# PHYTOREMEDIATION FIELD STUDIES DATABASE for CHLORINATED SOLVENTS, PESTICIDES, EXPLOSIVES, and METALS

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Prepared by

**Cynthia Green**
Environmental Careers Organization
and
**Ana Hoffnagle**
University of Arizona

for

U.S. Environmental Protection Agency
Office of Superfund Remediation and Technology Innovation
Washington, DC
www.clu-in.org

## NOTICE

This document was prepared by two undergraduate students under internships with United States Environmental Protection Agency (EPA). Ana Hoffnagle was sponsored by the University of Arizona and Cynthia Green was sponsored by the Environmental Careers Organization.

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The paper briefly explains the concept of phytoremediation, details phytoremediation site considerations, and summarizes the successes and failures of field-scale sites where phytotechnologies have been applied or proposed. Project tasks were accomplished by two summer interns via literature searches, site visits and personal communications with site managers and other officials. No attempts were made to independently confirm the resources used. It has been reproduced to help provide federal agencies, states, consulting engineering firms, private industries, and technology developers with information for use in determining whether phytoremediation technology is a feasible option for a site. The report is available on the Internet at www.clu-in.org/studentpapers/.

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# 1. OBJECTIVES

## 1.1 Scope of Project

The scope of this project is to compile a listing of sites where field-scale phytotechnologies have been applied to contain and remediate chlorinated solvents, pesticides, explosives and heavy metals in contaminated soil and groundwater. Phytomechanisms included in this project shall include phytoaccumulation, phytoextraction, rhizofiltration, phytostabilization, rhizodegradation, phytodegradation, phytovolatilization and hydraulic control. Older phytoremediation databases will be updated and appended by information extracted from government internet sources, literature searches and personal communication with site contacts.

## 1.2 Requirements

The following criteria have been set for the database:

1. Project scale shall be demonstration, pilot or full-scale. Laboratory, bench or greenhouse scale phytoremediation research shall not be included.
2. Phytoremediation installations of constructed wetlands sites, landfill vegetative cover sites, and riparian buffers shall be excluded from the database.
3. Media type shall be limited to soil and groundwater. Wastewater, surface water, sediment, and sludge applications shall not be included.
4. Vegetative types include all members of the plant kingdom and fungi.

## 1.3 Concept of Operation

The purpose of this compilation is to provide an understanding of the successes and failures of phytoremediation installations to-date. This paper will serve as a reference for federal, state, and site managers and others to compare their site with others having similar conditions in order to support the decision of whether or not to use phytoremediation as a treatment technology. A spreadsheet has been selected as the layout for the database in order to accommodate public navigation. Entries in the database shall attempt to summarize the relevant logistics, successes and failures of each site by defining twenty-one fields for each. These elements include:

1. Site Name
2. Site Location
3. Contaminant
4. Vegetation Type
5. Planting Descriptions
6. Media Type
7. Site Characterizations
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9. Climate
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21. Citation

Each site profile will allow users to quickly determine the nature of the site and the success of the technology while also providing avenues to pursue should they want further site information.

# 2. OVERVIEW

## 2.1 Phytoremediation

### *2.1.1 What Is Phytoremediation?*

Phytoremediation is the use of vegetation and its associated microorganisms, enzymes and water consumption to contain, extract or degrade contaminants from soil and groundwater. Both organic and inorganic contaminants can be successfully contained or degraded using phytoremediation in a variety of media (i.e. soil, sediment, sludge, wastewater, groundwater, leachate and air) (Susarla, 2002). The mechanisms of phytoremediation include:

- Phytoextraction – removal and storage of contaminants from the media into the plant tissue;
- Rhizodegradation – degradation of contaminants by microorganisms in the soil zone that surrounds and is influenced by the roots of plants, also known as the rhizosphere;
- Phytodegradation – degradation of contaminants within the plant tissue;
- Phytostabilization – isolation and containment of contaminants within soil through the prevention of erosion and leaching;
- Phytovolatilization – uptake and transpiration of contaminants from the media through the plant tissue into the atmosphere; and
- Hydraulic Control – containment of contaminants within a site by limiting the spread of a contaminant plume through plant evapotranspiration.

In depth details on phytoremediation mechanisms have been thoroughly documented in past literature and are not the focus of this document (McCutcheon, 2003).

### *2.1.2 History*

The concept of using plants to clean and restore soil and wastewater has been employed for over 300 years. Numerous bench-scale studies have been performed to determine plant toxicities and contaminant uptake abilities. In order for phytoremediation to achieve acceptance as a remedial method, field-scale applications need to be performed and documented. Constructed wetlands and vegetative covers have been extensively applied in the field to demonstrate their ability to remediate contamination and their data has been well documented (McCutcheon, 2003). More recently, field-scale studies of groundwater and soil plantations have been performed to determine their effectiveness in remediating contamination. The purpose of this paper is to document groundwater and soil plantation applications and their results, so that the information will be useful in assessing the feasibility of phytoremediation as a remedial technology for a site.

### *2.1.3 Advantages and Disadvantages*

Phytoremediation, like other technologies, has both advantages and disadvantages associated with it as shown in Table 1. Advantages and disadvantages are not ranked in any order. The weight each element carries will vary with each site.

**Table 1. Phytoremediation Advantages and Disadvantages (ITRC, 2004; EPA, 2001)**

| Advantages | Disadvantages |
|---|---|
| ▪ Cost reduced over traditional methods<br>▪ Low secondary waste volume<br>▪ Improved aesthetics<br>▪ Habitat creation - biodiversity<br>▪ Green technology<br>▪ More publicly accepted<br>▪ Provide erosion control<br>▪ Prevent runoff<br>▪ Reduce dust emission<br>▪ Reduce risk of exposure to soil<br>▪ Less destructive impact (applied in-situ) | ▪ Long remediation time requirement<br>▪ Effective depth limited by plant roots<br>▪ Phytotoxicity limitations<br>▪ Fate of contaminants often unclear<br>▪ Climate dependent/variable<br>▪ Seasonal effectiveness<br>▪ Potential transfer of contaminants (i.e. to animals or air)<br>▪ Harvesting and disposal of metals in biomass as hazardous waste may be required, although generally not<br>▪ Larger treatment footprint |

Not all listed advantages and disadvantages are specific to phytoremediation. Footprint size limitations may affect all remediation technologies. Advances in technology have been able to alleviate some of the disadvantages. Deeper root depths are achievable today than in the past due to engineered planting methods (see section 2.2.5). Phytotoxicity has become less of an issue as genetically modified plants (see section 2.2.7) have been developed to withstand higher concentrations of contaminants. More disadvantages may be overcome as the technology progresses.

*2.1.4 Use in a Treatment Train*

Though not always used as a stand alone technology, phytoremediation can still be a benefit to many hazardous waste sites. Few hazardous waste sites apply phytoremediation as the sole treatment method. The technology is often applied in conjunction with other traditional methods or as the final phase of a treatment train after contaminant concentrations have been reduced.

Phytoremediation can be used as part of a treatment train when time constraints require other methods to be employed to achieve a remediation goal in a short period of time. This usually occurs when high contaminant concentrations in sensitive areas (i.e. near drinking water sources) require quick reduction. A series of remediation efforts may be undertaken to reduce the concentrations to an acceptable level before applying phytoremediation as the last "polishing step" to remediate and contain low level concentrations.

Phytoremediation can also be applied in conjunction with other technologies to achieve a treatment goal. The natural solar-powered pumping of deep rooted trees may need to be coupled with traditional pump-and-treat systems to maintain treatment rates during the less effective growing months of the winter season. Vegetation may also be planted around site perimeters and "hot spots" to maintain hydraulic control and prevent contamination migration, while traditional methods are applied to remediate the source. Research on the addition of inorganic, organic and bio-amendments in conjunction with phytoremediation has also shown promising results (Kelley, et.al, 2000).

*2.1.5 Cost*

The first costs incurred when approaching any hazardous waste site are those of site assessment. Regardless of the technology applied, the nature and extent of contamination, hydrological and geological characteristics and site characteristics must all be assessed. Costs incurred during this phase are similar for all technologies. Beyond site assessment, phytoremediation will have unique costs associated with it. These cost considerations can be divided into four primary categories: (1) Design, (2) Installation (3) Operation and Maintenance, and (4) Sampling and Analysis.

Design considerations include feasibility studies, plant selection and the associated engineering costs. Land obstructions at the site may have to be incorporated into the design or removed. Green house studies or pilot scale testing may be needed to determine which plants to use and assess the possibility of phytoremediation as a treatment option for the site. Like all designs, the salaries of engineers performing conceptual work for the site will be the dominant cost in the design phase.

Installation costs include site preparation, soil preparation, materials and labor. In order to prepare the site, it may need to be cleared, leveled or fenced in. Soil preparation may involve pH adjustment, nutrient addition or tilling. Site and soil preparations will require labor and materials including heavy equipment, organic matter, irrigation systems, plant stock (including 10-20% excess for replanting needs (ITRC, 2004)) and vector protection materials for the plants.

Operation and Maintenance (O&M) costs will include monitoring equipment, power sources, maintenance for the equipment and labor are included. Specific O&M requirements for phytoremediation are detailed in section 2.5 of this document.

Sampling and Analysis costs may dominate the overall cost of the project due to the length of time monitoring is required and the extent of data necessary. Costs include labor or machinery to collect samples and lab work fees associated with analyzing samples. Data collected during sampling and analysis is crucial for thorough documentation of site progress and the performance of phytoremediation as a new technology. The EPA is collaborating with state and federal partners on implementing a streamlined approach to sampling, analysis and data management methods. This approach, called the Triad Approach, has the potential to reduce costs associated with sampling and analysis (EPA, 2004).

The costs associated with these four categories are relatively small compared to those of traditional remediation technologies. This is especially true in the operation and maintenance phase where the primary factor in cost reduction is the energy source of the operating systems. Traditional systems utilize electric power, at a substantial cost, to pump water, whereas phytoremediation systems take advantage of free solar energy. Individual sites will vary in cost regardless of the technology being applied. In general, phytoremediation is a low cost alternative to traditional methods as can be seen in the cost estimates of Table 2.

**Table 2. Cost Comparisons: Phytoremediation vs. Traditional Technologies**

| Traditional Method | Scenario | Estimated Cost | | Reference |
|---|---|---|---|---|
| | | Traditional Method | Phytoremediation | |
| Pump and Treat | 1-acre site with 20-foot-deep Aquifer | $660,000 | $250,000 | Gatliff, E. (1994) |
| Conventional Technology | Army Ammunition Plant | $1 trillion | $1.8 million | Matso, K. (1995) |
| Traditional Curb and Gutter | SEA Streets Runoff Buffer | $1 million | $850,000 | ITRC (2004) |
| Standard Landfill Cap | Landfill Vegetative Cap - College Park | $10 million | $3-4 million | ITRC (2004) |
| Activated Carbon System | Army Ammunition Plant - Milan | $4.00/ 1000 gal | $1.80/ 1000 gal | ITRC (2004) |
| Pump & Treat / Iron Barrier | PCE in Groundwater | 8.90/5.30 $/1000 gal | $2.00/1000 gal | Schnoor (2002) |
| Flushing/ Vitrification | Metals in Soils | 75-210/300-500 $/Ton | $25-100/Ton | Schnoor (2002) |

## 2.2 Contaminant Information

The database contained in this document focuses on four of the major contaminant groups found at hazardous waste sites.

### *2.2.1 Chlorinated Solvents*

The term *chlorinated solvents* refers to a family of colorless, liquid-phase hydrophobic organics containing one or more chlorine atoms. Most chlorinated solvents are only slightly soluble in water and, with the exception of vinyl chloride, have densities greater than that of water as shown in Table 3. This combination leads to their formation of dense non-aqueous phase liquid (DNAPL). Chlorinated solvent plumes tend to take a long time to remediate when DNAPL is present, because it acts as a slow releasing, continuous source. Common uses of chlorinated solvents include drycleaning operations, degreasing operations, polymer manufacturing and as a chemical intermediate. Because of their wide use, chlorinated solvents dominate the listings of hazardous waste at sites nation wide, with trichloroethylene (TCE) present at 40% off all Superfund sites in the United States (McCutcheon, 2003; USGS, 2004a). Contamination of soil and groundwater with chlorinated solvents is largely due to accidental spills and poor handling and disposal practices prior to regulation of the chemicals.

The primary chlorinated solvents at hazardous waste sites are trichloroethylene (TCE), perchloroethylene (PCE) and polychlorinated biphenyls (PCBs), with TCE and PCE being the most dominant (USGS, 2004a). TCE is primarily used as a metal cleaning agent and in specialty adhesives. It is a probable carcinogen and can affect kidneys, liver, lungs, and heart rate. PCE is primarily used as a drycleaning and metal cleaning agent. PCE is not classified as a carcinogen but has been known to affect the central nervous system and cause irritation of the skin, eyes, and upper respiratory system (Evans, 2000). PCBs are synthetic oils that do not readily react at room temperature. They are primarily used as coolants and/or insulators and were previously used as a spray to control dust on dirt roads (ASTDR, 2004). PCBs are classified as probable carcinogens by the EPA and the International Agency for Research on Cancer. PCB contamination is an ecological concern, because by-products from burning them at low temperatures are carcinogenic and their presence in the food chain has affected eggshell formation in birds (ASTDR, 2004).

Traditional methods for remediating chlorinated solvent contamination include natural attenuation, soil vapor extraction, air sparging and pump and treat. Phytoremediation mechanisms that have been successful in containing and/or remediating chlorinated solvents include rhizodegradation, phytodegradation, phytovolatilization and hydraulic control using hybrid poplar and willow trees as can be seen in the Database of Chlorinated Solvent Phytoremediation in Appendix A of this document.

**Table 3. Common Chlorinated Solvents**

| Compound Name | Chemical Formula | MW (g/mol) | Density (g/mL-20ºC) | Solubility (g/100mL-20ºC) | Log $K_{ow}$ |
|---|---|---|---|---|---|
| Carbon Tetrachloride | $CCl_4$ | 153.823 | 1.594 | 0.08048 | 2.64 |
| Chloroform | $CHCl_3$ | 119.3779 | 1.498 | 0.795 | 1.97 |
| 3,3-Dichlorobenzidine | $C_{12}H_{10}Cl_2N_2$ | 253.1304 | | 0.00123 | 3.21, 3.5 |
| 1,1-Dichloroethene | $C_2H_2Cl_2$ | 96.9438 | 1.213 | 0.225 | 1.32 |
| cis-1,2-Dichloroethene | $C_2H_2Cl_2$ | 96.9438 | 1.284 | 0.08 | 1.86 |
| trans-1,2-Dichloroethene | $C_2H_2Cl_2$ | 96.9438 | 1.257 | 0.63 | 2.09 [a] |
| 1,1-Dichloroethane | $C_2H_4Cl_2$ | 98.9596 | 1.176 | 0.506 | 1.79 |
| 1,2-Dichloroethane | $C_2H_4Cl_2$ | 98.9596 | 1.253 | 0.8608 | 1.48 |
| Methylene Chloride | $CH_2Cl_2$ | 84.9328 | 1.325 | 1.32 | 1.3 |
| Perchloroethylene | $C_2Cl_4$ | 165.834 | 1.623 | 0.015 | 3.4 |
| Polychlorinated Biphenyls | * | * | * | * | * |
| 1,1,1-Trichloroethane | $C_2H_3Cl_3$ | 133.404 | 1.3376 | 0.1495 | 2.49 |

| Compound Name | Chemical Formula | MW (g/mol) | Density (g/mL-20°C) | Solubility (g/100mL-20°C) | Log $K_{ow}$ |
|---|---|---|---|---|---|
| 1,1,2-Trichloroethane | $C_2H_3Cl_3$ | 133.404 | 0.442 | 1.4411 | 2.42 |
| Trichloroethylene | $C_2HCl_3$ | 131.388 | 1.462 | 0.11 | 2.42 |
| Vinyl Chloride | $C_2H_3Cl$ | 62.4987 | 0.9106 | 0.11 | 1.36 |

Data for this table extracted from the NIST Chemistry Webbook, Cambridge Chemfinder, the Agency for Toxic Substances and Disease Registry (ATSDR) ToxFaqs™ and Pankow and Cherry (1996)
* 209 possible PCBs. See the ATSDR internet resources at http://www.atsdr.cdc.gov/toxfaq.html for data.
[a] recommended.

Tree core sampling is an emerging technology that shows promising use as a tool to detect the presence of chlorinated solvents at sites. Researchers have been investigating the concentration of chemicals in tree trunks since 1990 (Vroblesky, 1990). Recently, the analysis of tree cores has gained interest in the field of phytoremediation as a low-cost and easily employable method to assess contamination presence. Core samples are collected from trees using a small borer and quickly placed in septum-capped vials to minimize loss of contaminant to volatilization. Vials are stored overnight at room temperature to allow diffusion of the volatile organic compounds from the core into the vial headspace. Headspace samples are analyzed and compared to standards using gas chromatography. Concentrations of the contaminants in the core are determined by assuming partitioning of contaminants from the cores is similar to that between air and water and taking into account recent findings on partitioning between air/wood and wood/water. Studies at the Riverfront Superfund Site show a strong relationship between contaminant concentrations in trees and shallow soils but a weak one between trees and groundwater (USGS, 2004b).

*2.2.2 Pesticides*

Pesticides are defined by the EPA as any substance or mixture of substances used for preventing, destroying, repelling, or mitigating any pest. The term is used broadly to include herbicides, fungicides, and other pest-control substances. In 1998 and 1999, world pesticide usage exceeded 5.6 billion pounds. US pesticide usage exceeded 1.2 billion pounds (EPA, 2002), and pesticides were applied at over 900,000 farms and 70 million households (Delaplane, 2000). Heavy usage over the years (mostly via direct land application) of some of the more persistent pesticides has resulted in their ubiquitous dispersal, most typically in aquatic environments (Chaudhry, 2002). For example, traces of a number of organochlorine pesticides have been found in Arctic environments where no previous application has occurred (Oehme, 1991).

EPA regulates pesticides because of risks that vary considerably depending on the toxicity of chemical components and dosage. For example, the most widely used class of pesticides, organophosphates, is implicated in a number of nervous system ailments and is first among pesticides most often implicated in symptomatic illnesses. Organophosphates, however, are typically not persistent in the environment (EPA, 1999). On the other hand, organochloride insecticides can be extremely recalcitrant. Several have had production curtailed or been banned due to deleterious environmental and health effects. Some especially recalcitrant pesticide pollutants, including aldrin, chlordane, DDT, dieldrin, endrin, heptachlor, toxaphene, mirex, and hexachlorbenzene, were placed on the 2001 Convention on Persistent Organic Pollutants "dirty dozen" list to immediately address regulatory concerns. Some properties of more commonly remediated pesticides, including persistence, $K_{ow}$, and health effects, are shown in table 4 on the next two pages.

Pesticide persistence in the environment depends on various chemical factors specific to the contaminant, such as volatility, solubility, chemical reactivity, soil-water ($K_d$) and octanol-water ($K_{ow}$) partitioning, and absorption and adsorption characteristics. In addition, biological degradability factors from microbial and plant activity also have significant effects (Chaudhry, 2002). The polar/nonpolar partitioning is particularly crucial in determining contaminant uptake and translocation in plants, with optimum log $K_{ow}$ conditions around 1.8 (Briggs,1982) and with uptake occurring roughly in the range of 1-3.5 (Hsu, 1992). Other issues to consider when evaluating the persistence of pesticides include the formation of tightly bound pesticide residues (Barraclough, 2004), degradation to still-active pesticide products, and decreased bioavailability as they age (Alexander, 2000). For example, a study by Knuteson *et al.* (2002) examined the effect of age on simazine uptake, finding that concurrent with an increase with age was increasing pesticide tolerance, but lower rates of uptake. Other studies have evaluated successful uptake of weathered chlordane in food crops (Mattina, 2000) and in pasture species (Singh, 1992), but less successful was the phytoremediation of dieldrin (Singh, 1992). More recently, White *et al.* (2003) studied the effect of weathered (aged) p-p'-DDE on uptake and translocation into 21 different cultivars (two subspecies) of summer squash. They found over an order-of-magnitude difference in p,p'-DDE tissue concentrations among the various cultivars' abilities to uptake the weathered contaminant, and attributed differences to subspecies variation of root exudate character.

Traditional methods of pesticide remediation include excavation and/or chemical oxidation processes (i.e. photocatalysis, ozonation, iron-catalyzed Fenton's reaction) or thermal processes (i.e. low temperature themal desorption, incineration). Bioremediation and phytoremediation are the biotic processes that are sometimes employed. The use of phytotechnologies to remediate these more persistent pesticides is only emerging. Difficulties remain, including the potential phytotoxicity of some compounds (i.e. herbicides) that were originally developed destroy plant material. Typically the mechanisms involved in pesticide phytoremediation are phytodegradation, rhizodegradation, and phytovolatilization. Recently, Karthikeyan *et al* (2004) reviewed various plant and rhizosphere systems that have shown potential in the laboratory for future pesticide phytoremediation.

**Table 4: Common Pesticides**

| Pesticide | Molecular formula | Molecular weight | Density (g/mL) | Aqueous Solubility (mg/L) | Log Kow | Persistence (Half-life) | Health Effects |
|---|---|---|---|---|---|---|---|
| Alachlor | $C_{14}H_{20}ClNO_2$ | 269.8 | 1.133 | 242 | 2.92 | 8 days | Effects on liver, spleen, kidney, iris, lung effects for long (6+ month) exposures |
| Aldrin | $C_{12}H_8Cl_6$ | 364.93 | 1.6 | 0.017 | 6.5 | 20 days to 1 year | Nervous system effects. Probable carcinogen. Large doses: convulsions, death. Moderate doses: dizziness, headaches, vomiting, uncontrolled muscle movement. |
| Atrazine | $C_6H_{14}ClN_5$ | 215.7 | 1.187 | 70 | 2.68 | 60 to 100 days | Acute: abdominal pain, diahrrea, skin and mucous membrane irritation (low levels); incoordination, muscle spasms, hypothermia, hypoactivity, prostration, convulsions, death (higher does). Chronic: respiratory distress, limb paralysis, structural/ chemical |
| Chlordane | $C_{10}H_6Cl_8$ | 409.78 | 1.6 | 0.056 | 6 | 4 years | Nervous system, digestive system, liver effects. Headaches, irritability, confusion, weakness, vision problems, vomiting, stomach cramps, diarrhea, and jaundice for lower doses. Higher doses: convulsions and death. |
| Dichlorodiphenyltri-chloroethane (DDT) | $C_{14}H_9Cl_5$ | 354.49 | 1.55 | 0.0055 | 6.19 | 2 to15 years | Nervous system effects (tremors, seizures); probable carcinogen |
| Dieldrin | $C_{12}H_8Cl_6O$ | 380.92 | 1.75 | 0.2 | 5.48 | Up to 7 years | Nervous system effects. Probable carcinogen. Large doses: convulsions, death. Moderate doses: dizziness, headaches, vomiting, uncontrolled muscle movement. |
| Endrine | $C_{12}H_8Cl_6O$ | 380.92 | 1.7 | 0.26 | 5.2 | Up to 12 years | Nervous system effects (large doses can cause severe central nervous system injury, convulsions, death; smaller doses can cause headaches, confusion, nausea, vomiting, and convulsions); birth defects |
| Heptachlor | $C_{10}H_5Cl_7$ | 373.32 | 1.58 | 0.18 | 5.47-6.10 | 0.4 to 2 years | Nervous system damage, liver and adrenal gland damage, tremors |
| Hexachlorobenzene (HCB) | $C_6Cl_6$ | 284.81 | 2.044 | 0.005 | 5.73 | 2.7 to 7.5 years | Damage to liver, thyroid, nervous system, bones, kidneys, blood, and immune systems; reasonably anticipated to be carcinogen |

| Pesticide | Molecular formula | Molecular weight | Density (g/mL) | Aqueous Solubility (mg/L) | Log Kow | Persistence (Half-life) | Health Effects |
|---|---|---|---|---|---|---|---|
| Metribuzin | $C_8H_{14}N_4OS$ | 214.28 | 1.28 | 1050 | 1.7 | 40 days | Skin irritation, reduced weight gain, blood chemistry changes, liver and kidney damage, enlarged liver and thyroid glands with chronic exposure. |
| Mirex | $C_{10}Cl_{12}$ | 545.55 | 1.8 | 0.085 | 7.18 | Up to 10 years | Stomach, intestine, liver, kidney, eye, thyroid, nervous system, and reproductive system effects; possible carcinogen |
| Pentachlorophenol (PCP) | $C_6Cl_5OH$ | 266.34 | 1.98 | 80 | 5.01 | 45 days | Respiratory irritation, lund oedema, dermatitis, and effects on cardiovascular system, central nervous system, kidneys, lungs, liver. |
| Toxaphene | $C_{10}H_{10}Cl_8$ | 414 | 1.66 | 0.55 | 5.78-6.79 | 1 to14 years | Damage to lungs, nervous system, kidneys, death at high doses; lower doses effect liver, kidneys, adrenal glands, and immune system; possible carcinogen |
| Data for this table extracted from the Cambridge Chemfinder, the Extension Toxicology Network, & the Agency for Toxic Substances and Disease Registry | | | | | | | |

*2.2.3 Explosives*

The term *explosive* refers to prepared chemicals subject to a rapid chemical reaction that produce or cause explosions. The three main classes of explosives are nitroaromatics, nitramines and nitrate esters. Nitroaromatics are characterized by an aromatic ring and nitro groups. The electronegativity of the nitro groups prevents explosives from readily falling under electrophilic attack. For this reason they are generally non-hygroscopic, insoluble in water and do not readily react with metals. Common uses of explosives include military weapons and pyrotechnic shows. Table 5 lists common explosives and some of their properties.

