradation, phytovolatilization, and perhaps phytoextraction.

### *3.9.2 Media*

Riparian corridors/buffer strips are used in the treatment of surface water and groundwater.

### *3.9.3 Advantages*

Secondary advantages include the stabilization of stream banks and prevention of soil erosion. Aquatic and terrestrial habitats are greatly improved by riparian forest corridors.

### 3.9.4 Disadvantages

The use of buffer strips might be limited to easily assimilated and metabolized compounds. Land use constraints may restrict application.

### 3.9.5 Applicable Contaminants/ Concentrations

Nutrient and pesticide contaminants are among the water-soluble organics and inorganics studied the most often using this technology. The nitrate concentration in groundwater was 150 mg/L at the edge of a field, 8 mg/L below a poplar buffer strip, and 3 mg/L downgradient at the edge of a stream (Licht and Schnoor 1993).

### 3.9.6 Root Depth

Uptake occurs within the root zone or the depth of influence of the roots.

### 3.9.7 Plants

Poplars have been used in riparian corridors and buffer strips.

### 3.9.8 Site Considerations

Sufficient land must be available for the establishment of vegetation. Typically a triple row of trees is installed, using 10 meters at minimum. Larger corridors increase capacity, and wider areas allow for more diverse ecosystem and habitat creation. Native Midwestern songbirds, for example, prefer corridors 70 meters and more.

#### 3.9.8.1 Soil Conditions

The primary considerations for this technology are the depth and concentration of contaminants that affect plant growth. Soil texture and degree of saturation are factors to be considered for use of this system. Planting technique can mitigate unfavorable soil conditions.

#### 3.9.8.2 Ground and Surface Water

Groundwater must be within the depth of influence of the roots.

#### 3.9.8.3 Climatic Conditions

The amount of precipitation, temperature, and wind may affect the transpiration rate of the plants.

### 3.9.9 Current Status

Buffer strips have been researched and installed commercially with success.

### 3.9.10 System Cost

Cost information is not available.

### 3.9.11 Selected References

Licht, L. A. 1990. Poplar Tree Buffer Strips Grown in Riparian Zones for Biomass Production and Nonpoint Source Pollution Control. Ph.D. Thesis, University of Iowa, Iowa City, IA.

This thesis describes the use of poplar trees to control nitrate-nitrogen contamination from agricultural fields. Methods and results of field work are presented. Poplar trees successfully established in riparian zones removed nitrate-nitrogen from soil and groundwater.

Licht, L. A., and J. L. Schnoor. 1993. Tree Buffers Protect Shallow Groundwater at Contaminated Sites. EPA Ground Water Currents, Office of Solid Waste and Emergency Response. EPA/542/N-93/011.

Uptake of nitrates by poplars planted between a stream and a corn field was studied at an agricultural field site. The poplars decreased nitrate levels from 150 mg/L in the field to 3 mg/L at the stream. Poplar trees were used with atrazine and volatile organic compounds in toxicity studies conducted in laboratory chambers and in the field. Atrazine was mineralized, and deep-rooted poplars slowed migration of volatile organics.

# Chapter 4
# Phytoremediation System Selection and Design Considerations

This chapter discusses considerations involved in the selection, design, and implementation of phytoremediation systems. It presents information that will help a site manager to identify whether phytoremediation may be appropriate for a site and to select a particular phytoremediation technology, based on the conditions occurring at or applicable to a site. This chapter introduces issues and concepts that should be considered in the design and implementation of a phytoremediation system. Because phytoremediation is not yet a developed technology, this discussion is not intended to serve as a design manual. Rather, it is a foundation on which to develop a phytoremediation system in consultation with phytoremediation professionals on a site-specific basis.

The main questions when considering phytoremediation as a remedial alternative are (1) What are my phytoremediation choices?; (2) Will phytoremediation be effective and economical in remediating the site?; and (3) What will it take to implement phytoremediation? This chapter discusses the considerations that need to be evaluated when answering these questions; however, economic considerations and potential costs of phytoremediation are discussed in Chapter 2.

The main considerations in the evaluation of phytoremediation as a possible remedial alternative for a site are the type of contaminated media, the type and concentration of contaminants, and the potential for effective vegetation to grow at the site. Recommendations for the selection of a particular type of phytoremediation technology are provided where appropriate, such as for a particular media and contaminant encountered at a site. Information on selection of appropriate vegetation is provided. Other site-specific factors that need to be considered to determine if a potential phytoremediation technology will work at a site are also discussed. This site-specific evaluation of phytoremediation considerations will lead to a decision regarding the selection of a phytoremediation technology to be used at a particular site. The more positive responses encountered when going through this list of considerations, the more phytoremediation is likely to work at the site.

This discussion can be considered as a checklist of items to evaluate that are specific to a particular site, and also as a reality check for the use of phytoremediation at a site. It is not meant to encourage or discourage the use of phytoremediation; rather, it indicates that the use of phytoremediation should be based on thorough and sound evaluation.

This discussion does not include a comparison of phytoremediation to other technologies, since the only intent is to provide information on phytoremediation. It is assumed, however, that such a comparison of effectiveness, cost, and time frames will be conducted. It is possible that other technologies might remediate a site more effectively.

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

- Define Problem
  - Conduct site characterization
  - Identify the problem: media/contaminant
  - Identify regulatory requirements
  - Identify remedial objectives
  - Establish criteria for defining the success of the phytoremediation system

- Evaluate site for use of phytoremediation
  - Perform phytoremediation-oriented site characterization
  - Identify phytoremediation technology that addresses media/contaminant/goals.
  - Review known information about identified phytoremediation technology
  - Identify potential plant(s)

- Conduct preliminary studies and make decisions
  - Conduct screening studies
  - Perform optimization studies
  - Conduct field plot trials
  - Revise selection of phytoremediation technology, if necessary
  - Revise selection of plant(s), if necessary

- Evaluate full-scale phytoremediation system
  - Design system
  - Construct system
  - Maintain and operate system
  - Evaluate and modify system
  - Evaluate performance

- Achieve objectives
  - Perform quantitative measurement
    - Meet criteria for success

When planning any remediation system, it is important to first define the desired remedial objectives: the desired fate of the contaminant(s) and the desired target concentration(s). An appropriate remediation technology, or different technologies as part of a treatment train, can then be selected based on the characteristics and performance of that technology in meeting the remedial goals. Remedial objectives are discussed in Chapter 5.

## 4.1 Contaminated Media Considerations

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

### *4.1.1 Soil, Sediment, and Sludge*

The following phytoremediation technologies are used in the treatment of these media:

- Phytoextraction
- Phytostabilization
- Rhizodegradation
- Phytodegradation
- Phytovolatilization (to a lesser degree)
- Vegetative cover

The primary considerations for phytoremediation of soil are the depth and volume of contamination and soil characteristics that affect plant growth, such as texture and water content (degree of saturation).

Phytoremediation is most appropriate for large areas of low to moderately contaminated soil that would be prohibitively expensive to remediate using conventional technologies. The contaminated soil should be within the root zone depth of the selected plant. Small volumes of contaminated soil concentrated in just a few areas are likely to be more efficiently remediated using other technologies.

### *4.1.2 Groundwater*

The following phytoremediation technologies are used in the treatment of groundwater:

- Phytodegradation
- Phytovolatilization
- Rhizofiltration
- Hydraulic control (plume control)
- Vegetative cover
- Riparian corridors/buffer strips

Groundwater, surface water, and wastewater have been treated using constructed wetlands or similar technologies; however, a discussion of those technologies is beyond the scope of this document.

Plants useful for groundwater phytoremediation include trees (especially Salix family — poplars, willows, cottonwoods), alfalfa, and grasses. The plant transpiration rate is an important consideration for groundwater phytoremediation (see Section 4.3).

The primary considerations for remediation of groundwater contamination are the depth to groundwater and the depth to the contaminated zone. Groundwater phytoremediation is essentially limited to unconfined aquifers in which the water table is within the reach of plant roots and to a zone of contamination in the uppermost portion of the water table that is accessible to the plant roots. Plant roots are very unlikely to reach through clean groundwater to a deeper contaminated zone. The seasonal fluctuation of the water table will affect the root depth: relatively little fluctuation is desirable to establish a root zone. If remediation of deeper contaminated water is desired, careful modeling must be done to determine if the water table can be lowered by the plants or through pumping, or if groundwater movement can be induced toward the roots.

Another consideration for groundwater phytoremediation is the rate of water movement into the root zone of the area to be treated. Groundwater remediation will be slow when the rate of water movement is low. Soil water content will also affect the rate of phytoremediation. Although root hairs can reach into relatively small pores and plant roots can extract water held at relatively high matrix suctions (about 15 bars), the low hydraulic conductivity of relatively dry soils will decrease the rate at which dissolved contaminants are moved toward the plant. Sufficient groundwater and precipitation must be available to serve the water requirements of the plants, or irrigation will be necessary.

For groundwater containment, the rate of groundwater flow should be matched by the rate of water uptake by the plants to prevent migration past the vegetation. Generally, the greater the groundwater flow rate, the larger the plants need to be, and/or the greater the density of the planting.

Groundwater geochemistry also must be conducive to plant growth. For example, saline waters will be detrimental to the plants unless halophytes (salt-tolerant plants) are used.

Canopy closure is the shading of soils by plant leaves, and total canopy limits evapotranspiration. Large plants provide a larger area of shading than small plants. Therefore, the mature size of the plants selected for remediation should be considered in the design of a treatment plot.

## 4.2 Contaminant Considerations

The applicability of phytoremediation has been researched for some of the most significant and widespread contaminant classes. Table 4-1 indicates the applications of phytoremediation and provides the relevant phytoremediation technology for different types of contaminants.

The following sections contain additional discussion on particular contaminants or classes of contaminants. After a potential phytoremediation technology is identified through a review of the information in this chapter, additional, specific information on the technology can be obtained in Chapter 3.

### *4.2.1 Organic Contaminants*

The hydrophobicity of an organic compound (as indicated by the octanol-water partition coefficient, $k_{ow}$) will affect the uptake and translocation of the compound. In general, moderately hydrophobic organic compounds (with log $k_{ow}$ between 0.5 and 3.0) are most readily taken up by and translocated within plants. Hydrophobic (lipophilic) compounds also can be bound to root surfaces or partition into roots but not be further translocated within the plant (Schnoor et al. 1995a; Cunningham et al. 1997).

### *4.2.2 Inorganic Contaminants*

Phytoextraction coefficients describe the relative ease of extraction of different metals; for example, one study showed that the easiest to most difficult to extract were: $Cr^{6+}$, $Cd^{2+}$, $Ni^{2+}$, $Zn^{2+}$, $Cu^{2+}$, $Pb^{2+}$, and $Cr^{3+}$ (Nanda Kumar et al. 1995). Phytoremediation may be different for mixtures of metals than for one metal alone (Ebbs et al. 1997). The interaction of the metals in a mixture might need to be investigated, especially in terms of the ability to take up one or more metals and nutrients.

### *4.2.3 Waste Mixtures*

Most phytoremediation research has focused on individual classes of contaminants and not on mixtures of different types of contaminants. Although there is some evidence that plants can tolerate mixed organic and metal contamination, it has generally not been investigated if one type of vegetation can successfully remediate different classes of contaminants (for example, heavy metals and chlorinated solvents at the same time). The use of several types of vegetation, each to remediate a different contaminant, might be required either at the same time or sequentially.

### *4.2.4 Contaminant Concentrations*

The primary consideration in this area is that the contaminant concentrations cannot be phytotoxic or cause unacceptable impacts on plant health or yield. A literature review or a preliminary laboratory or field plot screening study will be needed to determine if the given concentrations are phytotoxic.

The contaminant concentrations necessary for successful phytoremediation must be determined in comparison to the concentrations that could be treated by other, more effective remedial technologies. In general, the highest concentrations will comprise relatively small hot spots that

**Table 4-1.** Phytoremediation Technologies Applicable to Different Contaminant Types[1,2]

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

[1]The applicability of a particular method of phytoremediation to each contaminant type has been judged by the current state or stage of the application.
This is indicated in the table by the following designations:
T - The application is at the theoretical stage.
G - The application has been researched in the greenhouse or laboratory.
F - The application has been researched using field plots or has been applied in full-scale field systems.
[2]All contaminants can be controlled using vegetative covers. The vegetative cover, riparian corridors, buffer strips, and hydraulic control are not included in the table because they can be considered combinations of the other phytoremediation technologies.
[3]Reeves and Brooks 1983; Baker 1995, Salt et al. 1995; Nanda Kumar et al. 1995; Cornish et al. 1995.
[4]Salt et al. 1995; Nanda Kumar et al. 1995; Cornish et al. 1995.
[5]In constructed wetlands.

could be more effectively treated through excavation and other treatment means. However, costs and remedial time frames need to be considered as well as concentrations.

Higher concentrations of organics and nutrients might be tolerated more readily by plants than by soil microorganisms (Schnoor et al. 1995a). In addition, plants (as measured by seed germination tests) were less sensitive to heavy metals than were bacteria in toxicity screening (Miller et al. 1985). Thus, it might be possible that phytoremediation (except for microbially-based rhizodegradation) could be effective in cases where bioremediation fails due to the presence of metals or to high toxic levels of contaminants. This is speculative, however, because the relative tolerance of plants and microorganisms to high contaminant concentrations might be different under field conditions as compared to laboratory toxicity screening, due to acclimation of microorganisms in the field.

#### *4.2.5 Contaminant Depth and Distribution in the Soil Profile*

The contaminated soil must be within the root zone of the plants in order for the vegetation to directly impact the contamination. The depth to contamination is of less concern in the use of a vegetated cover designed to prevent infiltration.

#### *4.2.6 Contaminant Characteristics*

The contaminant type, pH, physical form of light nonaqueous phase liquid (LNAPL) or dense nonaqueous phase liquid (DNAPL), mixtures, or oily contamination can adversely affect the water movement, air movement, or uptake of nutrients necessary for plant growth. An NAPL or oily contaminant can significantly decrease plant growth.

Aged compounds in soil can be much less bioavailable. This may decrease phytotoxicity, but may also decrease the effectiveness of phytoremediation technologies that rely on the uptake of the contaminant into the plant. To judge the effectiveness of an actual phytoremediation design, it is important that treatability studies use contaminated soil from the site rather than uncontaminated soil spiked with the contaminant.

### 4.3 Plant Considerations

It must be remembered that engineers, hydrogeologists, and other professionals typically involved in site remediation are not farmers, and that it might be difficult to have vegetation conform to standard engineering practices or expectations. Phytoremediation adds an additional level of complexity to the remediation process because plants comprise a complex biological system that has its own characteristics.

#### *4.3.1 Phytoremediation Plant Selection*

The goal of the plant selection process is to choose a plant species with appropriate characteristics for growth under site conditions that meet the objectives of phytoremediation. There are several starting points for choosing a plant:

(1) Plants that have been shown to be effective or that show promise for phytoremediation. These plants have been discussed in this handbook, they can be found in research publications on phytoremediation, or they can be enumerated by phytoremediation specialists.

(2) Native, crop, forage, and other types of plants that can grow under regional conditions. A list of these plants can be obtained from the local agricultural extension agent.

(3) Plants can also be proposed based on those plants growing at the site, extrapolations from phytoremediation research, inferences drawn from unrelated research, or other site-specific knowledge. The efficacy of these plants for phytoremediation would need to be confirmed through laboratory, greenhouse, or field studies or through screening.

Ideally, there would be a plant common to lists (1) and (2), or there would be evidence that a plant common to lists (2) and (3) would be effective. These lists of plants can be narrowed down according to the criteria discussed in the outline of the steps for selecting a suitable plant (see Table 4-2). Following the Plant Selection Process outline, additional information on topics discussed in the plant selection process is provided.

During the plant selection process, additional information should be gathered regarding candidate plants. Information can be obtained by telephone or the Internet from local, state, or Federal agencies and offices, or from universities. The Internet has numerous locations with this information. One very useful source is the Plant Materials program of the USDA Natural Resources Conservation Service (*http://Plant-Materials.nrcs.usda.gov/*).

#### *4.3.2 Root Type*

A fibrous root system has numerous fine roots spread throughout the soil and will provide maximum contact with the soil due to the high surface area of the roots. Fescue is an example of a plant with a fibrous root system (Schwab et al. 1998). A tap root system is dominated by a central root. Alfalfa is an example of a plant with a tap root system (Schwab et al. 1998).

#### *4.3.3 Root Depth*

Root depth can vary greatly among different types of plants. It can also vary significantly for one species depending on local conditions such as depth to water, soil water content, soil structure, soil density, depth of a hard pan, soil fertility, cropping pressure, or other conditions. The bulk of root mass will be found at shallower depths, with much less root mass at deeper depths. The deeper roots will also provide a very small proportion of the water needed by the plant, except in cases of drought.

The depth of in situ contamination or of excavated soil generally should not exceed the root zone depth. Exceptions to this could be made if it is verified that upward movement of dissolved contaminants can be induced toward

**Table 4-2.** Plant Selection Process

1. Identify phytoremediation technology and remedial goals.
2. Gather site information.
   - Location (also relative to plant/vegetation/ecosystem zones)
   - Temperatures: averages, range
   - USDA plant hardiness zone (range of average annual minimum temperature)
   - Precipitation: amount, timing
   - Length of growing season
   - Amount of sun/shade
   - Soil texture, salinity, pH, fertility, water content, structure (hardpans, etc.)
   - Contaminant type, concentration, form
   - Site-specific conditions or considerations
   - Identify plants growing in contaminated portion of site. (Optional)
     - Do these provide a clue as to what plants to select?
     - If not, will these plants compete with the selected plant?
     - If the native plants do compete with the selected plant, are they easily removed?
   - Identify local plants and crops. (Optional)
     - Do these plants provide a clue as to what plants to select?
     - Will a selected plant interfere with local plants?
3. Identify important criteria for plant selection.

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

   Phytoremediation-related:
   - Demonstrated efficacy of plant: The plant can take up and/or degrade contaminants, produce exudates that can stimulate the soil microbes, or possess enzymes that are known to degrade a contaminant. The potential for the success of phytoremediation can be increased by screening plants for useful enzymes (Fletcher et al. 1995).
   - Phytotoxicity of contaminant: The contaminant should not be phytotoxic at the concentrations found at the site. Contaminant phytotoxicity and uptake information can be found in the phytoremediation and agricultural literature, or determined through preliminary germination and phytotoxicity screening studies. Chapter 3 provides examples of applicable contaminant concentrations. Databases such as PHYTOTOX or UTAB have been used to summarize and investigate phytotoxicity and uptake information (Fletcher et al. 1988; Nellessen and Fletcher 1993a, 1993b), although these databases might not be readily accessible.
   - Root type and shape: Fibrous root system versus tap root system.
   - Root depth: The range of root depths of a given plant must be considered.
   - Contaminant depth and distribution: The contaminant depth must be similar to the root depth. The distribution of the contamination at various soil depths is also important in planning the plant type and planting method. The contaminant concentrations in the seed bed layer of the soil profile may have a strong effect on the ability to establish vegetation. A surface layer with minimal contamination underlain by greater contaminant concentrations might allow more successful seed germination than if the surface layer is heavily contaminated. Root growth into the more contaminated layer is then desired, and since it is not guaranteed, must be verified. Make general decisions.
   - Deciduous/nondeciduous: Deciduous trees will be dormant for part of the year, resulting in lowered transpiration rates.
   - Monoculture vs. mixed species: The use of mixed species of vegetation can lead to more success due to the increased chance that at least one species will find a niche. However, there could be competition between plants for nutrients and space. A monoculture relies on just one plant type, possibly requiring more management to ensure its growth against adverse conditions. Despite this, a well-established stand of one plant that has been shown to be effective could be the most efficient means of phytoremediation.
   - Native vs. non-native: Native, nonagricultural plants are desirable for ecosystem restoration. In most applications, plants that are adapted to local conditions will have more chance of success than nonadapted plants.
   - Growing season: Warm season and cool season grasses could be used in combination to address different seasonal conditions, prolonging a vegetative cover throughout more of the year.

(Continued)

**Table 4-2.** (continued)

- Sterile/male/female: The ability to reproduce is necessary for the long-term establishment of vegetation. In cases where the spread of the plant to surrounding areas is undesirable, however, the plants should be selected to prevent reproduction.
- Plant rotation; planned or natural plant succession: The long-term establishment of vegetation at a site is dependent on the project goals and future uses of a site. For long-term, no-maintenance vegetation establishment as part of ecosystem restoration, it is likely that there will be a succession of plants at a site. If so, this succession could be planned when considering the types and timing of vegetation. Plant rotation could conceivably be important when short-lived vegetation is used that does not reach remedial goals and that should not be replanted in the same place.

5. Match above criteria with list of available/proposed plants.
   - Select all appropriate candidates (eliminate all inappropriate plants).
   - Conduct detailed evaluation of remaining candidates against criteria in items 1 to 4 of this table.
   - Conduct cost/benefit analysis of top candidates:
     - Plant costs
     - Plant effectiveness in reaching goal
     - Plant value (cash crop)
   - Conduct preliminary studies to assess germination, survivability, and biomass. It might not be possible to assess the success of some forms of phytoremediation (i.e., rhizodegradation) due to the insufficient time for preliminary testing. Because phytoremediation can be a long-term process, however, spending one or two years in preliminary trials won't substantially increase the overall remediation time.
     - Germination screening studies for phytotoxicity
     - Small-scale greenhouse or laboratory chamber studies
     - Field plot trials
6. Select plant and implement phytoremediation.
   - Monitor and evaluate plant growth and phytoremediation success.
   - Reevaluate plant selection on basis of observations: Variability in phytoremediation efficacy in varieties, cultivars, or genotypes of a given species has been encountered in alfalfa for hydrocarbon rhizodegradation (Wiltse et al. 1998). A screening of cultivars/varieties might be required.
   - Reseed/replant as necessary with same or different plant.

the roots, or if soluble root exudates can be transported deeper into the soil.

The root depth ranges provided below represent maximum depths:

- Legumes: Alfalfa roots can go quite deep, down to about 30 feet, given the proper conditions.

- Grasses: Some grass fibrous root systems can extend 8 to 10 feet deep (Sloan and Woodward 1996). The roots of major prairie grasses can extend to about 6 to 10 feet.

- Shrubs: The roots of phreatophytic shrubs can extend to about 20 feet (Woodward 1996).

- Trees: Phreatophyte roots will tend to extend deeper than other tree roots. Phreatophytic tree roots can be as deep as 80 feet. Some examples are mesquite tap roots which range from 40 to 100 feet and river birch tap roots which go to 90 to 100 feet (Woodward 1996).

- Other plants: Indian mustard roots generally are about 6 to 9 inches deep.