Contamination of soil with explosives is largely due to manufacturing, storage, testing and inappropriate waste disposal of explosive chemicals. The primary explosives at hazardous waste sites are 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (**R**oyal **D**emolition e**X**plosive-RDX) and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazine (**H**igh **M**elting e**X**plosive-HMX). TNT is a nitroaromatic constituent of many explosives. In a refined form, TNT is stable and can be stored over long periods of time. It is relatively insensitive to blows or friction. It is readily acted upon by alkalis to form unstable compounds that are very sensitive to heat and impact. Health effects due to exposure to TNT include anemia, abnormal liver function, skin irritation, and cataracts (ASTDR, 2004). RDX is a nitramine widely used as an explosive and as a constituent in plastic explosives. RDX can cause seizures when large amounts are inhaled or eaten. Long-term health effects on the nervous system due to low-level exposure to RDX are not known. HMX is a nitramine that explodes violently at high temperatures. It is used in nuclear devices, plastic explosives and rocket fuels. Insufficient studies on the effects of HMX to the health of humans and animals have been performed.

Incineration, landfilling and pump and treat systems are traditional methods applied to remove explosives contamination from soil and groundwater. These approaches are expensive and can cause air pollution with ash generation. Phytoremediation mechanisms that have been successful in containing and/or remediating explosives contamination include phytoextraction, phytodegradation and phytostabilization using tobacco, periwinkle, and parrot feather plants in constructed wetlands (Bhadra, 1999; Wayment, 1999; Hughes, 1997).

**Table 5. Common Explosives**

| Compound Name | Chemical Formula | MW (g/mol) | Density (g/mL-20ºC) | Solubility (g/100mL-20ºC) |
|---|---|---|---|---|
| 2,4-Dinitrotoluene (2,4DNT) | $C_7H_6N_2O_4$ | 182.1354 | 1.521 | 0.027 |
| 2,6-Dinitrotoluene (2,6DNT) | $C_7H_6N_2O_4$ | 182.1354 | 1.2833 | 0.0182 |
| 2-nitrotoluene | $C_7H_7NO_2$ | 137.1378 | 1.163 | 0.06 |
| 4-nitrotoluene | $C_7H_7NO_2$ | 137.1378 | 1.392 | <0.1 |
| Hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX) | $C_3H_6N_6O_6$ | 222.117 | 1.82 | Insoluble |

| Compound Name | Chemical Formula | MW (g/mol) | Density (g/mL-20ºC) | Solubility (g/100mL-20ºC) |
|---|---|---|---|---|
| Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX) | $C_4H_8N_8O_8$ | 296.156 | 1.90 | Insoluble |
| Tetryl | $C_7H_5N_5O_8$ | 287.1452 | | 0.02 |
| 2,4,6-trinitrotoluene (TNT) | $C_7H_5N_3O_6$ | 227.133 | 1.64 | 0.01 |

Data for this table extracted from the NIST Chemistry Webbook, Cambridge Chemfinder and the Agency for Toxic Substances and Disease Registry internet resources.

*2.2.4 Metals*

Metals include any of the class of chemical elements of atomic number 20 and greater with metallic luster, ductility, and the ability to conduct heat and electricity. Although metals are naturally present in the Earth's crust, concentrated metal pollutants enter the environment in several ways, primarily though the burning of fossil fuels, as a result of mining and smelting activities, from the application of pesticides and fertilizers, and via sewage and municipal wastes. Metals in soils can exist as free ions, soluble complexes, bound to organics, precipitated or insoluble compounds (i.e. as oxides, carbonates, and hydroxides), or in silicate minerals (Salt, 1995).

Although small amounts of various metals are necessary for cell maintenance, metals can be toxic to both plants and animals in large amounts. Table 6 shows common metal pollutants and their health effects. Due to their prevalence, toxicity, and exposure potential, several of these metals are found in the top 20 on the 2003 CERCLA Priority List of Hazardous Substances, including arsenic (ranked first), lead (ranked second), mercury (ranked third), cadmium (ranked seventh), and chromium (ranked seventeenth) (CERCLA, 2003).

Traditional methods of mitigating metal contamination in soils include various isolation, extraction, immobilization, and toxicity reduction methods, including physical barrier (i.e. concrete, steel) isolation; chemical solidification/ stabilization; hydrocyclone, fluidized bed, or flotation processes; electrokinetic processes; soil washing; and pump-and-treat systems (Mulligan, 2001). Phytoremediation presents itself as a low-cost, solar-powered, environmentally-friendly alternative to methods such as extraction and pump and treat systems, which can be prohibitively expensive, and soil washing, which can reduce the fertility and bioactivity of soils (Datta, 2004). Because metals are generally non-biodegradable, phytoextraction is the most common mechanism of metals phytoremediation, although both phytovolatilization (i.e. for Hg, Se, As) and phytostabilization mechanisms occur. In general, metal uptake and phytoextraction coefficients decrease in the order $Cr6+ > Cd2+ > Ni2+ > Zn2+ > Cu2+ > Pb2+ > Cr 3+$ (EPA, 2000).

Although the first metal-hyperaccumulating plants were identified in the mid-1970s, this information has only recently been explored for purposes of remediation. A 1989 Baker review of terrestrial hyperaccumulators and a 2003 Reeves review of over 30 years' work on tropical hyperaccumulators by Robert Brooks and his colleague, catalogue many of the known species able to extract metals (including arsenic, cadmium, chromium, copper, cobalt, iron, manganese, nickel, lead, zinc). Yet despite the breadth of morphological/ geographical information now available for over 400 identified hyperaccumulator species, most plants are restricted to highly metaliferous, ultramafic (igneous, iron and magnesium-rich) soils and tropical environments, of relatively small biomass and slow-growing (Pulford, 2003). Additionally, not much is known about exploiting these properties for phytoremediation (Reeves, 2003).

The limits of these hyperaccumulator plants are apparent after a review of the very few field-scale metal phytoremediation successes, despite several years of intense efforts to find a magic phyto-bullet. Disappointing performance of lead phytoextraction was illustrated at the Fort Dix Superfund site, where the amount of lead removed was less than the uncertainty in the heterogeneous soil profile and less than the amount of unaccounted "missing" lead (Rock, 2003). Similarly, ineffectiveness of lead removal was concluded at the Magic Marker Superfund site, where lead concentrations in phytoextracted tissue did not account for the reduction in soil lead concentrations (Rock, 2003). These inefficacies have led to current research interests in identifying those genes responsible for metal resistance and accumulation and in developing enhanced transgenic plants for application in the field. Recently, Song (2003) explored the effect of inserting yeast proteins into mouse ear cress (*Arabidopsis thaliana)* and Gisbert (2003) investigated genetically-modified shrub tobacco (*Nicotiana glauca*), in two independent efforts to develop a lead and cadmium tolerant plant that may lead to better field success in the future.

One of the most important factors determining metal phytoremediation success is contaminant bioavailability. Metal bioavailability is determined by physical factors (contaminant coarseness, soil texture, etc.), chemical factors (concentration, speciation, pH, Eh, cation exchange capacity, acidity, redox potential), and biological factors (plant, mychorrizal, and microogranism activity) (Ernst, 1996). Some of these factors can be altered in the development of a phytoremediation site, such as importing more amenable soils, adjusting pH and/or alkalinity, etc. For example, decreasing soil pH generally increases metal availability, but it is important to make sure plants are able to survive under the same pH conditions. Competition between metals can also have a profound effect: in general, increasing the metal loading rate in a soil (i.e. containing cadmium, chromium, copper, manganese, lead, and zinc) decreases the bioconcentration factor of metals in plants. (Wang, et al 2002).

**Table 6. Potential Human Health Effects of Metals**

| Metal | MW | Health Effect |
|---|---|---|
| Arsenic | 74.92 | Acute: Lung irritation, nausea, vomiting, blood vessel damage, abnormal hearth rhythm, death. Chronic: keratoses and skin effects; peripheral vascular disease; hypertension and cardiovascular disease; cancers of the bladder, kidney, liver, and lung; diabetes mellitus; possible neurological effects |
| Lead | 207.20 | Affects central nervous and reproductive system, damages kidneys, may cause anemia, decrease reaction time, cause weakness in fingers, wrists, ankles, and affect memory. |
| Mercury | 200.59 | Bronchitis, gingivitis, pulmonary edema, nervous system disorders, and permanent damage to brain, kidneys, and developing fetus. |

| Metal | MW | Health Effect |
|---|---|---|
| Cadmium | 112.41 | Pulmonary edema, emphysema, anemia, lung cancer, anosmia, kidney disease, fragile bones with long-term exposure. Acute exposure: lung damage, vomiting, diarrhea, and death |
| Chromium | 52.00 | Nosebleed, ulcers, stomach upsets, convulsions, kidney and liver damage, death. Cr (VI) is a carcinogen. |
| Zinc | 65.39 | Corneal ulceration, esophagus damage, pulmonary edema, skin irritation, stomach cramps, nausea, vomiting. |
| Nickel | 58.69 | Dermatitis, pneumonia, lung and nasal cancer, chronic bronchitis, effects on blood and kidneys. Probable carcinogen. |
| Silver | 107.87 | Blindness, skin lesions, pneumonoconiosis, arygria, lung irritation, stomach pains. |
| Copper | 63.55 | Acute: stomach and intestinal distress, liver and kidney damage, anemia. Chronic: headaches, dizziness, nausea, diarrhea. |
| Manganese | 54.94 | Liver cirrhosis, pneumonia, bronchitis, manganism, respiratory problems, sexual dysfunction |

Data for this table extracted from the Cambridge Chemfinder and the Agency for Toxic Substances and Disease Registry internet resources.

Chlorinated solvents, pesticides, explosives and metals are only four of several major contaminants found at hazardous waste sites and only one of many site characteristics that define a site. The varying nature of what can be found at a site poses a challenge for determining whether phytoremediation is a viable remediation technology for any particular site. The next section of this document details considerations for determining whether phytoremediation is appropriate for a site.

# 3. IS PHYTOREMEDIATION RIGHT FOR YOUR PROJECT?

## 3.1 Site Characteristics

*3.1.1 Site Characterization*

A thorough site analysis that includes contaminant, geological, hydrological, and soil assessments is essential to determine base line conditions, phytotoxic conditions, the potential for contaminant removal, and to meet treatment goals (Tsao, 2003). The ITRC has produced Decision Tree documents (1999, 2001) to aid in the evaluation of a potential phytoremediation sites, although a brief overview of some important considerations can be found below.

*3.1.1.1. Contaminant*

As discussed previously, the nature of the contaminant (recalcitrance, persistence, bioavailability, etc.) is crucial when developing effective phytoremediation strategies for a given site. High contaminant concentrations may limit phytoremediation as a treatment option due to phytotoxicity or the impracticality of using such a slow remediation method. Additionally, the physical location of the contaminant will determine the efficacy of treatment. Due to plant root limitations, phytoremediation of soils and sediments is typically employed for contaminants in the near surface environment within the root zone. For groundwater treatment, phytoremediation is limited to unconfined aquifer where the water table and the contaminant are both within reach of plant roots (either in direct contact or via transpiration).

*3.1.1.2. Site Area and Activities*

Past, current, and future site activities will affect phytoremediation system design. Past site activities will determine contaminant and soil properties (i.e. quantity, age, and quality) at the site and existing vegetation may influence the growth and stability of any introduced phytoremediating plant species. An area assessment will be required to consider the amount of space available for phytoremediation, to identify any physical obstacles, and to accommodate any concurrent activities. Chemical, physical, and biological impacts of vegetation on the site should also be determined. Because phytoremediation is a long-term remediation process, often on the order of several years, any proposed future site activities will also need to be considered and integrated into the final system design.

*3.1.1.3. Geological and Hydrological Conditions:*

Topography of the site will affect surface and subsurface flow patterns and drainage. A proper evaluation of the hydrologic regime includes measuring recharge, potentiometric levels, and discharge, and includes a determination of surface and subsurface runoff, infiltration, and water storage. The remediation of groundwater requires creating a cone of depression so contaminants can be transported to the plant root zone for treatment. The goal of hydraulic control is to have plume movement minimized as much as possible, where infiltration is roughly equal to the amount of evapotranspiration. Runoff and infiltration controls are necessary to prevent contaminant mobilization. At sites with very porous soils, lining may be required to control the amount of infiltration. Calculating the overall water balance of the system may be required to estimate whether phytoremediation will be effective at controlling contaminant plumes. The use of hydrological models, such as the USGS groundwater model MODFLOW, can aid in the assessment and characterization of aquifer and contaminant movement. For example, site characterization and groundwater flow modeling using MODFLOW at the Aberdeen Proving Grounds found phytoremediation processes to be more effective than groundwater circulation wells in the control and removal of dissolved-phase volatile organic compound (VOC) plumes contaminating the site (Hirsh, 2003).

*3.1.1.4. Soil Type*

Soil characteristics, such as moisture content, available oxygen, organic matter content, cation exchange capacity, pH, alkalinity, content, texture (particle size), and temperature will have significant effects on contaminant mobility and fate. For example, metal bioavailability in high clay and low organic content soils is decreased. Higher soil cation exchange capacity indicates greater sorption of metal contaminants. Soil fertility will determine whether additional fertilizers will be necessary. Soil pH affects metal contaminant solubility as well as plant growth, and a balance should be met to maximize both. The importance of soil conditions was made apparent in a recent study by Boyle and Shann (1998), who compared the growth response of three different plant species (sunflower, Timothy grass, and red clover) under varying soil conditions (coarse silty loam, fine clay loam, and fine-silty loam) and found soil type to be one of the most significant factor in rhizosphere degradation of a pesticide (2,4,5-trichlorophenoxyacetic acid). Characterization studies to assess horizontal and vertical distributions of soil properties should be undertaken prior to full-scale implementation.

#### *3.1.2 Climate*

At the macro scale, climate is one of the major factors affecting evapotranspiration rates and, subsequently, the amount of contaminant that can be contained. Optimal conditions for maximum evapotranspiration are high water, high solar radiation, high wind speed, warm temperature, low relative humidity (high vapor pressure gradient), and long growing-season environments (Vose, 2003). Evapotranspiration is linearly related to precipitation and the amount of water available in the soil. Solar radiation regulates the opening and closing of the stomata and wind speed affects convective flow across leaf surface area. Relative humidity and vapor pressure gradients on the leaf surface will limit the amount of transpiration. Frost dates serve as limits to effective duration of a phytoremediation season for most plant species.

#### *3.1.3 Time Constraints*

Phytoremediation is a long-term remediation strategy, but the time required varies and is hard to predict. It requires sufficient time for vegetation to become established and grow to levels associated with higher transpiration rates. Phytoremediation is also limited by climate variation and seasonal effects particular to a site, which lengthen the overall time required. For example, perennial plants require at least a year to establish, and for organic compounds, at least three or more years are needed to allow for plant stabilization (Davis, 2003). A rough estimate of the clean-up time required can be extrapolated from calculating the rate of contaminant uptake by a plant. The uptake rate requires knowing the efficiency of uptake (i.e. transpiration stream concentration factor, TSCF), the transpiration rate, and the concentration of contaminant in soil solutions (Schnoor, 2003).

### 3.2 Plant Considerations

#### *3.2.1 Plant Selection*

Selection of appropriate plants should take into consideration issues of contaminant tolerances, evapotranspiration rates, climate and weather (e.g. flood, drought) tolerances, growing season, root depth, and disease and pest resistance. Although no plant protocols have been established, an integration of this database with others (such as the U.S. Department of Agriculture [USDA] plants database) can be used to narrow down the possibilities.

#### *3.2.2 Types*

Plants used in phytoremediation include trees, grasses, flowers, and shrubs, and various aquatic plants. Although nearly all the phytoremediation sites to date have used terrestrial plants, several hydroponic and aquatic plant studies have been employed for use in constructed wetlands and in plant/ phytotoxicity screening to determine the efficacy of contaminant uptake from groundwater under idealized conditions. Aquatic plants have great potential for *in situ* remediation, such as with the use of constructed wetland biofilters, however they are not considered any further here. Plant selection requires demonstrated effectiveness at mitigating the pollutant of concern and a phytotoxicity evaluation. A perusal of the phytoremediation database shows that the species most commonly used in field-scale phytoremediation applications are (hybrid) poplar, (hybrid) willow, cottonwoods, ryegrass, fescue, alfalfa, Indian mustard, and parrot feather. The popularity of hybrid poplars is due to their quick growth, deep roots, and extremely high rates of evapotranspiration. Poplars and other plants, however, vary considerably across their genus in their phytoremediating abilities (i.e. growth rate, metabolic activity, rooting characteristics, disease and drought resistance, etc.), so care should be taken when selecting cultivars that have worked at a site with differing characteristics (Compton, 2003; White, 2003). For heavy metals, accumulator plants typically selected are not only able to tolerate and accumulate pollutants, but also have high above-and-below-ground biomass and are fast growing; however, Pulford (2003) proposes using non-accumulator plant species for heavy metal uptake in arrangement with optimized soil conditions (i.e. chelation) or via genetically-modified strains. For organics, vegetation should generally be fast growing, have high evapotranspiration rates, and transform contaminants to less toxic or nontoxic forms (ITRC, 1999). For remediation of chlorinated solvents, typically used species include hybrid poplar and hybrid willow (see database). For munitions, periwinkle (*Catharanthus roseus*) has been successful for munitions, in addition to the parrot feather (*Myriophyllum aquaticum*), although hybrid poplar is beginning to emerge as an alternative (Hughes, 1997; Bhadra, 1999; Wayment, 1999). Pesticides are most commonly treated using hybrid poplars, although various other crop, grass, and colonizing plant species have shown tolerance and phytoremediating potential in the laboratory, as summarized by Karthukeyan *et. al* (2004).

*3.2.3. Phytotoxicity and Treatability Evaluation*

Toxicity screening tests are use to determine possible plants for a set of contaminant, nutrient levels, pH, and salinity conditions. Using these bench-scale pot, hydroponic, or greenhouse studies is a prerequisite to actual implementation at a contaminated site. When evaluating plants in phytotoxicity studies, a general rule to follow for organic contaminants is that plants able to survive 10+ mg/L of organic contaminant are recommended, with plants surviving 1-10 mg/L conditions as additional possibilities; for inorganic contaminants, species able to tolerate 100+ mg/L are recommended, with plants surviving at 10-100 mg/L as additional possibilities (Gatliff, 2004). Treatability studies are used to estimate the rate of contaminant treatment, to determine fate and transport in the system, and to develop models and mass balances. In treatability studies under controlled conditions, it is imperative to replicate site conditions (site soils, humidity/ water availability, pH, etc.) as closely as possible. A review of the genetic and molecular basis of plant tolerance and phytotoxicity was recently undertaken, with special attention to chlorinated aliphatic compounds and explosives (Medina, 2003). Karthikeyan *et al* (2004) recently reviewed the laboratory-scale tolerances of various tree, grass, and crop species to various pesticide compounds.

*3.2.4. Root and Rhizosphere*

Roots have a variety of functions that include structural support for plants, the uptake of nutrients and water, and the release of exudates. For phytoremediation, treatment is limited to the roots' zone of influence and therefore the contaminant depth should not exceed root depth. For non-woody plants, the effective root depth usually does not extend more than a couple feet; however, for phreatophytes (i.e. poplar trees) this depth can be extended significantly by methods of deep rooting. Root exudates also play a crucial role in rhizosphere phytoremediation processes for both inorganic and organic contaminants.

Exudates are compounds released from plant roots that stimulate microbial growth and activity in the rhizosphere. Exudates can also alter soil pH, act as chelating agents, aid in nutrient recomplex with metals, and degrade organic compounds (Tsao, 2003). Root turnover is yet another mechanism of adding organic substrate to soils for the stimulation of microorganisms. Although rhizosphere processes are generally poorly understood, several plant species (e.g. legumes) are capable of sustaining active microbial populations, and may be selective in their capacity to degrade certain compounds, such as pesticides (Karthikeyan, 2004).

Root growth in the contaminant zone is a function of contaminant and water depths, climate, nutrient availability, water distribution, soil strength, and available oxygen (Negri, 2004). A few recent studies illustrate the importance of these factors. For example, Nzengung (2004) observed that available oxygen, nutrients (nitrate), root mortality, and redox conditions determined whether rhizodegradation of perchlorate in the root-zone was the favored phytoremediation mechanism. A 2003 study by Keller that compared the ability of various plant species to extract copper, zinc, and cadmium from soils found that a larger ratio of root density to above-ground biomass and generally large overall root area were positive factors. Modulating root temperature by the use of polyethylene mulches for enhancing cadmium and zinc extraction in potato plants was proposed by Baghour (2002).

*3.2.5 Planting Methods*

The method of planting will depend on the type of vegetation used in treatment. For example, grasses are usually dispersed as seeds, and trees such as poplar are transplanted from pots as whips or from cuttings. Planting dates are dependent on the climate at a given site. Seeding methods including depth of sowing, then “pelletizing” of smaller seeds, hand vs. machine sowing, density and distance between rows have been discussed in the literature (Angle, 2001). Typically, vegetation is planted at the leading edge of the contaminant plume, perpendicular to groundwater flow (Ferro, et. al 2003).

If deep rooting is required, poplars and willows are popular phreatophyte choices due to their natural predisposition to develop roots at greater depths, especially in porous soils and arid environments. Rooting below 1 meter usually involves installation in boreholes or trenches, along with engineered media to direct the root growth. Deep rooting can be feasibly engineered to depths of up to 40 feet. Engineered media includes backfill material to maintain favorable root growth conditions, and casings to direct root growth and reduce the amount of surface water available, as well as short-circuiting, in the system (Negri, 2003). Deep rooting may not always have desired effects. For example, Sung (2003) found that rooting at depth made no difference in TNT or PBB disappearance rates for Johnsongrass (*Sorghum halapense*) and Canadian wild rye (*Elymus canadensis*). Additionally, care should be taken to ensure there is a sufficient lateral root system to maintain structural support.

*3.2.6 Native versus Non-native Species*

Recent legislation, such as two recent Executive Orders (1994, 1999) and the 1996 Invasive Species Act and the 2000 Plant Protection Act, limit the introduction of invasive or non-native plant species to areas where they are not indigenous. In addition to regulatory reasons, indigenous species are recommended over non-native species for use in phytoremediation projects as they involve the least amount of human and ecological risk. Native species are often better adapted to the conditions of the environment (i.e. adapted to soil conditions and are tolerant to the hydraulic regime), require less maintenance, monitoring, and control, have lower energy requirements, and involve less residual disposal (Marmiroli, 2003; Compton, 2003). The hierarchy for selecting plants is native species > hybrid species > non-native/ introduced species > engineered species (ITRC, 2004).

*3.2.7 Plant Specificity*

Although most phytoremediation sites are developed assuming a rigid plant-contaminant specificity, there have been some interesting developments in studies on plants that are able to remediate more than one class of pollutant. For example, a field plot study by Mattina *et al* (2003), determined concurrent uptake of chlordane and heavy metals (As, Cd, Pb, Zn) by Zucchini (Cucurbita pepo) and spinach (Spinachia oleracea). The possibility of one plant remediating multiple categories of contaminant should be accounted for in project design to ensure that remediation objectives are met.

*3.2.8 Transgenics*

Genetic modification of a plant involves insertion of a piece of foreign DNA (e.g. for enhanced tolerance or accumulation) into the genome of the species of interest. Wolfe and Bjornstad (2002) hypothesize that phytoremediation using genetically-engineered plants would create more opposition and controversy than non-genetically engineered plants based on past public responses to the biotechnology applications.

The negative perceptions and widespread resistance to the use of genetically-engineered plants can be attributed to "the failure of the biotechnology industry to educate the community about the risks and benefits of transgenic technology," which Linacre (2003) suggests can be overcome by adopting a combined risk assessment (i.e. defining risks, associated probabilities, and dose/consequences), risk management, and risk communication strategy.

Despite the aforementioned social obstacles, research into transgenic plants has accelerated and modified, phytoremediating plants have been introduced at field-scale. While most past transgenic research has focused on developing hyperaccumulators or plants with enhanced biodegradation, some recent research has been undertaken to develop genes for "anti-contaminant/antibody fragments" capable of improved pollutant-accumulation (Chaudhry, 2002).

Genetically-modified lead accumulators were previously discussed, but a sampling of some recent GMO (genetically-modified organism) research follows: Transgenic mouse ear cress (Arabidopsis thaliana) has recently shown to hyperaccumulate arsenic in laboratory studies (Dhankher et. al, 2002). And in October 2003, the first commercial application of genetically modified species for phytoremediation was planted at a Danbury, CT brownfields site. In this particular case, bacterial genes that encode enzymes for conversion of toxic methyl mercury to volatile elemental mercury were inserted into cottonwood trees (APGEN, 2003).

## 3.3 Agronomic Considerations

*3.3.1. Plant Age and Metabolic Status*
While water content, diurnal cycles, temperature, and periods of dormancy are also important to determine metabolic status, frost dates for a given site is one of the largest determining factors (see database). Plant age determines plant size and overall leaf surface area, which in turn is responsible for evapotranspiration rates. For example, poplar transpiration rates are around 1.6-10 gallons per day (gpd) during the first two years, but transpiration rates increases to between 13-200 gpd after 10 years (ITRC, 2004). Plant age also determines contaminant tolerance; for example, in a study by Peralta-Videa (2003), the phytotoxicity of metals (i.e. Cd, Cu, Zn) to alfalfa plants decreased with plant age. Deciduous trees are dormant for a large part of year, while conifers continue to transpire at a reduced rate throughout the winter season and have higher overall rates of evapotranspiration due to higher total leaf surface area (Vose, 2003).

*3.3.2. Amendments*
The addition of inorganic, organic, and bio-amendments are often used to enhance phytoremediation, and there are a few recent applications of these to pesticides. Microbe-mediated rhizosphere degradation is a principal phytoremediation mechanism, and often the major limiting factor of pesticide biodegradation is a deficient population of microorganisms (Olson, 2003). One recent study showed that bacterial (*Actinomycete*) inoculants in soils increased the amount of 1,4-dioxane in soil that was mineralized, although their addition had little effect on the total amount of dioxane removed by hybrid poplars (Kelley *et al*, 2000). Laboratory studies have also shown that strains of *Agrobacterium tumefaciens* were capable of increasing root mass and stimulating PCB uptake by plants, an amendment method which may be applicable to pesticide remediation in the future (Chaudhry, 2002; Gleba, 1999).

Similarly, metal phytoextraction can be used as part of a treatment train or in combination with other remediation technologies. Popular alternatives include the addition of chelating agents such as EDTA, or organic acids such as citric acid that mimic natural plant excretion of organic ligands (Romkens, 2002). However, care must be taken when adding chelates and other amendments, because they may lead to uncontrolled releases and/or require costly engineered barriers to be put in place (Rock, 2003). Amendments should be evaluated in bench-scale studies prior to field application to ascertain optimum conditions. For example, citric acid may be degraded by microorganisms too quickly to be used in long-term remediation (Romkens, 2002), or the increased metal bioavailability with addition of EDTA and citric acid amendments may correspond to high levels of plant phytotoxicity (Chen, 2001; Turget, 2004). Adding biological amendments such as fungi and microorganisms, or integrating phytoremediation with another technology (e.g. electrokinetic remediation) is another possibility.

*3.3.3. Other Agronomic Issues*
Although monoculture plantations have often been used in phytoremediation in the past, there is increasing trend towards incorporating mixed cultures. Monoculture plantations have the advantage of reduced competition for nutrients and space, and it may be easier to

control undesirable organisms that do emerge. However, the use of a single plant species introduces several potential problems. Intensive monoculture cultivation requires high levels of irrigation, fertilizer, and amendments to sustain plant productivity. Monocultures are far less resistant to disease and invasive species than mixed cultures. Additionally, optimization of some phytomechanisms, such as rhizodegradation, requires a diverse and complex range of species interactions, which cannot occur under a single plant environment (Olson, 2003). If a mixed culture is used, the potential for alleopathy or interspecies competition between plants, which may lead to the subsequent inhibition of one plant, should be evaluated.

Plant rotation is commonly used in agronomic practices to recycle important nutrients in the soils, reduce the need for fertilizer and other amendments, and to alleviate stresses. Natural succession often results as an ecological community response to environmental stresses. Site operators may consider mimicking succession by first introducing a "pioneer" species to stabilize conditions, then adding a more and more diverse mix of plant species with time, improving disease and stress resistance (Olson, 2003). Additional agronomic recommendations include avoiding a grid pattern when planting, allowing for sufficient space between trees (for maintenance and monitoring activities), and installing monitoring equipment, drainage systems, etc. prior to planting (Compton, 2003).

### 3.4 Regulatory Considerations

Phytoremediation as a technology has experienced increased regulatory approval and standardization, although there are no federal regulations specific to phytoremediation to date. Regulations posed by the Resource Conservation and Recovery Act (RCRA), Comprehensive Environmental Response Compensation and Liability Act (CERCLA), Clean Air Act (CAA), Toxic Substances Control Act (TSCA), Federal Insecticide Fungicide and Rodenticide Act (FIFRA), Federal Food Drug and Cosmetic Act (FFDCA), Invasive Species Act, Plant Protection Act, statutes enforced by the USDA and state statutes must all be upheld when installing a phytoremediation system. USDA and state statues may govern the plant species used and the extent of vegetation allowed and/or required. Common issues faced under these regulations include:

- Transport of contaminants from the subsurface to the surface.
- Transport of contaminated media off-site
- Permits to dig on-site
- Permits to plant
- Handling of secondary waste/degradation products

Site managers must ensure all actions abide by the stipulated regulations and that proper permits are obtained.

### 3.5 Ecological and Social Considerations

It is obvious that success of a phytoremediation project is dependent on various technical aspects such as site, contaminant, and plant characterizations; equally imperative, yet less often considered, are numerous social considerations. Some issues that may affect community acceptability of phytoremediation include site aesthetics, odor production (i.e. with volatile contaminants), dust from tilling and maintenance, pest attraction, and production of pollen (i.e. aggravation of allergies). Additional issues may include the degree of perceived risk (i.e. contaminant concentrations and required length of treatment); unpredictability (i.e. the dearth of available data and research on this "emerging" technology); issues of genetic engineering; ecological impacts; the appropriateness of extrapolating demonstration to full-scale; and linking, or including as a part of a treatment train, phytoremediation to other, less acceptable technologies or practices. (Wolfe and Bjornstad, 2002).

There are several ecological concerns to be cognizant of when developing a phytoremediation site. As discussed previously, introduced species can become invasive if not controlled properly. Introduced and genetically-modified species can have possibly deleterious effects on nearby crops if interbreeding between species or cross pollination is allowed to occur. Monoculture plantations maybe more susceptible to disease, increasing the possibility of airborne plant diseases that may infect other ecological communities. Additionally, without proper pest and animal controls in place, bioaccumulated contaminants in vegetation may be enter the food chain.

Despite the aforementioned concerns, phytoremediation is generally regarded in a favorable manner because it is a solar-driven “green” technology that concurrently treats contaminants *in situ* and improves the aesthetics and habitat of the surrounding area.

### 3.6 Operation and Maintenance

Because phytoremediation uses living organisms, installations of the technology have unique O&M requirements when compared to other more traditional remediation systems. Maintaining a healthy system is crucial to the continuation and effectiveness of the remediation process. Varying plants, climates, and contaminants may cause a site to have some of, all of, or additional requirements to those listed here. Some unique operation and maintenance requirements for a phytoremediation site include:

- Visual inspections
- Fertilization
- Irrigation
- Weed control
- Mowing
- Harvesting
- Pest Control
- Replanting

Visual inspections, fertilization, irrigation and pest control are steps taken to ensure plant growth. Weed control aids in both plant growth and prevention of invasive species infiltration. Mowing is primarily implemented to facilitate easier monitoring and maintenance of the site. Harvesting plant tissue removes contaminants that have accumulated within the plant tissue. This storage of contaminants can be either a liability or an asset to a phytoremediation site. If the contaminant is a hazardous waste with no further use, the tissue must be disposed of as hazardous waste at an additional cost. Some contaminants accumulated in the plant tissue, such as heavy metals, may be reclaimed and sold in a practice known as phytomining. In such cases, these “cash crops” can be an asset to the project by defraying some of the total cost. Pest control is important to protect both the livelihood of the vegetation and also of the surrounding wildlife. Animals that eat or damage the vegetation can destroy plantations, thereby hindering remediation, but they can also harm themselves if they ingest contaminated plant tissue or water. Replanting is a maintenance issue necessary to ensure continuous contaminant uptake. Vegetation dies for several reasons (i.e. damage by animals, insects and weather) and needs to be replanted to maintain the root mass necessary for contaminant uptake and release of exudates. Dead plant matter, along with other debris, must be removed from the site. Site cleanup is a maintenance issue that helps facilitate easy monitoring and implementation of other maintenance needs. Vigilance, frequent site visitation, and maintenance during first year of a plantation is crucial and play a large factor in whether phytoremediating plants become established or not, with moisture availability and weed control being some of the more critical requirements (Compton, 2003).

### 3.7 Performance Monitoring

Some monitoring requirements for a phytoremediation system are similar to those of a traditional remediation system, such as contaminant concentration and groundwater levels. Phytoremediation installations also have unique characteristics that require monitoring. They include:

- Plant health
- Root depth and density
- Evapotranspiration
- Groundwater levels
- Tissue sampling
- Precipitation
- Soil moisture
- Microbial characterization

Plant health and root depth and density must be monitored to ensure continuous contaminant uptake and remediation in the target zone. Evapotranspiration and groundwater level monitoring, along with tissue sampling, can aid in confirming contaminant uptake and hydraulic control. Precipitation, soil moisture and microbial characterizations are monitored to classify the environment the system is operating in. This classification is important for two reasons. Firstly, data collected can be consulted when failures occur to aid in the determination of the cause. Notable changes in aspects of the environment can be investigated as possible remedies to the failure. Secondly, characterization of the climate is important to thoroughly document successful applications of phytoremediation. The varying nature of site characteristics suggests there is not one installation to be prescribed for all sites. Therefore, each site will have different monitoring requirements.

The site-specific nature of a phytoremediation prescription lends itself towards a need for thorough documentation of site installations. Experts in the field have given opinions about the kind of data that should be collected from each site in order for a phytoremediation database to be useful. The resulting compilation of phytoremediation sites has been organized into a database for easy navigation and implementation into searchable software programs if needed.

# 4. DATABASE

## 4.1 General Layout

The database is divided into four sections, one for each major contaminant class: chlorinated solvents, pesticides, explosives, and metals. Appendix A contains site contaminated with chlorinated solvents, Appendix B contains pesticide sites, Appendix C contains explosives sites, and Appendix D contains metals sites. Each appendix contains, at the beginning, a table of contents for every listed individual contaminant that details what sites contain what contaminant. In the pages following the table of contents, the data collected for each site have been compiled and are presented in a single page layout.

## 4.2 Soil and Climate Characterizations

In order to maintain uniformity for the entries in the database, a single classification system was necessary to define soil and climate characteristics. The need for a single system to be used in this database resulted in an extensive search and the eventual selection of one classification system. The USDA 1993 Soil Survey Manual was used for soil texture classification, because it contained a manageable range of classification terms. Others soil classification systems had too many or too few categories to sufficiently characterize soil. In addition, soil texture classes used in the USDA Manual were identical to those found in a majority of the existing site literature. The soil texture categories, containing a brief description, are listed in Appendix E.

Following a review of the available site data and consultation with experts, the critical climate parameters necessary for phytoremediation site determination were defined. These parameters include site average temperature ranges, elevation, average annual precipitation, and frost dates (growing season). The National Oceanic and Atmospheric Association (NOAA) Cooperative Institute for Research in Environmental Sciences (CIRES) Climate Diagnostics Center was the resource used to obtain temperature, elevation and precipitation data. The primary factor in this decision was the availability of multiple criteria from one source. Frost date data was taken from the Victory Seeds.com website because of its ease of use and its reliable source of information. Victory Seeds data comes from the *Climatography of the U.S.* No. 20, Supplement No. 1 document released in 1988 by the National Climatic Data Center, NOAA, and the U.S. Department of Commerce.

When information for a particular site location was not available, data was taken from the closest city containing all the existing parameters. A representative list of cities across the United States, including the four critical climate parameters, can be found in Appendix F.

# 5. CONCLUSION

## 5.1 Summary

A summary of findings for each of the four contaminant classes, including the number of field-scale sites, typical contaminants, most commonly planted species, and cost range of site implementation and operation, is provided below.

### *5.1.1 Chlorinated Solvents*

Appendix A contains 47 sites that have used phytoremediation to treat chlorinated solvents. The most common contaminants found at these sites are trichloroethene and perchloroethene. Hybrid poplar and phragmites are the typical plant species used in treatment. Total costs for installation, operation, and maintenance of these phytoremediation sites vary widely, from about $51,000 to $2.1 million per site. The higher costs associated with some of these sites generally reflect pilot or demonstration sites where extensive research operations and/or monitoring and are included as part of the total cost.

### *5.1.2 Pesticides*

Appendix B contains 19 sites for the phytoremediation of pesticides and herbicides. The most commonly remediated contaminants are atrazine and alachlor. Hybrid poplars are the most popular vegetation used in treatment. Costs for pesticide phytoremediation range between $6,000 and $5.4 million/acre, where the higher costs reflect pilot or demonstration sites.

### *5.1.3 Explosives*

Appendix C contains 12 field-scale sites that were used to remediate explosives. The most common explosive contaminants found at these sites are HMX (octahydrotetranitrotetrazocine), TNT (trinitrotoluene), and RDX (hexahydrotrinitrotriazine). Tobacco composting and constructed wetlands are most typically applied in treatment. Total costs for installation, operation, and maintenance of these sites vary between $60,000 and $1.8 million.

### *5.1.4 Metals*

Appendix D contains 44 sites for the remediation of metals and metalloids. The most commonly remediated metals are lead (in the past projects), and arsenic and mercury (currently). Metal-specific hyperaccumulator plants and poplars are most often planted to remediate metals contaminated sites. The cost of phytoremediation for these sites ranges between $5000 and $4 million per acre.

Referring to the compiled data, it can be deduced that no single application of phytoremediation is appropriate for all sites. Rather, a prescription must be made based on a thorough site assessment. Phytoremediation may be the sole solution to a remediation project in instances where time to completion is not a pressing issue. While phytoremediation may not be a stand alone solution to all hazardous waste sites, it can certainly be used as part of a treatment train for site remediation either during peak growing seasons or as a polishing step to clean up the last remaining “hard to get” low concentrations.

Phytoremediation is still a new technology looking for industry-wide acceptance. The number of field sites collected in this project indicates it has received greater acceptance for chlorinated solvents and metals while just starting to gain acceptance within the explosives and pesticides domains. Continued bench-scale studies are needed to determine plant toxicities, degradation pathways and contaminant fates and the resulting field scale applications are necessary to provide proof the technology works in order for phytoremediation to be fully accepted by the industry.

## 5.2 Outlook

The data compiled in this project may have a future as part of a larger database. EPA Region 5 and EnviroCanada are currently working on similar data compilation projects. EPA Region 5 is focusing on field sites applying phytoremediation to remediate radionuclides and EnviroCanada is focusing on total petroleum hydrocarbon (TPH) sites. Together, the three data sets will address six of the seven major contaminant groups, leaving only non-halogenated organics to be addressed.

Though plans have not been thoroughly investigated or confirmed, there is a possibility that the data collected in this project will be incorporated into a searchable software program for easier use and navigation in the future.

# Appendices

# Appendix A: Chlorinated Solvents Database

*Table of Contents*



PCE = Perchloroethene
TCE = Trichloroethene
DCE = Dichloroethene
TCA = Trichloromethane
DCA = Dichloromethane
PCA = Perchloromethane
DCM = Dichloromethane
VC = Vinyl Chloride
CT = Carbon Tetrachloride
CF = Chloroform
PCB'S = Polychlorinated Biphenols
PCDF = Polychlorinated dibenzofurans

| | |
|---|---|
| **Site Name** | Aberdeen Proving Grounds J-Field |
| **Site Location** | Edgewood, MD |
| **Contaminant** | 1,1,2,2-Perchloroethane, 1,1,2-Trichloroethane, Perchloroethylene, Trichloroethylene, Dichloroethylene, 1,2-Dichloroethane, Vinyl Chloride |
| **Vegetation Type** | Hybrid Poplar, Sweet gum, -Silver Maple, Magnolia trees(1996) |
| **Planting Descriptions** | 184-2 yr old hybrid poplars planted 2-6' bgs. Surficial drainage installed to remove precipitation quickly to allow roots to reach GW |
| **Media Type** | Groundwater, Soil: tight soils, silty sand |
| **Site Characterizations** | GW 0.3-2.5m bgs. Laterally continuous layer of clay prevents contamination moving deeper than 8' |
| **Evapotranspiration Rates** | Tree uptake is 1,091gpd, expected 1,999gpd after 30 yrs growth. |
| **Climate** | Temp. range: -7 to105; Elev: 148 ft; Mean annual precip: 105"; Growing season: 4/11 to 10/29 |
| **Mechanism** | Phytodegradation, Hydraulic Control |
| **Operation/Maintenance Requirements** | Insect Control, animal control, mowing |
| **Project Scale** | Full Scale - 1 acre |
| **Project Status** | Operational/In Progress. Planted April 1996 |
| **Cost** | Tree: $80 each Prep: $5,000 UXO Clearance: $80,000 OM: $30,000 |
| **Funding source** | DoD Lead, Federal Oversight |
| **Initial concentrations** | up to 260ppm |
| **Final Concentrations** | No reduction in concentrations. Continuous source. |
| **Lessons Learned** | |
| **Comments** | TCE was detected in leaf tissue during the first year of the project. A transect of monitoring wells has been used to evaluate the program's effect on groundwater and has shown significant hydraulic effects by the trees. GW sampling indicates contaminants have not moved off site. |
| **Primary Contact** | Steven Hirsh, US EPA (215) 566-3352 hirsh.steven@epa.gov |
| **Citation** | Phytotransformation Groundwater Capture on 1 Acre Plot, Phytoremediation: Technology Evaluation Report. GWRTAC TE-98-01 (p 8) |

| | |
|---|---|
| **Site Name** | Altus Air Force Base, Oklahoma |
| **Site Location** | Altus AFB, OK |
| **Contaminant** | TCE, cis-1,2-DCE, PCE |
| **Vegetation Type** | *Populus x Canadensis Nor'easter* trees |
| **Planting Descriptions** | 109 10-gallon trees |
| **Media Type** | |
| **Site Characterizations** | GW 5-8' bgs |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. range: -8 to 110; Elev: 1280; Mean Annual Precip: 33.3"; Growing season: 4/15-10/16 |
| **Mechanism** | Hydraulic control |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | 0.3 acre Demonstration |
| **Project Status** | Planted 3/1999 |
| **Cost** | |
| **Funding source** | AFCEE |
| **Initial concentrations** | TCE (2-1,400 ug/l), cis-1,2-DCE (1-540 ug/l), PCE (2-1,200 ug/l) |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Rafael Vazquez, AFCEE (210) 536-1431 rafael.vazquez@brooks.af.mil |
| **Citation** | Work Plan for the Phytostabilization of Chlorinated Solvents from Groundwater at Site 2, Altus Air Base, Oklahoma, NTIS: ADA381406, 1999 |

| | |
|---|---|
| **Site Name** | Amboer Road |
| **Site Location** | Milwauki, OR |
| **Contaminant** | PCE, degradation pdts |
| **Vegetation Type** | Hybrid Poplar |
| **Planting Descriptions** | |
| **Media Type** | Groundwater, Soil |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. Range: 6 to 107 F; Elev: 33 ft; Mean Annual Precip: 36.3"; Growing season: 4/16-10/18 |
| **Mechanism** | Phytoextraction, phytodegradation |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | Field Demonstration (pilot), 5 acres |
| **Project Status** | Operational/In Progress |
| **Cost** | ~ $120K |
| **Funding source** | |
| **Initial concentrations** | PCE, degradation pdts, 1ppm - 50ppb in groundwater, 100ppm in soil |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Lee Newman, U of SC (803)777-4795, Newman2@gwm.sc.edu |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Anonymous |
| **Site Location** | Tacoma, WA |
| **Contaminant** | TCE, CCl4, PCE |
| **Vegetation Type** | Populus trichocarpa x P. deltoides |
| **Planting Descriptions** | Whips hand planted. Ammonium nitrate used |
| **Media Type** | Soil: Sandy loam |
| **Site Characterizations** | GW 11+' bgs |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. range: -8 to 104; Elev: 36 ft; Mean annual precip.: 50.5", Growing season: 5/17 to 9/30 |
| **Mechanism** | Phytoextraction |
| **Operation/Maintenance Requirements** | Fertilization, irrigation |
| **Project Scale** | Field demonstration, 1200 sq yd |
| **Project Status** | Jun-96 |
| **Cost** | $1,000,000 |
| **Funding source** | |
| **Initial concentrations** | TCE, CCl4, PCE |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Most plants thrived. Contaminants added at 15-20 mg/l and removed in surplus water. |
| **Primary Contact** | Milton P. Gordon, U of WA (206) 543-1769, miltong@u.washington.edu |
| **Citation** | L. A. Newman et al. Remediation of trichloroethylene in an artificial aquifer with trees: A controlled field study Environ. Sci. Technol. 33:2257-2285 (1999) |

| | |
|---|---|
| **Site Name** | Argonne National Laboratory: 317/319 Area |
| **Site Location** | Lemont, IL |
| **Contaminant** | Perchloroethene, Trichloroethene, Carbon Tetrachloride, Chloroform, Zinc, Lead, Arsenic, Tritium |
| **Vegetation Type** | Eastern gamagrass, Hybrid Poplar, Golden Weeping Willow, Hybrid Prairie Cascade Willow, Laurel-leaved willow |
| **Planting Descriptions** | 800 whips planted. 420 poplars installed in deep, lined boreholes (TreeWells®) 389 willows and poplars planted at or near surface. Used patented TreeWells® and TreeMediation® (Applied Natural Sciences Inc) |
| **Media Type** | Groundwater, Soil: Top-Bottom: 10' silty clay, 2' shallow aquifer, 8' silty clay, 10' silt/sand/silty clay deep aquifer |
| **Site Characterizations** | Groundwater 25-30' bgs, aquifer 5' |
| **Evapotranspiration Rates** | |
| **Climate** | |
| **Mechanism** | Phytostabilization, phytoextraction, phytodegradation, rhizodegradation |
| **Operation/Maintenance Requirements** | Fertilization, replanting, and significant Health/Safety expenditures because of radiological and other concerns |
| **Project Scale** | Full-scale (4 acres) |
| **Project Status** | Ongoing (planted 1999) |
| **Cost** | $1.2M |
| **Funding source** | US DOE |
| **Initial concentrations** | n/a; varies considerably throughout site, from ppb to ppm |
| **Final Concentrations** | n/a; varies considerably throughout site, from ppb to ppm |
| **Lessons Learned** | TreeWells® installed in effort to achieve hydraulic control |
| **Comments** | TCE and PCE and breakdown products (trichloroacetic acid) were detected in branch tissue of trees planted in contaminated soil in less than a year. TCE and PCE present in trees down gradient of plume after 2 yrs. |
| **Primary Contact** | Cristina Negri, Argonne National Laboratory (630) 252-9662 negri@anl.gov<br>Ed Gatliff, Applied Natural Sciences (513) 895-6061 ans@fuse.net |
| **Citation** | Negri, M.C., et al 2003 Root Development and Rooting at Depths, in S.C.<br>McCutcheon and J.L. Schnoor, eds., Phytoremediation: Transformation and Control of Contaminants: Hoboken, NJ, John Wiley & Sons, Inc. p233-262, 912-913<br>Quinn, J.J., et al 200 Predicting the Effect of Deep-Rooted Hybrid Poplars on the Groundwater Flow System at a Phytoremediation Site: International Journal of Phytoremediation, vol. 3, no. 1, p. 41-60 |