These maximum depths are not likely to be reached in most situations, due to typical site conditions such as soil moisture being available in the surface soils or poorer soil conditions at greater depths. A review of the literature found that maximum depths of tree roots were generally 3 to 6 feet, with almost 90% of the roots in the top 2 feet (Dobson and Moffat 1995).

The effective depth for phytoremediation by most nonwoody plant species is likely to be only 1 or 2 feet. The effective depth of tree roots is likely to be relatively shallow, less than 10 or 20 feet. Gatliff (1994) indicates that for practical purposes, trees are useful for extraction of groundwater less than 30 feet deep. In addition, a contaminated zone below the water table is not likely to be reached by roots, as the roots will obtain water from above the water table.

### *4.3.4 Growth Rate*

The growth rate of a plant will directly affect the rate of remediation. Growth rates can be defined differently for different forms of phytoremediation. For rhizodegradation, rhizofiltration, and phytostabilization, for example, it is desirable to have fast growth in terms of root depth, density, volume, surface area, and lateral extension. For phytoextraction, a fast growth rate of aboveground plant mass is desirable.

A large root mass and large biomass are desired for an increased mass of accumulated contaminants, for greater transpiration of water, greater assimilation and metabolism of contaminants, or for production of a greater amount of exudates and enzymes. A fast growth rate will minimize the time required to reach a large biomass.

Metal hyperaccumulators are able to concentrate a very high level of some metals; however, their generally low biomass and slow growth rate means that the total mass of metals removed will tend to be low. For phytoextraction of metals, the metals concentration in the biomass and the amount of biomass produced must both be considered. A plant that extracts a lower concentration of metals, but that has a much greater biomass than many hyperaccumulators, is more desirable than the hyperaccumulator because the total mass of metals removed will be greater.

Poplars have been widely used in phytoremediation research and applications due to their fast growth rate. They can grow 9 to 15 feet/year (Gordon 1997).

### 4.3.5 Transpiration Rate

The transpiration rate of vegetation will be important for those phytoremediation technologies that involve contaminant uptake, and for hydraulic control. The transpiration rate depends on factors such as species, age, mass, size, leaf surface area, canopy cover, growth stage, and climatic factors, and will vary seasonally. Thus, well-defined numbers for a given type of vegetation cannot be assumed.

Estimates for certain cases, however, provide a rough guide to the order of magnitude that might be expected. For *Populus* species, approximately 26 gpd for a 5-year-old tree was estimated (Gordon 1997). It was reported that 5000 gpd was transpired by a single willow tree, which is comparable to the transpiration rate of 0.6 acre of alfalfa (Gatliff 1994). Individual cottonwood trees were estimated to transpire between 50 and 350 gpd, based on analysis of drawdown near the trees (Gatliff 1994).

These transpiration rates, given in terms of gpd for individual trees, should be viewed with caution because the transpiration rate varies with tree size and other factors, as mentioned above. A more appropriate measure would be to look at the total water usage in a given area of vegetation.

### 4.3.6 Seed/Plant Source

Important considerations for the source of the plant include:

- Are the plants/seeds local or from a comparable climate? It is important to have the seed or plant supplier verify where the seeds were produced since a supplier may sell seeds that have been collected from a wide variety of geographic locations. It is generally best to use seeds or plants (and varieties) that are local or from the region of the site so that the plants are adapted to the particular climatic conditions. The seed supplier or local agricultural extension agents can provide information regarding local seeds and plants. A comment during a phytoremediation presentation at the Fourth International In Situ and On-Site Bioremediation Symposium (April 28 - May 1, 1997, New Orleans, LA, sponsored by Battelle Memorial Institute) indicated that poplars were purchased for a project; however, the source was in a different climate, and all the trees died.

- Can the source supply the quantity needed when they are needed (whether in season or out of season)? Is the supplier reliable?

- Are there any transport/import/quarantine restrictions or considerations?

- Can the supplier provide information on the cultivation of the plants?

- Are the seeds/plants viable or healthy?

- The seeds/plants must be high quality: no undesirable weed seeds, diseases, etc.

### 4.3.7 Allelopathy

Allelopathy refers to the inhibition of growth of one plant species due to the presence of chemicals produced by a different plant species. Allelopathic effects could be investigated when considering co-establishment of several species of vegetation to ensure that one species won't hinder the growth of another. Allelopathic effects could also be due to plant residue that is incorporated into the soil in an attempt to increase the fertility of the soil. For example, root, stem, and leaf residues from canola inhibited the growth of corn, wheat, and barley (Wanniarachchi and Voroney 1997).

The phenomenon of allelopathy might also provide clues as to the usefulness of a particular plant species. The allelopathic chemicals produced by the plant could be investigated to determine if they are suitable chemical substrates for microbial cometabolism of soil contaminants. Allelopathy also indicates that compounds exuded by plant roots influence the surrounding soil. The distance that this influence extends could be estimated by examining the spacing between such allelopathic plants and their neighbors. This would provide a clue as to how far soil phytoremediation could reach.

### 4.3.8 Forensic Phytoremediation

Areas with contaminated soils or groundwater can become revegetated through the establishment of naturally-occurring plants. Forensic phytoremediation refers to the investigation of naturally-revegetated contaminated areas to determine which plants have become established and why, and to determine the impact of these plants on the contamination. This investigation can identify plants that are capable of surviving in contaminated areas, some of which might also be capable of contributing to the degradation of the contaminants.

Because the vegetation has often been present at the site for a relatively long period compared to the time interval for planned phytoremediation field studies, a researcher has the additional benefit of not having to wait many more years to investigate the effects of the revegetation (which are evident now at the naturally-revegetated site). Natural revegetation of a site is essentially a form of intrinsic bioremediation. Phytoremediation intrinsic bioremediation and forensic phytoremediation approaches have been intensively investigated at a petroleum refinery sludge impoundment that was naturally revegetated (Fletcher et al. 1997; Wong 1996).

### 4.3.9 Plants Used in Phytoremediation

A compilation of plants used in phytoremediation research or application is given in Appendix D. This Appendix includes a table giving the common name followed by the scientific name, and a table with the scientific name followed by the common name.

The following are examples of commonly-investigated or used plants:

- Trees:
  - Poplars (hybrids)/cottonwoods
  - Willows

- Grasses:
  - Prairie grasses
  - Fescue

- Legumes:
  - Alfalfa

- Metal-accumulators:
  - Hyperaccumulators
    - *Thlaspi caerulescens*
    - *Brassica juncea*
  - Accumulators
    - Sunflower

- Aquatic plants:
  - Parrot feather
  - Phragmites reeds
  - Cattails

### *4.3.10 Optimum Plant*

The following general plant characteristics are optimum for different forms of phytoremediation:

- Rhizofiltration and phytostabilization:
  - Able to remove metals.
  - No translocation of metals from the roots to the shoots.
  - Rapidly growing roots.

- Phytoextraction:
  - Tolerates, translocates, and accumulates high concentrations of heavy metals in the shoots and leaves.
  - Rapid growth rate and high biomass production.
  - Is not favored for consumption by animals (this decreases risk to the ecosystem).

- Rhizodegradation:
  - Possesses appropriate enzymes and should not take up the contaminant.
  - Appropriate root growth (depth and or extent).

- Phytodegradation:
  - Able to take up the contaminant.
  - Degradation products are not toxic.

- Phytovolatilization:
  - Able to take up the contaminant.

## 4.4 Site Considerations

### *4.4.1 Site Activities*

#### 4.4.1.1 Former Site Activities

Former site activities will affect the selection of plants for phytoremediation. The location, extent, degree, and age of contaminant are the primary considerations. However, any former incidental use of chemicals could affect phytoremediation, such as herbicide use at the site to suppress vegetation during site activities. The former or existing vegetation at the site can negatively influence the establishment of vegetation. Examples include allelopathic plants, well-established undesired vegetation, and soil pathogens in former vegetation. The former activities and vegetation could be investigated to determine if any of these factors could increase the difficulty of establishing the remedial vegetation.

#### 4.4.1.2 Current Site Activities

The site must have sufficient open space, and no physical structures or site activities could interfere with the vegetation. In addition, site facilities or debris may have to be removed. For ex-situ soil treatment, the volume of soil to be remediated is divided by the depth of the root zone to find the land area required for phytoremediation. The required land area must remain undisturbed by site activities, uses, or traffic.

The impact of tree roots on foundations and subsurface utility lines must be considered as well as the impact of tree branches on overhead utility lines. Potentially impacted utilities may have to be removed or relocated. Phytoremediation using trees would have to be curtailed if such removal or relocation cannot be done.

Fencing might have to be installed around the phytoremediation system to keep out animal pests that might damage the vegetation. Additionally, the site must have access to a water supply (groundwater, surface water, or municipal) if irrigation is required.

#### 4.4.1.3 Proposed Site Activities

Future activities planned for the site can impact the selection of a phytoremediation technology. Portions of the site might need to remain undisturbed to allow long-term plant growth. If use of the site is required in the near future, the establishment of trees or the use of slow-growing metal accumulators is not desirable. Fast-growing trees such as hybrid poplars might be grown for a short period, however, and then harvested if the remediation is predicted to be relatively short-term.

Future use of the site might be for industrial, residential, or recreational purposes. Different remedial criteria could apply to these different uses. Institutional controls might be necessary, depending on the proposed use of the site.

Agricultural uses of the site such as for grazing or for crops will entail more concern regarding accumulation of toxic compounds within the plants. Ecosystem or habitat restoration uses will also raise concerns about possible effects on the food chain.

### *4.4.2 Climatic Considerations*

Climatic factors cannot be predicted with certainty, and their effects cannot always be controlled. As a complex biological system, a phytoremediation system can be severely impacted by extreme weather events; thus, this possibility must be considered during the planning of remedial activities.

*Precipitation*. The amount and timing of rainfall and snowmelt will determine the time of soil preparation, time of planting, and need for irrigation.

*Air temperature*. The mean, extremes, and fluctuations in air temperature will affect the ability of plants to grow.

*Sunlight*. The amount of sunlight affects plant growth, air temperature, and evapotranspiration.

*Shade*. The amount of shading from nearby buildings or from mixed vegetation can affect the ability of plants to grow.

*Length of growing season*. Phytoremediation processes are more likely to be active during the growing season. The length of the growing season must be considered in predicting overall remedial timeframes.

*Wind*. The amount of wind affects evaporation, causes damage to plants, and disperses volatiles and debris. Windbreaks may need to be installed.

*Location*. Regional and local weather patterns will affect the factors described above.

### *4.4.3 Water Considerations*

Surface water drainage and runoff will affect how soon the soil can be worked, the soil temperature, and the stability of the soil, seeds, and plants. Subsurface water drainage will affect soil water content and soil temperature. Artificial drainage might need to be provided to encourage remedial success. Poor growth and shallow roots in buffalograss (*Buchloe dactyloides*) and warm season prairie grasses resulted from water-logging during a field test of phytoremediation in soils contaminated with relatively low levels of PAHs and PCP (Qiu et al. 1997).

Irrigation is likely to be necessary during phytoremediation. The source, availability, volume, cost, quality, and timing of the irrigation water need to be considered.

### *4.4.4 Potential Adverse Effects/ Neighborhood Concerns*

Phytoremediation could potentially have adverse impacts on the site or surroundings. The list of potential adverse impacts listed below is not meant to discourage the potential use of phytoremediation, but rather to make the reader aware of potential pitfalls. Possible adverse impacts or disadvantages of phytoremediation include:

- Dust from tilling operations.
- Odor: Soil preparation that generates odors from volatile contaminants might be required during phytoremediation, but not with other remedial technologies. The selected plant might be odorous at certain stages of growth or decay.
- Aesthetics: The presence of weeds and plant debris can affect the perception and acceptance of a phytoremediation site.
- Inappropriate plant introduction: The introduction and spreading of a potentially undesirable plant (noxious or invasive weeds) that will take over local vegetation must be avoided. Plants should not have an adverse effect on the local ecosystem. The vulnerability of the surrounding area to the selected vegetation and the vegetation's impact must be examined.
- Pollen and allergies: If plants are used that would contribute an unacceptable amount to local allergen loadings, the plants must be harvested before release of the allergen or treated to decrease the impact.
- Effect on nearby crops and vegetation:
  - Pesticide drift: If pesticides are used during preparation or maintenance of the system, the impact of any spraying must be carefully monitored, and negative impacts on nearby crop or residential areas pre vented.
  - Interbreeding: The impact of the selected plants on the surrounding vegetation must be examined to ensure that hybridization does not occur in a nearby crop.
  - Airborne plant diseases could impact nearby vegetation.
- Attraction of pests: The plants might attract unwelcome animals that become pests, such as birds (noise and droppings), poisonous snakes (danger to humans), rats (disease-carriers or food-destroyers), or insects (disease-carrying vectors).
- Safety issues: blocked vision/sightlines, tree limbs, concealment, fire hazard due to accumulated plant matter.
- Plant toxicity to people, birds, mammals (such as foraging animals), other plants (through allelopathy), or beneficial insects such as honeybees. The inherent toxicity of useful plants, such as that of *Datura innoxia* (thornapple), must be considered in any risk analysis. Potential bioconcentration of toxic contaminants in plants is a concern, and the fate of the plant must be controlled to prevent chemical or toxin ingestion by animals or humans.
- Root damage to foundations, underground utilities, or other structures.
- Impact on contaminant transport: The interactions of the plants and all contaminants at the site could be studied. Fertilizer application to optimize plant growth may result in an increase in the mobility of some metals in the soil because many common nitrogen-containing fertilizers lower the pH of soil. This might result in leaching of metals to groundwater.

Phytoremediation might positively or negatively impact other remediation activities. A potential positive impact is that vegetation could be a visual, odor, dust, and noise barrier to block other site activities from the surrounding areas. Potential negative impacts include the need to have healthy vegetation, which requires that the plants not be significantly disturbed. Thus, vehicles or equipment should not be used or stored on the vegetated areas, which might limit activities that could otherwise occur at the site.

### *4.4.5 Agronomic Considerations for System Installation and Maintenance*

All of the factors that must be considered in successful agriculture also must be considered during phytoremediation. These factors will be more critical or more difficult to control due to the additional stress placed on the system by the contamination.

#### 4.4.5.1 Pre-Plant Selection

Pre-plant selection includes the following:

- Soil must have a pH range that will allow plant growth. The soil pH might need to be modified and controlled through liming to increase pH or through acidification to lower pH.
- Soil fertility and nutrient content
- Soil structure
- Soil tilth
- Soil salinity
- Soil water content
- Air-filled porosity: Affects aeration.
- Soil texture: Affects moisture content and drainage.
- Soil temperature: Affects germination of seeds.
- Soil depth: The depth to bedrock, a hardpan, or infertile soil (along with soil water contents and soil nutrients) can control the maximum depth of roots.
- Irrigation requirements
- Control of plant pests: birds, grazers, insects

#### 4.4.5.2 Post-Plant Selection

Post-plant selection includes the following:

- Soil preparation: This preparation can include screening out debris or rocks, and (if desired) mixing and diluting of the contaminated soil. Bulking agents and organic matter amendments might need to be added to improve the fertility or moisture-holding capacity of the soil. Adding metal-chelating agents (such as EDTA), maintaining a moderately acid pH, and adding reducing organic acids to alter the redox status of the soil can all increase the bioavailability of metals.
- Seed bed preparation: Preparation of the soil will likely be required before seeding or planting. Various types of tilling might need to be done to prepare the seed bed. A good seed bed will increase the chances for the establishment of a healthy stand of vegetation. Dust will need to be suppressed during soil preparation work or tilling.
- Planting considerations include the density, timing, and method of applying seeds or plants.
- pH maintenance
- Mulching
- Fertilization: Fertilizers or organic matter amendments might be necessary. The effect of fertilizers on soil pH (for phytoremediation of metals) and on soil microbes (for rhizodegradation) could be assessed.
- Irrigation equipment and scheduling
- Control of plant pests/desirable animals/undesirable pests
  - Birds: netting
  - Grazers, vermin: fences, trapping
  - Insects: pesticides
  - Plant competitors: herbicides
  - Diseases: pesticides, nutrients, pH, drainage
- Aesthetics/debris cleanup (wind damage, fallen leaves, etc.)
- Odor control: from plant, from soil prep, from contaminant
- Biomass disposal
  - Harvesting: determine method
  - Plant debris (uncontaminated): occasional, periodic
  - Plant debris (contaminated, biomass with metals)
- Effect of contaminant on nutrient or toxin availability (some metals, or modification to enhance metal solubility or chelation, may make nutrients unavailable or enhance adverse impacts of toxins).

### *4.4.6 Disposal Considerations*

Due to the growth of vegetation, the mass of plant material will increase with time. Depending on the type of phytoremediation, the biomass that must be removed from the active system will vary. Relatively permanent long-term systems that rely on the establishment of mature vegetation (e.g., poplar trees or grass for rhizodegradation) will not require periodic planned removal of the biomass. In all phytoremediation systems, however, some biomass such as dead or diseased plants, fallen leaves, fallen limbs, or pruned material might have to be removed occasionally to maintain good operation of the system. These uncontaminated plant materials will need to be harvested, stored, and disposed of as necessary. It will be important to confirm that the plant material does not contain any hazardous substances. After this confirmation, the material could be composted or worked into the soil on site. If that is not possible, off-site disposal will be required.

The operation of some phytoremediation systems, such as with phytoextraction and rhizofiltration, does depend on the periodic removal of biomass. In these cases, proper harvesting, storage, and disposal of contaminated biomass (e.g., containing heavy metals or radionuclides) will be necessary to prevent potential risk pathways such as introduction to the food chain. An appropriate disposal facility must be identified, and it is likely that costs will be greater than with uncontaminated biomass. Regulatory requirements for the handling and disposal of this material will have to be followed.

If the selected phytoremediation technology results in uncontaminated biomass, it might be possible to harvest the vegetation as a cash crop to offset some of the remedial costs. Examples include the harvest of grasses or alfalfa for animal feed, or lumber from poplars. It must be verified, however, that the plant materials do not contain hazardous substances.

## 4.5 Treatment Trains

Phytoremediation could be part of a treatment train at a site. Pretreatment of soil or water might be necessary before application of phytoremediation, such as with the adjustment of inflow water chemistry into an engineered rhizofiltration system. Phytoremediation might also be used as a finishing step to decrease contaminant concentrations below what is achieved by a different initial remedial technology, such as land treatment biodegradation. The disposal or treatment of plant matter that contains the contaminants will be the final step in a treatment train. In general, however, research has focused on phytoremediation as a stand-alone technology, with little or no integration of phytoremediation with other remedial technologies.

Phytoremediation could be a partial solution at a site. For example, excavation of highly-contaminated soil and treatment by other remedial technologies could be followed by a phytoremediation technology. A backup remedial technology might also be necessary for times when the phytoremediation system is not working effectively, such as during winter when plant growth has stopped or when the vegetation is damaged by pests or weather.

## 4.6 Additional Information Sources

Successful phytoremediation requires a multidisciplinary approach. This approach will call for the knowledge, input, and/or participation of a wide range of professionals and practitioners. Many of these fields have conducted research on topics relevant to phytoremediation before the applied concept of phytoremediation was developed. In addition, valuable information on potentially useful local plants or cultural practices can be obtained from less-commonly-used resources such as farmers, agricultural extension services, and even local garden clubs and nurseries.

Relevant disciplines, resources, and information sources are described below. Since a typical phytoremediation system is not likely to be a research project, all of these information sources do not need to be fully utilized. As more experience is gained in researching and applying phytoremediation, the most relevant disciplines will likely be identified and more specific information can be provided as to how the following professionals can assist in phytoremediation.

*Agricultural extension agents* or *state university agricultural departments* can provide invaluable information on the particular plants that grow in the local region, the cultural practices for these plants, and the local soils. Most information is likely to be about commodity crops grown in the region and the weeds that affect these crops.

*Agricultural engineers* are more likely to have experience with soil properties, drainage, tilling equipment, and irrigation than other engineers.

*Agronomists* can provide assistance in working with soil and crops.

*Botanists* can provide critical information on the identification, growth, properties, and behavior of plants.

*Ecologists* will be crucial when hazardous waste site remediation is also part of a longer-term ecosystem restoration project.

*Environmental/civil engineers* have significant experience using many technologies to characterize and remediate hazardous waste sites.

*Food scientists, vegetable crop specialists*, and *pomologists* can provide information on contaminants in food crops and fruits; this information can provide clues as to which plants are useful in the uptake of contaminants.

*Foresters* can provide tree propagation and culture information.

*Hydrogeologists* can evaluate the contaminated media in the system and can evaluate the interactions with surface water, groundwater, and soil water.

*Land reclamation specialists* have knowledge of the plants and techniques used to restore degraded land; some of the contaminants at hazardous waste sites, however, have not been encountered in most cases of land reclamation.

*Landscape architects* can advise on the selection and placement of plants.

*Nurseries* and *seed companies* can provide advice on the selection and care of seeds and plants under local conditions.

*Soil scientists* are specialists in understanding soil properties.

*Soil microbiologists* will be particularly useful for work involving rhizodegradation, and as an aid in explaining how soil microorganisms will interact with plant exudates, contaminants, and any amendments to the soil.

# Chapter 5
# Remedial Objectives, Treatability, and Evaluation

## 5.1 Remedial Objectives

The remedial objectives that will be appropriate for a particular site are determined by site-specific conditions and the requirements of the Federal or state program under which the cleanup action will be conducted. Such cleanup programs include the RCRA Corrective Action and Underground Storage Tank Remediation programs, which are Federal programs typically implemented by the states; the Federal Superfund program; and state cleanup programs. These cleanup programs generally require that remedial measures be taken to:

- Prevent contaminants from reaching human or environmental receptors above acceptable risk levels (prevent exposure);
- Control further migration of contaminants from source materials to groundwater or surface water (source control); and
- Control further migration of contaminated groundwater (plume control).

Some programs have additional requirements. For example, the Superfund program generally requires that treatment remedies be used for source materials that are determined to be "principle threat" wastes, and generally allows containment remedies for source materials determined to be "low level threat" wastes. Also, the Superfund and RCRA Corrective Action programs generally require that contaminated groundwater be restored to cleanup levels appropriate for current or future beneficial uses (e.g., drinking water). Remedies that involve treatment of source materials and restoration of groundwater will also set cleanup levels to be attained by the remedy.

Two factors must be considered to determine the remedial objectives for phytoremediation projects: 1) the target concentration for each contaminant in each type of media (soil, water, etc.) and 2) the desired fate of each contaminant, i.e., containment, uptake and removal, destruction, or a combination of these options.