| | |
|---|---|
| **Site Name** | Ashland, Inc. |
| **Site Location** | Milwaukee, WI |
| **Contaminant** | Dichloroethene, Perchloroethene, Trichloroethene, Benzene, Toluene, Ethyl benzene, Xylene, gasoline and diesel-range organics |
| **Vegetation Type** | Hybrid poplar trees, under story grasses |
| **Planting Descriptions** | 485 trees planted |
| **Media Type** | Groundwater, soil: Fill soil, concrete and rock |
| **Site Characterizations** | GW 10' bgs |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. range: -26 to 103; Elev.: 672 ft; Mean annual precip.: 34"; Growing season: 5/20-9/26 |
| **Mechanism** | Phytoextraction, rhizodegradation, hydraulic control |
| **Operation/Maintenance Requirements** | Mowing, weeding, composting, insecticide |
| **Project Scale** | Full-scale, 0.4 acres |
| **Project Status** | Active. Planted in May 2000 |
| **Cost** | $80,000 |
| **Funding source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Tree survival = 88% initially, 99% after replanting phytotoxic areas. Trees have tripled in height since planting. Roots observed at 10' depth during first growing season. Subsurface aeration has increased soil oxygen levels from 5% to 15%. |
| **Primary Contact** | Jim Vondracek, RMT (614) 790-6146 jevondracek@ashland.com |
| **Citation** | McLinn, E., Vondracek, J., and E. Aitchison. 2001. "Monitoring Remediation with Trembling Leaves: Assessing the Effectiveness of a Full-Scale Phytoremediation System". In: A. Leeson, E. Foote, M. Banks, and V. Magar (eds.) Phytoremediation, Wetlands, and Sediments, p121-127. Battelle Press, Columbus, Ohio. |

| | |
|---|---|
| **Site Name** | ATK Thiokol |
| **Site Location** | Elkton, MD |
| **Contaminant** | Chlorinated VOCs, TCA, TCA |
| **Vegetation Type** | TCA 25-26ppm, TCE 170ppb |
| **Planting Descriptions** | |
| **Media Type** | Willows |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. Range: -14 to 102; Elev.: 36 ft; Mean annual precip.: 40.8"; Growing season: 4/25-10/15 |
| **Mechanism** | |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | |
| **Project Status** | |
| **Cost** | |
| **Funding source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | No recent monitoring of concentrations |
| **Citation** | Dave Gosen, Alliant Tec Systems (952) 351-2664 dave.gosen@atk.com |

| | |
|---|---|
| **Site Name** | Bofors-Nobel Superfund Site |
| **Site Location** | Muskegon, MI |
| **Contaminant** | 3,3 Dichlorobenzidine, vinyl chloride, Perchloroethene, Aniline, Azobenzene, Benzidine, 3,3 Dichlorobenzidine Toluene |
| **Vegetation Type** | hybrid poplar |
| **Planting Descriptions** | |
| **Media Type** | Groundwater, soil |
| **Site Characterizations** | GW 6' bgs |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. Range: -15 to 99; Elev.: 644; Mean annual precip.: 32.6"; Growing season: 5/24-9/24 |
| **Mechanism** | Rhizodegradation, phytoextraction, phytodegradation |
| **Operation/Maintenance Requirements** | cutting down any tree species that does not survive in the contained area |
| **Project Scale** | Pilot scale. Approximately 20 acres of planted tree species, with another (approx.) 20 acres of engineered treatment wetlands. |
| **Project Status** | On hold. Planted 6/2004 |
| **Cost** | Estimated total remedy cost can be from about $ 15 million up to $ 30 million. |
| **Funding source** | PRP, Federal/State overview |
| **Initial concentrations** | Up to 3000-10000 ppm for halogenated and nonh semi vol |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Phytoremediation is not the main goal of the remedy. The main goal is containment using the underground barrier (slurry) wall, with phyto as an enhancement. |
| **Primary Contact** | John Fagiolo, USEPA (312) 886.0800 fagiolo.john@epa.gov<br>Ari Ferro, Phytokinetics (435) 750-0985 ariferro@phytokinetics.com |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Carswell Naval Air Station (NAS) Golf Club |
| **Site Location** | Fort Worth, TX |
| **Contaminant** | TCE, cis-1,2 DCE |
| **Vegetation Type** | *Eastern Cottonwood (Populus Deltoides)* |
| **Planting Descriptions** | 660 - whips and 2.5-3.8 caliper trees. Planting long side perpendicular to GW flow. |
| **Media Type** | Groundwater, soil: medium sand |
| **Site Characterizations** | GW 2.5-4m bgs, Aquifer thickness= 0.5-1.5m, K=6m/day, η=.25 |
| **Evapotranspiration Rates** | Whips: 2.4(Jun) - 0.42(Oct) gal/tree-day Calipers: 3.89(Jul) -0.24(Oct) gal/tree-day |
| **Climate** | Subhumid. Temp Range: -1 to 113; Elev.: 574; Mean annual precip.: 33.7"; Growing season: 4/8-10/24 |
| **Mechanism** | Phytodegradation Hydraulic control |
| **Operation/Maintenance Requirements** | Irrigation, fertilization, mulching |
| **Project Scale** | 0.5 acre Field Demonstration |
| **Project Status** | 8/1996 - 2001 |
| **Cost** | $8/5-gal tree, 29 wells (surveying, drilling, testing) - $200,000; biomass - $60,000. |
| **Funding source** | USAF, DoD's ESTCP, EPA's SITE |
| **Initial concentrations** | Avgs on 12/1996: TCE = 610 μg/L, cis-1,2-DCE = 130 μg/L, trans-1,2-DCE = 4 μg/L |
| **Final Concentrations** | Avgs on 7/1997: TCE = 550 μg/L, cis-1,2-DCE = 170 μg/L, trans-1,2-DCE = 4 μg/L |
| **Lessons Learned** | No hydraulic control was observed during dormant season from Nov-Mar |
| **Comments** | Although TCE conc. did not decrease, the mass of TCE in the plume down gradient of the study area decreased 11%, reducing the mass of contaminants moving off site. |
| **Primary Contact** | Steven Rock, USEPA (513) 569-7149 rock.steven@epa.gov Gregory Harvey, Wright-Patterson AFB (937) 255-7716 gregory.harvey@wpafb.af.mil |
| **Citation** | EPA/540/R-03/506 |

| | |
|---|---|
| **Site Name** | Combustion Superfund |
| **Site Location** | Denham Springs, LA |
| **Contaminant** | 1, 2-dichloroethane, polychlorinated biphenyls, benzene, lead, mercury, nickel, silver, toluenediisocyante, toluene diamine |
| **Vegetation Type** | Eucalyptus, Poplar, Native Willows |
| **Planting Descriptions** | Potted Stock |
| **Media Type** | Groundwater |
| **Site Characterizations** | 5-10' depth of impact |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. Range: -8 to 102; Elev.: 59 ft; Mean annual precip.: 60.8"; Growing season: 3/18-11/4 |
| **Mechanism** | Hydraulic control, rhizodegradation, phytovolatilization |
| **Operation/Maintenance Requirements** | Mowing |
| **Project Scale** | Full-Scale |
| **Project Status** | Planted 2002 |
| **Cost** | Est. Present Worth: Capital Cost = $1,700k, O&M Cost = $561k, Total Cost = $2,261k<br>Est. Present Worth: Site Long-Term Care O&M Cost = $123k<br>Est. Present Worth Pond Area GW Monitoring: Capital Cost = $13k, O&M Cost = $69k, Total Cost = $82k<br>TOTAL: Present Worth Capital Cost = $1,713k, Present Worth O&M Cost = $753k, Present Worth Total Cost = $2,466k |
| **Funding source** | Combustion Superfund |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | In-situ hot spot treatment plus phytoremediation and monitored natural attenuation. 5-10 ft (depth of impact) |
| **Primary Contact** | Katrina Coltrain, US EPA (214) 665-8143 Todd Thibodeaux, LDEQ (225) 219-3225<br>David Tsao, BP Remediation Mngmt Function (630) 836-7169 tsaodt@bp.com |
| **Citation** | LDEQ, EPA6 |

| | |
|---|---|
| **Site Name** | Contaminated Paint Factory |
| **Site Location** | Czech Republic |
| **Contaminant** | Polychlorinated Biphenyls |
| **Vegetation Type** | Ash, Austrian pines, Black locust and Willow trees |
| **Planting Descriptions** | 4-24 year old pre-established trees (no planting) |
| **Media Type** | Soil |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | |
| **Mechanism** | Rhizodegradation |
| **Operation/Maintenance Requirements** | None |
| **Project Scale** | Field Demonstration |
| **Project Status** | |
| **Cost** | |
| **Funding source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lesson learned** | |
| **Comments** | Austrian pine and Black locust significantly increased the number of PCB-degrading bacteria in their rhizospheres. |
| **Primary Contact** | |
| **Citation** | Leigh, M.B., J. Fletcher, D.P. Nagle, P. Prouzova, M. Mackova and T. Macek (2003) Rhizoremediation of PCBS: Mechanistic and Field Investigations |

| | |
|---|---|
| **Site Name** | Edward Sears Property |
| **Site Location** | New Gretna, NJ |
| **Contaminant** | PCE, TCE, DCM |
| **Vegetation Type** | Hybrid Poplars |
| **Planting Descriptions** | 118 trees 9'bgs. Deep rooted 10' bare root cuttings. Holes were drilled and plant installed, and backfilled with sand peat mix. 100 trees planted shallow 3'bgs. Hole drilled to top of clay 4-5 feet below grade. |
| **Media Type** | Groundwater, Soil: Sand 0-5' bgs sand/silt/clay 5-18' bgs. Equal parts sand silt clay. Below 18' sands and gravel. |
| **Site Characterizations** | GW 7-11' bgs |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. Range: -2 to 102; Elevation: 52 ft; Mean annual precip: 36.7"; Growing season: 5/15-9/28 |
| **Mechanism** | Phytodegradation Hydraulic control |
| **Operation/Maintenance Requirements** | Fertilization, control of deer, insects & unwanted vegetation. NPK and lime added annually. |
| **Project Scale** | Field demonstration/full scale, 1 acre |
| **Project Status** | Operational/In Progress. 12/1996-on-going. Data as of 1999 |
| **Cost** | $105,000 |
| **Funding Source** | USAF, DoD, SITE |
| **Initial concentrations** | PCE(1): 160ppb, PCE(2): 100ppb; TCE(1): 390ppb, TCE(2): 9ppb, TCE(3): 99ppb; DCM (1): 490,000ppb, DCM(2): 12,000ppb, DCM(3): 680ppb, DCM(4): 420ppb |
| **Final Concentrations** | As of 1999: PCE(2): 56ppb; TCE(1): 390ppb, TCE(2): 35ppb, TCE(3): 42ppb; DCM(1): 615ppb; DCM(2): ND, DCM(3): ND, DCM(4):1.2 |
| **Lessons Learned** | |
| **Comments** | Contamination in sand/silt/clay unit, Most plants survived, DCM concentrations substantially reduced in GW also reductions in TCE after 6 years of treatment |
| **Primary Contact** | George R. Prince, USEPA (732) 321-6649 prince.george@epamail.epa.gov |
| **Citation** | NATO/CCMS Pilot Study 1998 Annual Report Number 228 EPA/542/R-98/002 Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater (Phase III) |

| | |
|---|---|
| **Site Name** | Eka Chemicals Site |
| **Site Location** | Gothenburg, Sweden |
| **Contaminant** | |
| **Vegetation Type** | PCDFs, chlor-alkalis |
| **Planting Descriptions** | |
| **Media Type** | |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | |
| **Mechanism** | |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | |
| **Project Status** | |
| **Cost** | |
| **Funding Source** | MISTRA – COLDREM Programme |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Maria Greger, Stockholm University: maria.greger@botan.su.se |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Ellsworth Air Force Base, South Dakota |
| **Site Location** | SD |
| **Contaminant** | TCE, cis-1,2-DCE |
| **Vegetation Type** | Hybrid Poplars (NM 6, DN 17, and DN 182) |
| **Planting Descriptions** | 1,027 trees |
| **Media Type** | |
| **Site Characterizations** | GW 5-30' bgs |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. Range: -23 to 109; Elev.: 3427 ft; Mean annual precip.: 18.6"; Growing season: 5/26-9/14 |
| **Mechanism** | Hydraulic control |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | 1 acre Demonstration |
| **Project Status** | Planted 6/2001 |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | TCE (240 ug/l), cis-1,2-DCE (100 ug/l) |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Rafael Vazquez, AFCEE (210) 536-1431 rafael.vazquez@brooks.af.mil |
| **Citation** | |

| | |
|---|---|
| **Site Name** | ERP Site 17, Beale Air Force Base |
| **Site Location** | Marysville, CA |
| **Contaminant** | TCE, DCM |
| **Vegetation Type** | Native Cottonwood (*P. fremontii*), Live Oak (*Quercus wislizenii*), deer grass (*Muhlenbergia rigens*), meadow barley (*Hordeum brachyantherum*), clustered field sedge (*Carex praegracilis*) and narrow-leaved willow (*Salix exigua*) |
| **Planting Descriptions** | |
| **Media Type** | Groundwater |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | Temp Range: 18-115; Elevation: 69 ft; Mean annual precip: 17.5"; Growing season: 3/23-11/14 |
| **Mechanism** | Hydraulic control |
| **Operation/Maintenance Requirements** | Irrigation |
| **Project Scale** | 5 acres |
| **Project Status** | Planted in 2000 |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | TCE, DCM |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Groundwater levels inside the slurry wall need to be maintained at 12 to 14 feet below land surface. (depth of impact). Although the primary purpose of the vegetation is to provide "phyto pumping", is anticipated that VOC mass removal will also occur as a result of transpiration through the plants. |
| **Primary Contact** | Michael O'Brien, Beale AFB (530) 634-3856 Michael.O'Brien@beale.af.mil Martin Barackman, CH2M HILL (530) 229-3401 mbarackm@CH2M.com |
| **Citation** | Jordahl, J., R. Tossell, M. Barackman and G. Vogt (2003) Phytoremediation for Hydraulic Control and Remediation: Beale Air Force Base and Koppel Stockton Terminal. *Abstracts from US EPA International Applied Phytotechnologies Workshop* March 3-5, 2003 Chicago, IL |

| | |
|---|---|
| **Site Name** | Fairchild Air Force Base, Washington |
| **Site Location** | WA |
| **Contaminant** | TCE, DCM |
| **Vegetation Type** | Hybrid Poplar (*P. trichocarpa x P. deltoides, P. trichocarpa x P. nigra, P. deltoides x maximoxiczii*) |
| **Planting Descriptions** | 1,134 cuttings |
| **Media Type** | |
| **Site Characterizations** | GW 9-11' bgs |
| **Evapotranspiration Rates** | |
| **Climate** | Temp Range: -25 to 108; Elevation: 1922 ft; Mean annual precip: 16.5"; Growing season: 5/20-9/19 |
| **Mechanism** | Hydraulic control |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | 1 acre Demonstration |
| **Project Status** | planted 4/2001 |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | TCE, DCM |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Rafael Vazquez, AFCEE (210) 536-1431 rafael.vazquez@brooks.af.mil |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Fort Lewis Army Base |
| **Site Location** | Tacoma, WA |
| **Contaminant** | trichloroethene and dichloroethene; PAH |
| **Vegetation Type** | Hybrid Poplar |
| **Planting Descriptions** | |
| **Media Type** | Groundwater |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | Temp Range: -8 to 104; Elevation: 36 ft; Mean annual precip: 50.5"; Growing season: 4/20-10/25 |
| **Mechanism** | Phytoextraction, phytodegradation |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | Field Demonstration (pilot), 10 acres |
| **Project Status** | Proposed |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | TCE - 5 µg/L |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Bob Kievit, US EPA (360) 753-9014 kievit.bob@epa.gov |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Fringe drain area |
| **Site Location** | Argonne, IL |
| **Contaminant** | Trichloroethylene |
| **Vegetation Type** | Hybrid poplar, willow |
| **Planting Descriptions** | 809 trees; deep-rooted and planted as 10-16 ft tall trees |
| **Media Type** | Soil, Groundwater (silty clay) |
| **Site Characterizations** | The edge of the zone of influence for groundwater is 22 ft bgs. The physical aquifer is 30 ft bgs |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: -27 to 104; Elevation: 658 ft; Mean annual precipitation: 35.8"; Growing season: 4/25-10/22 |
| **Mechanism** | Phytodegradation, Hydraulic Control |
| **Operation/Maintenance Requirements** | None |
| **Project Scale** | Full-scale (5 acres) |
| **Project Status** | Ongoing (Planted 1999) |
| **Cost** | $750,000 for initial planting; $15,000-$20,000/year operation and maintenance costs (includes research costs). These costs include both Fringe Area and the 317/319 (see separate listing) Argonne sites. |
| **Funding Source** | Department of Energy |
| **Initial concentrations** | TCE: up to 10-15 ppm (average) |
| **Final Concentrations** | |
| **Lessons Learned** | Uptake of tritium and TCE is obseved in plants, but no clear consensus in soil concentrations because they vary widely across site due to inumerable factors |
| **Comments** | Early tree growth was severely limited as a result of early summer planting in 1999 and a cool summer in 2000. In 2001 and 2002, tree growth has substantially improved with poplar trees achieving 4-6 ft of growth per year. Hydraulic effects by the trees on groundwater were measurable in 2001. Measurable uptake of TCE and Tritium from groundwater is not expected to be realized until late in 2002 or 2003, because of the slow early growth of the trees. 20-30 ft. below ground surface (depth of impact) |
| **Primary Contact** | Ed Gatliff, Applied Natural Sciences (513) 895-6061 ans@fuse.net |
| **Citation** | Quinn, J., Negri, M., Hinchman, R., Moos, L., Wozniak, J., and E. Gatliff. 2001. “Predicting the Effect of Deep-Rooted Hybrid Poplars on the Groundwater Flow System at a Large-Scale Phytoremediation Site”. International Journal of Phytoremediation. 3(1): 41-60. |

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|---|---|
| **Site Name** | Ft Wayne |
| **Site Location** | Ft Wayne, IN |
| **Contaminant** | TCE, DCE |
| **Vegetation Type** | Hybrid Poplar |
| **Planting Descriptions** | 800 trees |
| **Media Type** | |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | Temp Range: -22 to 106; Elevation: 856 ft; Mean annual precip: 34.7; Growing season: 5/15-9/25 |
| **Mechanism** | |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | |
| **Project Status** | |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Graham Crockford, RMT (734) 971-7080 graham.crockford@rmtinc.com |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Grand Forks Air Force Base – AOC-539 |
| **Site Location** | Grand Forks, ND |
| **Contaminant** | TCE, DCM |
| **Vegetation Type** | Eastern Cottonwood (P. deltoides), Carolina Poplar (P. canadensis), Imperial Carolina Poplar (P. deltoides x P. nigra DN-34 (P. canadensis), Russian Olive (Elaeagnus angustifolia) |
| **Planting Descriptions** | All bare root material. Trees planted in 18-inch diameter auger borings 18 to 24 inches deep. Selected trees planted in borings 4 feet deep, but all trees planted at normal depth, i.e., same depth as grown in nursery. Tree spacing is 12' between rows, and 6'between trees within the row. |
| **Media Type** | Groundwater, soil |
| **Site Characterizations** | Soil: sandy loam 0-1'bgs, clay at 4-10'bgs. Depth to groundwater was 4.3-9.4' in 9/2001, and 2.7-5.8' in 9/2003. Estimated hydraulic gradient prior to site installation was 0.017 ft/ft. In the fall of 2003, gradients ranged from 0.0066-0.016 ft/ft. The estimated hydraulic conductivity is 0.371 ft/day. |
| **Evapotranspiration Rates** | Projected ET by 2006 - 28.9 inches (per acre) |
| **Climate** | Long term average precipitation - 19.16 inches |
| **Mechanism** | Hydraulic control, rhizodegradation, phytodegradation, phytovolatilization |
| **Operation/Maintenance Requirements** | Mowing, pruning, irrigation, replanting, animal control, insect control |
| **Project Scale** | 0.7 acre full scale pilot test |
| **Project Status** | Planted 2001 |
| **Cost** | Planning/design/implementation through 1 year monitoring: approximately $320,000 |
| **Initial concentrations** | Sept 2001: TCE in soil - max. 2.4 mg/kg, TCE in groundwater - 4900 µg/L, TPH, in soil - max. 1300 mg/kg TPH in groundwater - max. 2400 µg/L |
| **Final Concentrations** | Sept 2003: TCE in groundwater - 2700 µg/L, TPH in groundwater - max. 1900 µg/L |
| **Funding Source** | Air Force - - Federal Government |
| **Lessons Learned** | Winter injury can be a significant factor in site establishment at northern latitudes, but extent of damage appears to be less with increasing tree age. Winter injury from jackrabbits can be significant. Some damage to poplars was noted in the first year despite tree guards (plastic protective sleeves around stem). Significant damage to some Russian olive trees was noted in the second winter. |
| **Comments** | Groundwater flow patterns are complex, but to date no significant groundwater depression as a result of evapotranspiration of the trees has developed. |
| **Primary Contact** | Larry Olderbak, Grand Forks AFB Environmental (701) 747-4183 larry.olderbak@grandforks.af.mil<br>Al Erickson, CH2M Hill (414) 847-0303 Al.Erickson@CH2M.com |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Hill AFB Operable Unit 4 |
| **Site Location** | 30 miles north of Salt Lake City, UT |
| **Contaminant** | Dichloroethane, cis-1,2-Dichloroethylene, Perchloroethene, 1,1,1-Trichloroethane, Trichloroethene, chromium, cadmium, manganese, and arsenic |
| **Vegetation Type** | Hybrid Poplar |
| **Planting Descriptions** | 11 ft whips were implanted at depths of 8-10 ft bgs in order to get roots started nearer water table. |
| **Media Type** | Groundwater, soil: silty sands to very fine sands |
| **Site Characterizations** | GW 6-10' bgs |
| **Evapotranspiration Rates** | avg evapotranspiration = 914 mm water |
| **Climate** | temp range 3.9-23.8C ; elevation: 4225 ft; avg precipitation=16.2 in; growing season: April - mid October |
| **Mechanism** | Phytovolatilization, Hydraulic control |
| **Operation/Maintenance Requirements** | Irrigation |
| **Project Scale** | Field Demonstration |
| **Project Status** | Ongoing |
| **Cost** | approx $175K |
| **Funding Source** | Air Force Center for Environmental Excellence |
| **Initial concentrations** | trichloroethene, 84 to 560 ug/L |
| **Final Concentrations** | no notable decrease has been noted |
| **Lessons Learned** | Plants may have a greater impact on TCE attenuation at sites with lower rainfall. |
| **Comments** | Estimates of TCE phytovolatilization by whole trees range from 2-53 mg/tree-yr. Note that main object of this effort was not to reduce TCE concentration but was to attempt to provide hydraulic control of groundwater to minimize the continued migration of groundwater contaminants. |
| **Primary Contact** | Sandra Bourgeois, US EPA (303) 312-6666 bourgeois.sandra@epa.gov<br>Kyle Gorder, Hill AFB (801) 775-2559 Kyle.Gorder@hill.af.mil |
| **Citation** | Final Addendum Report No. 1 to the Interim Technical Report for the Demonstration of Phytostabilization of Shallow Contaminated Groundwater using Tree plantings at Hill Air Force Base, UT (July 2003), prepared for the Air Force Center for Environmental Excellence Science and Engineering Division (AFCEE/ERS), Brooks City-Base, TX. Prepared by Parsons. |

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|---|---|
| **Site Name** | I-5 Spill |
| **Site Location** | Central Point, OR |
| **Contaminant** | 1,1,1-trichloroethane |
| **Vegetation Type** | Hybrid Poplar |
| **Planting Descriptions** | 800 trees planted in neat ranks |
| **Media Type** | |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: -25 to 100; Elevation: 4099 ft; Mean annual precip: 12.6"; Growing season: 6/28-8/31 |
| **Mechanism** | |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | |
| **Project Status** | Planted Nay 1997 |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Milton P. Gordon, University of WA (206) 543-1769, miltong@u.washington.edu<br>Lee Newman: University of SC, (803)777-4795, Newman2@gwm.sc.edu<br>Stuart Strand, University of WA (206) 543-5350 sstrand@u.washington.edu |
| **Citation** | Schmiedeskamp, M. (1997) POLLUTION-PURGING POPLARS *Scientific American* Dec97m Vol. 27, Issue 6 |