Ecosystem restoration could be a primary or secondary objective in combination with soil or groundwater remediation. Although remediation might be a secondary goal as opposed to reestablishment of vegetation and habitat, destruction of the contaminant is preferred over contaminant containment. Processes that transfer the contaminant to another location or phase are also less desirable.

### *5.1.1 Cleanup Levels*

The target concentration for each contaminant may be driven by environmental regulations such as RCRA, CERCLA, the Clean Water Act, or state-specific cleanup requirements. For example, surface water discharges, if any, from the site may be required to meet National Pollutant Discharge Elimination System (NPDES) limitations. If soil or water is removed from the site for treatment or disposal, RCRA standards are applicable.

A specified contaminant concentration is often a goal in soil or groundwater remediation. Because phytoremediation is an emerging technology, there is still uncertainty regarding the contaminant concentrations that are achievable by the various types of phytoremediation. The information compiled in Chapter 3 provides a rough guide as to the contaminant concentrations that have been achieved in research studies.

### *5.1.2 Fate of the Contaminant*

Destruction of each contaminant is the preferred remedial objective. However, depending on the phytoremediation technology selected, contaminants may be contained and left in place, or extracted or taken up by the plant into the plant tissue and then left in place, removed, or volatilized. Table 5-1 summarizes the methods of contaminant control for each phytoremediation technology.

**Table 5-1.** Summary of Phytoremediation Technologies and Method of Contaminant Control

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

[a] Phytoremediation cover.
[b] Evapotranspiration cover .

## 5.2 Treatability Studies

Phytoremediation techniques are almost by definition innovative. Most have not been applied very often. In spite of the body of information concerning applications of phytoremediation to contaminated soils, groundwater, and surface waters, there is still a need to determine *a priori* if the specific plant(s) and treatment procedures indicated for cleanup will work to remediate the contaminant(s) in the soil or water at a specific site. Many factors will influence the success of phytoremediation at a given site, including contaminant concentration, availability of nutrients, daily maximum and minimum temperature, rainfall or possibility of irrigation, grade on site, aesthetic considerations, daily illumination level, relative humidity, wind patterns, and/or the presence of growth-suppressing contaminants. The desired level of cleanup and the desired rate of decontamination also need to be considered. All of these factors need to be evaluated prior to a substantial expenditure of time and money on a large-scale phytoremediation effort.

### *5.2.1 Optimization Studies*

The phytoremediation system should be optimized prior to the actual field application. There may be a need to modify the soil or water pH or to add soil amendments such as chelating agents (to make metals more bioavailable), nutrients (to increase rate of plant growth), and/or organic matter (to facilitate the growth of the desired plant species or to improve soil microbial viability). Organic amendments used in phytoremediation studies have included leaf mulch, ground corn stalks, peanut shells, cotton gin debris, and ground bark. Caution should be exercised in the use of plant-derived amendments because some plant materials have been shown to possess phytotoxic properties. Canola leaf and root residues have been shown to suppress the growth of corn, barley, and wheat (Wanniarachchi and Voroney 1997). Such naturally occurring phytotoxins probably have an evolutionary advantage by suppressing competition for nutrients. Prior to full-scale implementation, candidate amendments should be tested in small-scale studies for their ability to suppress the growth of the desired phytoremediating species.

Dibakar (1997) recommends groundwater monitoring if amendments might mobilize contaminants. An interesting example of a pilot study using amendments is the work by Blaylock et al. (1997) concerning the use of several chelates at multiple concentrations. In this study, the phytoremediation potential of Indian mustard (*Brassica juncea*) was tested for removing metals from soils. This study and other studies are discussed in section 5.2.5.

Amendments have also been used to adsorb contaminants so that they could later be available to plants or degraded by soil microbes. Cunningham et al. (1995b) assessed the stabilization of lead in soil by adding an alkalizing agent, phosphates, mineral oxides, organic matter, or biosolids.

Phytoremediation might also be enhanced by the addition of microbial innocula that would increase rhizosphere degradation or uptake. Successful enhancements to phytoremediation have been noted such as the inoculation of wheat seeds with TCE-degrading bacteria (Yee et al. 1998).

### *5.2.2 Other Considerations*

Treatability studies could also provide information relating to disposal of contaminated biomass. Such disposal is a major consideration in the cleanup of metal-containing soils. Depending on regulations and plant concentrations of metals, plants may need to be landfilled, or the metals reclaimed through smelting, pyrolysis of biomass, or extraction. In a discussion of the reclamation of metal-contaminated plant tissue by smelters, Dibakar (1997) stated that plant tissue with a dry-weight concentration of over one percent metal was amenable to reclamation.

Insecticides or herbicides might be used at the field treatment site to preserve the plant species selected for phytoremediation or to prevent the overgrowth of hardy indigenous species. The site survey should consider the prevalence of insect pests and invasive native species. Subsequent laboratory trials may need to evaluate pesticide usage to ensure that it does not interfere with phytoremediation.

Treatability studies often use radiolabeled contaminant preparations to assess the toxicity of plant-generated metabolites of the contaminant(s) of interest or to assess the possibility of volatilization or solubilization of toxic contaminants. This use of radiolabels allows for a much greater sensitivity in the analysis for contaminant or metabolites (much lower detection limit), thereby facilitating the tracking of metabolic transformation of the contaminant in the phytoremediation system. Studies using radiolabeled contaminants are usually performed in greenhouses or growth chambers, although limited studies have been done in the field using nonvolatile radiolabeled contaminants and encasing the plant roots in an impermeable barrel-like container to prevent migration of radiolabels into the surrounding soil or into the groundwater. If volatility of contaminant or metabolites is a concern, then studies should be performed in a greenhouse. A gas-tight barrier can be installed between the soil surface and the air so that evaporation from the soil can be differentiated from plant uptake and subsequent volatilization. Several studies are underway using *Populus* species in an attempt to discern the mechanism(s) by which poplars remove TCE from contaminated groundwater.

As a special case, phytoremediation studies that deal with contaminant removal from aqueous media (groundwater, waste water, wetlands) might use a radiolabeled contaminant to address the comparative rates of transpiration, bioconcentration, and/or degradation. Pilot studies have been performed with radiolabeled contaminants to evaluate phytoremediation treatment of groundwater to remove persistent herbicides (Burken and Schnoor 1997) and metals (Salt et al. 1997).

Treatability studies often also use hydroponic systems in initial, proof-of-concept trials. Although hydroponic systems should not be used to infer the rate of uptake or degradation for soil systems, such studies can determine if a particular plant can be used with a particular contaminant. Hydroponic systems are often used for screening several options (e.g., several concentrations of a contaminant), since these systems are inexpensive and allow rapid growth of plant tissue.

The issue of available time should be considered in the design of treatability studies. The candidate plant species must have sufficient time to develop roots and biomass (and possibly metabolic enzymes) to perform the phytoremediation. The ability of a plant to degrade or to take up a contaminant varies with the age and metabolic status of the plant (water content, diurnal cycles, temperature). Factors to consider include growth rate, period of dormancy (deciduous plants), and any other known factors, such as the development of metabolizing enzymes, that change with the age of the plant. Table 5-2 shows experimental factors to consider in conducting treatability studies.

**Table 5-2.** Experimental Factors for Testing in Treatability Studies

| Essential | Optional |
|---|---|
| Contaminant reduction | Different soil types on site |
| Phytotoxicity of contaminant(s) at site | Different contaminant levels on site |
| Growth of plant species on site (soil type, nutrients, temperature, rainfall, illumination) | Allelopathy |
| Rate of cleanup | Aesthetic considerations |
| Level of cleanup | Soil amendments<br>Microbial innocula<br>Pesticide usage<br>Disposal options for plant materials (metals, radioisotopes) |

### 5.2.3 Experimental Design for Plant Selection

If a contaminant has not been studied for phytoremediation, but a chemically similar contaminant was successfully treated, a trial might be conducted to determine if the species used to treat the chemically similar contaminant would work. If initial trials with one species are unsuccessful, then different cultivars/strains, or related species in the same genus, or related genera in the same plant family might be assessed.

A survey of the site vegetation should be undertaken to determine what species of plants are able to grow on that site. Plants from the site can be assessed for uptake of the contaminant, bioconcentration, and/or biodegradation.

The species chosen for a field study must be suited to the soil, terrain, and climate at the site. If a plant species previously used elsewhere for phytoremediation cannot be successfully grown at a specific field site, then (as is the case for chemically similar compounds) similar strains/cultivars, species, or genera should be assessed in a pilot study.

Soil samples should be taken in conjunction with plant samples from the site to assess the concentration of contaminants in the immediate soils around the plants at the site; soil contaminants have been shown to be degraded by the microbial population found around the roots of plants growing in contaminated soils (Anderson and Walton 1995). These soil samples might also serve as sources of innocula for microbial seeding of soils, seeds, or roots during subsequent remediation studies.

The greenhouse or laboratory trial should use soil or water from the site, if possible. This allows for assessment of soil toxicity and assessment of the possibility of migration of the contaminant in the soil column (leachability). Soil toxicity should be assessed using Standard Practice E 1598-94 from the American Society for Testing and Materials (ASTM). The soil-dwelling microflora that aid in phytoremediation are affected by the type and level of contamination in the soil on site. These microflora are estimated to take 2 to 16 weeks to recover from pesticide treatment, more than 10 years to recover from toxic insult due to oil spills on soil, and 50 to 100 years to recover from metal contamination (Shimp et al. 1993). If soil from the site cannot be secured, then a soil of the same USDA type should be used and adjusted for pH at the site. Commercial suppliers of standard USDA soil types should be contacted as needed. In most studies, soils are screened through a coarse mesh to remove rocks and large biomasses; however, this process may perturb the soil sample (Nwosu 1991).

The trial should duplicate the illumination and moisture conditions at the site as closely as possible since these factors often have a significant influence on the rate of remediation. Temperature and relative humidity have also been shown to affect the rate of uptake of contaminants (Dibakar 1997). If the site has several soil types, samples of each soil type should be collected to assess growth in each type. If uncontaminated areas are within the site, then soils should be collected from these areas also for use as experimental controls and for use in assessing the maximum tolerable level for a plant species to a given contaminant through addition of the contaminant of interest to the uncontaminated soil. Table 5-3 summarizes factors to consider in designing a phytoremediation trial.

### 5.2.4 Experimental Design

Most published phytoremediation pilot studies have utilized a block design, with a first-level assessment of all possible combinations of several key factors (e.g., several plant species/several pH levels/several chelators). A second series of tests could then evaluate the best combination of first-level factors (e.g., the best combination of plant/pH/chelator) for another set of factors (e.g., plant-tolerated level of contaminant and rate of cleanup). Such an

**Table 5-3. Information Needed for a Pilot Treatability Study**

- Identification of contaminant(s)
- Level (concentration) of contaminant(s)
- pH
- Average monthly temperature, plus expected maximum and minimum temperatures
- Soil nutrient levels (P, K, N) and organic matter levels
- Average monthly rainfall
- Grade on site
- Aesthetic considerations (proximity to commercial or residential properties or recreational areas)
- Daily illumination
- Average relative humidity
- Wind patterns (prevailing direction and velocity)
- Presence of growth-suppressing contaminants

experimental design allows for the efficient use of time and funds, with assessment of multiple factors concurrently. Information can be collected on interactions between factors affecting phytoremediation, and an optimal field phytoremediation plan can be developed. The analysis of data from such studies can be complex. Analysis of variance methods (ANOVA) can be used if certain conditions are met. Standard statistics texts present a discussion of ANOVA procedures. The best approach, however, is to consult a statistician experienced in experimental design.

### 5.2.5 Completed Pilot-Scale Studies

Several pilot studies of phytoremediation options have been published. The following paragraphs include brief notes on the methods used, the experimental design, and other information relevant to the design of a pilot study.

Rhizosphere soils (soils around the plant roots) were collected from several plant species growing in an area with prior herbicide application. These soils were dosed with $^{14}C$-labeled metolachlor and incubated in biometer flasks under controlled conditions. Evolution of $^{14}CO_2$ was measured as an indication of herbicide degradation (Anderson and Coats 1995).

A greenhouse study evaluated the efficacy of the remediation of PAH-contaminated soil by eight species of prairie grasses. Reaction units were PVC pipe, capped at one end. The eight reaction units were dosed with a mixture of four PAHs; of these units, four were seeded and four were not seeded. Additional controls were four undosed units (two seeded and two unseeded). The concentration of the PAHs was measured in the soils and leachates (Aprill and Sims 1990).

Soil additives ($KH_2PO_4$, limestone, gypsum, sulfur, various iron compounds, and various organic carbon sources) were used in soils taken from three industrial sites to immobilize lead for subsequent phytoremediation. A test for immobilization/leaching potential was described (Berti and Cunningham 1997).

Studies in growth chambers used a USDA standard soil amended with lime and fertilizer and dosed with metal salt solutions (Cd, Cu, Pb, or Zn). Five chelating agents were evaluated at four concentrations to determine their ability to enhance uptake of the metals by Indian mustard, *Brassica juncea* (Blaylock et al. 1997).

Hybrid poplar cuttings were rooted in aqueous medium and planted in 1-liter bioreactors filled with uncontaminated soil or sand. Each bioreactor system was dosed with $^{14}C$-labeled atrazine. After controlled incubation, uptake and degradation were measured and metabolites were identified, where possible. $^{14}C$ was rinsed from some sand-containing bioreactors, and it was demonstrated that degradation of atrazine could be accomplished in plant tissue. A mathematical model was developed to describe atrazine uptake, distribution, and metabolism (Burken and Schnoor 1997).

In a review paper, Cunningham et al. (1995a) discuss soil amendments and their use in phytoremediation.

A greenhouse study evaluated three conditions (nutrient-amended soil/ryegrass, nutrient amended soil/no plants, and unamended soil/no plants) for remediation of soils contaminated with pentachlorophenol or a mixture of polycyclic aromatic hydrocarbons. Replicate soil columns, subjected to the three treatments, were analyzed over time for contaminant concentration (Ferro et al. 1997).

In a small-scale field trial, a series of self-contained plots was established with or without poplar trees and with/without trichloroethylene (TCE), which was added to the water supply during the growing season. The poplar/TCE and the poplar/no TCE plots were replicated, while the other conditions were not. Removal of TCE from the water and metabolite formation were measured (Newman et al. 1997c).

Axenic tumor plant cell cultures were utilized to demonstrate metabolism of TCE in plant tissue, as contrasted with metabolism by rhizosphere microbes (Newman et al. 1997a).

Soil was collected at a contaminated site, and the germination of cucumber and wheat seeds was assessed in containers incubated on site. Seed germination was evaluated against matched controls composed of the same seeds planted in clean sand and incubated on site (Nwosu et al. 1991).

A static renewal bioassay was developed in which plants, grown several weeks in uncontaminated soil in a greenhouse, were then exposed to several different concentrations of a solution of nutrients and the contaminant of interest. Growth was evaluated through measurement of dry weight, visual observation, and chlorophyll assay. This process was used to establish tolerance levels for a contaminant-plant system (Powell et al. 1996).

After a preliminary seed germination study, tall fescue grass was chosen as the best grass species to use in this study. Triplicate microcosms of vegetated and unvegetated soils were dosed with benzo(a)pyrene or hexachlorobiphenyl, both of which were $^{14}C$ labeled. Offgassing of radiolabeled metabolite was monitored. Degradation of the contaminants in soil and binding to soil were also measured. A complete randomized block design was used and data were analyzed by two-way ANOVA (Qiu 1995).

Four species of aquatic plants grown in glass tanks under controlled conditions were evaluated to determine their ability to accumulate either $HgCl_2$ or $CH_3HgCl$. Tests were run in duplicate with two water sources and three sediment types. Uptake of Hg and plant growth were measured (Ribeyre and Boudou 1994).

Indian mustard seedlings were grown in aerated water under controlled conditions and dosed with $^{210}Pb$, $^{85}Sr$, $^{109}Cd$, $^{63}Ni$, $^{51}Cr$, or $^{134}Cs$. Bioaccumulation of metal-associated radiolabel was measured. Effects of competing ions ($Ca^{++}$, $Mg^{++}$, $K^+$, $SO_4^=$ and $NO_3^-$) were also assessed (Salt et al. 1997).

Ten plant species were evaluated for remediation of TNT and other explosives in groundwater. By-product formation, plant density, and rhizosphere interactions were evaluated. Time-course studies were performed and kinetics were described (Saunders 1996).

Phytoremediation of diesel-fuel-contaminated soils was studied in this small-scale field study. Four treatments were used: clover, fescue, bermuda grass, and no plants. Six replicates were made of each treatment, and each replicate plot contained four sampling sites. Decreases in total petroleum hydrocarbons and plant growth were measured over a 1-year period (Schwab and Banks 1995).

Shimp et al. (1993) published a review paper containing an overview of factors affecting the phytoremediation of soils and groundwater containing organic contaminants. The paper's emphasis is on rhizosphere mechanisms along with a list of plants/contaminants that have been studied.

## 5.3 Monitoring for Performance Evaluation

The phytoremediation system must be monitored and periodically evaluated to measure progress toward the remedial objective.

### *5.3.1 Performance Evaluation*

To evaluate the performance of soil remediation, contaminant and degradation product concentrations in the soil must be measured. In rhizodegradation, the microbial populations could be counted and/or identified to confirm biodegradation. In collecting and analyzing the soil, samples should be collected from the root zone because the proximity and influence of the root zone, as well as the density of the roots, may affect how much rhizodegradation or phytostabilization is measured.

To evaluate the performance of groundwater remediation, the contaminant and degradation product concentrations should be measured. The depth, flow rate, and volume of groundwater should be monitored to evaluate the success of hydraulic control. Periodic water content measurements should be made, or tensiometers used to measure soil moisture tension, which then could be related to water content through site-specific calibration. To evaluate processes designed to impact water movement, the transpiration rate should be determined.

Because phytoremediation is an emerging technology, standard performance criteria for phytoremediation systems have not yet been completely developed. Data are being gathered and assessed to develop performance measures that can be used to assess the function of an individual system.

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

### *5.3.2 Monitoring Plan*

A monitoring plan for the phytoremediation system should be prepared to collect data to:

- Optimize operation of the phytoremediation system.
- Monitor potential adverse impacts to the ecosystem.
- Measure progress toward the remedial objectives, i.e., destruction, extraction, or containment of contaminants.

The monitoring plan should contain the following elements:

- Constituents, parameters, or items to be monitored
- Frequency and duration of monitoring
- Monitoring/sampling methods
- Analytical methods
- Monitoring locations
- Quality assurance/quality control (QA/QC) requirements.

Table 5-4 lists common parameters monitored in a phytoremediation system. This list is not all-inclusive and is dependent upon the individual phytoremediation system.

Modeling may be necessary to optimize the phytoremediation system or to predict behavior. Modeling may be especially relevant to evapotranspirative covers where the water balance is critical to the success of the system. Plant uptake models may be used to predict the rate at which a contaminant will be degraded within a plant.

Monitoring of the ecosystem for potential adverse effects may be necessary for some phytoremediation systems. If the system uses phytovolatilization, air sampling might be necessary to address concerns about contaminants or deg-

**Table 5-4.** Summary of Monitoring Parameters

| Monitoring Parameter | Reason for Monitoring |
|---|---|
| Climatic data | |
| •Temperature | •Maintenance requirements (irrigation) |
| •Precipitation | •Determine water balance and evapotranspiration rates |
| •Relative humidity | |
| •Solar radiation | |
| •Wind speed and direction | |
| Plants | |
| •Visual characteristics (viability, signs of stress, damage from insects or animals, growth, leaf mass, etc.) | •Maintenance (plant replacement, fertilizer, pesticide application, etc.) |
| •Tissue composition (roots, shoots, stems, leaves, etc.) | •Quantify contaminants and byproducts |
| •Transpiration gases | •Quantify and/or predict system operation |
| •Transpiration rate | |
| •Root density | |
| Soil | |
| •Geochemical parameters (pH, nutrient concentrations, water content, oxygen content, etc.) | •Optimize vegetative, root, or microbial growth<br>•Determine water balance and evapotranspiration rates |
| •Microbial populations | •Quantify contaminants and byproducts |
| •Contaminant and breakdown product levels | •Quantify and/or predict system operation |
| Groundwater | |
| •Aquifer information (direction and rate of flow, depth to groundwater, specific yield, etc.) | •Quantify contaminants and byproducts<br>•Quantify and/or predict system operation |
| •Contaminant and breakdown product levels | |

radation products that may be released to the environment. If soil additives are used to enhance the bioavailability of metals in soil, monitoring may be required to ensure the metals are not migrating to groundwater. Extraction of contaminants by plants with uptake to edible portions of the plant such as leaves and seeds may require monitoring of the food chain for bioaccumulation of the contaminant.

The monitoring plan should include QA/QC procedures for sample collection, analysis, and data interpretation. Since remedial site and analytical personnel may not be experienced in sampling, preservation, or analytical methods for plant matter, properly developed and validated methods must be used to ensure conclusions are valid.

# Chapter 6
# Case Studies

The six case studies presented in this chapter illustrate specific field applications of phytoremediation. Site descriptions, design considerations, monitoring recommendations, status, and cost of various phytoremediation processes are presented. The completeness of the information provided varies based on the status of the project (i.e., complete costs or degree of contaminant removal may not be fully defined because the project is ongoing).

## 6.1 Edgewood Area J-Field Toxic Pits Site Aberdeen Proving Grounds Edgewood, Maryland

| | |
|---|---|
| Site name: | Edgewood Area J-Field Toxic Pits Site |
| Location: | Aberdeen Proving Grounds, Edgewood, Maryland |
| Media: | Groundwater (8 ft bgs) |
| Primary contaminants and maximum concentration: | 1,1,2,2-tetrachloroethane (1122-TCA), 170 ppm<br>Trichloroethylene (TCE), 61 ppm |
| Type of plant: | *Populus tricocarpa x deltoides* (Hybrid poplar) |
| Area of planting: | 1 acre |
| Date of planting: | March/April 1996 |

### *6.1.1 Site Description*

The Aberdeen Proving Grounds (APG) in Maryland began serving as a U.S. Army weapons testing facility in 1918. Military weapons testing and past disposal activities over the years have caused extensive pollution throughout the soil and groundwater of the Proving Grounds. As a result, the entire Edgewood area of Aberdeen appears on the Superfund National Priority List (NPL). The Department of Defense (DOD) and the U.S. Environmental Protection Agency (EPA) are jointly funding field-scale applications of innovative treatment technologies around the facility. At the J-Field Site in the Edgewood Area, EPA's Environmental Response Team (ERT) coordinated the planting of hybrid poplars over a shallow plume of chlorinated solvents in an effort to hydraulically contain the contaminants and treat the groundwater.