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|---|---|
| **Site Name** | Jones Island CDF |
| **Site Location** | Milwaukee, WI |
| **Contaminant** | Polychlorinated biphenyls (PCB), Polycyclic aromatic hydrocarbons (PAH), diesel range organics (DRO) and metals |
| **Vegetation Type** | Established: Reed Canary Grass (*Phalaris arundinacea*), Sandbar Willow (*Salix interior*), Tall Nettle (*Urtica procera*)<br>Tested: clover (*Trifolium* spp.), corn (*Zea mays*), and willow (*Salix* spp.) |
| **Planting Descriptions** | Cuttings planted in 2001 |
| **Media Type** | Soil |
| **Site Characterizations** | Brown to black silt |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: -26 to 103; Elevation: 672 ft; Mean annual precip: 32.9"; Growing season: 5/20-9/26 |
| **Mechanism** | Rhizodegradation |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | Field demonstration |
| **Project Status** | Continuous. Planted 2001 |
| **Cost** | |
| **Funding Source** | US Army |
| **Initial concentrations** | PCB: 0-4 mg/kg , PAH: 0-120 mg/kg , DRO: 5-1300 mg/kg |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Composting also implemented using woodchips, biosolids and dredged material. |
| **Primary Contact** | Steven A. Rock, US EPA (513) 569-7149 |
| **Citation** | McCutcheon and J.L. Schnoor, eds., Phytoremediation: Transformation and Control of Contaminants: Hoboken, NJ, John Wiley & Sons, Inc. |

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|---|---|
| **Site Name** | Kauffman & Minteer |
| **Site Location** | Jobstown, NJ |
| **Contaminant** | *cis* 1,2-dichloroethene; Trichloroethene, Perchloroethene, Dichlorodiphenyltrichloroethane, endosulfan sulfate, ethyl benzene, 2-methylnapthalene, styrene, toluene, |
| **Vegetation Type** | Hybrid poplar and black willow (*Salix Nigra*) |
| **Planting Descriptions** | (Populus maximowiczii x P. trichocarpa) 265 trees. Initially 8-10' bare root trees were deep planted 6-8' below grade in sonotubes or other root barriers. 1999 plantings were shallow with no root barriers. |
| **Media Type** | Groundwater, soil: silty sand |
| **Site Characterizations** | GW 5+' bgs |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: -4 to 102; Elevation: 190 ft; Mean annual precip: 42"; Growing season: 4/15 to 10/23 |
| **Mechanism** | Rhizodegradation |
| **Operation/Maintenance Requirements** | Replanting |
| **Project Scale** | 5 acres |
| **Project Status** | Planted Spring 1998. Bay wash area planted Spring 1999. |
| **Cost** | |
| **Funding Source** | EPA ERT, EPA Region 2 |
| **Initial concentrations** | Groundwater: 15,000µg/L Trichloroethene; 22,000µg/L *cis* 1, 2 dichloroethene. Soil: 230ppm perchloroethene, 3100 ppm trichloroethene, 1600 ppm 1,1,1-trichloroethane, 1100ppm 1,2-dichloroethene |
| **Final Concentrations** | lower concentrations |
| **Lessons Learned** | Imported backfill had low pH of 4.5. Liming and watering helped. |
| **Comments** | Heavy rains and aggressive string trimming resulted in death of 45 trees in 1998 |
| **Primary Contact** | George R. Prince: USEPA, 732-321-6649, prince.george@epamail.epa.gov |
| **Citation** | Compton, H.R. et al. 2003. "Phytoremediation of Dissolved Phase Organic Compounds: Optimal Site Considerations Relative to Field Case Studies". *REMEDIATION,* summer 2003. |

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|---|---|
| **Site Name** | Lake City Army Ammunition Plant |
| **Site Location** | Kansas City, KS |
| **Contaminant** | Halogenated Volatiles |
| **Vegetation Type** | Hybrid Poplar |
| **Planting Descriptions** | |
| **Media Type** | Soil: Top 5 feet is sand (fill), clay below sand layer |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: -19 to 110; Elevation: 742 ft; Mean annual precip: 36.1"; Growing season: 4/30 to 10/9 |
| **Mechanism** | Phytostabilization, phytoextraction |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | 20,000 square feet, 200,000 square feet, 40,000 square feet, 7-10 acres |
| **Project Status** | Proposal |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Carol Dona, TVA/AEC (816)-426-7340 carol.l.dona@mrk01usace.army.mil |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Metal Plating Facility |
| **Site Location** | Findlay, OH |
| **Contaminant** | Chromium, cadmium, nickel, zinc, lead, trichloroethylene |
| **Vegetation Type** | Hybrid Poplar, Ryegrass; Indian mustard |
| **Planting Descriptions** | 30 trees, deep rooted and planted when 10-16 ft tall |
| **Media Type** | Soil (silt loam) |
| **Site Characterizations** | GW 10-15' bgs |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: -19 to 104 ; Elevation: 804 ft; Mean annual precip: 34.5"; Growing season: 5/19 to 9/24 |
| **Mechanism** | Phytoextraction, Hydraulic Control |
| **Operation/Maintenance Requirements** | sampling groundwater |
| **Project Scale** | Full-Scale (10,000 sq ft) |
| **Project Status** | Operational/In Progress. Planted 1997 |
| **Cost** | voluntary |
| **Funding Source** | State |
| **Initial concentrations** | TCE: up to 150 mg/L |
| **Final Concentrations** | |
| **Lessons Learned** | Dramatic drop of, on average, 30 ppm to less than 5 ppm. However, the source area continues to supply site with contaminants. |
| **Comments** | SITE Program. Trees have grown at a rate of 4-8 ft/year. Results of the first 3 years indicated significant reduction of TCE concentrations in the aquifer in addition to demonstration of hydraulic effects on groundwater flow |
| **Primary Contact** | Michael Blaylock, Edenspace, (703) 961-8700, blaylock@edenspace.com or Edd Gatliff, Applied Natural Sciences, (513) 895-6061 ans@fuse.net |
| **Citation** | Phytoremediation of TCE in Groundwater using Populus. http://www.clu-in.org/products/phytotce.htm |

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|---|---|
| **Site Name** | Montezuma West |
| **Site Location** | Medford, OR |
| **Contaminant** | 1,1,1-trichloroethane |
| **Vegetation Type** | Hybrid Poplar |
| **Planting Descriptions** | Planted 5/1997 |
| **Media Type** | Groundwater, soil |
| **Site Characterizations** | GW 8m bgs |
| **Evapotranspiration Rates** | |
| **Climate** | Very hot dry summers. Temp range: -25 to 100; Elevation: 4099 ft; Mean annual precip: 12.6"; Growing season: 6/28 to 8/31 |
| **Mechanism** | Phytoextraction, phytodegradation |
| **Operation/Maintenance Requirements** | Irrigation, weeding, thinning. |
| **Project Scale** | Field Demonstration (pilot), 1 acre |
| **Project Status** | 1997 Operational/In Progress |
| **Cost** | ~ $120,000 |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Tissue analyses indicate that plants are taking up TCA. Fall site preparation is invaluable. Do not wait until spring. |
| **Primary Contact** | Lee Newman, U of SC (803)777-4795, Newman2@gwm.sc.edu |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Moonachie |
| **Site Location** | Moonachie, NJ |
| **Contaminant** | Toluene |
| **Vegetation Type** | DN 34, Hybrid Poplar |
| **Planting Descriptions** | Planted 5/1997. Six trees were replaced in the spring of 1998. |
| **Media Type** | Groundwater; clay soil |
| **Site Characterizations** | GW 2-7' bgs; 2-12' to contamination. -1.77E-3 to 2.71E-6 m/m hydraulic gradient; 1.98E-7 to 3.21E-6 m/sec hydraulic conductivity |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: -8 to 105; Elevation: 7 ft; Mean annual precip: 43.9"; Growing season: 4/15 to 10/26 |
| **Mechanism** | Phytovolatilization, rhizodegradation. |
| **Operation/Maintenance Requirements** | Mowing, replanting, monitoring: insect/animal damage, wells |
| **Project Scale** | Field Demonstration (pilot) |
| **Project Status** | Operational/In Progress (1996-1998) |
| **Cost** | $51,005 |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Approximately 10% mortality due to transplanting and/or phytotoxicity effects were observed. Project will continue to be monitored. Trees need to be planted earlier in the spring to reduce transplanting shock. |
| **Primary Contact** | Ari M. Ferro, Phytokinetics (435) 750-0985 ariferro@phytokinetics.com |
| **Citation** | No |

| | |
|---|---|
| **Site Name** | NASA Kennedy Space Center Hydrocarbon Burn Facility |
| **Site Location** | Merritt Island, Cape Canaveral, FL |
| **Contaminant** | Dichloroethene, Trichloroethene, Vinyl Chloride, Chromium, TPH |
| **Vegetation Type** | Hybrid poplar trees, under story grasses |
| **Planting Descriptions** | 4400 trees and under story grasses |
| **Media Type** | Groundwater, Soil: Medium-coarse sand |
| **Site Characterizations** | GW 1-12' bgs |
| **Evapotranspiration Rates** | 950L/m2-yr |
| **Climate** | Semi-tropical. Temp range: 25 to 96 ; Elevation: 9 ft; Mean annual precip: 127cm; Growing season: 2/7 to 12/22 |
| **Mechanism** | Hydraulic control, phytovolatilization, rhizodegradation, phytoextraction |
| **Operation/Maintenance Requirements** | Mowing, irrigation |
| **Project Scale** | Full-Scale, 3 acres |
| **Project Status** | Active. Planted 4/1998 |
| **Cost** | $70,000 for Ecolotree portion |
| **Funding Source** | |
| **Initial concentrations** | 0.5 ± 0.09-65 ± 26mg/L trichloroethene; <1.1-1200μg/L 1,1-dichloroethene; 65-4800 μg/L cis-1,2 dichloroethene, <1.65-110μg/L trans-1,2 dichloroethene; <2-456 μg/L vinyl chloride, Chromium > 50 ppb ; TPH = 110-760 ppm |
| **Final Concentrations** | |
| **Lessons Learned** | Not able to establish phytoplantation due to competing vegetation (grasses) and drought. |
| **Comments** | Organic chemical spill site, 1-12 ft. (depth of impact) |
| **Primary Contact** | Louis A. Licht: Ecolotree, (319) 665-3547 lou-licht@ecolotree.com Eric Aitchison, Ecolotree (319) 665-3547 eric-aitchison@ecolotree.com |
| **Citation** | Phytoremediation. Ed. McCutcheon, S.C., Schnoor, J.L. 2003 |

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|---|---|
| **Site Name** | Naval Undersea Warfare Station |
| **Site Location** | Keyport, WA |
| **Contaminant** | 1,1,1 Trichloroethane, halogenated volatiles |
| **Vegetation Type** | Hybrid Poplar |
| **Planting Descriptions** | 900 cuttings |
| **Media Type** | Groundwater |
| **Site Characterizations** | GW 15-20' bgs |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: 9 to 96; Elevation: 125 ft; Mean annual precip: 37.1"; Growing season: 4/20 to 10/27 |
| **Mechanism** | Phytoextraction, phytodegradation |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | Field Demonstration (pilot), 8 acres |
| **Project Status** | Operational/In Progress Started 4/2001 to 2009 |
| **Cost** | |
| **Funding Source** | Superfund |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Shallow groundwater elevation data shows no significant effect from the phytoremediation plantation. No significant effect on VOC concentrations is expected until the trees mature. |
| **Primary Contact** | Lee Newman: University of South Carolina, (803)777-4795, Newman2@gwm.sc.edu |
| **Citation** | Rohrer, W., Newman, L., and B. Wallis. 2000. "Monitoring Site Constraints at NUWC Keyport's Hybrid Poplar Phytoremediation Plantation". In: G. Wickramanayake, A. Gavaskar, B. Alleman, and V. Magar (eds.) Bioremediation and Phytoremediation of Chlorinated and Recalcitrant Compounds, p467-476. Battelle Press, Columbus, Ohio. |

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|---|---|
| **Site Name** | Northern Iowa Chlorinated Solvent Plume |
| **Site Location** | Northern IA |
| **Contaminant** | Dichloroethene, perchloroethene, trichloroethene |
| **Vegetation Type** | Hybrid poplar trees, under story grasses |
| **Planting Descriptions** | 700 trees trenched 10' below ground. 15' tall trees to bottom of trench. |
| **Media Type** | Groundwater, silty clay loam |
| **Site Characterizations** | GW 9-11' bgs |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: -30 to 104; Elevation: 1174 ft; Mean annual precip: 34"; Growing season: 5/20 to 9/16 |
| **Mechanism** | Hydraulic control, rhizodegradation, phytoextraction |
| **Operation/Maintenance Requirements** | Mowing, weeding |
| **Project Scale** | Full-Scale, 1 acre |
| **Project Status** | Active. Planted April 2002 |
| **Cost** | $100,000 1st year |
| **Funding Source** | PRP/Site owner |
| **Initial concentrations** | Perchloroethene(up to 15mg/L); trichloroethene(up to 50mg/L) |
| **Final Concentrations** | Greater than 30% reduction of TCE |
| **Lessons Learned** | |
| **Comments** | Tree survival > 95% in year one. |
| **Primary Contact** | Roland Newton, GSI, 505-270-6542 Eric Aitchison, Ecolotree (319) 665-3547 eric-aitchison@ecolotree.com |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Oregon Poplar |
| **Site Location** | Clackamas, OR |
| **Contaminant** | 1,1-dichloroethane; 1,1-dichloroethene; 1,2-dichloroethene; perchloroethene, trichloroethene, vinyl chloride, benzene, toluene, ethyl benzene, xylene |
| **Vegetation Type** | Native and hybrid poplars |
| **Planting Descriptions** | Not planted in rows to facilitate future use of site as park. Planted 12-18" dormant hardwood cuttings or live stakes. More than 900 trees planted. |
| **Media Type** | Groundwater |
| **Site Characterizations** | GW 2-10' bgs. Silty clay to 10' bgs. Below silty clay is 15-20' poorly sorted gravel-to-cobble. |
| **Evapotranspiration Rates** | Some of the larger trees show uptake as much as 25 gal of groundwater per day during the summer. |
| **Climate** | Temp range: 6 to 107; Elevation:33 ft; Mean annual precip: 36.3"; Growing season: 4/26 to 10/18 |
| **Mechanism** | Phytodegradation, phytovolatilization |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | |
| **Project Status** | Planted 1997 |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | Additional wells may need to be installed to further define the plume. |
| **Comments** | Contaminants found in tissue and transpiration gases indicating trees are utilizing contaminated groundwater and/or soil. Pore water sampling in a nearby stream with passive diffusion bags indicates VOCs are present below State criteria for surface waters. |
| **Primary Contact** | Alan M. Humphrey, US EPA (732) 321-6748 humphrey.alan@epa.gov |
| **Citation** | Compton, H.R. et al. 2003. "Phytoremediation of Dissolved Phase Organic Compounds: Optimal Site Considerations Relative to Field Case Studies". *REMEDIATION,* summer 2003. |

| | |
|---|---|
| **Site Name** | Portsmouth Gaseous Diffusion Plant – X-740 TCE Plume |
| **Site Location** | Piketon, OH |
| **Contaminant** | Trichloroethene (TCE), Perchloroethene (PCE), Dichloroethene (DCE), Vinyl Chloride (VC) |
| **Vegetation Type** | Hybrid Poplars(NE-19, DN-34, NM-6) |
| **Planting Descriptions** | 765 trees planted with "trench and sand-stack" method to a depth of 10' |
| **Media Type** | Groundwater, Soil |
| **Site Characterizations** | GW 32' bgs, semi contained aquifer |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: -19 to 101; Elevation: 833 ft; Mean annual precip: 38.1"; Growing season: 5/9 to 10/3 |
| **Mechanism** | Hydraulic Control, phytoremediation |
| **Operation/Maintenance Requirements** | Mowing and tree care mostly |
| **Project Scale** | 2.6 acre Full-scale pilot project |
| **Project Status** | 3/1999 |
| **Cost** | $500,000 |
| **Funding Source** | US Dept of Energy |
| **Initial concentrations** | TCE: up to about 4,000 ppb |
| **Final Concentrations** | TCE: 2-2200µg/L |
| **Lessons Learned** | Learned from X-740 Area that we needed to dig the trenches deeper for X-749 Area |
| **Comments** | GW levels show direct impact, analytical results less profound. Both phytoremediation areas are relatively young, so concentrations have not changed much yet. |
| **Primary Contact** | David E Rieske, Pro2Serve Technical Solutions, (740) 897-2550, riesked@p2s.com |
| **Citation** | Brewer, R.D. and D.E. Rieske (2003) TCE Plume Phytoremediation at the Portsmouth Gaseous Diffusion Plant. *Abstracts from US EPA Intn'l Applied Phytotechnologies Workshop* March 3-5, 2003 Chicago, IL<br>Rieske, D.E., et al (2003) Removal of Chlorinated Solvents by Phytoremediation Using Trench and "Sand-Pipe" *Abstracts from US EPA Intn'l Applied Phytotechnologies Workshop* March 3-5, 2003 Chicago, IL |

| | |
|---|---|
| **Site Name** | Portsmouth Gaseous Diffusion Plant – X-749/X-120 TCE Plume |
| **Site Location** | Piketon, OH |
| **Contaminant** | Trichloroethene (TCE), Perchloroethene (PCE), Dichloroethene (DCE), Vinyl Chloride (VC) |
| **Vegetation Type** | Hybrid Poplars (*Populus Nigra x Populus maximowiczi* (NM-6)) |
| **Planting Descriptions** | 3,450 trees planted in 12-15' deep trenches with 8" sand-stacks every 20'. |
| **Media Type** | Groundwater |
| **Site Characterizations** | GW 32' bgs, semi contained aquifer. Soil: Unconsolidated alluvial sand and gravel, lacustrian silts and clays |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: -19 to 101; Elevation: 833 ft; Mean annual precip: 38.1"; Growing season: 5/9 to 10/3 |
| **Mechanism** | Hydraulic Control, phytoremediation |
| **Operation/Maintenance Requirements** | Mowing and tree care mostly |
| **Project Scale** | 41 acre full scale Large-scale remediation project |
| **Project Status** | Planted spring 2003 |
| **Cost** | |
| **Funding Source** | U.S. Department of Energy |
| **Initial concentrations** | TCE: 2-2200µg/L |
| **Final Concentrations** | TCE: up to about 500 ppb |
| **Lessons Learned** | |
| **Comments** | This project is due to results of demo at same site in 1999. Both phytoremediation areas are relatively young, so concentrations have not changed much yet. |
| **Primary Contact** | David E Rieske, Pro2Serve Technical Solutions, (740) 897-2550, riesked@p2s.com<br>Roger Brewer, Tetra Tech, Inc. brewer@ttnus.com |
| **Citation** | Brewer, R.D. and D.E. Rieske (2003) TCE Plume Phytoremediation at the Portsmouth Gaseous Diffusion Plant. *Abstracts from US EPA Intn'l Applied Phytotechnologies Workshop* March 3-5, 2003 Chicago, IL<br>Rieske, D.E., et al (2003) Removal of Chlorinated Solvents by Phytoremediation Using Trench and "Sand-Pipe" *Abstracts from US EPA Intn'l Applied Phytotechnologies Workshop* March 3-5, 2003 Chicago, IL |

| | |
|---|---|
| **Site Name** | Sangamo Electric Dump/ Crab Orchard National Wildlife Refuge (USD01) |
| **Site Location** | Marion, IL |
| **Contaminant** | explosives, polychlorinated biphenyls, trichloroethene and other chlorinated solvents-lead, cadmium, chromium, arsenic |
| **Vegetation Type** | Hybrid poplar trees |
| **Planting Descriptions** | |
| **Media Type** | Groundwater |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: -12 to 104; Elevation: 314; Mean annual precip: 46.9"; Growing season: 4/6 to 10/29 |
| **Mechanism** | |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | Planned. Planned installation 2004 |
| **Project Status** | |
| **Cost** | |
| **Funding Source** | PRP Lead/ Federal Oversight |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Nanjunda Gowda, US EPA (312) 353.9236 gowda.nanjunda@epa.gov |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Savannah River, North Carolina |
| **Site Location** | Savannah River, NC |
| **Contaminant** | DCE, PCE, VC |
| **Vegetation Type** | Hybrid Poplars, loblolly pines |
| **Planting Descriptions** | |
| **Media Type** | |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range:-7 to 95; Elevation: 2239 ft; Mean annual precip: 38.8"; Growing season: 4/24 to 10/11 |
| **Mechanism** | Hydraulic Control |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | Two one-acre plots |
| **Project Status** | Planted ~ 3/2002 |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | DCE, PCE, VC |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | April 2002 tissue sampling results do not indicate the presence of TCE |
| **Primary Contact** | Cassandra Bayer: Bechtel Savannah River, Inc. |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Savannah River Site |
| **Site Location** | Aiken, SC |
| **Contaminant** | Perchloroethene (PCE), trans-1,2-dichloroethylene, trichloroethene (TCE), trichloromethane |
| **Vegetation Type** | Grass, legume, herb, Loblolly Pine, hybrid poplar |
| **Planting Descriptions** | |
| **Media Type** | Groundwater, Soil: Mostly Udorthents firm substratum with low permeability (basin resulted from removal of much of developed surface soil) |
| **Site Characterizations** | Confined to upper 10m of vadose zone. 67.5% sand, 9.0% silt and 23.5% clay. |
| **Evapotranspiration Rates** | |
| **Climate** | Abundant rainfall. Warm, humid conditions prevail. Temp range: -1 to 108; Elevation: 134 ft; Mean annual precip: 44.6"; Growing season: 4/15 to 10/23 |
| **Mechanism** | Phytodegradation, rhizodegradation, hydraulic control |
| **Operation/Maintenance Requirements** | Irrigation |
| **Project Scale** | 4 acre-Pilot Scale |
| **Project Status** | Operations began 10/2001, scheduled for 3 years. |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | TCE: 900-1400ppb, PCE: <200ppb |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Groundwater irrigated over plants. |
| **Primary Contact** | Dawn Taylor, US EPA (404) 562-8575 taylor.dawn@epa.gov |
| **Citation** | Walton, B.T and Anderson, T.A. 1990. "Microbial Degradation of Trichloroethylene in the Rhizosphere: Potential Application to Biological Remediation of Waste Sites". Applied and Environmental Microbiology, Apr 1990, p. 1012-1016. Kim, RH et. Al. (2003) Remediation of VOC-Contaminated Groundwater at the Savannah River Site by Phyto-Irrigation. *Abstracts from US EPA International Applied Phytotechnologies Workshop* March 3-5, 2003 Chicago, IL |

| | |
|---|---|
| **Site Name** | SRSNE (Solvent Recovery Service New England) |
| **Site Location** | Southington, CT |
| **Contaminant** | Trichloroethane, Dichloroethane, 1,1-Dichloroethylene, Vinyl Chloride, Polychlorinated biphenols |
| **Vegetation Type** | Hybrid Poplar (DN 34), white willow, pin oak, river birch, sweet gum, silver maple, tulip tree, eastern red bud, eastern white pine |
| **Planting Descriptions** | ~1000 hybrid poplars. 3' trenches backfilled w/sand & peat moss. |
| **Media Type** | Groundwater, Soil |
| **Site Characterizations** | GW 3' bgs; contamination 3' to bedrock 30' bgs. |
| **Evapotranspiration Rates** | Water use rates for 2001 averaged 7.8 gpd per tree for willows and 8.4 gpd per Poplar. |
| **Climate** | Temp range: -26 to 102; Elevation: 174 ft; Mean annual precip: 44.1"; Growing season: 5/12 to 9/23 |
| **Mechanism** | Phytovolatilization, rhizodegradation, hydraulic control |
| **Operation/Maintenance Requirements** | Mowing, fertilization, replanting, monitoring insect/animal damage |
| **Project Scale** | 0.8 acre Field Demonstration (pilot) |
| **Project Status** | Operational/In Progress. Planted 5/1998. Completion of project planned 2030. |
| **Cost** | Estimate $500,000/year |
| **Funding Source** | PRP Group-lead, SRSNE Superfund Site-Oversight |
| **Initial concentrations** | Trichloroethane 0.1-35mg/kg, Dichloroethane 0.1-25mg/kg |
| **Final Concentrations** | |
| **Lessons Learned** | Trees need to be planted earlier in the spring to reduce transplanting shock. |
| **Comments** | 10% mortality due to transplanting and/or phytotoxicity effects were observed. Manual labor for installation was intense. |
| **Primary Contact** | Karen Lumino , US EPA (617) 918-1348 lumino.karen@epa.gov |
| **Citation** | Ferro, A., Chard, B., Gefell, M., Thompson, B., and R. Kjelgren. 2000. “Phytoremediation of Organic Solvents in Groundwater: Pilot Study at a Superfund Site”. In: G. Wickramanayake, A. Gavaskar, B. Alleman, and V. Magar (eds.) Bioremediation and Phytoremediation of Chlorinated and Recalcitrant Compounds, p461-466. Battelle Press, Columbus, Ohio.; Ferro, A., Kennedy, J., Kjelgren, R., Rieder, J., and S. Perrin. 1999. “Toxicity Assessment of Volatile Organic Compounds in Poplar Trees”. International Journal of Phytoremediation. 1(1): 9-17. |