J-Field is located at the tip of Gunpowder Neck, in the Edgewood Area of APG. Two pits measuring 10 x 15 x 200 feet were used for the disposal of chemical warfare agents, munitions, and industrial chemicals from the 1940s to the 1980s. Disposal methods included open burning of waste material such as high explosives, nerve agents, mustard agents, and smoke-producing materials. Wood and fuel were used to feed the fire. Decontaminating agents used in the operations were solvent-based. During this burning process, large volumes of various chlorinated solvents were discharged. As a result, a plume of chlorinated solvents formed in the aquifer below the burning pits. The predominant solvents in the groundwater are 1,1,2,2-tetrachloroethane (1122-TCA) and trichloroethylene (TCE), with maximum concentrations in the groundwater of 170 ppm and 61 ppm, respectively. Total volatile organic compound (VOC) concentrations in the groundwater range up to 260 ppm.

### *6.1.2 Design, Goals, and Monitoring Approaches*

Several technologies were considered for cleaning the soil and groundwater at the site. Soil washing, vapor extraction, and capping were considered for cleaning up soils, while pump-and-treat and air sparging were considered for remediating the groundwater. These technologies were eliminated from consideration for a number of reasons. Technologies that involved a rigid installation design were eliminated because of the potential for unexploded bombs buried on site. Pumping and treating the water would be difficult because of the high concentrations of contaminants and strict discharge regulations. Thus, the pump-and-treat system would need to remove high concentrations of contaminants from large volumes of groundwater, and then discharge the groundwater after it had been treated. Soil excavation was eliminated from consideration due to the presence of unexploded ordnance (UXO) and its high cost. After eliminating the other possibilities, project managers decided the J-Field site was a candidate for a pilot-scale phytoremediation system.

Based on site conditions and the possible presence of UXO at the J-Field Toxic Pits Site of APG, phytoremediation was deemed a viable remedial alternative to hydraulically contain the contaminants and treat the groundwater. Applied Natural Sciences, Inc., was subcontracted to design and install the phytoremediation system. The phytoremediation strategy employed at the J-Field site began in September 1995 with a phytotoxicity assessment of on-site pollutants to determine any nutrient deficiencies that would hinder tree growth. Four planting areas were designated at the J-Field site, totaling approximately 1-acre. Holes were augered to a depth of 8 feet to allow homogenization of soil layers. Soil samples were collected and analyzed for VOCs, metals, and chloride. The design was based on the location of the toxic pits, various wells which would be utilized in monitoring the system, and the flow of contaminated groundwater.

In March and April 1996, 184 bare-root hybrid poplars (*P. trichocarpa x deltoides* [HP-510]) were purchased from a tree farm in Pennsylvania and planted 2 to 6 feet below ground surface (bgs) in the areas of highest pollutant concentration around the leading edge of the plume. These trees were planted in an attempt to intercept groundwater, thus preventing further contamination of the nearby marsh. The phytoremediation planting area covers approximately 1 acre southeast of the toxic pits, and is surrounded by wooded areas and scattered thickets. Groundwater flows from the toxic pit area to the south and southeast. Perched groundwater in the planting area varies throughout the year from 2 to 8 feet below ground surface (bgs). To promote growth down to the saturated zone, each tree was planted with a plastic pipe around its upper roots. A long piece of rubber tubing was also added from the surface to the deeper roots in order to provide oxygen. A drainage system was installed in May 1996 to remove rainwater and thus encourage the plants' roots to seek groundwater. A sweetgum tree growing on site prior to installation of the phytoremediation system was left standing. It will be monitored along with the poplars.

Since the Aberdeen project involves a new treatment strategy, extensive monitoring is taking place to determine the fates of the pollutants, the transpiration rates of the trees, and the best methods for monitoring phytoremediation sites. Groundwater contaminant levels, water levels, tree growth, tree transpiration rates, tree transpirational gas and condensate water contaminant levels, soil community, and tree tissue contaminant levels were monitored over the second year growing season to determine the effectiveness of this emerging technology. The monitoring approaches are summarized in Table 6-1. The sampling design of the site involves collecting soils, transpiration gases, and tree tissues from the roots, shoots, stems, and leaves. Results will help determine the concentrations of contaminants and their metabolites along each step of the translocation pathway.

Nine wells were located in the surficial aquifer near the study area at the time of tree planting. To determine the effects of the phytoremediation study on groundwater, an additional five wells and four lysimeters were installed in November 1996. Monitoring wells were screened from 4 to 14 feet bgs. Two sets of two lysimeters were installed near the new monitoring wells. The lysimeters were placed in pairs and set at depths of 4 and 8 feet bgs. These depths allow for coverage of the capillary zone during seasonal highs and lows. Groundwater and lysimeters were monitored on a quarterly basis for VOCs, metals, and chloride. The data obtained from the lysimeters are currently being compared with the surrounding tree tissue and transpirational gas data to determine the degree of success of the study.

**Table 6-1.** Monitoring Approaches at the J-Field Site.

| Type of Analysis or Observation Used | Parameters Tested or Methods |
|---|---|
| Plant growth measurements and visual observations | Diameter, height, health, pruning, replacement |
| Groundwater and vadose zone sampling and analysis | 14 wells and 4 lysimeters to sample for VOCs, metals, and nutrients |
| Soil sampling and analysis | Biodegradation activity, VOCs, metals |
| Tissue sampling and analysis | Degradation products, VOCs |
| Plant sap flow measurements | Correlate sap flow data to meteorological data |
| Transpirational gas sampling and analysis | Explore various methods |

Source: Tobia and Compton (1997)

### *6.1.3 Results and Status*

Plant tissue samples were taken from certain trees and analyzed for VOCs and metals. Results have shown parent compounds and degradation products increasing in concentration through mid-growing season and waning in the fall.

Weather parameters were measured by an on-site meteorological station, correlated with tree data, and were utilized to estimate seasonal, daily, and yearly water uptake. These parameters included precipitation, incident solar radiation, temperature, humidity, and wind speed. All of these factors play a role in transpiration rates and sap flow.

Tree sap flow rates are being monitored in order to determine the pumping rates of the trees. A noninvasive technique was used to measure sap flow on certain trees during the various sampling seasons. The Dynamax Flow32™ Sap Flow System was used to measure the water flux of the trees in grams of water/hour/tree by utilizing the heat balance method.

Transpiration gas sampling was performed by placing a 100-L Tedlar™ bag over a section of branch on each of the selected trees. Air was drawn from the sealed branch by using a carbon Tenax tube, summa canister, Sciex Trace Atmospheric Gas Analyzer, and on-site Viking Gas Chromatograph/Mass Spectrometer (GC/MS). The most reliable results were obtained by collection into the summa canister, then analysis by laboratory GC/MS. The results show similar patterns to those found in the leaf tissue. The parent compounds of 1122-TCA and TCE were detected at increasing levels through the mid-growing season (maximum 2,000 ppb), with subsequent decreasing concentrations in the fall. Condensate water was collected from the bags and analyzed for VOCs. There was a strong correlation (0.92) between condensate water and transpiration gas, with a maximum concentration of 640 ppb of 1122-TCA in the condensate water.

Soil samples were collected from the rhizosphere of the selected trees. These samples were analyzed for VOCs, chloride, and metals, and utilized for soil community comparisons. There were noteworthy changes to the nematode functional group populations. The nematode community appears to have increased, both in diversity and concentration, from previous samples taken from the area before the trees were planted. Studies are planned to assess chlorinated solvent degradation by soil microbes.

Growth measurements, visual observations, and maintenance were performed on all trees during planting and at the end of each growing season to monitor tree growth and health. Tree diameter and height were measured and tree health observed, including monitoring of insect damage, chlorosis, and wilting. Approximately 10% of the trees have been killed by frost, deer rub during rutting season, and insect predation.

Sap flow rate data indicate that on a daily scale, maximum flow occurs in the morning hours. In addition, increasing amounts of solar radiation seem to increase sap flow rates, as would be expected in a tree. Groundwater monitoring data from May 1997 indicate that the trees are pumping large amounts of groundwater. Data indicate that there is roughly a 2-foot depression in the water table beneath the trees in comparison to data from April 1996. Tree tissue samples indicate the presence of trichloroacetic acid (TCAA), a breakdown product of TCE. These data correlate with the results from University of Washington greenhouse scale studies that also found TCAA in plant tissues in both axenic poplars cell cultures and hybrid poplar tissues. Site managers at Aberdeen are also finding that chlorinated solvents (TCE and 1,1,2,2-tetrachloroethane) are being evapotranspirated by the trees. To date, no mass balance studies have been performed to quantitatively determine the different fates of chlorinated solvents in this treatment system. Future monitoring of the site will hopefully answer some of the questions about solvent fate. To accomplish this, additional types of monitoring will be employed, such as on-site infrared spectrometry and on-site GC/MS.

Based on tree containment measurements, the results of the second growing season show that the trees are removing contaminants from the groundwater and transpiring parent compounds and their degradation products. The groundwater table has been lowered by tenths of feet in the planting area at the end of the growing season, indicating possible groundwater withdrawal by the trees for containment of the contaminated groundwater in future growing seasons. The trees are utilizing the groundwater at rates of 2 to 10 gpd/tree.

#### *6.1.4 Costs*

Tree installation cost is about $80/tree, or approximately $15,000 for the installation of 184 trees. The costs of monitoring are highly varied due to the numerous monitoring techniques employed at the site.

#### *6.1.5 Conclusions*

Phytoremediation using trees to clean up groundwater contaminated with volatile organic compounds may be an ideal choice for this site and others due to the low cost, low maintenance, and low impact associated with the technology. Much more work needs to be performed to further confirm: (1) the correlation between transpiration gas and condensate water; (2) soil community contaminant degradation rate; (3) soil flux rate of VOCs; (4) contaminant exposure to the root zone versus sap and condensate water; (5) leaf litter exposure pathway; and (6) microwells to determine the zone of contamination.

The environment benefits from the presence of trees regardless of whether or not the technology is effective in removing contamination. These environmental benefits include habitat for wildlife, protection of the soil against wind and water erosion, reduction of rainwater infiltration and flushing, an increase in organic matter, and an increase in soil aeration and microbial activity.

#### *6.1.6 Contacts*

Harry Compton
US EPA Environmental Response Team
Edison, NJ 00837
(732) 321-6751

Steve Hirsh
US EPA Region 3
Philadelphia, PA 19103
(215) 814-3352

### 6.2 Carswell Site Fort Worth, Texas

| | |
|---|---|
| Site name: | Former Carswell Air Force Plant |
| Location: | Fort Worth, Texas |
| Media: | Groundwater (12 ft bgs) |
| Primary contaminant and maximum concentration: | Trichloroethylene (TCE), <1,000 ppb |
| Type of plant: | *Populus deltoides* (Eastern Cottonwood) |
| Area of planting: | 1 acre |
| Date of planting: | April 1996 |

#### *6.2.1 Site Description*

The efficacy and cost of phytoremediation with respect to the cleanup of shallow trichloroethylene (TCE) contaminated groundwater are being evaluated at the field scale in a multiagency demonstration project in Fort Worth, Texas. This U.S. Air Force project, which is being conducted as part of the Department of Defense's (DOD) Environmental Security Technology Certification Program (ESTCP), as well as the U.S. Environmental Protection Agency's (EPA) Superfund Innovative Technology Evaluation (SITE) Program, entails the planting and cultivation of Eastern Cottonwood (*Populus deltoides*) trees above a dissolved TCE (<1,000 ppb maximum concentration) plume in a shallow aerobic aquifer to investigate the ability of these trees to control and degrade the plume. The plume is located near Air Force Plant 4 at the Naval Air Station Ft. Worth, also known as the Carswell Air Force Base. Data are being collected to determine the ability of trees planted as short-rotation woody crops to perform as a natural pump-and-treat system.

### 6.2.2 Design, Goals, and Monitoring Approaches

The U.S. Air Force (USAF) Acquisition and Environmental Management Restoration Division and the EPA National Risk Management Research Laboratory (NRMRL) carried out the design and implementation of the phytoremediation strategy at Carswell Site. In April 1996, the USAF planted 660 cottonwoods in an effort to contain and remediate a plume of dissolved TCE located in a shallow alluvial aquifer (<12 feet below ground surface). The species *P. deltoides* was chosen over a hybridized species of poplar because it is indigenous to the region. Therefore it has proven its ability to withstand the Texas climate, local pathogens, and other localized variables that may affect tree growth and health.

Two sizes of trees were planted: whips and 5-gallon buckets. The whips were approximately 3/4 inch in diameter and were about 18 inches long at planting. The whips were planted so that about 2 inches remained above ground and the rest of the tree was below ground to take root. The 5-gallon bucket trees were about 1 inch in diameter and 7 feet tall when planted. The 5-gallon bucket trees were estimated to have about twice as much leaf mass as the whips when planted, and thus they were expected to have higher evapotranspiration rates.

The layout for the project (see Figure 6-1) involved planting a separate plot of trees for the whips and the 5-gallon buckets, with both plots perpendicular to the contaminant plume. The plume is moving to the southeast, so the plots were laid out on a northeast axis. The whips section was planted to the northwest of the 5-gallon buckets, so that the plume would first travel through the root zone of the whips and then through the root zone of the 5-gallon buckets. A control area with monitoring wells was placed to the northwest of the whips, and another in between the whips and the 5-gallon buckets, along with monitoring wells throughout the treatment site. These control areas enable data to be collected on the amount of contaminant that enters each of the treatment areas (whips and 5-gallon buckets), so that

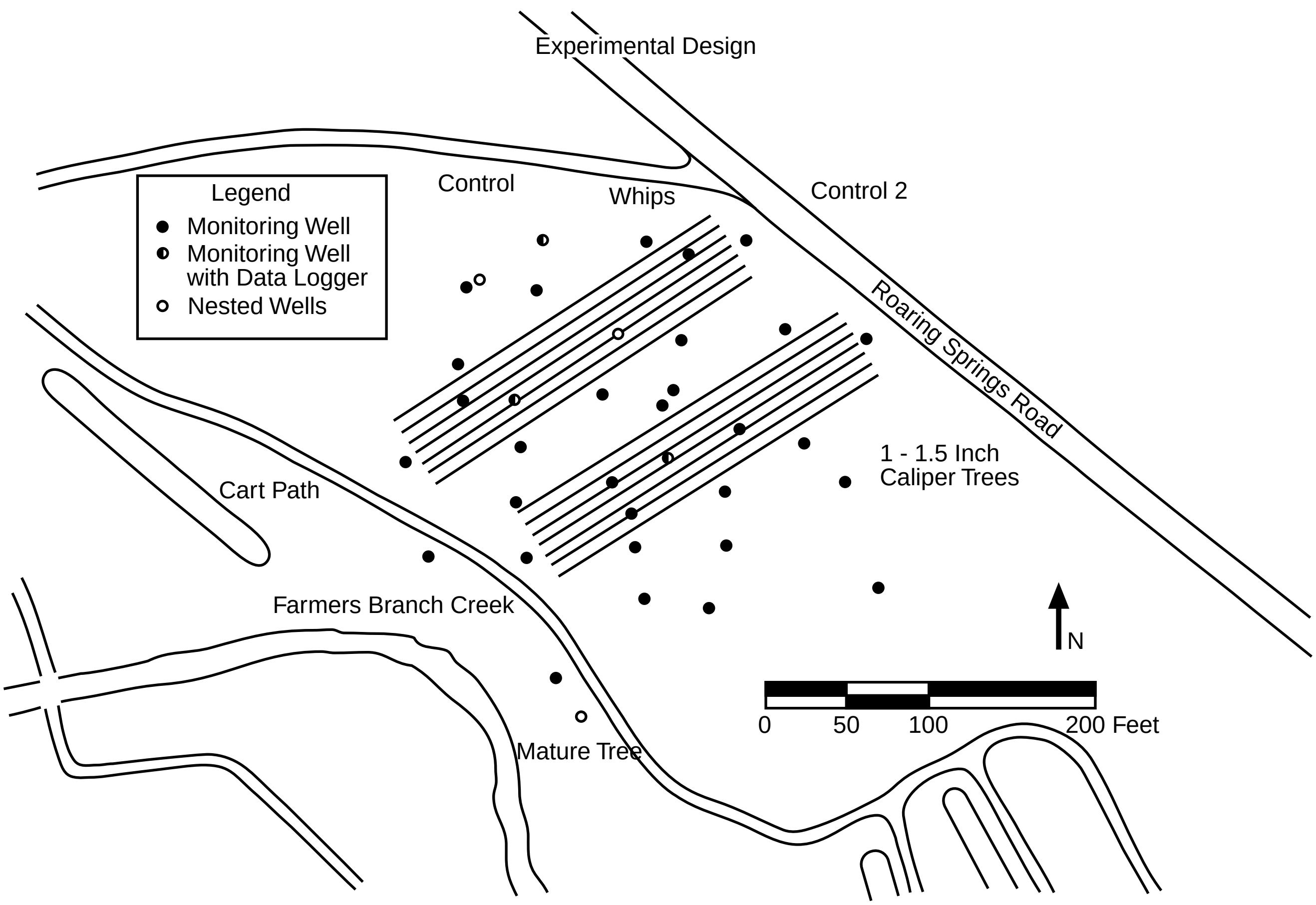


**Figure 6-1.** Experimental Design

a comparison of the performance of each type of tree can be made.

One unique aspect of Carswell Site is the 19-year-old mature cottonwood growing on the site. This 70-foot-tall tree is located just southeast of the planting area on the other side of a cart path. Groundwater monitoring wells were installed around this tree, and it has been sampled in a similar manner to the planted cottonwoods to see how well a mature tree functions in this phytoremediation system.

### *6.2.3 Results and Status*

Seventeen months after the trees were planted (summer 1997), several trenches were dug adjacent to selected trees, and it was determined that the tree roots had reached the water table (Hendrick 1997). Although the trees are pumping water from the contaminated aquifer, they have not yet begun to hydraulically control the plume. Combined results of a transpiration model and a groundwater flow model will be used to determine when hydraulic control of the plume might occur. Transpiration measurements indicate that the largest planted trees pumped approximately 3.75 gpd during summer 1997; the mature 19-year-old cottonwood tree near the planted trees was determined to pump approximately 350 gpd (Vose 1997).

Some analytical work has been done on the tree tissues at the site, but this type of information is still in the early stages of collection. Data from November 1996 indicated TCE in the whips that were planted over an area where the groundwater was the shallowest. This indicates that the young trees were capable of evapotranspirating TCE after just one growing season. Qualitatively, both types of trees were capable of evapotranspiring TCE, and the 5-gallon trees are evapotranspiring more water than the whips. This was to be expected because of the greater total surface area of the leaves of the 5-gallon trees. In addition, the transpiration rates were generally higher in June than May, which is likely due to a combination of warmer weather and more fully developed leaves. There also appeared to be a midday decline in transpiration during June, indicating that the plants were experiencing water stress during the hottest part of the day in the summer months. Thus, the water demand for the tree exceeded the supply during that time. There was also a notable difference in transpiration rates between days in June, with cloudier days resulting in lower transpiration rates. In addition to evapotranspiration information, some tree growth data have also been collected. In 16 months the whips grew about 20 feet, and the 5-gallon bucket trees have grown faster than the whips. Now that the trees have been on site for over an entire growing season, site managers at Carswell Site have increased monitoring at the site to include a whole suite of water, soil, air, and tree tissue sample analysis. Some of the more unique data they are collecting (in relation to the other case study sites) are analyses of microbial populations and assays of TCE-degrading enzymes in the trees.

Laboratory experiments conducted on root samples from the site show the disappearance of perchloroethylene (PCE) in the presence of roots from the cottonwood trees. The products of degradation are anaerobic in the rhizosphere and aerobic (haloacetic acids and carbon dioxide) in the canopy. Increased amounts of vinyl chloride and a trace of TCE as well as iron- and sulfur-reducing conditions in the rhizosphere were detected at the end of these experiments (Harvey 1998). The disappearance of PCE in the presence of roots from a willow tree near the site was even more remarkable (Wolfe 1997). These experiments indicate that cottonwoods and willows produce enzymes that can degrade PCE and TCE. Researchers trying to determine how the trees change the geochemistry of an aerobic aquifer contaminated with TCE and its breakdown product found that labile organic matter from the cottonwoods and several other species of trees is promoting reducing conditions conducive to the degradation of TCE (Harvey 1998).

Groundwater samples had been collected from the 29 monitoring wells and analyzed on three occasions as of August 1997. Concentrations of TCE, cis-DCE, trans-DCE, and vinyl chloride were determined from these samples. They ranged from 2 to 930 ppb TCE in the groundwater, with most samples falling in the 500- to 600-ppb range (see Figure 6-2). Average concentrations of the contaminants on the three sampling dates are provided in Table 6-2, with the exception of vinyl chloride. Vinyl chloride was only detectable in a handful of samples and generally at low levels; thus, an average concentration was not determined.

TCE concentrations in groundwater samples collected beneath the 19-year-old cottonwood tree during summer 1997 were about 80% less than concentrations in groundwater beneath the planted trees, and cis-1,2 DCE (byproduct of TCE degradation) concentrations were about 100% greater. These data, along with additional geochemistry data from the site, are consistent with microbial degradation of TCE beneath the mature tree (Lee 1997). Microbes with the ability to readily degrade TCE require an environment that is low in dissolved oxygen and high in an appropriate source of organic carbon. These conditions, which are often lacking at sites contaminated with TCE, exist in the aquifer under the mature tree and are likely due to the introduction of organic matter from tree-root activity. Once the planted cottonwood trees have established more mature root systems, an environment could develop in the aquifer beneath the trees that would promote biodegradation and result in an additional mechanism for attenuation of TCE. The effect of other mature trees such as willows, oaks, junipers, mesquite, ashes, and sycamores on the geochemistry of the groundwater in the winter and spring is also being explored.