| | |
|---|---|
| **Site Name** | Tibbetts Road |
| **Site Location** | Barrington, NH |
| **Contaminant** | Trichloroethylene, polychlorinated biphenols. Arsenic, benzene, toluene |
| **Vegetation Type** | Hybrid poplar trees (Deltoides x Nigra), under story grasses |
| **Planting Descriptions** | 1,400 one-year-old rooted plants |
| **Media Type** | Groundwater, soil |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: -33 to 102; Elevation: 338 ft; Mean annual precip: 36.4"; Growing season: 6/9 to 9/8 |
| **Mechanism** | Hydraulic control, phytoextraction, rhizosphere |
| **Operation/Maintenance Requirements** | Mowing, weeding |
| **Project Scale** | Full-Scale, 2 acres |
| **Project Status** | Operational. Planted 1998. Estimate completion 2015. |
| **Cost** | $40,000 for Ecolotree portion of project. Entire remedy (including source removal, demolition, water supply extension, controls and monitoring) estimated at $8M |
| **Funding Source** | Superfund |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Trees have grown well and now stand over 15' tall. Tree survival in 1998 was 99%. |
| **Primary Contact** | Neil Handler, USEPA (617) 918-1334 handler.neil@epa.gov |
| **Citation** | http://yosemite.epa.gov Waste Site Cleanup & Reuse in New England-TIBBETTS ROAD<br>ITRC (2004) White Paper Case Study. Making the Case for Ecological Enhancements. ECO-1. January 2004 |

| | |
|---|---|
| **Site Name** | Travis Air Force Base |
| **Site Location** | CA |
| **Contaminant** | Trichloroethene |
| **Vegetation Type** | Red ironbark (*Eucalyptus sideroxylon* 'Rosea') |
| **Planting Descriptions** | 480 trees |
| **Media Type** | Groundwater |
| **Site Characterizations** | GW 5-8m bgs |
| **Evapotranspiration Rates** | 2003 Potential ET: Jan-Apr: 45mm, May-Oct, negligible, Nov: 25mm, Dec:125mm |
| **Climate** | Temp range: 18 to 115; Elevation: 69 ft; Mean annual precip: 17.5"; Growing season: 3/23 to 11/14 |
| **Mechanism** | Hydraulic control |
| **Operation/Maintenance Requirements** | Irrigation |
| **Project Scale** | 2.5 acre Demonstration |
| **Project Status** | Planted 11/1998 |
| **Cost** | |
| **Funding Source** | AFCEE/ERS |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | No evidence of hydraulic control thru 5th season. Roots found in well near water table. No irrigation applied since 2002. Site will continue to be monitored. |
| **Primary Contact** | Rafael Vazquez, AFCEE (210) 536-1431 rafael.vazquez@brooks.af.mil<br>John Lucey, US EPA (415) 972-3243 lucey.john@epa.gov |
| **Citation** | "Phytostabilization Demonstration at Travis Air Force Base, California" poster |

| | |
|---|---|
| **Site Name** | Union Carbide Corporation |
| **Site Location** | Texas City, TX |
| **Contaminant** | 1,2 DCA, BCEE |
| **Vegetation Type** | Poplar and Mulberry |
| **Planting Descriptions** | 40 trees planted |
| **Media Type** | Groundwater, soil: sands, silty sands |
| **Site Characterizations** | GW 30-35' bgs, K=5E-6cm/s |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: 7 to 107; Elevation: 102 ft; Mean annual precip: 47"; Growing season: 3/17 to 11/14 |
| **Mechanism** | Hydraulic Control |
| **Operation/Maintenance Requirements** | Fertilization, irrigation, replanting, pruning, mulching |
| **Project Scale** | Full Scale |
| **Project Status** | Operational/In Progress |
| **Cost** | $20,000 |
| **Funding Source** | PRP |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Supplement to traditional pump/treat |
| **Primary Contact** | Richard J. Chapin, Union Carbide Corp (DOW Chemical) chapinrj@dow.com |
| **Citation** | Basel Al-Yousfi A. et al. (2000). "Phytoremediation-The Natural Pump-and-Treat and Hydraulic Barrier System." Practice Periodicals of Hazardous, Toxic, and Radioactive Waste Management, April 2000, p 73-77. |

| | |
|---|---|
| **Site Name** | Unspecified |
| **Site Location** | SC |
| **Contaminant** | DCE, PCE, VC |
| **Vegetation Type** | Hybrid Poplar and willow |
| **Planting Descriptions** | |
| **Media Type** | Groundwater |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | |
| **Mechanism** | Hydraulic Control, phytoremediation |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | |
| **Project Status** | |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | David McMillan, Natresco (717) 583-2100 dmcmillan@natresco.com |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Unspecified chemical manufacturing facility |
| **Site Location** | Aurora, IL |
| **Contaminant** | TCE (up to 25 mg/L) |
| **Vegetation Type** | Hybrid poplar, willow |
| **Planting Descriptions** | 200 poplars, 50 willows |
| **Media Type** | |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: -27 to 104; Elevation: 658 ft; Mean annual precip: 35.8"; Growing season: 4/25 to 10/22 |
| **Mechanism** | Phytodegradation, Hydraulic Control |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | |
| **Project Status** | planted 2000 |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | TCE (up to 25 mg/L) |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Trees have grown consistently (up to 8 ft/year for the Poplar). Comparison of groundwater concentrations from pre-installation of the TreeMediation system and 2 growing seasons later indicate significant reduction of the TCE concentrations in the aquifer both at the source area and on the property boundary. Hydraulic effects on the groundwater flow have also been demonstrated. 10-15 ft below surface (depth of impact) |
| **Primary Contact** | Ed Gatliff, Applied Natural Sciences (513) 942-6061 ans@fuse.net |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Vandenberg Air Force Base, California |
| **Site Location** | CA |
| **Contaminant** | DCE, PCE, VC |
| **Vegetation Type** | Hybrid poplar (*P. trichocarpa x P. deltoides, P. trichocarpa x P. nigra, P. deltoides x maximoxiczii*) |
| **Planting Descriptions** | 1,260 cuttings |
| **Media Type** | |
| **Site Characterizations** | G' 5-10' bgs |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: 20 to 109; Elevation: 16 ft; Mean annual precip: 16.2"; Growing season: 2/26 to 12/4 |
| **Mechanism** | Hydraulic control |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | 1 acre |
| **Project Status** | Planted 8/2001 |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Rafael Vazquez, AFCEE (210) 536-1431 rafael.vazquez@brooks.af.mil |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Wayne County |
| **Site Location** | Wayne County, MI |
| **Contaminant** | DCE, PCE, VC |
| **Vegetation Type** | Hybrid Poplar |
| **Planting Descriptions** | 60 trees deep rooted and planted when 10-16 ft tall. |
| **Media Type** | Groundwater, Soil |
| **Site Characterizations** | Groundwater 8-10 ft bgs |
| **Evapotranspiration Rates** | |
| **Climate** | Temperature Range: -13 to 103 F; Mean Annual precipitation: 26.6"; Elevation: 619 ft; Average growing season: 5/12-10/9 |
| **Mechanism** | Phytodegradation |
| **Operation/Maintenance Requirements** | Pruning, monitoring |
| **Project Scale** | Full-Scale |
| **Project Status** | Inactive (1997-2002) |
| **Cost** | 30,000 |
| **Funding Source** | Private |
| **Initial Concentrations** | TCE: 600 ppb |
| **Final Concentrations** | TCE: 30 ppb |
| **Lessons Learned** | Although the site had early successes, by 2002 street salt leaching into groundwater was killing trees. Salinity is too high to support vegetation and there are no trees, and no phytoremediation taking place at site now. |
| **Comments** | TCE substantially reduced, 8 ft below ground surface (depth of impact) |
| **Primary Contact** | Ed Gatliff, Applied Natural Sciences (513) 895-6061 ans@fuse.net |
| **Citation** | http://www.treemediation.com |

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|---|---|
| **Site Name** | Weyerhaeuser - Timber Processing Site |
| **Site Location** | Klamath Falls, OR |
| **Contaminant** | Polychlorinated biphenols, Pentachlorophenol, chromate |
| **Vegetation Type** | Hybrid poplar trees, under story grasses |
| **Planting Descriptions** | |
| **Media Type** | Soil: Sandy-loess soil |
| **Site Characterizations** | GW 2' bgs |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: -25 to 100; Elevation: 4099 ft; Mean annual precip: 12.6"; Growing season: 6/28 to 8/31 |
| **Mechanism** | Phytoextraction, Rhizodegradation, Phytovolatilization |
| **Operation/Maintenance Requirements** | Mowing |
| **Project Scale** | Full-Scale, 7 acres |
| **Project Status** | Inactive. Planted 1994,1995 |
| **Cost** | |
| **Funding source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Industrial wastewater containing PCP and PCB is irrigated onto 10 acres of hybrid poplars, thus reducing point-source discharge to receiving streams. Approximately 5% tree loss in year 1 attributed to shallow concrete foundations inhibiting root development. |
| **Primary Contact** | Jeannine Brown, US EPA (206) 553-1058 brown.jeannine@epa.gov, Eric Aitchison, Ecolotree (319) 665-3547 eric-aitchison@ecolotree.com |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Wisconsin |
| **Site Location** | central WI |
| **Contaminant** | TCE |
| **Vegetation Type** | Hybrid Polar |
| **Planting Descriptions** | 300 trees |
| **Media Type** | Groundwater, Soil: Loamy sand |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | Temp range: -36 to 99; Elevation: 1191 ft; Mean annual precip: 33"; Growing season: 5/22 to 9/6 |
| **Mechanism** | |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | |
| **Project Status** | Planted Spring 2004 |
| **Cost** | $40,000 1st year |
| **Funding source** | Federal Facility |
| **Initial concentrations** | less than 1mg/L |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Louis A. Licht: Ecolotree, (319) 665-3547 lou-licht@ecolotree.com Eric Aitchison, Ecolotree (319) 665-3547 eric-aitchison@ecolotree.com |
| **Citation** | |

# Appendix B: Pesticides Database

*Table of Contents*

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|---|---|
| **Site Name** | Aberdeen Pesticide Dumps |
| **Site Location** | Aberdeen, NC |
| **Contaminants** | Dieldrin, hexachlorobenzene, hexachlorahexane |
| **Vegetation Type** | Hybrid Poplar trees and groundcover grasses |
| **Planting Descriptions** | Depth of planting: 1.5-12 ft. |
| **Media Type** | Groundwater (soil: sand and silty clay) |
| **Site Characterizations** | Groundwater: Avg. gradient = 0.008 ft/ft; Hydraulic conductivity: 3.82e-4 to 2.03e-3 cm/sec; avg velocity: 343 ft/yr |
| **ET Rates** | 4 million gallons in 1999 growing season |
| **Climate** | Elevation: 339 ft; Mean annual precip: 50.3"; Growing season: 4/23 to 10/13 |
| **Mechanism** | Hydraulic control, Rhizodegradation |
| **OM Requirements** | Mowing, fertilizing, amendments(?), contact Mann |
| **Project Scale** | Full scale (7.5 acres, 3500 trees) |
| **Project Status** | Ongoing (began 1999) |
| **Cost** | $450,000 |
| **Funding Source** | PRP |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | 87,000 tons of soil removed for thermal treatment prior to plant installation |
| **Primary Contact** | Luis. E Flores, USEPA, (404) 562-8807, flores.luis@epa.gov or Tom Mann, 864-609-9111 |
| **Citation** | EPA Superfund: Record of Decision, 1999 and Annual Repot, March 2004 |

| | |
|---|---|
| **Site Name** | Amana #1 & #2 |
| **Site Location** | Amana, IA |
| **Contaminants** | Atrazine, alachlor |
| **Vegetation Type** | Corn, Fescue, Hybrid Poplar, Sunflowers (Heianthus annus) |
| **Planting Descriptions** | |
| **Media Type** | Groundwater, Soil |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | Temp range: -28 to 104 F; Elevation: 902 ft; Mean annual precipitation: 33.4"; Growing season: 5/13 to 9/25 |
| **Mechanism** | Phytoextraction, phytotransformation |
| **OM Requirements** | |
| **Project Scale** | Demonstration/Pilot (1 mile x 25 feet) |
| **Project Status** | Completed |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Designed as a riparian buffer zone with Ecolotree buffer. Reduction of 10-20% of applied atrazine |
| **Primary Contact** | Jerry Schnoor, University of Iowa, (319) 335-5585, jschnoor@engineering.uiowa.edu |
| **Citation** | Schnoor, J. L., L.A. Licht, S.C. McCutcheon, N.L. Wolf, and L.H. Carreira. 1995. Phytoremediation of organic and nutrient contaminants. Environmental Science & Technology, 29(7): 318A-323A. |

| | |
|---|---|
| **Site Name** | Bofors-Nobel Superfund Site |
| **Site Location** | Muskegon, MI |
| **Contaminant** | 3,3 Dichlorobenzidine, vinyl chloride, Perchloroethene, Aniline, Azobenzene, Benzidine, 3,3 Dichlorobenzidine, Toluene |
| **Vegetation Type** | hybrid poplar |
| **Planting Descriptions** | |
| **Media Type** | Groundwater, soil |
| **Site Characterizations** | GW 6' bgs |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. Range: -15 to 99 F; Elev.: 644; Mean annual precip.: 32.6"; Growing season: 5/24-9/24 |
| **Mechanism** | Rhizodegradation, phytoextraction, phytodegradation |
| **Operation/Maintenance Requirements** | cutting down any tree species that does not survive in the contained area |
| **Project Scale** | Pilot scale. Approximately 20 acres of planted tree species, with another (approx.) 20 acres of engineered treatment wetlands. |
| **Project Status** | On hold. Planted 6/2004 |
| **Cost** | Estimated total remedy cost can be from about $ 15 million up to $ 30 million. |
| **Funding source** | PRP, Federal/State overview |
| **Initial concentrations** | Up to 3000-10000 ppm for halogenated and nonhalogenated semi-volatiles |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Phytoremediation is not the main goal of the remedy. The main goal is containment using the underground barrier (slurry) wall, with phyto as an enhancement. |
| **Primary Contact** | John Fagiolo, USEPA (312) 886.0800 fagiolo.john@epa.gov<br>Ari Ferro, Phytokinetics (435) 750-0985 ariferro@phytokinetics.com |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Cantrall |
| **Site Location** | Cantrall, IL |
| **Contaminant** | Nitrate nitrogen, herbicides/insecticides, atrazine, alachlor |
| **Vegetation Type** | Hybrid Poplar |
| **Planting Descriptions** | 200 poplar trees |
| **Media Type** | Groundwater, Soil (Glacial soils; silt; clay) |
| **Site Characterizations** | Groundwater varies 4-17 feet bgs seasonally. |
| **ET Rates** | |
| **Climate** | Temperature Range: -22 to 106 F; Mean Annual Precipitation: 35.3"; Elevation: 617 ft; Growing season: 5/1 to 10/6 |
| **Mechanism** | Phytodegradation, rhizodegradation, phytostabilization |
| **OM Requirements** | Pruning; mowing; drip irrigation of contaminated water. |
| **Project Scale** | Full-Scale (2 acres) |
| **Project Status** | Operational (planted 1992) |
| **Cost** | Planting & irrigation: $300,000; O&M: $0/yr (currently) |
| **Funding Source** | Private |
| **Initial concentrations** | Nitrate: 150 ppm |
| **Final Concentrations** | Nitrate: 50 ppm |
| **Lessons Learned** | |
| **Comments** | Primarily for the reduction of nitrates and herbicides in groundwater. Soils have not been retested to date. Groundwater collection/ irrigation system installed with trees to serve as recirculating in-situ treatment system. |
| **Primary Contact** | Paul Thomas, Thomas Consultants, (513) 271-0092, pt@thomasconsultants.com or Todd Gross, IL State EPA, (217) 524-4862, |
| **Citation** | Thomas Consultants, Inc. Project Descriptions document |

| | |
|---|---|
| **Site Name** | Clarence Coop Martelle Plant |
| **Site Location** | Martelle, IA |
| **Contaminant** | Atrazine,  herbicides, nitrate, ammonia/ammonium |
| **Vegetation Type** | Hybrid poplar trees and understory grasses |
| **Planting Descriptions** | 1100 trees planted |
| **Media Type** | Groundwater, Soil (Silty soil underlain by glacial till) |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | Temp Range: -28 to 104 F; Mean Annual Precipitation: 33.4"; Elevation: 902 ft; Growing season: 5/13 to 9/25 |
| **Mechanism** | Phytostabilization, rhizodegradation, phytoextraction |
| **OM Requirements** | Observe insect predation; Mowing, weeding, replanting in areas where ammonia was toxic to trees. |
| **Project Scale** | Full-Scale (0.3 acre) |
| **Project Status** | Inactive (1993) |
| **Cost** | $15,000 |
| **Funding Source** | Clarence Coop |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Agrochemical spill site (Ecolotree Buffer, EBuffer). Ammonia proved to be toxic to hybrid poplars in some areas.  Replanting successfully completed in 1994 by amending soil with compost and adding lime to raise soi pH and convert ammonium to ammonia gas.  Many trees over 20' tall after three growing seasons |
| **Primary Contact** | Louis A. Licht, Ecolotree, (319) 358-9753, lou-licht@ecolotree.com |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Connecticut Agricultural Experiment Station |
| **Site Location** | New Haven, CT |
| **Contaminant** | p,p'-dichlorodiphenyldichloethylene (p-p'-DDE), chlordane |
| **Vegetation Type** | Cucurbita species |
| **Planting Descriptions** | |
| **Media Type** | |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | Temperature Range: -26 to 102 F; Mean Annual Precipitation: 44.1"; Elevation: 174 ft; Growing season: 5/12 to 9/23 |
| **Mechanism** | |
| **OM Requirements** | |
| **Project Scale** | |
| **Project Status** | |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Jason White, (203)-974-8523, Jason.White@po.state.ct.us |
| **Citation** | 2003 Phytotechnologies Conference Abstract |

| | |
|---|---|
| **Site Name** | Fort Winwright |
| **Site Location** | Fairbanks, AK |
| **Contaminants** | Aldrin, DDD, DDT, dieldrin, petroleum hydrocarbons |
| **Vegetation Type** | Felt leaf willow dominant |
| **Planting Descriptions** | Invasive species (felt leaf willow) took over site\ |
| **Media Type** | Soil |
| **Site Characterizations** | Groundwater varies between 5-15 feet bgs |
| **ET Rates** | |
| **Climate** | Temperature Range:-62 to 96 F; Mean Annual Precipitation:10.9"; Elevation: 499 ft; Growing season: 5/25 to 8/25 |
| **Mechanism** | Rhizodegradation, Phytoextraction |
| **OM Requirements** | Corn syrup, alcohol amendments, saturated, fertilized, irrigated, fenced |
| **Project Scale** | Full scale (850 cubic yards) |
| **Project Status** | Completed (1997-2002) |
| **Cost** | |
| **Funding Source** | US Army |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | Aldrin concentrations decreased; dieldrin concentrations did not. After treatment, soils from site were deposited in Fort Wainwright landfill rather than an offsite hazardous waste landfill. |
| **Comments** | Soil excavated and relocated into lined treatment cells for phytoremediation. |
| **Primary Contact** | Diane Soderland, EPA, (907)271-3425, soderlund.dianne@epa.gov |
| **Citation** | First Five Year Review Report for Fort Wainwright, Alaska; Sept. 2001 |

| | |
|---|---|
| **Site Name** | Illinois Fertilizer/Herbicide Spill Site |
| **Site Location** | IL |
| **Contaminants** | Nitrogen, herbicides |
| **Vegetation Type** | Hybrid poplar trees and understory grasses |
| **Planting Descriptions** | 440 trees planted |
| **Media Type** | Soil and groundwater |
| **Site Characterizations** | Groundwater at 4-6' bgs |
| **ET Rates** | |
| **Climate** | |
| **Mechanism** | Hydraulic control, phytoextraction, rhizodegradation |
| **OM Requirements** | Mowing, weeding, fertilization |
| **Project Scale** | Full-scale |
| **Project Status** | Active (began 4/1999) |
| **Cost** | |
| **Funding Source** | Facility owner |
| **Initial concentrations** | Nitrate/nitrite = 20-200 mg/L; alachlor = 0.1-3 mg/L |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Agrochemical spill site. The trees grew 15 feet in the 17 months following planting, and appear to have taken up a significant volume of groundwater. Only 6,000 gallons of groundwater were obtained from an on-site recovery well in 2000, compared to 16-23,000 gallons per year for |
| **Primary Contact** | Louis A. Licht, Ecolotree, (319) 358-9753, lou-licht@ecolotree.com |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Iowa State University microplot |
| **Site Location** | Ames, IA |
| **Contaminant** | Atrazine, metolachlor, pendimethalin, trifluran |
| **Vegetation Type** | big blue stern, indian yellow grass, switchgrass, and mixtures of grasses |
| **Planting Descriptions** | from pots, inoculated with pesticides prior to transplantation into soil |
| **Media Type** | Soil (loamy soil, 1.6% organic matter) |
| **Site Characterizations** | Microplots were 24x30x18 cm deep |
| **ET Rates** | |
| **Climate** | Temperature Range:  F; Mean Annual Precipitation: "; Elevation:  ft; Growing season: |
| **Mechanism** | |
| **OM Requirements** | Fortified soil (pesticides added) |
| **Project Scale** | Field microplot |
| **Project Status** | 4 year study |
| **Cost** | |
| **Funding Source** | Partial funding from Center for Health Efects of Environmental Contaminants at University of Iowa |
| **Initial concentrations** | Atrazine: 25 mg/kg; metolachlor: 35 mg/kg; trifluran: 25 mg/g; pendimethalin: 110 mg/g |
| **Final Concentrations** | Atrazine: 10 mg/kg |
| **Lessons Learned** | |
| **Comments** | No significant difference between vegetated and non-vegetated microplots for atrazine and metolachlor, despite increased dissipation into prarie grasses. Pendimethalin and trifluran were more persistent. No vegetation differences for pendimenthalin but for trifluran concentrations were significantly lower in vegetated plots |
| **Primary Contact** | Joel Coats, IA State Univ, (515) 294-4776, jcoats@iastate.edu or Todd A. Anderson, Texas Tech University, (806) 885-4567, todd.anderson@ttu.edu |
| **Citation** | Final Report: EPA Grant Number r825549c045. Available at http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/5250/report/F<br>Belden, JB; Clark, BW; Phillips, TZ; Hendersen, KL; Arthur, EL; Coats, JR. 2003. Detoxification of Pesticide Residues in Soil Using Phytoremediation. *ACS Symposium Series 863: Pesticide Decontamination and Detoxification*, Chapter 12. Ed: JJ Gan, PC Zhu, SD Aust, AT Lemley. American Chemical Society, 2003. |