### *6.2.4 Costs*

Some rough estimates of cost for the Carswell Site have been provided by site managers. These estimates can be found in Table 6-3. Since this site involves an innovative treatment technology, these costs are substantially inflated due to the heavy monitoring taking place at the site. Also, long-term projected costs and/or total project costs are not available because the time involved in remediating the site is uncertain. In addition to the costs in the table, $200,000

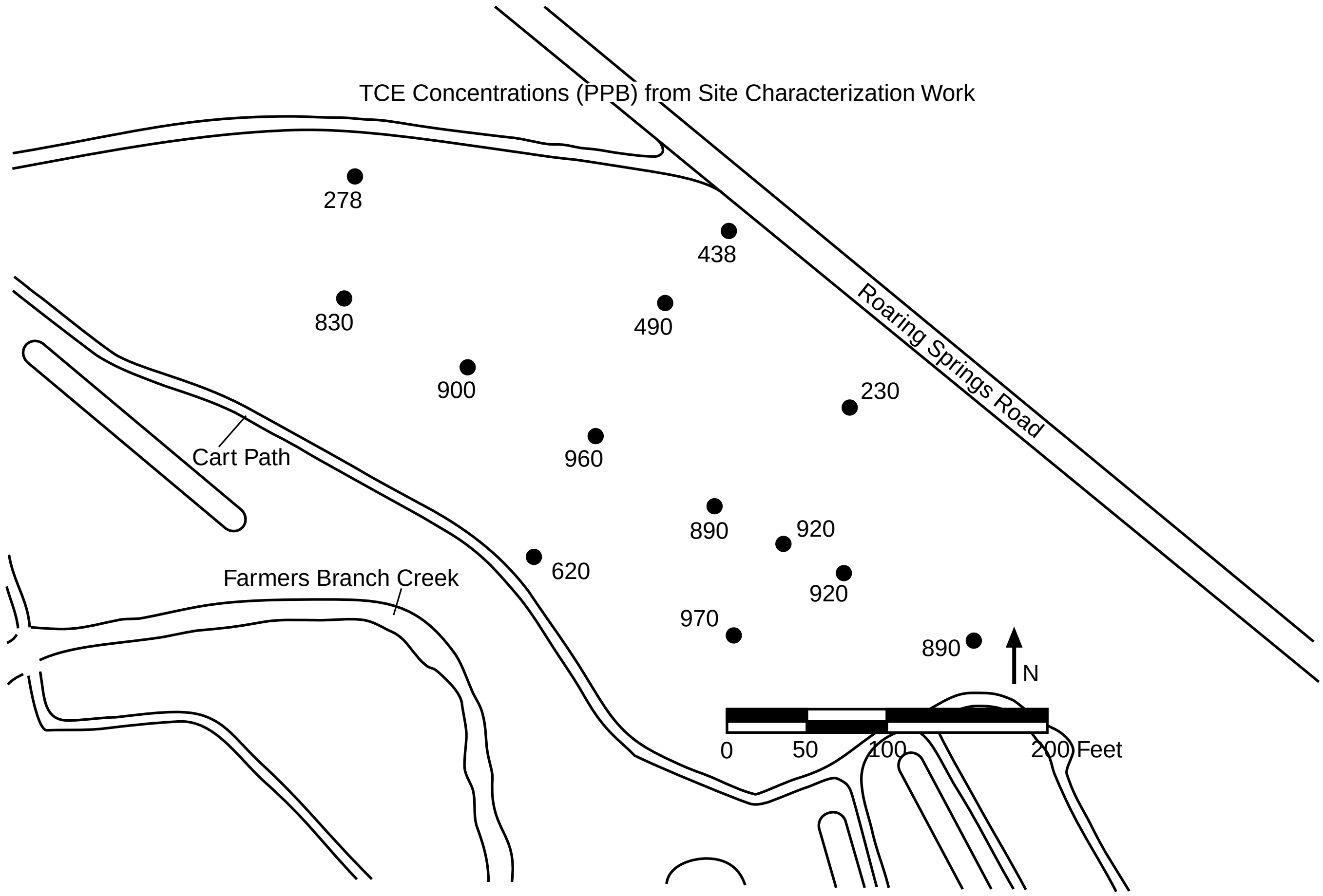


**Figure 6-2.** TCE Concentrations

**Table 6-2.** Average Concentrations of TCE, cis-DCE, and trans-DCE at Carswell Site.

| Contaminant | Average Concentration (ppb) | | |
|---|---|---|---|
| | December 1996 | May 1997 | July 1997 |
| TCE | 610 | 570 | 550 |
| *cis*-DCE | 130 | 140 | 170 |
| *trans*-DCE | 4 | 2 | 4 |

**Table 6-3.** Estimated Cost of Phytoremediation at the Carswell Site.

| Activity | Estimated Cost |
|---|---|
| Wholesale cost of trees (does not tree | $8/tree for 5-gallon bucket |
| include delivery or installation costs) | $0.20/tree for whips |
| 29 wells (including surveying, drilling and testing) | $200,000 |
| Subsurface fine biomass study (the vertical and lateral extent of tree roots less than 2 mm in diameter) | $60,000 |

will be spent for extensive site monitoring that would not normally be associated with a phytoremediation system; thus, this amount was not included in the cost estimates.

More extensive cost and performance data from the demonstration are being compiled to assist others in selecting phytoremediation as a treatment technology. The subsurface fine biomass study will also define the volume of soil exploited by the trees at any given point in time. A typical poplar plantation grown as a short rotation woody crop can produce up to 50,000 to 75,000 miles of fine roots per acre. Also, a groundwater flow and transport model of the site is planned to help determine the relative importance of various attenuation processes in the aquifer to guide data collection at future sites. The model will also be used to help predict the fate of TCE at the demonstration site in an effort to gain regulatory acceptance of this remedial action.

### *6.2.5 Conclusions*

There are over 900 Air Force sites with TCE contamination within 20 feet of land surface that could be reviewed for potential application of phytoremediation by use of poplar trees (Giamonna 1997). Costs may be 10 to 20% of those for mechanical treatments. Scale-up costs for large scale applications of phytoremediation can be minimized by exploiting the body of data developed for the Department of Energy on the planting and cultivation of poplar trees for the purpose of biomass production.

### 6.2.6 Contacts

Greg Harvey
US Air Force ASC/EMR
WP AFB, OH 45433
(937) 255-7716, Ext. 302

Steven Rock
US EPA National Risk Management Research Laboratory
Cincinnati, OH 45268
(513) 569-7149

## 6.3 Edward Sears Properties Site New Gretna, New Jersey

| | |
|---|---|
| Site name: | Edward Sears Properties Site |
| Location: | New Gretna, New Jersey |
| Media: | Groundwater (9 ft bgs) |
| Primary contaminant and maximum concentration: | Trichloroethylene (TCE), <400 ppb |
| Type of plant: | *Populus charkowiieensis x incrassata* (Hybrid Poplar) |
| Area of planting: | 1/3 acre |
| Date of planting: | December 1996 |

### 6.3.1 Site Description

From the mid-1960's to the early 1990's, Edward Sears repackaged and sold expired paints, adhesives, paint thinners, and various military surplus materials out of his backyard in New Gretna, NJ (see Figure 6-3). As a result, toxic materials were stored in leaking drums and containers on his property for many years. The soil and groundwater were contaminated with numerous hazardous wastes, including methylene chloride, tetrachloroethylene, trichloroethylene, trimethylbenzene, and xylene. After his death, no one could be found responsible for the site or its cleanup; thus, On-Scene Coordinators (OSC) from EPA's Region 2 Removal Action Branch were called in to remove the leaking drums of hazardous materials, including off-specification paints and solvents. Soil sampling indicated that two areas, 35 x 40 feet and 15 x 20 feet, were very heavily contaminated with solvents. These soils were removed to 8 feet below ground surface (bgs) (just above the water table). Further excavation could not be achieved without pumping and treating large volumes of groundwater. The excavated areas were backfilled with clean sand and the OSC activated the EPA's Environmental Response Team (ERT) of Edison, NJ to determine the extent of groundwater and deep soil contamination.

Using innovative hydraulic-push groundwater sampling techniques, the ERT investigation revealed localized, highly contaminated groundwater. Based on this information, a limited number of monitoring wells (see Figure 6-4) were installed to determine vertical contaminant migration and to conduct aquifer tests necessary to evaluate pump-and-treat options. A pilot test for a pump-and-treat system with air stripping and activated carbon was then conducted. The aquifer tests revealed a high yield aquifer, which would require severe over pumping to create any substantial cone of influence around the pumping wells. Contaminants trapped in the silty-clay lens beneath the site would be difficult to extract in this manner because the transfer rate of contaminants into the groundwater is slow. As a result, large volumes of groundwater would need to be pumped to the surface for treatment, and this water would contain low concentrations of contaminant. Also, neighbors of the property would be disturbed by the noise created by a pump-and-treat system.

Based on these results, a pump-and-treat option would be expensive and inefficient for the Edward Sears site. Site managers then moved to consider a phytoremediation option. This site was judged as a potential candidate for a phytoremediation system due to the nature of the soils and groundwater. There is a highly permeable sand layer about 4 to 5 feet bgs, but below that exists a much-less-permeable layer of sand, silt, and clay from 5 to 18 feet bgs. This silt, sand, and clay layer acts as a semiconfining unit for water and contaminants percolating down toward an unconfined aquifer from 18 to 80 feet bgs. This unconfined aquifer is composed primarily of sand and is highly permeable. The top of the aquifer is about 9 feet bgs, which lies in the less-permeable sand, silt, and clay layer. Most of the contamination is confined from 5 to 18 feet bgs; thus, site managers decided to plant hybrid poplars in order to prevent further migration of the contaminants and ultimately remove contaminants from the groundwater.

Samples were taken from temporary well points throughout the site. Data from these sampling efforts indicated trichloroethylene (TCE) concentrations in the groundwater ranged from 0 to 390 ppb. Most of the TCE was concentrated in a small area on the site. Seven monitoring wells were installed based on the information obtained from the temporary well points. Monitoring Well 1 was installed in the area of highest TCE contamination. Little or undetectable TCE was found in the groundwater samples from the other six wells.

### 6.3.2 Design, Goals, and Monitoring Approaches

Under the Response Engineering and Analytical Contract (REAC), a pilot phytoremediation test was conducted at the Sears site to determine whether hybrid poplar trees can be used to reduce soil and groundwater VOC contamination levels in the planted area and to prevent further offsite migration of contaminated groundwater. In October and November 1996, the site was cleared of debris and a 4-inch clay layer was placed approximately 1 foot bgs to prevent penetration of rainwater into the upper root zone, thus promoting root growth into the underlying aquifer. This was followed by the replacement and grading of the native surface soil.

Thomas Consultants, Inc. of Cincinnati, OH were subcontracted to lay out the phytoremediation design. In December 1996, 118 hybrid poplar saplings (*Populus*

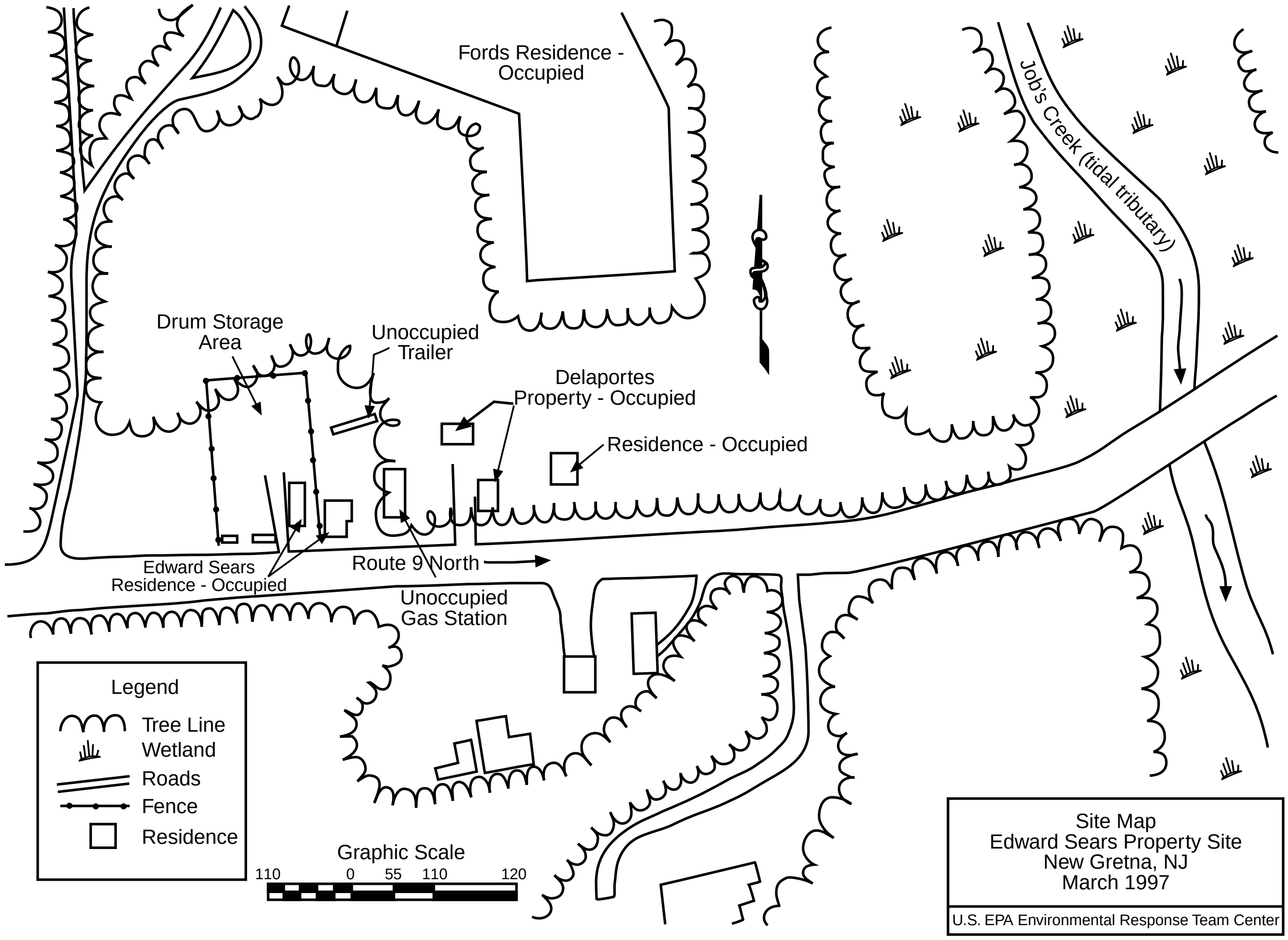


**Figure 6-3.** Site Map

*charkowiieensis x incrassata*, NE 308) were planted by ERT, REAC, and Thomas Consultants personnel in a 1/3-acre plot. The trees were planted 10 feet apart on the axis running from north to south and 12.5 feet apart on the east-west axis.

A process called deep rooting was used to plant the trees. In deep rooting, the roughly 12-foot trees were buried 9 feet so that only about 2 to 3 feet remained on the surface. Deep rooting the trees involved drilling 12-inch-diameter holes to a depth of 13 feet. These holes were then back filled to 5 feet below ground surface with amendments such as peat moss, sand, limestone, and phosphate fertilizer. This backfill was installed to provide nutrients to the roots as they penetrated down through the soils. Waxed cardboard cylinders 12 inches in diameter and 4 feet long were installed above the backfill to promote root growth down into the groundwater. These barriers settled about 1 foot into the planting holes; therefore, 5-gallon buckets with the bottoms cut out were placed on top of the cylinders to create a 5-foot bgs root barrier. The trees were placed in the cylinders and the remaining 5 feet to surface was filled with clays removed during the boring process.

About 90 poplars still remained after the deep rooting was completed. These extra trees were planted along the boundary to the north, west, and east sides of the site. These trees were only planted to a depth of 3 feet, or shallow rooted. The shallow-rooted trees were added to prevent rainwater infiltration from off site and to replace any loss of deep-rooted trees. These trees were planted very close together (about 3 feet apart) under the assumption that natural thinning would take place over subsequent growing seasons. A surface water control system was then installed by planting grasses over the entire site. These grasses came from commercially available seeds purchased from a lawn and garden store.

ERT is conducting an ongoing maintenance and monitoring program at Edward Sears. Monitoring of the site includes periodic sampling of groundwater, soils, soil gas, plant tissue, and evapotranspiration gas. Continued growth

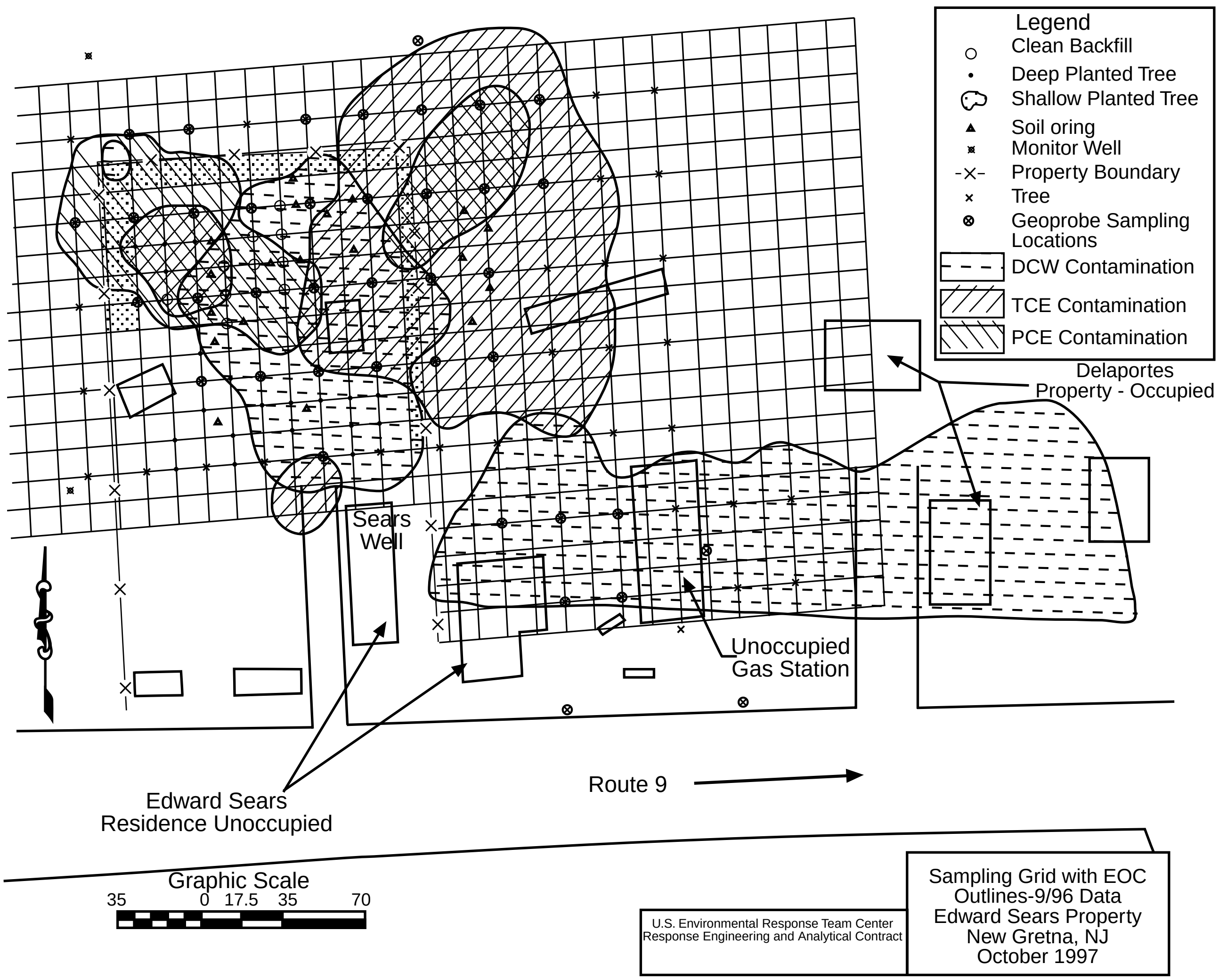


**Figure 6-4.** Sampling Grid

measurements will also be made as the trees mature. In the fall of 1997, the surface water control system was replaced due to a summer drought that killed much of the grass. Site maintenance also involves the prevention of deer and insect damage. Bars of soap were hung from the trees to deter deer from rubbing their antlers on the trees. Some damage was inflicted by an insect larva known as the poplar leaf caterpillar. This caterpillar lives on poplar trees and makes its cocoon by rolling itself in a poplar leaf. A spray containing *Bacillus thuringesis*, a bacteria that produces toxins specific to various insects, was applied to the site. This spray has been effective in killing most of the caterpillars living on the trees.

### 6.3.3 Results and Status

Because the trees had only one full growing season, very little performance data are available; however more data are expected in the next growing season. Evapotranspiration gas was sampled by placing Tedlar™ bags over entire trees. Data from these air samples suggest that the trees are evapotranspirating some of the VOC's. However, the VOC concentration in the Tedlar™ bags matches the background concentrations of VOCs in control samples. This could be due to VOCs volatilizing from the soils, or it could be due to evapotranspirated VOCs that may have gotten into the control samples. Future sampling designs will attempt to determine accurate background VOC concentrations. The trees have grown about 30 inches since planting. Site managers plan to sacrifice one tree either after or during the next growing season to determine the extent of root growth.

### 6.3.4 Costs

The total cost for the installation of 118 deep-rooted and 90 shallow-rooted trees was approximately $25,000. Additionally, installation of the surface water control system and one year of on-site maintenance totaled about $15,000.

### 6.3.5 Contacts

George Prince
US EPA Environmental Response Team
Edison, NJ 00837
(732) 321-6649

## 6.4 Bioengineering Management: U.S. Nuclear Regulatory Commission Beltsville, MD

| | |
|---|---|
| Site name: | Bioengineering Management |
| Location: | U.S. Nuclear Regulatory Commission Beltsville, Maryland |
| Media: | Landfill cover |
| Primary contaminant and maximum concentration: | Cover was installed over a lysimeter |
| Type of plant: | Pfitzer juniper and fescue |
| Area of planting: | 70 m x 45 m test plots |
| Date of planting: | 1987-present |

### 6.4.1 Site Description

Three distinct landfill cover concepts were investigated at the University of Maryland Agricultural Experiment Station, sponsored by the Office of Nuclear Regulatory Research, in Beltsville, MD. The purpose of the full-scale demonstration was to examine and demonstrate various approaches for minimizing water infiltration through landfill covers. The study, initiated in 1987, evaluated the following type of design concepts: resistive layer barrier (compacted clay design), conductive layer barrier (capillary design), and bioengineering management surface barrier (runoff control/evapotranspiration design).

Among the three basic design types in the study, the bioengineering management design demonstrated the greatest potential for preventing water infiltration and for managing subsidence conditions. The bioengineering management surface barrier utilizes the evapotranspiration processes of vegetation and enhancements to runoff to prevent water infiltration to underlying waste. By diverting enough annual precipitation to runoff and by removing moisture from the soil profile using evapotranspiration processes, the design can potentially prevent deep percolation on a yearly basis.

The bioengineering management design is based on a similar cover design applied at Maxey Flats, KY. In the Maxey Flats project, a bioengineered cover was constructed by partially covering fescue grass with an engineered cover of stainless steel that resulted in no measured percolation of water through the cover.