| | |
|---|---|
| **Site Name** | Lockwood Farm |
| **Site Location** | Hamden, CT |
| **Contaminants** | p-p'-DDE (p,p'-dichlorodiphenyldichloehtylene) |
| **Vegetation Type** | 21 cultivar varieties of Cucurbita pepo |
| **Planting Descriptions** | Planted from seedlings |
| **Media Type** | Soil (fine sandy loam) |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | Temperature Range: -26 to 102 F; Mean Annual Precipitation: 44.1"; Elevation: 174 ft; Growing season: 5/12 to 9/23 |
| **Mechanism** | |
| **OM Requirements** | Weeding, irrigation, harvesting |
| **Project Scale** | Demonstration/ Pilot |
| **Project Status** | Completed (destroyed Aug 2002) |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | p-p-DDE: 200-1200 ng/g (dry weight) |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Certain cultivars of C. pepo are better able to phytoextract highy weathered POP's than others, likely due to variations in exudate quantity and composition across cultivars. |
| **Primary Contact** | Jason White, (203)-974-8523, Jason.White@po.state.ct.us |
| **Citation** | White, JC; Wang, X; Gent, MPN; Iannucci-Berger, W; Eitzer, BD; Schultes, NP; Arienzo, M; Mattina, MI. 2003. Subspecies Level Variation in the Phytoextraction of Weathered p,p'-DDE by Cucurbita pepo. *Environmental Science and Technology*. 37(2003): 4368-4373. |

| | |
|---|---|
| **Site Name** | McCormick and Baxter Superfund Site |
| **Site Location** | Portland, OR |
| **Contaminant** | Pentachlorophenol (PCP); fluoroanthene; pyrene; chrysene; Benzo(k)fluoroanthene, polyaromatic hydrocarbons |
| **Vegetation Type** | Hybrid Poplar, ryegrass |
| **Planting Descriptions** | |
| **Media Type** | Soil (surface soil is sand) |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | Temperature Range: 6 to 107 F; Mean Annual Precipitation: 36.3"; Elevation: 33 ft; Growing season: 4/26 to 10/18. Additional details: 65C average summer temperature; 40C average winter temperature; 60 percent average relative humidity in mid-afternoon; 60 percent possible sunshine in summer; 14 km/hr average maximum windspeed. |
| **Mechanism** | Rhizdegradation; Phytodegradation |
| **OM Requirements** | Irrigation; Fertilization |
| **Project Scale** | Full scale (225 sq meters) |
| **Project Status** | Completed (3/97-?) |
| **Cost** | U.S. EPA SITE Emerging Technology Program Award ($300,000). Budget includes both greenhouse and field-scale studies for years 1996 and 1997. |
| **Funding Source** | |
| **Initial concentrations** | PCP = 80.4 +/- 23.4 mg/kg; fluoroanthene = 21.8 +/- 6.1 mg/kg; pyrene = 33.5 +/-10.7 mg/kg; chrysene = 11.3 +/-2.6 mg/kg; Benzo(k)fluoroanthene = 4.2 +/- 1.0 mg/kg |
| **Final Concentrations** | |
| **Lessons Learned** | Variability in soil contaminant concentrations may obscure treatment effects. Variability can be reduced by normalizing data for soil moisture and correcting soil contaminant concentrations by comparison with a recalcitrant soil contaminant. Pre-mixing |
| **Comments** | |
| **Primary Contact** | Ari M. Ferro, Phytokinetics, (801) 750-0950, ariferro@phytokinetics.com |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Mid-Lakes Farm Service Cooperative |
| **Site Location** | Bonduel, WI |
| **Contaminant** | Pesticides, herbicides, volatile organic compounds (VOCs) |
| **Vegetation Type** | Grass, Hybrid Poplar |
| **Planting Descriptions** | |
| **Media Type** | Soil, groundwater (sandy soil) |
| **Site Characterizations** | 10' of sandy soil underlain by peat and sandstone bedrock. Groundwater is 4-7 below ground surface |
| **ET Rates** | |
| **Climate** | Temperature Range: -29 to 99 F; Mean Annual Precipitation: 28.8"; Elevation: 699 ft; Growing season: 5/26 to 9/18 |
| **Mechanism** | Hydraulic control, phytoextraction, rhizodegradation, soil stabilization, rhizofiltration |
| **OM Requirements** | Mowing, weeding, insect control |
| **Project Scale** | Full-Scale (0.3 acres) |
| **Project Status** | Operational (began May 1996) |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Hybrid poplars planted as an Ecolotree-cap on 1 acre. Results are pending. |
| **Primary Contact** | Louis A. Licht, Ecolotree, (319) 358-9753, lou-licht@ecolotree.com |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Oconee, IL |
| **Site Location** | Oconee, IL |
| **Contaminant** | alachlor, atrazine, metoachlor, metribuzin |
| **Vegetation Type** | Hybrid poplar |
| **Planting Descriptions** | Planted from cuttings |
| **Media Type** | Groundwater, soil (silt loam) |
| **Site Characterizations** | Groundwater located between 4-10 ft bgs |
| **ET Rates** | |
| **Climate** | Temperature range: -22 to 106 F; Mean annual precipitation: 39.4"; Elevation: 535 ft; Average growing season: 5/1 to 10/6 |
| **Mechanism** | Rhizosphere degradation |
| **OM Requirements** | irrigation to use groundwater, treatment |
| **Project Scale** | Full-scale (1.5 acres) |
| **Project Status** | Ongoing (began 1988) |
| **Cost** | $30000 (Including $10,000/acre planting) |
| **Funding Source** | Private |
| **Initial concentrations** | Alachlor: 750 ppb groundwater, 150 ppm soil; Atrazine: 1200 ppb groundwater, 850 ppm soil; Metoachlor: 1000 ppb groundwater, 50 ppm soil; Metribuzin: 300 ppb groundwater |
| **Final Concentrations** | Alachlor: 100 ppb groundwater (1996), <10 ppm soil (1990); atrazine: 60 ppb groundwater (1996), <10 ppm soil (1990); Metoachlor: 1000 ppb groundwater (1996), <10 ppm soil (1990); Metribuzin: < 10 ppb groundwater (1996) |
| **Lessons Learned** | Periods of continuous data logging and monitoring |
| **Comments** | Concentration data is approximate, estimated from graphic |
| **Primary Contact** | Edd Gatliff, Applied Natural Sciences, Inc., (513) 942-6061, ans@fuse.net or Paul Thomas, Thomas Consultants, (513) 271-0092, pt@thomasconsultants.com |
| **Citation** | http://www.treemediation.com/ |

| | |
|---|---|
| **Site Name** | Former Orchard Site |
| **Site Location** | Picatinny Arsenal, New Jersey |
| **Contaminant** | Arsenic (from arsenical pesticides) |
| **Vegetation Type** | Brake Fern |
| **Planting Descriptions** | Transplanted from pots |
| **Media Type** | Soil (loam soil) |
| **Site Characterizations** | Groundwater >20 feet below ground surface |
| **ET Rates** | |
| **Climate** | Temperature Range: -4 to 102 F; Elevation: 171 ft; Mean annual precipitation: 45.9"; Growing season: 4/15-10/26 |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Irrigation, lime amendments, and fertilizer |
| **Project Scale** | Demonstration plots (10,000 sq ft) |
| **Project Status** | Ongoing (2001) |
| **Cost** | |
| **Funding Source** | US Army |
| **Initial concentrations** | As: 10 ppm to 60-70 ppm |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Original turf grass was removed. A greenhouse was constructed on site for overwintering ferns |
| **Primary Contact** | Michael Blaylock, Edenspace, (703) 961-8700, blaylock@edenspace.com |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Union Pacific Railroad |
| **Site Location** | Laramie, WY |
| **Contaminant** | pentachlorophenol, polyaromatic hydrocarbons |
| **Vegetation Type** | Cottonwood, willow, hackberry bushes, alfala, dryland grass mixture |
| **Planting Descriptions** | |
| **Media Type** | Soil |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | Temperature Range: -50 to 94 F; Mean Annual Precipitation: 10.6"; Elevation: 7186 ft; Growing season: 6/26 to 8/26 |
| **Mechanism** | |
| **OM Requirements** | Nutrient amendments added |
| **Project Scale** | Full-scale (140 acres) |
| **Project Status** | Ongoing |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Other treatments used at site: 2 mile slurry wall, dual-drain liner system, nutrient amendments |
| **Primary Contact** | Felix Flechas, EPA, 303-312-6014, flechas.felix@epa.gov |
| **Citation** | US EPA REACHIT: http://www.epareachit.org/ |

| | |
|---|---|
| **Site Name** | Weyerhauser - Timber Processing Site |
| **Site Location** | Klamath Falls, OR |
| **Contaminant** | Halogenated semi-volatiles (PCP, PCB) and metals (chromate) |
| **Vegetation Type** | Hybrid poplar trees and understory grasses |
| **Planting Descriptions** | |
| **Media Type** | Soil (Sandy-loess soil) |
| **Site Characterizations** | GW 2' bgs |
| **ET Rates** | |
| **Climate** | Temperature Range: -25 to 100 F; Mean Annual Precipitation: 12.6 "; Elevation: 4099 ft; Growing season: 6/28 to 8/31 |
| **Mechanism** | Phytoextraction, Rhizodegradation, Phytovolatilization |
| **OM Requirements** | Mowing |
| **Project Scale** | Full-Scale (7 acres, 10 acres) |
| **Project Status** | Operational |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Industrial wastewater containing PCP and PCB is irrigated onto 10 acres of hybrid poplars, thus reducing point-source discharge to receiving streams. Approximately 5% tree loss in year 1 attributed to shallow concrete foundations inhibiting root development. |
| **Primary Contact** | Louis A. Licht, Ecolotree, (319) 358-9753, lou-licht@ecolotree.com |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Whitewater |
| **Site Location** | Whitewater, WI |
| **Contaminant** | Nitrate Nitrogen, herbicides/insecticides, silvex |
| **Vegetation Type** | Grass, Hybrid Poplar, Legumes |
| **Planting Descriptions** | Trees were deep rooted and planted when 10-16 ft tall. |
| **Media Type** | Groundwater, Soil |
| **Site Characterizations** | Site is situated on a porous aquifer medium of fractured bedrock. Groundwater is 5 to 10 feet bgs. |
| **ET Rates** | |
| **Climate** | Temperature Range: -30 to 104 F; Mean Annual precipitation: 30.9"; Elevation: 872 ft; Average growing season: 5/13-9/25 |
| **Mechanism** | Hydraulic control |
| **OM Requirements** | None, aside from brief monitoring in early stages of project |
| **Project Scale** | Full-Scale (10 acres) |
| **Project Status** | Operational (began 1990) |
| **Cost** | $30,000 |
| **Funding Source** | private |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Industrial wastewater containing PCP and PCB is irrigated onto 10 acres of hybrid poplars, thus reducing point-source discharge to receiving streams. Approximately 5% tree loss in year 1 attributed to shallow concrete foundations inhibiting root development. Overall reductions in concentrations observed. |
| **Primary Contact** | Ed Gatliff, Applied Natural Sciences, Inc., (513) 942-6061, ans@fuse.net |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Former farm market |
| **Site Location** | WI |
| **Contaminant** | Pesticides, nitrates, ammonium |
| **Vegetation Type** | Hybrid poplars |
| **Planting Descriptions** | |
| **Media Type** | Soil, groundwater |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | |
| **Mechanism** | |
| **OM Requirements** | |
| **Project Scale** | |
| **Project Status** | Ongoing (began Spring 1992) |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Louis A. Licht, Ecolotree, (319) 358-9753, lou-licht@ecolotree.com |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Wilmington |
| **Site Location** | Wilmington, NC |
| **Contaminant** | Nitrate nitrogen, pesticides, ammonium |
| **Vegetation Type** | Hybrid Poplar |
| **Planting Descriptions** | Trees were deep rooted and planted when 10-16 ft tall. Nutrients added prior to planting |
| **Media Type** | Groundwater, Soil (sandy, coastal soil) |
| **Site Characterizations** | Groundwater is 10-15 ft bgs |
| **ET Rates** | |
| **Climate** | Temperature range: 0 to 102 F; Mean annual precipitation: 54.2"; Elevation: 52 ft; Average growing season: 4/11 to 11/3 |
| **Mechanism** | Hydraulic control |
| **OM Requirements** | None |
| **Project Scale** | Full-Scale (6 acres) |
| **Project Status** | Operational (1992- 2002) |
| **Cost** | $30,000 |
| **Funding Source** | Private |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | Reduction of contaminants was observed at first, but then a site on the property boundary became a continuous source of contamination |
| **Comments** | Nitrogen levels in downgradient wells have steadily fallen. |
| **Primary Contact** | Edd Gatliff, Applied Natural Sciences, Inc., (513) 942-6061, ans@fuse.net |
| **Citation** | |

# Appendix C: Explosives Database

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| C5 | | | | | X | | | |
| C6 | X | X | | | | X | | |
| C7 | X | X | | | | X | | |
| C8 | | | | | | | | |
| C9 | X | X | | | | X | | |
| C10 | X | | X | | | | X | X |
| C11 | | | | | | X | | |
| C12 | X | | X | | | | | |
| C13 | X | | | | | | | |

TNT = trinitrotoluene
RDX = 1,3,5-trinitro-1,3,5-triazine
HMX = 1,3,5,7-tetranitro-1,3,5,7-tetraazocyclooctane
DNT = dinitrotoluene
PC = perchlorate
AN = Ammonium Nitrate
2NT = 2-nitrotoluene
4NT = 4-nitrotoluene

| | |
|---|---|
| **Site Name** | ICI Explosives Americas Engineering |
| **Site Location** | Joplin, MO |
| **Contaminant** | Ammonium nitrate; Dinitrotoluene |
| **Vegetation Type** | Bald Cypress, Hybrid Poplar, Ninebark, Willow |
| **Planting Descriptions** | 18,000 trees in various arrangements, rooted and bare-root cuttings |
| **Media Type** | Groundwater, Soil (in situ), Surface Water |
| **Site Characterizations** | Surface water and small drainages; wetlands systems; shallow groundwater; soils and sediments and sandy silts. |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. Range: -15 to 108 F; Elev: 987 ft; Mean annual precip.: 43.2"; Growing season: 4/25-10/22 |
| **Mechanism** | Rhizodegradation, phytoextraction |
| **Operation/Maintenance Requirements** | Irrigation, weeding |
| **Project Scale** | Field Demonstration. 3.2 acres |
| **Project Status** | Active remedial. Planted 2/1996 |
| **Cost** | $40, 000-installation, $20,000-oversight and planning. |
| **Funding Source** | The cost of management was born by the client. |
| **Initial concentrations** | Ammonium nitrate = 20-1,000 mg/kg soil; Dinitrotoluene = 0.8-200 ug/L water. |
| **Final Concentrations** | |
| **Lessons Learned** | Management (weeding, watering of upland plants) is essential for a good rate of plant establishment. Effective design and installation is futile unless there is a solid management program later in the growing season and during subsequent years. |
| **Comments** | Many trees died, especially trees planted on upland areas, because of extremely poor management following planting. |
| **Primary Contact** | Ari M. Ferro, Phytokinetics (435) 750-0950 ariferro@phytokinetics.com |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Iowa AAP |
| **Site Location** | Middletown, IA |
| **Contaminant** | RDX (hexahydro 1,3,5-trinitro-1,3,5triazine) and TNT (2,4,6-trinitro-toluene) |
| **Vegetation Type** | hybrid poplar tree Populus Deltoides X Nigra DN34 |
| **Planting Descriptions** | 700 Hybrid Poplar Trees per acre, planted as 8 ft "whips". |
| **Media Type** | Soil |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | Temp Range: -23 to 101 F; Elevation:533 ft ; Mean annual precip:34.5"; Growing season: 5/3 to 10/5 |
| **Mechanism** | |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | Full Scale Constructed Wetlands |
| **Project Status** | |
| **Cost** | |
| **Funding Source** | CERCLA |
| **Initial concentrations** | RDX: 800ppb |
| **Final Concentrations** | RDX: <0.25ppb |
| **Lessons Learned** | RDX disappearance in gw slower than TNT. Wetlands estimated to remove approx 0.016-0.019 mg/L TNT and 0.133-0.291 mg/L-day RDX at 25ºC @steady state. Plant growth reduced, but still considerable. Toxic ranges of TNT and RDX were estimated to be 5 to 7 mg/L (in hydroponic culture). |
| **Comments** | acute toxicity assays (<14 d) showed poplar had a significant tolerance to explosives concentrations of 5 mg/L |
| **Primary Contact** | Jerry Schnoor, University of Iowa (319) 335-5649 jschnoor@engineering.uiowa.edu<br>Kevin Howa, Omaha Corps of Engineers kevin.m.howe@usace.army.mil |
| **Citation** | Kiker, J.H., S. Larson, D.D. Moses, and R. Sellers. Use of Engineered Wetlands to Phytoremediate Explosives Contaminated Surface Water at the Iowa Army Ammunition Plant, Middletown, Iowa. |

| | |
|---|---|
| **Site Name** | Joliet Army Ammunition Plant |
| **Site Location** | Joliet, IL |
| **Contaminant** | trinitrotoluene (TNT), Tetryl, cyclotrimethylenetrinitramine (RDX) |
| **Vegetation Type** | Hybrid poplars (*Populus* spp.) or willows (*Salix* spp.) or native prairie grasses |
| **Planting Descriptions** | slurry reactor |
| **Media Type** | Groundwater |
| **Site Characterizations** | Shallow aquifer |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. Range: -27 to 104 F; Elev: 658 ft; Mean annual precip.: 35.8"; Growing season: 4/25 to 10/22 |
| **Mechanism** | Hydraulic Control, phytodegradation |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | |
| **Project Status** | 1998, proposal |
| **Cost** | $191,000 research grant |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | The site did not use phytoremediation for remediation. Costs estimated at $15M from investigation through remediation including excavation and off-site disposal) |
| **Primary Contact** | Jerry Schnoor, University of Iowa (319) 335-5586.<br>GRACE Bioremediation Technologies, Inc. [DARAMEND®] Missauga, Ontario, Canada<br>Bill Rainey, Plexus Scientific brainey@plexsci.com 301-622-9696 |
| **Citation** | Multiple Biotechnology Demonstrations of Explosives-Contaminated Soils, http://aec.army.mil/prod/usaec/et/restor/ecsoils.htm, 2000. |

| | |
|---|---|
| **Site Name** | Longhorn Army Ammunition Plant, Burning Ground #3 |
| **Site Location** | Marshall, Texas |
| **Contaminant** | Perchlorate |
| **Vegetation Type** | hybrid poplar trees (Populus Deltoides Nigra, DN34) |
| **Planting Descriptions** | 425 poplar trees were planted |
| **Media Type** | Groundwater |
| **Site Characterizations** | GW 168-171' bgs. Clayey soils |
| **Evapotranspiration Rates** | 1,000,000 gal/acre/yr (groundwater is pumped up and drip irrigated onto trees) |
| **Climate** | Temp Range: 3 to 107 F; Elevation: 417 ft; Mean annual precipitation: 50"; Growing season: 4/2-10/27 |
| **Mechanism** | Phytodegradation, Rhizodegradation |
| **Operation/Maintenance Requirements** | Complete Environmental Service: Trees inspected & irrigated regularly, amendments, sample collection |
| **Project Scale** | 0.7 acre Demonstration |
| **Project Status** | Planted March 17, 2003, continuing through 2005 |
| **Cost** | installation and maintenance costs $42,000; research, analysis and monitoring $200,000 |
| **Funding Source** | Department of the Army, Operations Support Command |
| **Initial concentrations** | Perchlorate: ~100 mg/L |
| **Final Concentrations** | Perchlorate: 10 mg/L |
| **Lessons Learned** | The mass of perchlorate taken up by poplar trees and/or degraded within in the rhizosphere was essentially zero (-0.261 ± 0.016 kg/d). Therefore, between April 2003 and March 2004, no perchlorate was removed from the groundwater by the hybrid poplar trees and/or the microbes that grow in the root zone. However, due to a complicated hydrogeological setting and trenching, it is difficult to obtain a tight water balance and mass balance on perchlorate to prove efficacy of treatment in the field. |
| **Comments** | Trees are growing well; phytoremediation system is functioning well. Only 5% of trees have died over the first growing season. Test plot was irrigated with perchlorate contaminated water since the water level was too deep for the roots of the poplar trees to reach. Approximately 116,320 gallons of water was applied to the site between April and November 2003. Irrigation was discontinued for the remainder of the non-growing season on November 17. |
| **Primary Contact** | Jerry Schnoor, University of Iowa (319) 335-5649 jschnoor@engineering.uiowa.edu |
| **Citation** | Schnoor, J.L., et al. (2004) Demonstration Project of Phytoremediation and Rhizodegradation of Perchlorate in Groundwater at the Longhorn Army Ammunition Plant, The University of Iowa, Dept of Civil and Envi Engr. |

| | |
|---|---|
| **Site Name** | Milan AAP |
| **Site Location** | Milan, Tennessee |
| **Contaminant** | trinitrotoluene (TNT), cyclotrimethylenetrinitramine (RDX), and cyclotetramethylenetetranitramine (HMX) |
| **Vegetation Type** | Aquatic and wetlands plants. Parrot feather, |
| **Planting Descriptions** | Constructed wetland |
| **Media Type** | Groundwater, soil |
| **Site Characterizations** | Field-scale wetland demonstration |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. Range: -13 to 105 F; Elevation: 420 ft; Mean annual precip: 55.2"; Growing season: 4/8 to 10/27 |
| **Mechanism** | Phytodegradation |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | 1/8 acre field demonstration |
| **Project Status** | June 1996-Sept 1997 |
| **Cost** | $1.8M |
| **Funding Source** | DoD |
| **Initial concentrations** | TNT (1.8mg/l), RDX (2.2mg/l), HMX (0.13 mg/l) |
| **Final Concentrations** | Lagoon and gravel-bed wetlands are reducing TNT below 0.002 mg L-l. Lagoon wetland is not as effective with removal efficiencies of only 47 and 20%, respectively. |
| **Lessons Learned** | |
| **Comments** | Growth of most plants except parrot-feather, was reduced in groundwater containing 1.5 to 3.7 mg TNT L-1 |
| **Primary Contact** | Darlene Bader-Lohn, US AEC (410) 436-6861 darlene.bader-lohn@aec.apgea.army.mil |
| **Citation** | Army Environment Center, Aberdeen Proving Grounds, *report* SFIM-AEC-ET-CR-97059<br>Sikora, F.L. et al (1997), "Phytoremediation of explosives in groundwater at the Milan Army Ammunition Plant using innovative wetlands-based treatment technologies". *Presentation 15. In 12th Annual Conference on Hazardous Waste Research - Abstracts Book, May 19-22, 1997, Kansas City, MO.*<br>Best, E.P.H. et al (1997), Fate and mass balances of [14C]-TNT and [14C]-RDX in aquatic and wetland plants in groundwater from the Milan Army Ammunition Plant<br>*Presentation 14. In 12th Annual Conference on Hazardous Waste Research - Abstracts Book, May 19-22, 1997, Kansas City, MO.* |

| | |
|---|---|
| **Site Name** | New Mexico State University |
| **Site Location** | Las Cruces, NM |
| **Contaminant** | 2,4,6-trinitrotoluene (TNT), 1,3,5-trinitro-1,3,5-triazine (RDX), 1,3,5,7-tetranitro-1,3,5,7-tetraazocyclooctane (HMX) |
| **Vegetation Type** | Datura innoxia |
| **Planting Descriptions** | Cell suspension cultures |
| **Media Type** | |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. Range: -8 to 112 F; Elev: 3908 ft; Mean annual precip: 8.8"; Growing season: 4/14 to 10/28 |
| **Mechanism** | Phytodegradation |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | Bench scale |
| **Project Status** | Completed 1999 |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | TNT (750-1000 ppm) |
| **Final Concentrations** | Within 12 h, less than 1% of the initial TNT remained in the growth medium |
| **Lessons Learned** | |
| **Comments** | Aminodinitrotoluenes (ADNTs), metabolites of TNT, accumulated transiently in cell lysates, and to a lesser extent in cell media. ADNT concentrations started to decrease after 3 h. After 12 h, less than 5% of the initial TNT could be detected as ADNT. Total ADNTs never exceeded 26% of initial TNT, suggesting that additional biotransformation steps also occurred |
| **Primary Contact** | |
| **Citation** | M. E. LUCERO, W. MUELLER, J. HUBSTENBERGER, G. C. PHILLIPS, and M. A. O'CONNELL, Tolerance to Nitrogenous Explosives and Metabolism of TNT by Cell Suspensions of Datura Innoxia. *Society for In Vitro Biology* (1998) |