During the Beltsville, MD 9-year study, the bioengineering management surface layer also prevented deep percolation. In addition, this type of design is easily repairable and involves a minimum amount of materials, equipment, and labor for construction. Thus, this system provides a potentially effective approach for addressing damages from active subsidence conditions.

### 6.4.2 Goals

The goal of the project was to assess several landfill cover designs for controlling water infiltration in a humid region. Results of the demonstration could be applicable to various types of disposal materials such as radioactive waste, uranium mill tailings, hazardous waste, and sanitary waste.

### 6.4.3 Design

Cover performance was demonstrated in six large-scale lysimeters with dimensions of 70 ft x 45 ft, a slope grade of 5%, and the bottom of the lysimeters at 10 ft below grade. For each lysimeter, underlying waste conditions were simulated by applying the contents of 55-gallon steel drums one-third filled with gravel and by tilling the remaining area with native soil. Table 6-4 summarizes the design type for each lysimeter.

The bioengineering management surface barrier in Lysimeters 1 and 2 was installed in May 1987. The bioengineering management technique utilizes a combination of engineered enhanced runoff and vegetation to minimize water infiltration. The covers consisted of 4-ft-wide rows of alternative aluminum and fiberglass panels with Pfitzer Junipers planted between the panels at 4-inch widths. The alternating aluminum and fiberglass panels covered over 90% of the surface layer of the cap. Pfitzer Juniper was chosen in part because of its drought-resistant characteristics and the success that the Maxey Flats project encountered using this type of vegetation. The water levels for Plots 1 and 2 were approximately 35 and 75 inches above the bottom of the lysimeters, respectively. The water levels were used to simulate the water table in the flooded disposal cell.

In May 1987, reference Lysimeters 3 and 4 were constructed alongside Lysimeters 1 and 2. The reference lysimeters are similar in design to Plots 1 and 2. However, the cover designs for the reference plots contain only fescue grass; no impermeable cap was installed. Additionally, Plot 4 was discontinued as a reference lysimeter in February 1988 and converted to a rip-rap surface layer and gravel drainage layer over a compacted clay layer cover. The cap design in Lysimeter 5 was a vegetated soil surface layer,

**Table 6-4.** Design Type and Completion Dates for the Experimental Covers.

| Lysimeter | Description of Design | Date of Completed Construction |
|---|---|---|
| 1 | Bioengineering Management | May 1987 |
| 2 | Bioengineering Management | May 1987 |
| 3 | Vegetated Crowned Soil Cover (reference plot) | May 1987 |
| 4 | Vegetated Crowned Soil Cover (reference plot) | May 1987 |
| 4 | Rip-Rap over Resistive Layer Barrier | October 1988 |
| 5 | Resistive Layer over Conductive Layer Barrier | January 1990 |
| 6 | Vegetation over Resistive Layer Barrier | April 1989 |

gravel drainage layer, and compacted clay layer over a gravel capillary barrier. In Plot 6, the cap design consisted of a vegetated surface layer and gravel drainage layer over a compacted clay layer.

### 6.4.4 Monitoring Approaches

For the 9-year study, several water balance parameters were measured, such as annual precipitation and runoff. Additionally, neutron probe measurements of soil moisture in all six lysimeters were taken continuously for 8 years. To increase the accuracy of the measurements, the neutron probe apparatus was calibrated with the native soil used for each of the lysimeters or plots. Instruments were placed between liners to measure leakage at each lysimeter. Four liners were used in each plot to create a closed system for a complete water balance system.

### 6.4.5 Results and Status

During the 9-year period (1988-1996), the bioengineered covers in Lysimeters 1 and 2 experienced no deep percolation. Additionally, the water tables for both plots were eliminated by July 1989. Table 6-5 illustrates the percentage of rainfall managed by runoff, evapotranspiration, and deep percolation at the two bioengineering management surface barriers. The percent of precipitation associated with evapotranspiration increased annually because of the greater vegetative canopy.

The moisture content of the soil profiles for Lysimeters 1 and 2 decreased annually. Thus, after the water table was eliminated from both lysimeters, the soil profiles continually "dried out." However, the soil moisture content for both lysimeters, although much lower in the soil profile than at the beginning of the study, still increased with depth. In addition, seasonal cyclical variations in moisture content occurred throughout the study. For example, high moisture peaks in the soil profile were observed during high incidents of rainfall events and periods of low evapotranspiration.

A majority of precipitation for reference Lysimeters 3 and 4, with only fescue grass, was managed by evapotranspiration. However, this process was not adequate to prevent the rise of the water table. Subsequently, both lysimeters were pumped to prevent the water from overflowing. As a result, a rip-rap surface layer cover was installed on Lysimeter 4 in February 1988. Lysimeter 3 continued as a reference plot throughout the study, although results continuously indicated deep percolation. For example, deep percolation accounted for 40% of the fate of total precipitation during 1993-1994.

The bioengineering management surface barrier has been implemented at two sites in Hawaii and New York. At the Marine Corps Base in Kaneohe Bay, Hawaii, a 14-month study was conducted to demonstrate diversion and removal of annual precipitation by runoff control and evapotranspiration. The Kaneohe Bay study evaluated two types of designs: 20% enhancement of runoff and 40% enhancement of runoff, along with a conventional soil cover design. The covers with the runoff enhancements used rain gutters and several native types of vegetation such as grasses and shrubs (primarily of the genera Acacia and Panicum). Results of the study demonstrated that the two design types increased runoff by a factor of 2 to 3 over the conventional soil design cover. Additionally, the data indicated a reduction in percolation by a factor of 2 to 3 from the two infiltration control covers over the soil cover, although these differences were not statistically significant. Finally, statistical tests indicated no advantage of using the 40% enhancement of runoff over the 20% enhancement of runoff: both produced the same amount of runoff and percolation.

In 1993, the New York State Energy Research and Development Authority implemented a bioengineering management system at a low-level waste facility in West Valley, NY. The bioengineered cover was only installed over one trench at the site, 550 ft x 35 ft, for a total cost of $70,000. Soil moisture and trench leachate data have shown no vertical infiltration to date.

**Table 6-5.** Summary of Run-off, Evapotranspiration, and Deep Percolation From the Bioengineered Plots.

| Year | Runoff | Evapotranspiration | Deep Percolation |
|---|---|---|---|
| | | Percent of Precipitation | |
| 1988 | 80 | 20 | 0 |
| 1989 | 74 | 26 | 0 |
| 1990 | 70 | 30 | 0 |
| 1991 | 67 | 33 | 0 |
| 1992 | 63 | 37 | 0 |
| 1993 | 61 | 39 | 0 |
| 1994 | 61 | 39 | 0 |
| 1995 | 58 | 39 | 0 |
| 1996 | 57 | 43 | 0 |

### 6.4.6 Contacts

Edward O' Donnell
NRC Project Manager
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
(301) 415-6265

## 6.5 Lakeside Reclamation Landfill Beaverton, Oregon

| | |
|---|---|
| Site name: | Lakeside Reclamation Landfill |
| Location: | Beaverton, Oregon |
| Media: | Landfill Cover |
| Primary contaminant and maximum concentration: | NA |
| Type of plant: | Hybrid Poplars and Rye Grass |
| Area of planting: | 8 acres |
| Date of planting: | 1990-present |

### 6.5.1 Site Description

The Lakeside Reclamation Landfill (LRL), located near Beaverton, OR, is actively receiving nonrecyclable construction demolition debris for disposal on the 60-acre site. As the waste cells fill to capacity, the owner/operator of the landfill is required to install covers to fulfill final closure requirements. In April 1990, a 0.6-acre prototype cap consisting of hybrid poplar trees, primarily cottonwoods, was installed on a recently filled waste cell. The demonstration cover was an alternative to using a conventional cover consisting of a geosynthetic membrane and several soil layers. The objective of the initial project was to demonstrate the application of hybrid poplar trees to effectively prevent infiltration of water to underlying waste. The prototype plot was designed to provide the data required to meet regulatory compliance and to provide enough information to close the entire landfill using this capping technique. The migration of contaminated leachate is a concern to the Oregon Department of Environmental Quality (DEQ) because the Tualatin River is located adjacent to the LRL.

The waste buried at Lakeside Reclamation Landfill is restricted primarily to construction demolition debris, tree stumps, yard wastes, and packaging and crating materials. The contaminants of concern are metals, nitrates, and phosphorous leachate.

Based on the results of the initial prototype cap, the demonstration was expanded to a 2-acre area in 1991. To date, the cap has expanded to a total of 8 acres and has demonstrated no deep percolation. For the final closure of the landfill, the vegetative cover will enclose an area of approximately 40 acres at the Lakeside Reclamation Landfill.

For the LRL landfill, the Oregon DEQ has issued a permit for final closure requirements under Condition 3 of Schedule C, Solid Waste Disposal Permit No. 214. The final cover must meet or exceed the mandatory minimum groundwater quality protection requirements.

### 6.5.2 Goals

The goal of the initial project was to demonstrate an effective cover design for preventing water infiltration and acquire enough data from the prototype cap to satisfy the Oregon DEQ. Concurrently, the project must meet or exceed the regulatory requirements for groundwater quality protection and establish a capping technique for the entire landfill. Other objectives of installing this cover design were to provide a low-cost manageable cover that provides a wildlife habitat, stable soils, and a sustainable ecosystem.

### 6.5.3 Design

The cover design for the prototype cap is composed of hybrid poplars (primarily cottonwood trees) and silt loam soils. The waste cells of the landfill were initially covered with two layers of silty loam soil at a thickness of roughly 5 ft and graded at a 3% slope. The layer installed over the waste is approximately 1 ft of compacted silt loam soil that has a high-clay content. The surface layer consists of loosely placed loam soil at a depth of 4 ft.

The hybrid poplar tree cuttings and cool-season grasses were selected as the type of vegetation to be planted on the initial demonstration cell cover. Hybrid poplars were selected primarily because of the research being conducted at the University of Iowa using these trees for buffer systems. Secondly, the landfill borders the Tualatin River riparian area populated by both deciduous and conifer trees, thus providing evidence that the site is capable of growing hybrid poplars. Thirdly, the hybrid poplars had a relatively long growing season, extending from mid-March through November. Finally, hybrid poplars offered the potential for dense tree population, deep root placement, and large quantities of water to be transpired per tree.

In April 1990, approximately 7,455 tree cuttings were planted on the 0.6-acre site (60 ft x 600 ft), for an average plant density of 3.4 $ft^2$ per tree. The rows are 42 inches apart with roughly 1 ft of spacing between the trees in each row. Three different hybrid poplar varieties were planted in the prototype cover: DO-1 variety trees from Dula Nurseries, Canby, OR; Imperial Carolina variety from Ecolotree, Inc., Iowa City, IA; and NE-19 variety from Hramoor Nurseries, Manistee, MI. All tree varieties were available in 5-ft cutting lengths and were planted at a depth of 40 inches. The Imperial Carolina and DO-1 variety were also available in 2-ft cutting lengths and planted at 15-inch depths. No soil stabilizers, fertilizers, or pre-emergent weed herbicides were used to plant the tree cuttings.

The area of the demonstration was expanded by an additional 1.3 acres in 1991 and a new planting density of 5.2 $ft^2$ per tree. To diversify the cultivar base, 18 new tree varieties were planted. The new tree cuttings planted were composed of varieties that had the capability to grow in the Pacific Northwest region. For the 1992 growing season, a cool-season grass crop, rye grass, had been established on a portion of the demonstration site. The addition of grasses to the design improved the cover by increasing the evapotranspiration process during the tree's dormant period, controlling weed growth, and increasing the overall soil stability during the early periods of tree development. In addition, as an alternative to grass, another portion of the cover was mulched with bark chips.

### 6.5.4 Monitoring Approaches

Lysimeters, piezometers, and tensiometers were installed in May 1990 to collect water samples and measure moisture content in the soil cover. Four instrument “nests” were placed on the landfill cover. Each instrument nest contained three suction lysimeters and three ceramic cup tensiometers installed at 1-, 3-, and 5-ft depths. Another instrument nest was installed off the prototype cap to provide background measurements.

### 6.5.5 Results and Status

The survival rate for the hybrid poplar trees planted in April 1990 was greater than 85% and there were no observed losses for the 1991 growing season. The survival rates for the Imperial Carolina tree variety and the DO-1 tree variety were greater than 90%. However, the NE-19 variety had only a 54% survival rate. The low survival rate was likely due to a December freeze that damaged the cuttings. Despite this relatively low survival rate, the NE-19 variety is desirable to plant because of its longer growing season. The base diameter of the tree stem and terminal bud height was measured to estimate tree growth and vigor. The extent of tree growth was illustrated by comparing measurements in August 1990 to those in March 1992, which demonstrated a mean height of 6.8 ft and 12.7 ft, respectively.

Weekly tensiometer data were collected to determine the moisture content of soils at various locations both on and off the 0.6 acre cover. The moisture content is described in general terms, "wet" or "dry." The tensiometers were not calibrated to the variable soil conditions because of the mixture of repacked soils in the landfill material. From September to December 1990, the tensiometer indicated moisture content, at the 1-ft horizon, fluctuated considerably from saturated to very dry depending on precipitation, solar intensity, air temperature, relative humidity, ground cover, and shade at the soil surface. In addition, during the growing season, there was no apparent impact on the tensiometer reading at the 3- and 5-ft depths, implying no change in the moisture content. Significantly less water was present at the 5-ft soil profile in 1991, than in 1990. In addition, moisture content observed in December 1991 indicated the soil profile had more storage capacity available than was available in measurements taken the previous year.

Samples of the soil water were acquired through suction lysimeters as part of the instrumental nest monitoring. Only one set of samples was screened in May 1990 for nutrients. Nitrate concentrations in this set of lysimeter samples did not measure above the EPA's Maximum Contaminant Level (MCL).

During 1993 and 1994, the Oregon Graduate Institute of Science and Technology conducted a field experiment at LRL to investigate leachate production potential under a grass cap and a hybrid poplar cap. The soil moisture was monitored in 25 wells (20 in the hybrid poplar plot and 5 in the grass plot) using a neutron probe and later a capacitance probe. The depths of the wells varied from 32.5 to 59 inches. Annual precipitation was 37 inches for 1993 and 59 inches for 1994. In general, the results of the 2-year study indicate that the average soil moisture under the grass cover was higher than that under the hybrid poplar cover. Additionally, the vertical soil moisture profile study revealed that soil moisture varied less under the poplar trees than under the grasses.

Currently, the cap has been expanded to 8 acres and consists of 25 varieties of hybrid poplars (cottonwoods). The diversity in tree species prevents a single disease from destroying the entire tree population and allows for a broader growing season for the cap. In addition, another 25 varieties of hybrid poplars are being evaluated in a greenhouse at LRL for incorporation into the cap. To date, monitoring data has indicated that moisture has only penetrated to a maximum depth of 4 feet.

### *6.5.6 Contacts*

Howard Grabhorn
Owner/Operator
Lakeside Reclamation, Grabhorn, Inc.
Beaverton, OR 97006
(503) 628-1866

Wesley M. Jarrell
Professor
Oregon Graduate Institute of Science & Technology
P.O. Box 9100
Portland, OR 97291
(503) 690-1183

Louis A. Licht
President
Ecolotree, Inc.
102A Oakdale Hall
Iowa City, IA 52319
(319) 358-9753

Mark F. Madison
Agricultural Engineer
CH2M Hill
Portland, OR
(503) 235-5002 Ext. 4453

## 6.6 Alternative Landfill Cover Demonstration Laboratories Sandia National Albuquerque, NM

| | |
|---|---|
| Site name: | Alternative Landfill Cover Demonstration |
| Location: | Sandia National Laboratories<br>Albuquerque, New Mexico |
| Media: | Landfill Cover |
| Primary contaminant and maximum concentration: | Covers were installed over lysimeters with no waste or contaminants |
| Type of plant: | Wheat Grass, Indian Ricegrass, Alkali Sacaton, Sand Dropseed and Four-Wing Saltbrush |
| Area of planting: | 10 m X 10 m test plots |
| Date of planting: | 1995-1996 |

### *6.6.1 Site Description*

The Alternative Landfill Cover Demonstration (ALCD) is a large-scale field test comparing final landfill cover designs at Sandia National Laboratories, located on Kirtland Air Force Base in Albuquerque, New Mexico. The demonstration is testing innovative landfill covers using currently accepted EPA cover designs as baselines. Two conventional and four alternative cover designs were constructed in 1995 and 1996 and are currently being monitored. The two traditional cover designs are a RCRA Subtitle D Soil Cover and a RCRA Subtitle C Compacted Clay Cover, and the four alternatives are Geosynthetic Clay Cover, Capillary Barrier, Anisotropic Barrier, and Evapotranspiration Cover. Of the four alternatives, the Evapotranspiration Cover utilizes vegetation, along with soil texture and depth, as the primary mechanism to minimize infiltration of water into underlying waste. To a lesser degree, the Capillary Barrier and the Anisotropic Barrier are also designed to enhance evapotranspiration using vegetation and encourage water storage for the prevention of water infiltration. In addition, the ALCD includes a side study to assess eight different enhancement techniques to the vegetation planted on several of the covers.

### *6.6.2 Goals*

The purpose of the demonstration is to evaluate the various cover designs based on their respective water balance performance, reliability and ease of construction, and cost for arid and semiarid environments. Also, the data from the demonstration will be available for validation of EPA's HELP (Hydrologic Evaluation of Landfill Performance) model.

### *6.6.3 Design*

All of the test covers are installed and instrumented in a side-by-side demonstration. Each of the plots are 100 m x 13 m, crowned in the middle with a constructed 5% slope for each layer. Hence, the slope lengths are 50 m each and sloping to the west and east. The western slope of each cover is monitored under ambient or passive conditions. For the eastern slope, a sprinkler system is utilized to facilitate additional precipitation to the test plots, providing hydrological stress to the various covers. This system represents peak or worse case precipitation events.

The two conventional cover designs were installed to provide a baseline for comparison among the four alternatives. The Soil Cover design satisfies the minimum requirements set forth for

RCRA Subtitle D landfills, which are typically municipal solid waste landfills. The second baseline cover is a Compacted Clay Cover designed to meet the RCRA Subtitle C requirements for hazardous waste landfills. Among the four alternative cover designs, the Geosynthetic Clay Cover is the most similar in design and function to the traditional compacted clay cover. The Geosynthetic Clay Cover design is identical to the compacted clay cover except for the clay barrier layer which consists of a manufactured sheet, a geosynthetic clay liner (GCL).

The Evapotranspiration (ET) Cover consists of a single, vegetative soil layer constructed with an optimum mix of soil texture, soil thickness, and vegetation cover. The cover is engineered to increase water storage and enhance evapotranspiration to minimize the infiltration of water. The design of the cover was based on the results of a computer model and the climate conditions of the area. The Albuquerque climate is an arid/semiarid environment with average annual rainfall of 20.6 cm/yr. Based on the results, a 90-cm-thick monolithic soil cap was installed. The origin of soil was from on-site cut excavations. The bottom 75 cm was placed in 15-cm-deep lifts and compacted, while the top 15 cm was loosely placed topsoil. The type of vegetation used in the design was based on the premise of extending the evapotranspiration process of the plants over as much of the growing season as possible. Therefore, the vegetation consisted of an optimum mixture of species (such as grasses, shrubs, or trees) and an optimum blend of cool and warm weather plants. The vegetation drill-seeded for the cover was composed of native species, primarily grasses such as crested wheat grass, Indian ricegrass, alkali sacaton, sand dropseed, and four-wing saltbrush.

A side study was established to assess enhancements to induce the growth of vegetation seeded on the ET Cover. Twenty-four 10-m x 10-m test plots were installed alongside the cover. Accordingly, there are three sets of eight different surface augmentations for statistical analysis. Soil moisture is being sampled at a depth of 1.2 m to evaluate the effect of the surface enhancements on evapotranspiration.

The Capillary Barrier is designed to use the difference in hydraulic conductivity of the two soil layers under unsaturated flow conditions to cause water to be retained in the upper soil layer. The cover design of this capillary barrier was composed of four primary layers: surface layer, upper drainage layer, barrier layer, and lower drainage layer. In general, the cover design consisted of the barrier layer and lower drainage layer forming the capillary barrier. The upper drainage layer, composed of pea-gravel and sand, served as both a filter to prevent clogging and allowed for lateral water movement. The surface layer, 30 cm of topsoil, is placed to provide a medium for growth of vegetation and enhance evapotranspiration. It also protects the barrier soil layer from desiccation and protects against surface erosion.

The Anisotropic Barrier is composed of layered capillary barriers that function to limit downward movement of water while enhancing lateral movement. The cover design consists of four layers: top vegetation layer, soil layer, interface layer, and sublayer. The top vegetation layer is 15 cm thick and is composed of topsoil and pea gravel (gravel to soil mixture is 25% by weight). The vegetation is for encouraging the evapotranspiration processes of the vegetation, while the pea gravel is primarily for minimizing erosion effects. The soil layer is 60 cm of native soil and functions for water storage and a rooting medium for vegetation. The interface layer serves as a drainage layer to laterally divert water that has infiltrated the soil layer. Both the interface layer and sublayer function as bio-barriers to prevent roots and burrowing animals from intruding into the underlying material.

### *6.6.4 Monitoring Approaches*

Continuous water balance and meteorological data are being collected for all six covers. In addition, periodic measurements are being taken to produce data on vegetation. Continuous water balance data include soil moisture status, soil temperature, runoff and erosion, and percolation and interflow. At a weather station installed at the ALCD site, meteorological data is being collected for the following parameters: precipitation, air temperature, relative humidity, wind speed and direction, and solar radiation. Finally, several attributes of vegetation are being measured seasonally, such as biomass, leaf area index, and species composition.

### *6.6.5 Results and Status*

Monitoring data will be collected for a minimum of 5 years after construction of the covers. Additionally, the data will be made available on a yearly basis. Table 6-6 displays the results from the first year of collecting data for the six cover designs (May 1997 through March 1998).

**Table 6-6.** Summary of Percolation and Precipitation Rates From May 1997 Through March 1998 for the Six Cover Designs.

| Description | Percolation (L) | Precipitation (L) | Percolation/ Precipitation (%) |
|---|---|---|---|
| RCRA Subtitle D Soil Cover | 6,724 | 380,380 | 1.77 |
| RCRA Subtitle C Compacted Clay Cover | 46 | 380,380 | 0.01 |
| Geosynthetic Clay Liner Cover | 572 | 380,380 | 0.15 |
| Evapotranspiration Cover | 80 | 380,380 | 0.02 |
| Capillary Barrier | 804 | 380,380 | 0.21 |
| Anisotropic Barrier | 63 | 380,380 | 0.02 |

According to Stephen Dwyer, the site manager, the amount of percolation through the Capillary Barrier can be attributed to the initial design of the cap. The fine layer of the cover was installed below the surface to protect against desiccation, freeze-thaw cycles, etc. Unfortunately, this design specification does not allow for maximum enhancement of evapotranspiration processes. This concept is further illustrated by the Anisotropic Barrier, designed with the fine layer at the surface, which seems to be performing adequately to date.

### *6.6.6 Costs*

The individual construction cost for each cover is presented in Table 6-7. These values only represent construction costs and do not include instrumentation equipment, monitoring provisions, or other items associated with cover testing.

### *6.6.7 Contact*

Stephen F. Dwyer
Sandia National Laboratories (MS 0719)
P.O. Box 5800
Albuquerque, NM 87185
(505)844-0595

**Table 6.7** Construction Costs for the Final Landfill Covers

| Description | Cost ($/ m$^2$) |
|---|---|
| RCRA Subtitle D Soil Cover | 52.42 |
| RCRA Subtitle C Compacted Clay Cover | 157.58 |
| Geosynthetic Clay Liner Cover | 92.89 |
| Evapotranspiration Cover | 72.66 |
| Capillary Barrier | 96.45 |
| Anisotropic Barrier | 74.92 |

# Appendix A
# Glossary

**Accumulation coefficient**: The ratio of a contaminant concentration in biomass to the contaminant concentration in soil.

**Alpine pennycress (*Thlaspi caerulescens*):** A potentially useful, but slow-growing and low- biomass hyperaccumulator plant.

**Application(s):** Something that is done by a phytoremediation technology; e.g., remediation of TCE in groundwater.

**Bioaccumulation coefficient**: The ratio of metal concentration in the plant ( g metal/g dry weight tissue) to the initial solution concentration of the metal (mg metal/L), for rhizofiltration of metals (Salt et al. 1995).

**Bioconcentration factor ($B_v$)**: The concentration in aboveground plant parts (on a dry-weight basis) divided by the concentration in the soil for organic compounds (Paterson et al. 1990).

**Biogeochemical prospecting:** Exploration for mineral deposits through analysis of metal concentrations in plants that might indicate underlying ore bodies.

**Constructed wetlands:** Artificial or engineered wetlands used to remediate surface water or waste water.

**Eastern cottonwood (Poplar) (*Populus deltoides*):** A widely studied tree with potential for hydraulic control, phytodegradation, and phytovolatilization.

**Ecosystem restoration:** "The process of intentionally altering a site to establish a defined, indigenous ecosystem. The goal of this process is to emulate the structure, function, diversity, and dynamics of the specified ecosystem." (Parks Canada. http://parkscanada.pch.gc.ca/natress).

**Evapotranspiration cap (or cover):** A cap composed of soil and plants, engineered to maximize evaporation and transpiration processes of plants and the available storage capacity of soil to minimize infiltration of water. Synonym: Water-balance Cover

**Fibrous root:** A root system that has numerous fine roots dispersed throughout the soil.

**Forensic ecology:** Investigation of a site to determine the history and causes of the current flora and fauna.

**Forensic phytoremediation**: Investigation of a naturally-revegetated site to establish that remediation has occurred or has begun to occur.

**Geobotanical prospecting:** The visual study of plants as indicators of the underlying hydrogeologic and geologic conditions.

**Geobotany**: The use of plants to investigate the underlying geology, especially related to metal ores.

**Halophyte:** A salt-resistant-plant; one that will grow in saline soil. Salt cedar is an example.

**Humification/fixation**: The incorporation of contaminants into biomass in soil.

**Hydrologic control:** The use of plants to rapidly uptake large volumes of water to contain or control the migration of subsurface water. Synonym: Phytohydraulics.

**Hyperaccumulators**: Metallophytes that accumulate an exceptionally high level of a metal, to a specified concentration or to a specified multiple of the concentration found in other nearby plants. Alpine pennycress is an example.

**Indian mustard (*Brassica juncea*):** A potentially useful and relatively high biomass hyperaccumulator plant that can accumulate metals and radionuclides.

**Indicator plants:** Plants with a metal concentration in the aboveground biomass that reflects the soil concentration of the metal. Bladder campion is an example.

**Land reclamation:** The revegetation of eroded or nonvegetated land to decrease erosion of the soil or to increase the beneficial uses of the soil.

**Metal-tolerant plants:** Plants that can grow in metal-rich soils without accumulating the metals.

**Metallophytes:** Plants that can only grow in metal-rich soils.

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

**Phytoaccumulation**: The uptake and concentration of contaminants (metals or organics) within the roots or aboveground portion of plants.

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

**Phytoextraction**: The uptake of contaminants by plant roots and translocation into the aboveground portion of the plants, where it is generally removed by harvesting the plants. This technology is most often applied to metal-contaminated soil or water. See also: Phytoaccumulation.

**Phytoextraction coefficient**: The ratio of metal concentration in the plant ( g metal/g dry weight tissue) to the initial soil concentration of the metal ( g metal/g dry weight soil), for phytoextraction of metals (Nanda Kumar et al. 1995).

**Phytoinvestigation:** The examination of plants at a site for information about contaminant presence, distribution, and concentration.

**Phytoremediation:** The direct use of living green plants for in situ risk reduction for contaminated soil, sludges, sediments, and groundwater, through contaminant removal, degradation, or containment. Synonyms: Green remediation, Botano-remediation.

**Phytoremediation cap (or cover):** A cap consisting of soil and plants, designed to minimize infiltration of water and to aid in the degradation of underlying waste.

**Phytoremediation natural attenuation**: Intrinsic bioremediation processes (in soil or groundwater) enhanced by the presence of naturally-occurring plants.

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

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

**Process, mechanism:** Something that a plant does; e.g., uptake, transpiration.

**Rhizodegradation**: The breakdown of a contaminant in soil through microbial activity that is enhanced by the presence of the root zone. Synonyms: Plant-assisted degradation, Plant-assisted bioremediation, Plant-aided in situ biodegradation, Enhanced rhizosphere biodegradation.

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

**Rhizosphere:** The zone around plant roots that has significantly higher microbial numbers and activity than in the bulk soil.

**Root concentration factor (RCF):** The concentration in the roots divided by concentration in external solution, for non-ionized organic compounds taken up by plants with nonwoody stems (Ryan et al. 1988; Paterson et al. 1990).

**Root exudates:** Chemical compounds such as sugars or amino acids or that are released by roots.

**Stem concentration factor (SCF):** The concentration in the stem divided by the concentration in the external solution, for non-ionized organic compounds (Ryan et al. 1988; Paterson et al. 1990).

**System:** The overall picture; e.g., a constructed field plot that uses mechanisms within technologies for a particular application.

**Tap root:** A root system that has one main root.

**Technology:** A combination of processes and mechanisms; e.g., phytoextraction, rhizodegradation (BP uses and favors this terms).

**Transpiration stream concentration factor (TSCF):** The concentration in the transpiration stream divided by the concentration in the external solution, for organic compounds (Paterson et al. 1990).

**Vegetative cap (or cover):** A long-term, self-sustaining cap of plants growing in and/or over materials that pose environmental risk; a vegetative cover reduces that risk to an acceptable level and requires minimal maintenance. Two specialized types of vegetative caps are the Evapotranspiration Cap and the Phytoremediation Cap.

**Vegetative soil stabilization:** The holding together of soil by plant roots to decrease wind or water erosion or dispersion of soil.

# Appendix B
# Phytoremediation Database

| Project Name/ Location | Size of Area | Primary Contaminant | Media and Properties | Vegetative Type | Date Planted |
|---|---|---|---|---|---|
| Aberdeen Pesticide Dumps Site - NC | 7 acres | VOCs, Pesticides/ Herbicides | Groundwater | Hybrid Poplar and ground cover grasses | |
| Aberdeen Proving Grounds J - Field Toxic Pits Site - MD | 1 acre | Halogenated Volatiles | Soil and groundwater | Hybrid Poplar | March 1996 |
| ACME landfill - NC | | | Groundwater | Poplar | |
| AGI - WA | ~ 2 acres (proposed) | Phenols | Surface water | Wetland plants | Not planted yet |
| Agricultural Cooperative - WI | ~ 0.3 acres | Pesticides, herbicides; VOCs | Soil and groundwater | Hybrid poplar | May 1996 |
| Agricultural Cooperative - WI | 0.9 acres | Ammonia | Soil | Hybrid poplar and grass | June 1997 |
| Aluminum Manufacturing Facility - SC | 6 acres | Heavy metals | Soil and groundwater; sandy clay | Hybrid poplar | May 1992 |
| Aluminum Processing Facility - NV | 6 acres | Saline wastewater from cooling tower | Dune sand | Hybrid willows | May 1997 |
| Amargosa Desert Research | | Radionuclides | | | |
| Amarillo - TX | | | | | |
| Amboer Road - OR | ~ 5 acres | Chlorinated Solvents | Groundwater and soil | Hybrid and native poplar | April 1999 |
| Anderson - SC | 17 acres | Heavy Metals | Groundwater and soil | Hybrid poplar, Grasses | 1993 |
| Annette Island Site - AK | Each plot 100 square ft. | Semi-volatile Petroleum Products | Native soil | Fescue;, ryegrass, and clover | Summer 1998 |
| Anonymous - KS | ~ 100 acres | TPH | | Cottonwood, hybrid poplar | Spring 1998 |
| Army Ammunition Plant - IL | | | | | |
| Artemont, CA | | Municipal and hazardous waste | | Various trees | |
| DOE Facility - OH | | Uranium, cesium, strontium | Groundwater and wastewater | Sunflowers | November 1997 |
| Barje Landfill - Slovenia | 10 acre | Other, Heavy Metals | Subsurface soil | Hybrid poplar | 1993, 1994 |

| Project Name/ Location | Size of Area | Primary Contaminant | Media and Properties | Vegetative Type | Date Planted |
|---|---|---|---|---|---|
| Barrow Site - AK | Each plot is ~ 120 square ft. | VOCs and Semi-volatiles | Soil. Soils marine beach | Mix of grasses and legumes planned for spring 1999 | Spring 1999 |
| Bayonne - NJ | 1,000 square ft. | Heavy metals | Soil to 15 cm bgs | Indian Mustard | Spring 1997 |
| Beltsville, MD | 70' x 45' x 10' | Radioactive - low level waste | | Pfitzers junipers | 1987 |
| Bluestem Landfill #1 - IA | 3 acres | Leachate | Subsurface soil | Hybrid poplar and grass | 1994 |
| Bluestem Landfill #2 - IA | 5 acres (2 test plots) | | Subsurface soil | Hybrid poplar and grass | 1994 |
| Bofors-Nobel - MI | | Pesticides, herbicides, dyes | Soil, sediments | Trees and wetland plants | Spring 1999 |
| British Steel - South Wales, UK | 18 hectares | Coke oven effluent | Effluent | Soil based reed bed | |
| Bunker Hill - ID | 1,050 acres | Heavy metals | Soil | Mix of herbaceous species | 1998-2001 |
| C-H Plant Area - TX | 27 acres | Salt, metals (possible radionuclides | Groundwater | Trees | Planned 1999 |
| Calhoun Park - SC | 0.5 acre | Non-halogenated Semi-volatiles | Ground 1 to 5' bgs | Native trees and shrubs | |
| Campion Site - AK | Each plot is ~ 375 square ft. | Volatile and Semi-volatile Petroleum Products | Soils will be more fully characterized fall 1998 | Mix of grasses and legumes | Summer 1998 |
| Cantrall - IL | 1-3 acres | Pesticides/Herbicides | Soil and groundwater | Hybrid poplars | 1992 |
| Carswell AFB (former) - TX | 1 acre | Halogenated volatiles | Groundwater | Eastern Cottonwood | April 1996 |
| Brookhaven National Labs - NY | ~ 1/4 acre | Radionuclides | Landscaping soils to ~ 6 inches in depth. | Redroot Pigweed | May 1998 |
| Chernobyl - Ukraine | | Radionuclides | Soil, groundwater, water | Sunflowers, Indian Mustard | |
| Chevron Facility No. 129-0334 - UT | | Volatile petroleum products | Groundwater | Hybrid poplar trees (DN 34) | April 1996 |
| Chevron Site - CA | 30 acres, 90 acres | Volatile petroleum products | Soil at root level, groundwater, wastewater | Fescue, Cowpeas, cattails | |
| Chevron Station No. 7-7992 - CO | 300 x 15 ft. area (120 poplar trees) | Volatile petroleum products | Groundwater | Hybrid poplar trees | April 1995 |
| Childerburg - AL | | Explosives | Soil at root level | Parrot Feather | |
| City of Glendale Landfill - AZ | 1 acre (2 test covers) | | Silty sand soils | Ryegrass, Bermuda grass | |
| City of Madras WWTP Reuse - OR | 1257.5 acres | Wastewater; nitrogen; phosphorus | | Turf grass | Already planted |
| WWTP Sludge Lagoon - OR | 4,200 acres | Heavy metals, PCB's | Old sewage sludge applied to grazing land | | 1990 |
| Natural Treatment System (NTS) - OR | | Land-applied wastewater | Wastewater | Poplars | |
| City of Woodburn WWTP - OR | 7 acres | Other (Wastewater reuse) | Soil | Hybrid Poplar | 1995 |

| Project Name/ Location | Size of Area | Primary Contaminant | Media and Properties | Vegetative Type | Date Planted |
|---|---|---|---|---|---|
| Closed Disposal Facility - IL | 26 acres | Petroleum Hydrocarbons | Surface water | Groundcover plants in combination with phreatophyte trees | |
| Closed Terminal - RI | ~ 1 acre | PAHs | Surface soils | Indigenous plants/ trees | |
| Coffin Butte Landfill - OR | 14.4 acre overland polishing system | Landfill leachate | Leachate | Grass, hay, and native trees | Existing |
| Columbus - OH | 1 acre | Volatile petroleum Hydrocarbons | Soil | Hybrid poplars; ground cover | 1997 |
| Corvallis - OR | | | | | |
| Craney Island Fuel Terminal - VA | ~ 180' x 100' (4 plots with replicates | TPH, PAHs | Soil | Fescue, rye, clover | |
| Dearing (Cherokee County) - KS | 1 acre | Heavy metals | Soil | Hybrid poplars | March 1995 |
| Chevron Bulk Facility 100-1838 - OR | 0.6 acres planted with grass | Volatile petroleum products | Surface soil | Tall fescue | April 1995 |
| Delaware Solid Waste Authority - DE | | | | | |
| Diashowa Paper Mill - WA | | Fuel Hydrocarbons | Soil | Variety of grasses and clovers. | |
| Dieners - CA | 5 hectares | Heavy metals | Soil, groundwater and effluent are affected | Brassica sp. | 1995 |
| Dorchester - MA | ~ 1,200 square ft. | Lead | Soil | Indian Mustard | June 1997 |
| Eagle Flat - TX | | Radionuclides - Low level waste | | Semiarid prairie | |
| East Ravendale - Yorkshire, UK | 240 square miles | BOD, suspended solids | WWTP Effluent | Soil based reed bed | 1991 |
| Edward Sears Site (Superfund) - NJ | 1/3 acre, 0.5 acre | Halogenated volatile petroleum products | Soil and groundwater | Hybrid poplar, willow | December 1996 |
| Farm Service Facility - MN | 0.4 acres | Ammonia | Soil | Hybrid poplar and grass | May 18, 1998 |
| Farmer's Loop Site - AK | Multiple plots, each ~ 10' x 10', 2-3' deep | Semi-volatile petroleum products | Soil | Ryegrass and red fescue | Summer 1995 |
| Fertilizer Plant Site - SD | | Nitrogen | Soil and groundwater | Hybrid poplars | May 1996 |
| Fly ash Landfill Covercap - MO | 6 acres | | | Hybrid poplars | |
| Fly ash Landfill - MO | | Fly ash | | Hybrid poplars | |
| Forest Grove WWTP - OR | 5 acres | | Soil | Hybrid poplar and grass | May 1994 |
| Chevron Terminal No. 129-0350 - UT | ~ 5 acres | Volatile petroleum products | Groundwater and vadose zone are contaminated | Hybrid poplars, fescue, alfalfa | |
| Former Farm Market - WI | 1 acre | Pesticides, nitrates, and ammonium | Soil, groundwater | Hybrid poplars | Spring 1992 |
| Former Farm Market - IL | 1 acre | Pesticides, nitrates, and ammonium | Silt loam with clay | Hybrid poplars | Spring 1992 |

| Project Name/ Location | Size of Area | Primary Contaminant | Media and Properties | Vegetative Type | Date Planted |
|---|---|---|---|---|---|
| Former Farm Market - SC | 1 acre | High salt concentrations | Surface soil | Various trees and grasses | Spring 1993 |
| Former Farm Market - IL | 1 acre | Pesticides, nitrates, ammonium | Silt loam soils | Hybrid poplars | Spring 1992 |
| Former Fertilizer Facility - OK | 4 acres | Nitrates and ammonium | Soil and groundwater | Prairie grasses | Irrigation est. 1990 |
| Former Fertilizer Facility - NC | 1 acre | Ammonium and nitrate nitrogen | Groundwater | Hybrid poplar | Spring 1992 |
| Former Fertilizer Facility - NJ | 1 acre | Ammonium and nitrate nitrogen | Soil and groundwater | Hybrid poplar and Australian willows | Fall 1992; spring 1992; spring 1994 |
| Former Municipal Landfill - NY | 3 acres border area | Heavy metals | Groundwater | Hybrid poplars | June-July 1998 |
| Petroleum Processing Facility - PA | 2 acres | TPH in fill soil; BTEX | Ash and cinder with soil fill | Hybrid poplar and hybrid willows | June 1996 |
| Standard Oil Facility No. 100-1348 - WA | 5 acres | Volatile petroleum products | Perched aquifer | Hybrid poplars (DN 34) | April 1995 |
| Former Truck Depot - LA | 0.5 acres | TPH in fill soil; BTEX | Groundwater and soil | Hybrid poplar, hybrid willows | June 1995 |
| Fort Carson (Landfills 5 and 6) - CO | 20-40 acres | Municipal/mixed waste | | | |
| Fort Lewis Army Base - WA | ~ 10 acres | Chlorinated solvents | Groundwater | Hybrid poplar | Proposed for Spring 2000 |
| Fort Richardson - AK | | | Soil | | |
| Fort Riley - KS | 4,800 square ft. | Semi-volatile petroleum products | Contaminated sediments | Grasses and legumes | September 1997 |
| Fort Wainwright - AK | | Pesticides/Herbicides, Other | Soil and groundwater | Felt Leaf willow | |
| **Gardner Avenue - CY** | 2.5 acres | Pesticides/Herbicides, Heavy metals | Soil, groundwater | | |
| Great River Regional Waste Authority - IA | 6 acres | | Leachate and subsurface soil | Hybrid poplar and grass | 1997-1998 |
| Green II Landfill - OH | 30 acres | VOCs and other organics in leachate | Leachate and soil | Hybrid poplar and hybrid willows | Fall 1998 |
| Greenbelt Project - WY | 40 acres | Wood preservatives | Soil | Poplar, herbaceous | |
| Greenhouse studies of Phytoremediation | ~ 20' x 4' per experiment | Heavy metals, halogenated volatiles | Soil to 15' bgs, groundwater | Gamagrass, poplars willows | March 1995-1997 |
| Grundy County Landfill - IA | 5 acres, 2 acres | Leachate | Subsurface soil | Hybrid poplar | 1993, 1994 |
| Gulfcoast Site | 1,800 square ft. | Volatile petroleum products | Soil to 6", groundwater | Sorghum, Cowpeas Sweet clover, rye | |
| Hanford Barrier - WA | 1 acre | No waste | | | |
| Hawaii | ~ 1 acre | Pesticides | Groundwater | Koa (native plant) | June 1998 |
| Hill Air Force Base - UT | | No waste | Groundwater | Vegetative cover | |
| Hillsboro Landfill Wetlands - OR | 54 acres | | | | |

| Project Name/ Location | Size of Area | Primary Contaminant | Media and Properties | Vegetative Type | Date Planted |
|---|---|---|---|---|---|
| Hollola Landfill - Hollola, Finland | 3 hectares | Ash, oily waste | | | |
| ICI - Billingham, UK | 5 hectares | COD | Effluent | Soil based reed bed | 1990 |
| ICI Explosives Americas Engineering - MO | ~ 3.2 acres | Explosives, fertilizers | Surface soils, surface water, and groundwater | Willows, ninebark and cypress | February 1996 |
| IMC Global Limited - Ontario, Canada | 100 acres | | Leachate | Poplar | |
| IMC, Port Maitland - Canada | 100 acres | | | Hybrid poplar | Spring 1998 |
| Indianapolis - IN | 1-1.5 acres | Pesticides/Herbicides | Groundwater | Hybrid poplar | 1995 |
| Industrial Landfill - TN | 3 acres | Volatile organic compounds and thallium | Groundwater | Hybrid poplar with grass | Spring 1998 |
| Iowa | | Heavy metals, pesticides/ herbicides | Soil 0 to 48 cm | Knotweed, crabgrass | |
| Army Ammunition Depot - IA | | Explosives | Wastewater, soil and pond water | Wetland and terrestrial | Spring 1997 |
| Jackson Bottoms Wetland - OR | | | | | |
| Johnson County Landfill - IA | 9 acres | Halogenated volatiles, heavy metals, other | Subsurface soil | Hybrid poplar and grass | 1992, 1993 |
| Juniper Utility Co. WWTP Effluent Reuse - OR | 64.5 acres | Wastewater; nitrogen; phosphorus. Secondary effluent biosolids | | Ryegrass and Kentucky bluegrass | |
| Kaiser Hill - CO | 15 to 46 acres | Radionuclides | Shallow groundwater and surface streams | Native cottonwoods; Hybrid poplar | Not yet. |
| Kauffman and Minteer - NJ | 1) 50' x 300' and 2) 30' x 30' | TCE; DCE | Soil and groundwater | Black willow; hybrid poplar | April 1998 |
| Keyport Naval Warfare Facility - WA | ~ 8 acres | Chlorinated solvents, PCB's | Groundwater | Hybrid poplars | Site in preparation |
| Klamath Falls site - OR | 12 acres (1994) | Halogenated semi-volatiles | Shallow soil | Hybrid poplar and grass | 1994, June 1995 |
| Kurdjaly - Bulgaria | | Heavy metals | Soil | Alpine pennycress | September 1997 |
| Lakeside Reclamation Landfill - OR | 0.6 acres; 8 acres | Landfill leachate | Soil and water | Hybrid poplar, grass | April 1990 |
| Lamb-Weston Food Processing Reuse - OR | >5,000 acres | Food processing wastewater | | Grass, wheat, barley, corn, alfalfa | |
| Lanti Landfill - Finland | 17 hectares | Ash | | | |
| Liquid Fertilizer Plant - ND | ~ 0.25 acres | Nitrogen | Soil and groundwater | Hybrid poplar | May 10, 1996 |
| Los Banos - CA | 0.5 hectares | Heavy metals | Clay, loam | Indian Mustard, Fescue, Trefoil, Brassica sp. | 1991 |
| Magic Marker Site - NJ | 0.25 acre, 1 acre, 4500 square ft. study area | Heavy metals | Shallow soil | Indian Mustard (Brassica juncea) | June 1997 |

| Project Name/ Location | Size of Area | Primary Contaminant | Media and Properties | Vegetative Type | Date Planted |
|---|---|---|---|---|---|
| Magnesite Processing Plant - WA | 1 acre | Ammonia | Soil | Hybrid poplar (5 varieties) | May 19-20, 1995 |
| Manchester Site - UK | 2 pilot beds each 3m x 5m | Starch factory effluent | Effluent | Soil based reed bed | 1995 |
| Manufacturing Facility - MI | 0.5 acres | Halogenated volatiles | Groundwater, silty clay soil | Hybrid poplar | June 1996 |
| Manufacturing Facility - WI | 2 acres | TPH in fill soil | Ash and cinder with soil fill | Hybrid willow | June 1996 |
| Matoon - IL | 3 acres | Nitrate nitrogen | soil | Hybrid poplar | 1994 |
| Maxey Flats - KY | | Radioactive - low level waste | | | |
| Metal Plating Facility - OH | | Heavy metals, halogenated volatiles | Soil | Indian Mustard | |
| Milan Army Ammunition Plant (MAAP) - TN | Demonstration scale | Explosives (TNT, RDX, HMX, TNB); BOD5, nutrients | Groundwater | Grass, sweetflag, parrotfeather | April-May 1996 |
| Military site | Feasibility study test cells | Explosives | Soil | Proprietary | |
| Mill Creek Correctional Facility - OR | 3.5 acres | Nitrogen | Groundwater and soil | Native black cottonwood; Hybrid poplar (total of 8,500 planted perpendicular to groundwater flow) | May 1997 |
| Mississippi Site | ~ 3 acres | Volatile and nonvolatile petroleum products | Soil and groundwater | Under consideration | Spring 1999 |
| Monmouth Site - NJ | | Radionuclides | | | |
| Montezuma West - OR | ~ 1 acre | Chlorinated volatiles | Groundwater | Hybrid poplars | May 24, 1997 |
| Monticello - UT | | Radionuclides | | | |
| Moonachie - NJ | 2 acres - 46 trees | Volatile petroleum products; Halogenated volatiles | Groundwater | Hybrid poplars; DN 34 (Populus deltoids x P. nigra) | May 28, 1997 |
| MS Service Station - NJ | ~ 0.3 acre | GROs | Groundwater | Phreatophyte trees | Spring 1999 |
| Kennedy Space Center - FL | 3 acres | Halogenated volatiles, volatile petroleum products, heavy metals | Soil and groundwater | Hybrid poplars and grass | March - April 1998 |
| NCASI Test Cells - MI | | | | | |
| New Hampshire Landfill - NH | | Halogenated volatiles | | | |
| Nitrogen Contaminated Site - MN | 2.3 acres | Nitrate and ammonia | Soil and groundwater | Hybrid poplars, and grass | May 1993 |
| Nitrogen Products Site - AK | Six buffer areas (total 5 acres) | Pesticides, herbicides | Soil | Hybrid poplar | March 5-10 1995 |
| Northeast Site | 2000 square ft. | Volatile petroleum products | Soil to 2' bgs, groundwater | Perennial Warm Season Grass, Sorghum | May 1993 |
| Nu-Glo Site - OH | 0.5 acres | TCE, PCE | Soil and groundwater | Hybrid poplar and willows | Fall 1998 |

| Project Name/ Location | Size of Area | Primary Contaminant | Media and Properties | Vegetative Type | Date Planted |
|---|---|---|---|---|---|
| Oconee - IL | 1-3 acres | Pesticides/Herbicides | Groundwater and soil | Alfalfa, corn, and Hybrid poplar | |
| Ohio Location | ~ 2 acres | Volatile petroleum products | Soil and shallow groundwater | Hybrid poplars; rye grass | May 1997 |
| Ohio Site | 25' x 100' | Volatile petroleum products | Shallow groundwater | Hybrid poplars | April 1997 |
| Oil Refinery - Perth, Australia | 10-100 square meters | Semi-volatile petroleum products | Soil | Rye, legumes, fescue, sedges | Sept 1998 - Dec 1999 |
| Gas Station - OR | 75 square ft. | VOCs and semi-volatiles | groundwater | Hybrid poplars (DN-34) | May 1997 |
| OREMET Titanium, Inc. - OR | 5 acres | | Wastewater | Hybrid poplar | 1995 |
| Osage River Riparian Buffer - MO | 0.15 acres | | Streambank soil | Hybrid poplar and willow | June 1997 |
| Osh Kosh - WI | 9 square meters | | Soil 0 to 30 cm | Fungi, chrysanthemum p. sordida | |
| Palmerton - PA | 25 square meters | Heavy metals | Soil at 12 cm | Campion, alpine pennycress | |
| Palo Alto - CA | 1 acre | Heavy metals | Groundwater | Tamarisk, Eucalyptus | Nov 1997 |
| Paper Industry | | Semi-volatile petroleum products | Soil | Hybrid poplar | |
| Petroleum Company - KS | 0.5 acres | Petroleum Hydrocarbons | Soil | Hybrid poplars | April 1998 |
| Phytoremediation of Soils from Argonne West - ID | Greenhouse | Cesium 137, Cr, Hg, Zn, Ag, Se | Soil | Hybrid willow, canola, Brassica | April 1998 |
| Piketon DOE Facility - OH | 5 acres | Halogenated volatiles | Shallow and deep groundwater | Hybrid poplars; rye grass | Spring 1999 (planned) |
| Pipeline Site OBJ - MO | 1.25 acres | Petroleum Hydrocarbons | Soil and groundwater | Alfalfa, Phreatophyte trees | Sept 1998 |
| Poppy Lane - AK | | Volatile petroleum products, Heavy metals | Soil, root level | Willow, Elderberry, Alder, Cottonweed | |
| Port Hueneme | | | Groundwater | Eucalyptus | |
| Prineville Golf Course Reuse - OR | 160 acres | BOD and TSS | Wastewater | Turf grass | 1993 |
| Rail Tie Yard - TN | 0.75 acres | Semi-volatile petroleum products | Soil | Hybrid poplar and grass | 1997 |
| Red Mud Coastal Restoration Project - LA | Test area ~ 2 acres | Iron Sesquioxides | Sludge | Grass, alfalfa, willow, black locust | Fall 1992 |
| Refinery - CA | 7,000 square ft. | Hydrocarbons | Soil | Grasses | 1995 |
| Reliable Plating Site - OH | 0.5 acres | TPH in fill soil; BTEX in groundwater | Excavated soil | Hybrid poplars and hybrid willows | June 1995 |
| Residual Petroleum Waste Remediation | 0.8 acres | Petroleum Hydrocarbons | Soil | Hybrid poplar and alder | 1999 (Proposed) |
| Reuben Gaunts - Leeds - UK | 450 square meters | Dyes, Residual OPs, COD | Effluent | Soil based reed bed | 1997 |
| Riparian Buffer, Grande Ronde Valley - OR | Various, most are a few acres | Agricultural runoff | Grande Ronde River | Poplar and other | 1997-1998 |

| Project Name/ Location | Size of Area | Primary Contaminant | Media and Properties | Vegetative Type | Date Planted |
|---|---|---|---|---|---|
| Rocky Mountain Arsenal - OR | 74 acres | Radionuclides - low level waste | | Trees | |
| Saginaw Mill - WA | ~ 5-8 acres | Formaldehyde | Groundwater | Poplar, Alder, and Native willow | |
| Sandia National Laboratories - NM | 40' x 300' for each cover | No contaminant | | Various | |
| Savannah Ricer Site - SC | | Halogenated volatiles | Groundwater | Loblolly Pine, grasses | March 1999 |
| Sludge Lagoon - CT | | Herbicides, metals | | Hybrid poplar | |
| SRSNE - CT | 2 acres | Halogenated volatiles | Groundwater | Hybrid poplar | May 18, 1998 |
| Tama County Landfill - IA | 12 acres, 14 acres | Leachate | Shallow soil | Hybrid poplar | 1993-1995 |
| Tanfield Lea - Newcastle - UK | 1,800 square meters | Heavy metals, TDS, COD | Leachate effluent | Soil based reed bed | 1997 |
| Tennessee Site | 2 acres | Volatile and nonvolatile petroleum products | Soil and groundwater | Hybrid poplar | May 1997 |
| Texaco - WA | 18 acres | Petroleum Hydrocarbons | Soil | Grass and clover | |
| Texas Land Treatment Facility - TX | 22 acres | PAHs and O&G | Residuals in soils | Groundcover plants (grasses) | Proposed 4th Qtr 1998 |
| Texas Site | 5-10 acres | Volatile petroleum products | Soil | Grasses | Spring 1999 |
| Thiokol Corp. | | Halogenated Volatiles | Groundwater - 2-3' depth | 185 Willow Trees | Planted 1996 |
| Tippee Beef Facility - IA | 1.5 acres | | Surface water, soil, groundwater | Hybrid poplars and grass | May 1998 |
| Trucking Terminal - NJ | ~ 1 acre | Volatile petroleum products | Shallow soil and groundwater | Hybrid poplars | June 1998 |
| Twin Cities Army Ammunition Plant - MN | Two demo areas 0.2 acres | Heavy metals for both sites | Soil | Corn, white mustard | 2 yr. demo is May-Oct 1998 & 1999 |
| Union Carbide - TX | 1 acre | RCRA K-waste, semi-volatiles | Sludge | Mulberry, grasses hackberry | |
| Unknown - NJ | | Non-halogenated Semi-volatiles | Soil | Alfalfa, switch and bluestem grass | |
| Unknown - NJ | | Heavy metals | Soil, rocky, root level | Ragweed, Hemp, Dogbane, Musk, Nodding, Thistle | |
| Unknown - MD | | | Sludge | Poplars | |
| Unknown - ID | | Heavy metals, Radionuclides | Soil | | |
| Upper Plant Area - NJ | 0.1 acre | GROs and DROs | Groundwater | Alfalfa, Phreatophyte trees | Sept 1998 |
| Upper Silesia, Poland | | Heavy metals | Clay and silt, 0-20 cm | Cereals, Potatoes | |
| US Generating - OR | >5,000 acres | Heat (cooling water) | | Grass, wheat, barley corn, alfalfa | |
| USA Waste-Chambers Development - VA | 10 acres | | Subsurface soil | Hybrid poplar | 1995 |

| Project Name/ Location | Size of Area | Primary Contaminant | Media and Properties | Vegetative Type | Date Planted |
|---|---|---|---|---|---|
| USA Waste Riverbend Landfill - OR | 14.3 acres irrigated | VOCs, Heavy metals, Other | Leachate | Hybrid poplar, Grass | 1992 |
| Vernon Brincks Site - IA | | | | Hybrid poplar | 1991 |
| Volunteer Army Ammunition Plan - TN | | Explosives | Water | | |
| Whitewood Creek - SD | 300' buffer strip | Heavy metals | Soil | Hybrid poplar | 1991, 1993 |
| Whyalla Site - Australia | 8 pilot beds ~ 3m x 10m; field = 2 hectares | Coke oven effluent | Effluent | Soil based reed bed | 1993 |
| Widen - WV | <1 acre | Volatile petroleum products | Soil and groundwater | Hybrid poplar | 1994 |
| Wilmington - NC | | Nitrate-Nitrogen, ammonium-nitrogen | Groundwater and soil | Hybrid poplar | |
| Wisconsin Site - WI | 17 acres | BTEX and TPH | Soil | Species under consideration | Spring 1999 |
| Woodlawn Landfill - MA | ~ 21 acres | Halogenated volatiles and metals | Groundwater | Hybrid poplars | Pending approval |
| YPLMO - Edinburg, UK | 2,000 square meters | Surfactants, petroleum, hydrocarbons, organics | Groundwater | Soil based reed bed | 1997 |

# Appendix C
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# Appendix D
# Common and Scientific Names of Referenced Plants

## Common Name Listed First

| Common Name | Scientific Name |
|---|---|
| Alfalfa | *Medicago sativa* |
| Algae stonewort | *Nitella* |
| Alyssum | *Alyssum wulfenianum* |
| Bean | *Phaseolus coccineus* L. |
| Bean, bush | *Phaseolus vulgaris* cv. “Tender Green” |
| Bermuda grass | *Cynodon dactylon* |
| Birch, river | *Betula nigra* |
| Black locust | *Robinia pseudoacacia* |
| Black willow tree | *Salix nigra* |
| Bladder Campion | *Silene vulgaris* |
| Bluestem, big (prairie grass) | *Andropogon gerardi* Vit. |
| Bluestem, little | *Andropogon scoparius* |
| Bluestem, little | *Schizachyrium scoparius* |
| Boxwood | *Buxaceae* |
| Buffalo grass | *Buchloe dactyloides* |
| Canada wild rye (prairie grass) | *Elymus canadensis* |
| Canola | *Brassica napus* |
| Cattail | *Typha latifolia* |
| Cherry bark oak | *Quercus falcata* |
| Clover | genus Trifolium |
| Colonial bentgrass | *Agrostis tenuis* cv Goginan |
| Colonial bentgrass | *Agrostis tenuis* cv Parys |
| Cottonwood, Eastern, tree | *Populus deltoides* |
| Cottonwood (poplar) | *Populus* |
| Crab apple | *Malus fusca* Raf. Schneid |
| Crested wheatgrass (Hycrest) | *Agropyron desertorum* (Fisher ex Link) Schultes |
| Cypress, bald | *Taxodium distichum* |
| Duckweed | *Lemna minor* |
| Eastern Cottonwood tree | *Populus deltoides* |
| European milfoil / yarrow | *Achillea millefolium* |
| Felt leaf willow | *Salix alaxensis* |
| Fescue, hard | *Festuca ovina* var. *duriuscula* |
| Fescue, red | *Festuca rubra* cv Merlin |
| Fescue, tall | *Festuca arundinacea* Schreb. |
| Four-wing saltbrush | *Aicanescens* |
| Grama, side oats (prairie grass) | *Bouteloua curtipendula* |
| Grama, blue | *Bouteloua gracilis* |
| Grass, cool season (colonial bentgrass) | *Agrotis tenuis* |
| Grass, warm season (Japanese lawngrass) | *Zoysia japonica* |
| Horseradish (roots) | *Armoracia rusticana* |
| Hybrid poplar tree | *Populus deltoides* X *nigra* DN-34, Imperial California; *Populus charkowiieensis* x *incrassata*; *Populus tricocarpa* x *deltoides* |

| Common Name | Scientific Name |
|---|---|
| Hycrest, crested wheatgrass | *Agropyron desertorum* (Fisher ex Link) Schultes |
| Indiangrass (prairie grass) | *Sorghastrum nutans* |
| Indian mustard | *Brassica juncea* |
| Indian ricegrass | *Oryza sativa* subsp. *indica* |
| Japanese lawngrass | *Zoysia japonica* |
| Jimson weed | *Datura innoxia* |
| Kenaf | *Hibiscus cannabinus* L. cv. Indian |
| Koa haole | *Leucaena leucocephala* |
| Kudzu | *Pueraria lobata* |
| Lambsquarter | *Chenopodium* |
| Legume | *Lespedeza cuneata* (Dumont) |
| Little bluestem (prairie grass) | *Schizachyrium scoparius* |
| Loblolly pine | *Pinus taeda* (L.) |
| Mesquite | *Prosopis* |
| Millet, Proso | *Panicum miliaceum* L. |
| Mulberry, red | *Morus rubra* L. |
| Mustard, Indian | *Brassica juncea* |
| Mustard weed | *Arabidopsis thaliana* |
| Oak, cherry bark | *Quercus falcata* |
| Oak, live | *Quercus virginiana* |
| Osage orange | *Maclura pomifera* (Raf.) Schneid |
| Parrot feather | *Myriophyllum aquaticum* |
| Pennycress | *Thlaspi rotundifolium* |
| Pennycress, Alpine | *Thlaspi caerulescens* |
| Pennyworth | *Hydrocotyle umbellata* |
| Poplar, cottonwood | *Populus* |
| Poplar | *Populus* |
| Poplar, hybrid | *Populus deltoides* X *nigra* DN-34, Imperial California; *Populus charkowiieensis* x *incrassata*; *Populus tricocarpa* x *deltoides Populus charkowiieensis x incrassata* |
| Poplar, yellow | *Liriodendron tulipifera* |
| Red fescue | *Festuca rubra* cv Merlin |
| Reeds | *Phragmites* |
| Rice | *Oryza sativa* L. |
| Sacaton, alkali | *Sporobolus wrightii* |
| Sea pink; wild thrift | *Armeria maritima* |
| Salt marsh plant | *Spartina alterniflora* |
| Sand dropseed | *Sporobolu cryptandrus* |
| Soybean | *Glycine max* (L.) Merr, cv Davis. |
| Spearmint | *Mentha spicata* |
| Sugarcane | *Saccharum officinarum* |
| Sundangrass | *Sorghum vulgare* L. |
| Sunflower | *Helianthus annuus* |
| Switchgrass (prairie grass) | *Panicum virgatum* |
| Tall fescue | *Festuca arundinacea* Schreb. |
| Thornapple (or jimson weed) | *Datura innoxia* |
| Thrift (wild); sea pink | *Armeria maritima* |
| Tobacco | *Nicotiana tabacum* |
| Water hyacinth | *Eichhornia crassipes* |
| Water milfoil | *Myriophyllum spicatum* |
| Water velvet | *Azolla pinnata* |
| Wheat grass, slender | *Agropyron trachycaulum* |
| Wheat grass, western (prairie grass) | *Agropyron smithii* |
| Willow tree, black | *Salix nigra* |
| Willow tree, felt leaf | *Salix alaxensis* |

Scientific Name Listed First

| Scientific Name | Common Name |
|---|---|
| *Achillea millefolium* | European milfoil; yarrow |
| *Agropyron desertorum* (Fisher ex Link) Schultes | Hycrest crested wheatgrass |
| *Agropyron smithii* | western wheatgrass (prairie grass) |
| *Agropyron trachycaulum* | slender wheatgrass |
| *Agrostis tenuis* cv Goginan | Colonial bentgrass |
| *Agrostis tenuis* cv Parys | Colonial bentgrass |
| *Aicanescens* | four-wing saltbrush |
| *Alyssum wulfenianum* | Alyssum |
| *Andropogon gerardi* | big bluestem |
| *Andropogon scoparius* | little bluestem prairie grass |
| *Arabidopsis thaliana* | mustard weed |
| *Armeria martima (var. halleri)* | Sea pink; wild thrift |
| *Armoracia rusticana* | horseradish |
| *Azolla pinnata* | water velvet |
| *Betula nigra* | river birch |
| *Bouteloua curtipendula* | side oats grama (prairie grass) |
| *Bouteloua gracilis* | blue grama (prairie grass) |
| *Brassica juncea (B. Juncea)* | Indian mustard |
| *Brassica juncea* (L.) Czern | Indian mustard |
| *Brassica napus* | canola |
| *Buchloe dactyloides* | buffalo grass |
| *Buxaceae* | includes boxwood |
| *Chenopodium* | lambsquarter |
| *Cynodon dactylon* | Bermuda grass |
| *Datura innoxia* | jimson weed or thornapple |
| *Eichhornia crassipes* | water hyacinth |
| *Elymus canadensis* | Canada wild rye (prairie grass) |
| *Festuca arundinacea* Schreb. | tall fescue |
| *Festuca ovina* var. *duriuscula* | hard fescue |
| *Festuca rubra* cv Merlin | red fescue |
| *Glycine max* (L.) Merr. | soybean |
| *Helianthus annuus* | sunflower |
| *Hibiscus cannabinus* L. cv. Indian | Kenaf |
| *Hydrocotyle umbellata* | pennyworth |
| *Lemna minor* | duckweed |
| *Lespedeza cuneata* (Dumont) | a legume |
| *Leucaena leucocephala* | Koa haole |
| *Liriodendron tulipifera* | yellow poplar |
| *Maclura pomifera* (Raf.) Schneid | osage orange |
| *Malus fusca* Raf. Schneid | crab apple |
| *Medicago sativa* | alfalfa |
| *Mentha spicata* | spearmint |
| *Morus rubra* L. | red mulberry |
| *Myriophyllum aquaticum* | parrot feather |
| *Myriophyllum spicatum* | water milfoil |
| *Nicotiana tabacum* | tobacco |
| *Nitella* | algae stonewort |
| *Oryza sativa* L. | rice |
| *Oryza sativa* subsp. *indica* | Indian ricegrass |
| *Panicum miliaceum* L. | proso millet |
| *Panicum virgatum* | switchgrass (prairie grass) |
| *Phaseolus coccineus* L | Bean |
| *Phaseolus vulgaris* cv. Tender Green | bush bean |
| *Phragmites* | reeds |

| Scientific Name | Common Name |
|---|---|
| *Pinus taeda* (L.) | Loblolly pine |
| *Populus* | Poplar, cottonwood |
| *Populus charkowiieensis* x incrassata | hybrid poplar |
| *Populus deltoides* X *nigra* DN-34, Imperial California | hybrid poplar tree (eastern cottonwood) |
| *Populus tricocarpa* x deltoides | a hybrid poplar tree |
| *Prosopis* | mesquite |
| *Pueraria lobata* | Kudzu |
| *Quercus falcata* | cherry bark oak |
| *Quercus virginiana* | live oak |
| *Robinia pseudoacacia* | black locust |
| *Saccharum officinarum* | sugarcane |
| *Salix alaxensis* | felt leaf willow |
| *Salix nigra* | black willow tree |
| *Schizachyrium scoparius* | little bluestem prairie grass |
| *Silene vulgaris* | bladder campion |
| *Sorghastrum nutans* | indiangrass (prairie grass) |
| *Sorghum vulgare* L. | sudangrass (prairie grass) |
| *Spartina alterniflora* | salt marsh plant |
| *Sporobolu crypandrus* | sand dropseed |
| *Sporobolus wrightii* | Sacaton, alkali |
| *Taxodium distichum* | bald cypress |
| *Thlaspi caerulescens* | Alpine pennycress |
| *Thlaspi rotundifolilum* | Pennycress |
| Trifolium (genus) | clover |
| *Typha latifolia* | cattail |
| *Zoysia japonica* | Japanese lawngrass (warm season grass) |