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|---|---|
| **Site Name** | NIKE Missile Site |
| **Site Location** | Kent County, MD |
| **Contaminant** | Trichloroethene |
| **Vegetation Type** | poplar trees |
| **Planting Descriptions** | several hundred trees planned |
| **Media Type** | |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | Estimate will pump 50gal/day |
| **Climate** | Temp. Range: -7 to 105 F; Elev: 148 ft; Mean annual precip: 40.7 "; Growing season: 4/11 to 10/29 |
| **Mechanism** | |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | |
| **Project Status** | Proposal |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | >5ppb limit |
| **Final Concentrations** | Kent County Forestry Board - seek private funding |
| **Lessons Learned** | |
| **Comments** | Expects positive results in 4-5 years |
| **Primary Contact** | |
| **Citation** | DoD (2001) County Considers Phytoremediation Of TCE at Former Nike Missile Site. *Defense Cleanup* Feb. 9, 2001, v12 i9, p 45 |

| | |
|---|---|
| **Site Name** | University of Iowa |
| **Site Location** | Iowa City, IA |
| **Contaminant** | Trinitrotoluene (TNT), cyclotrimethylenetrinitramine (RDX), 1,3,5,7-tetranitro-1,3,5,7-tetraazocyclooctane (HMX) |
| **Vegetation Type** | *Populus Deltoides x Nigra* |
| **Planting Descriptions** | greenhouse study |
| **Media Type** | Hydroponic Solution |
| **Site Characterizations** | |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. Range: -28 to 104 F; Elev: 902 ft; Mean annual precip.: 33.4"; Growing season: 5/13 to 9/25 |
| **Mechanism** | Phytodegradation |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | 12 day greenhouse study |
| **Project Status** | Completed as of 2003 |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | TNT, RDX, and HMX show different fates in poplars. Leachability and toxicity of unknown metabolites should be considered. |
| **Comments** | HMX removed more slowly than RDX, and TNT removed faster than nitramine explosives in 12 days. |
| **Primary Contact** | |
| **Citation** | Yoon, J.M, B. Van Aken, B. Flokstra and J.L. Schnoor (2003) Uptake and Fate of Explosives: TNT, RDX, and HMX in Popular Tissues (Populus Deltoides x Nigra) |

| | |
|---|---|
| **Site Name** | Volunteer AAP |
| **Site Location** | Chattanooga, TN |
| **Contaminant** | Trinitrotoluene (TNT), 2,4-Dinitrotoluene (2,4DNT), 2,6-Dinitrotoluene (2,6DNT), 2-nitrotoluene (2NT), and 4-nitrotoluene (4NT) |
| **Vegetation Type** | Elodea Canadensis Rich. in Michx. (Elodea) and the emergent Typha angustifolia L. (narrow-leaved cat-tail). July: Ceratophyllum demersum L. (coontail) and Potamogeton nodosus Poir (American pondweed). |
| **Planting Descriptions** | Constructed wetland |
| **Media Type** | Surface Water |
| **Site Characterizations** | Top foot contaminant. Sandy soil |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. Range: -10 to 105 F; Elev: 689 ft; Mean annual precip: 53.5"; Growing season: 4/18 to 10/19 |
| **Mechanism** | |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | Green house scale |
| **Project Status** | Completed. 115-day Field demonstration May-September 1996 |
| **Cost** | Estimated $50,000 |
| **Funding Source** | U. S. Army Engineer District, Omaha (Missouri River Organization), the U. S. Department of Defense Environmental Security Technology Certification Program (ESTCP), and the Department of Defense Strategic Environmental Research and Development Program (SERDP). |
| **Initial concentrations** | 2.7 mg/L TNT, 16.7 mg/L 24DNT, 5.2 mg/L 26DNT, 42.6 mg/L 2NT, and 30.5 mg/L 4NT |
| **Final Concentrations** | planted sediment reactors in full sunlight removed 22 g TNT, 104 g 24DNT and 38 9 26DNT (592-L system) over the 115-day operational period; the unplanted sediment reactors in full sunlight removed 34 9 TNT,779 24DNT and 62 9 26DNT(1071-L system); and the unplanted sediment reactors in LV-filtered sunlight removed 25 9 TNT, 34 9 24DNT and 26 9 26DNT (1071-L system) |
| **Lessons Learned** | Elodea failed to grow in VAAP water, coontail and American pondweed both failed to survive in VAAP water. |
| **Comments** | The hydraulic retention time was 7 days. |
| **Primary Contact** | Darlene Bader-Lohn, US AEC (410) 436-6861 darlene.bader-lohn@aec.apgea.army.mil |
| **Citation** | Miller, J.L., E.P.H. Best, and S.L. Larson (1997), "Degradation of explosives in groundwater at the Volunteer Army Ammunition Plant in flow-through systems planted with aquatic and wetland plants" Presentation 13.12th Annual Conference on Hazardous Waste Research - Abstracts Book, May 19-22, 1997, Kansas City, MO. |

| | |
|---|---|
| **Site Name** | Wainwright Firing range |
| **Site Location** | Alberta, Canada |
| **Contaminant** | Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX), copper, lead, zinc, barium |
| **Vegetation Type** | Alfalfa(*Medicago sativa*), bush bean(Phaseolus vulgaris), canola(Brassica rapa), wheat(Triticum aestivum) and perennial rye grass(Lolium perenne) |
| **Planting Descriptions** | |
| **Media Type** | |
| **Site Characterizations** | Sandy Loam: 60% sand, 20% silt by weight |
| **Evapotranspiration Rates** | |
| **Climate** | Dry prairie climate |
| **Mechanism** | Phytoextraction |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | Greenhouse study with site soil. Analysis of vegetation existing at site. |
| **Project Status** | |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | HMX: 32ppm, copper: 790-1000ppm, lead: 85-96ppm, zinc: 100-120ppm, barium: 100-120ppm |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Sampling of indigenous plants at site revealed prairie grass, brome grass, wild bergamot, low bush blueberry, anemone, common thistle, western sage and Drummond's milk vetch to contain extractable HMX, but TNT or RDX. |
| **Primary Contact** | |
| **Citation** | Groom, C.A, A. Halasz, L. Paquet, N. Morris, L. Olivier, C. Dubois and J. Hawari (2002) Accumulation of HMX (Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine) in Indigenous and Agricultural Plants Grown in HMX-Contaminated Anti-Tank Firing-Range Soil. *Environ. Sci. & Technol.* 2002, Vol 36, Issue 1 p112-118 |

| | |
|---|---|
| **Site Name** | Weldon Spring Former Army Ordnance Works |
| **Site Location** | MO |
| **Contaminant** | trinitrotoluene, dinitrotoluene, lead |
| **Vegetation Type** | Treatment slurry |
| **Planting Descriptions** | |
| **Media Type** | Surface water, Soil, Sludge, and Sediment |
| **Site Characterizations** | Clayey gravel with sand |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. Range: F; Elev: ft; Mean annual precip.: "; Growing season: |
| **Mechanism** | |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | Demonstration/Bench scale |
| **Project Status** | 1993 |
| **Cost** | Estimated $147/m^3 with possible additional $131/m^3 for additional technical assistance, nutrients, carbon source and other process enhancers. |
| **Funding Source** | USEPA/SITE |
| **Initial concentrations** | TNT: 1500 mg/kg dry weight |
| **Final Concentrations** | TNT: 8.7 mg/kg dry weight. TNT reduced by 99.4% over 9 months |
| **Lessons Learned** | Treatment time found to be approximately 9 months. |
| **Comments** | Treatment slurry |
| **Primary Contact** | Tom Lorenz, US EPA (913) 551-7292 lorenz.thomas@epa.gov |
| **Citation** | Ex-Situ Anaerobic Bioremediation System: TNT, J. R. Simplot Company  EPA 540-R-95-529 |

| | |
|---|---|
| **Site Name** | Werk Tanne |
| **Site Location** | Harz, Germany |
| **Contaminant** | trinitrotoluene |
| **Vegetation Type** | white rot fungi, mycorrhiza; spruce; poplar; elder |
| **Planting Descriptions** | Heavy duty soil grader loosened, aerated and homogenized top 30cmof soil. Straw with white rot fungi added followed by layer of bark mulch. |
| **Media Type** | Soil |
| **Site Characterizations** | Brown soil from loessy loam |
| **Evapotranspiration Rates** | |
| **Climate** | Cool, humid mountain climate. Altitude: 560m, Precipitation: 1,300mm/a, Avg Annual Temperature: 6.2ºC. |
| **Mechanism** | Rhizodegradation |
| **Operation/Maintenance Requirements** | |
| **Project Scale** | 25m X 20m |
| **Project Status** | May-99 |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | 1000mg TNT / mg dm soil |
| **Final Concentrations** | Lower TNT concentrations brought to near detection limits within 6 months after grading. Higher TNT concentrations lowered, but not down to detection limit. |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Dr. Hartmut Koehler, University of Bremen 49-421-218-4179 a13r@uni-bremen.de |
| **Citation** | Koehler, H., J. Warrelmann, T. Frische, P. Behrend, and U. Walter. (2002) In-Situ Phytoremediation of TNT-Contaminated Soil. *Acta Biotechnologia* 22:1-2, 67-80. |

# Appendix D: Metals Database

*Table of Contents*



An = Antimony
As = Arsenic
Ba = Barium
Be = Beryllium
Cd = Cadmium
Cr = Chromium
Co = Cobalt
Cs = Cesium
Cu = Copper
Pb = Lead
Ni = Nickel
Ag = Silver
Tl = Thallium
V = Vanadium
Zn = Zinc

| | |
|---|---|
| **Site Name** | 317/319 Area - Argonne National Laboratory |
| **Site Location** | Lemont, IL |
| **Contaminant** | Perchloroethene, Trichloroethene, Carbon Tetrachloride, Chloroform, Zinc, Lead, Arsenic, Tritium |
| **Vegetation Type** | Eastern gamagrass, Hybrid Poplar, Golden Weeping Willow, Hybrid Prairie Cascade Willow, Laurel-leaved willow |
| **Planting Descriptions** | 800 whips planted. 420 poplars installed in deep, lined boreholes (TreeWells®) 389 willows and poplars planted at or near surface. Used patented TreeWells® and TreeMediation® (Applied Natural Sciences Inc) |
| **Media Type** | Groundwater, Soil: Top-Bottom: 10' silty clay, 2' shallow aquifer, 8' silty clay, 10' silt/sand/silty clay deep aquifer |
| **Site Characterizations** | Groundwater 25-30' bgs, aquifer 5' |
| **Evapotranspiration Rates** | |
| **Climate** | Temp. Range: -27 to 104 F; Elev: 658 ft; Mean annual precip.: 35.8"; Growing season: 4/25-10/22 |
| **Mechanism** | Phytostabilization, phytoextraction, phytodegradation, rhizodegradation |
| **Operation/Maintenance Requirements** | Fertilization, replanting, and significant Health/Safety expenditures because of radiological and other concerns |
| **Project Scale** | Full-scale (4 acres) |
| **Project Status** | Ongoing (planted 1999) |
| **Cost** | $1.2 million |
| **Funding Source** | US DOE |
| **Initial Concentrations** | n/a; varies considerably throughout site, from ppb to ppm |
| **Final Concentrations** | n/a; varies considerably throughout site, from ppb to ppm |
| **Lessons Learned** | TreeWells® installed in effort to achieve hydraulic control |
| **Comments** | TCE and PCE and breakdown products (trichloroacetic acid) were detected in branch tissue of trees planted in contaminated soil in less than a year. TCE and PCE present in trees down gradient of plume after 2 yrs. |
| **Primary Contact** | Cristina Negri, Argonne National Laboratory (630) 252-9662 negri@anl.gov<br>Ed Gatliff, Applied Natural Sciences (513) 895-6061 ans@fuse.net |
| **Citation** | Negri, M.C., et al 2003 Root Development and Rooting at Depths, in S.C.<br>McCutcheon and J.L. Schnoor, eds., Phytoremediation: Transformation and Control of Contaminants: Hoboken, NJ, John Wiley & Sons, Inc. p233-262, 912-913<br>Quinn, J.J., et al 200 Predicting the Effect of Deep-Rooted Hybrid Poplars on the Groundwater Flow System at a Phytoremediation Site: International Journal of Phytoremediation, vol. 3, no. 1, p. 41-60 |

| | |
|---|---|
| **Site Name** | Anaconda Smelter Site, MT |
| **Site Location** | Anaconda, MT |
| **Contaminant** | Arsenic, cadmium, copper, and zinc |
| **Vegetation Type** | Various; over 36 grass, forb, and sub-shrub species and excessions |
| **Planting Descriptions** | Planted from seeds, native species was focus although cultivated species were grown to evaluate performance |
| **Media Type** | Soil (loam) |
| **Site Characterizations** | 3-5% grade, sloping north; groundwater depth > 100 ft |
| **ET Rates** | |
| **Climate** | Temperature range: -52 to 99 F; Elevation: 4467 ft; Mean annual precipitation: 14.7"; Growing season: 6/19-8/31 |
| **Mechanism** | Phytostabilization; no evidence of phytoextraction |
| **OM Requirements** | Fertilization (NPK 12-16-30, applied at rate of 500 lb/acre, 6" depth), amendments (lime kiln dust, applied 22 tons/acre to 12" depth) |
| **Project Scale** | Full-scale (1.5 acres) |
| **Project Status** | Ongoing (began mid 1990's, EPA work began 2001) |
| **Cost** | $350,000 (10 years, total); $200,000 (EPA, since 2001) |
| **Funding Source** | EPA, State of Montana Natural Resources Damage Program |
| **Initial concentrations** | Cu: range 1020-2180 mg/kg (pre-tillage), pH: 4.00-4.9 (0-6" rooting zone) |
| **Final Concentrations** | Cu: average 832 mg/kg, range 525-1080 mg/kg (post-planting) |
| **Lessons Learned** | Soil amendments (lime) and fertilizer greatly help to establish vegetation. Native species perform better than commercially available cultivated species. |
| **Comments** | Pre-tilling pH was phytotoxic to plants, amendments and fertilization added prior to establishment of vegetation. |
| **Primary Contact** | Jay Cornish, MSE Technology, (406) 494-7329, jay.cornish@mse-ta.com |
| **Citation** | Development of Acid/ Heavy Metal Tolerant Cultivars (DATC) Project Bi-Annual Report. 2003. Prepared for the EPA Mine Waste Technology Program (Activity III Project 30) and the State of Montana Natural Resource Damage Program (Contract#600121) by Leslie Marty, DATC |

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|---|---|
| **Site Name** | Anderson |
| **Site Location** | Anderson, SC |
| **Contaminant** | Lead, cadmium, sulfate, nitrate |
| **Vegetation Type** | Grass, Hybrid Poplar |
| **Planting Descriptions** | live cuttings, deep-rooted |
| **Media Type** | Groundwater, Soil (sandy clay and weathered rock 0-100 feet consisting of mica and saprolite) |
| **Site Characterizations** | Groundwater varies 0-18 feet (topographical) |
| **ET Rates** | |
| **Climate** | Temperature Range: -6 to 103 F; Mean Annual Precip: 50.6"; Elevation: 956 ft; Growing season: 4/15-10/19 |
| **Mechanism** | Phytostabilization |
| **OM Requirements** | Mowing; pruning, replanting |
| **Project Scale** | Full-scale (17 acres) |
| **Project Status** | Operational (began 1993) |
| **Cost** | Maintenance and monitoring costs: $20,000/ yr. Planting costs: $40,000 |
| **Funding Source** | Private |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | Concentration of metals in surface water has decreased significantly. |
| **Comments** | Phytoremediation is combined with passive anoxic limestone drain system to treat groundwater. |
| **Primary Contact** | Paul Thomas, Thomas Consultants, (513) 271-0092, pt@thomasconsultants.com |
| **Citation** | Personal communication |

| | |
|---|---|
| **Site Name** | Argonne NL West 1 |
| **Site Location** | Idaho Falls, ID |
| **Contaminant** | Cesium-137 |
| **Vegetation Type** | Koshia scoparia |
| **Planting Descriptions** | hydro-seeded |
| **Media Type** | Soil; 40% bondfarm loamy sand, 30% rock outcrop, 20% grassy butte loamy sand |
| **Site Characterizations** | Effective rooting depth is 10-20 inches. Available water capacity is low |
| **ET Rates** | |
| **Climate** | Northern high desert, very low humidity, short growing season, less than 5 days above 100 C, 45 C typical nighttime temperature. Temperature range: -38 to 102 F; Elevation: 4728 ft; Mean annual precipitation: 230 mm; Growing season: 6/14 to 9/4 |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Irrigation (system with automated sensors based on soil moisture content), Manure addition, non-potasssium fertilizer, pest control (Roundup), harvesting (manual) |
| **Project Scale** | Demonstration/ Pilot (1500 cubic yards) |
| **Project Status** | Inactive |
| **Cost** | 2.5 million |
| **Funding Source** | Government agency, PRP |
| **Initial concentrations** | Cs-137: 30.53 pCi/g |
| **Final Concentrations** | Data available Fall '04 |
| **Lessons Learned** | |
| **Comments** | Initial costs could be reduced significantly from this project because of readily available information that currently exists |
| **Primary Contact** | Scott Lee, Argonne West, 208-533-7829, scott.lee@anlw.anl.gov |
| **Citation** | Various CERCLA documents, including EPA Superfund Record of Decision: Idaho National Engineering Laboratory, OU 21. 9/29/98. EPA/ROD/R10-98/061 1998. (http://www.epa.gov/superfund/sites/rods/fulltext/r1098061.pdf) |

| | |
|---|---|
| **Site Name** | Argonne NL West 2 |
| **Site Location** | Idaho Falls, ID |
| **Contaminant** | Silver |
| **Vegetation Type** | Hybrid willow |
| **Planting Descriptions** | hand-planted, spaced 18 inches apart |
| **Media Type** | Soil; 40% bondfarm loamy sand, 30% rock outcrop, 20% grassy butte loamy sand |
| **Site Characterizations** | Effective rooting depth is 10-20 inches. Available water capacity is low |
| **ET Rates** | n/a |
| **Climate** | Northern high desert, very low humidity, short growing season, less than 5 days above 100 C, 45 C typical nighttime temperature. Temperature range: -38 to 102 F; Elevation: 4728 ft; Mean annual precipitation: 230 mm; Growing season: 6/14 to 9/4 |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Irrigation (system with automated sensors based on soil moisture content), Manure addition, non-potasssium fertilizer, pest control (Roundup), harvesting (manual) |
| **Project Scale** | Demonstration/ Pilot (500 cubic yards) |
| **Project Status** | Inactive |
| **Cost** | 2.5 million |
| **Funding Source** | Government agency, PRP |
| **Initial concentrations** | Silver: 352 mg/kg |
| **Final Concentrations** | Data available Fall '04 |
| **Lessons Learned** | |
| **Comments** | Initial costs could be reduced significantly from this project because of readily available information that currently exists |
| **Primary Contact** | Scott Lee, Argonne West, 208-533-7829, scott.lee@anlw.anl.gov |
| **Citation** | Various CERCLA documents, including EPA Superfund Record of Decision: Idaho National Engineering Laboratory, OU 21. 9/29/98. EPA/ROD/R10-98/061 1998. (http://www.epa.gov/superfund/sites/rods/fulltext/r1098061.pdf) |

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|---|---|
| **Site Name** | Argonne NL West 3 |
| **Site Location** | Idaho Falls, ID |
| **Contaminant** | Mercury |
| **Vegetation Type** | Hybrid willow |
| **Planting Descriptions** | hand-planted, spaced 18 inches apart |
| **Media Type** | Soil; 40% bondfarm loamy sand, 30% rock outcrop, 20% grassy butte loamy sand |
| **Site Characterizations** | Effective rooting depth is 10-20 inches. Available water capacity is low |
| **ET Rates** | n/a |
| **Climate** | Northern high desert, very low humidity, short growing season, less than 5 days above 100 C, 45 C typical nighttime temperature. Temperature range: -38 to 102 F; Elevation: 4728 ft; Mean annual precipitation: 230 mm; Growing season: 6/14 to 9/4 |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Irrigation (system with automated sensors based on soil moisture content), Manure addition, non-potasssium fertilizer, pest control (Roundup), harvesting (manual) |
| **Project Scale** | Demonstration/ Pilot (500 cubic yards) |
| **Project Status** | Inactive |
| **Cost** | 2.5 million |
| **Funding Source** | Government agency, PRP |
| **Initial concentrations** | Mercury: 3.94 mg/kg |
| **Final Concentrations** | Data available Fall '04 |
| **Lessons Learned** | |
| **Comments** | Initial costs could be reduced significantly from this project because of readily available information that currently exists |
| **Primary Contact** | Scott Lee, Argonne West, 208-533-7829, scott.lee@anlw.anl.gov |
| **Citation** | Various CERCLA documents, including EPA Superfund Record of Decision: Idaho National Engineering Laboratory, OU 21. 9/29/98. EPA/ROD/R10-98/061 1998. (http://www.epa.gov/superfund/sites/rods/fulltext/r1098061.pdf) |

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|---|---|
| **Site Name** | Argonne NL West 4 |
| **Site Location** | Idaho Falls, ID |
| **Contaminant** | Chromium and mercury |
| **Vegetation Type** | Hybrid willow |
| **Planting Descriptions** | hand-planted, spaced 18 inches apart |
| **Media Type** | Soil; 40% bondfarm loamy sand, 30% rock outcrop, 20% grassy butte loamy sand |
| **Site Characterizations** | Effective rooting depth is 10-20 inches. Available water capacity is low |
| **ET Rates** | n/a |
| **Climate** | Northern high desert, very low humidity, short growing season, less than 5 days above 100 C, 45 C typical nighttime temperature. Temperature range: -38 to 102 F; Elevation: 4728 ft; Mean annual precipitation: 230 mm; Growing season: 6/14 to 9/4 |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Irrigation (system with automated sensors based on soil moisture content), Manure addition, non-potasssium fertilizer, pest control (Roundup), harvesting (manual) |
| **Project Scale** | Demonstration/ Pilot (500 cubic yards) |
| **Project Status** | Inactive |
| **Cost** | 2.5 million |
| **Funding Source** | Government agency, PRP |
| **Initial concentrations** | Mercury: 3.94 mg/kg; Chromium: 709 mg/kg |
| **Final Concentrations** | Data available Fall '04 |
| **Lessons Learned** | |
| **Comments** | Initial costs could be reduced significantly from this project because of readily available information that currently exists |
| **Primary Contact** | Scott Lee, Argonne West, 208-533-7829, scott.lee@anlw.anl.gov |
| **Citation** | Various CERCLA documents, including EPA Superfund Record of Decision: Idaho National Engineering Laboratory, OU 21. 9/29/98. EPA/ROD/R10-98/061 1998. (http://www.epa.gov/superfund/sites/rods/fulltext/r1098061.pdf) |

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|---|---|
| **Site Name** | Atlas Tack Corporation Superfund Site |
| **Site Location** | Fairhaven, MA |
| **Contaminant** | Benzene, Copper, Chromium, cyanide, Mercury, Nickel, Zinc |
| **Vegetation Type** | To be determined |
| **Planting Descriptions** | |
| **Media Type** | Groundwater |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | Temperature Range: -12 to 95 F; Elevation: 15 ft; Mean annual precipitation: 47.9"; Growing season: 4/20-10/22 |
| **Mechanism** | |
| **OM Requirements** | |
| **Project Scale** | Full-scale |
| **Project Status** | Pre-design |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Phytoremediation will follow Phase I (demolition) and Phase II (dredging) activities. |
| **Primary Contact** | **Elaine Stanley, EPA, 617-918-1332, stanley.elainet@epa.gov** |
| **Citation** | Not available: pre-design |

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|---|---|
| **Site Name** | Austin, TX Residential Site |
| **Site Location** | Austin, TX |
| **Contaminant** | Arsenic (from CCA) |
| **Vegetation Type** | Hyperaccumulating fern (Pteris) |
| **Planting Descriptions** | Ferns transplanted from pots |
| **Media Type** | Soil (silt loam) |
| **Site Characterizations** | |
| **ET Rates** | Groundwater > 15 feet bgs |
| **Climate** | Temperature Range: 4 to 106 F; Elevation: 617 ft; Mean annual precipitation: 31.9"; Growing season: 3/21 to 11/5 |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Owner prepared soil, fertilization, 50 kg/hectare N , no P,50 kg/hectare K, irrigatation (hose), harvesteing |
| **Project Scale** | Demonstration/Pilot (500 sq ft) |
| **Project Status** | Completed (May 2003-Sept 2003) |
| **Cost** | $3000-$4000 |
| **Funding Source** | EPA |
| **Initial concentrations** | As: 30-40 ppb |
| **Final Concentrations** | As: 20 ppb |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Backyard residential site after deck removal; homeowner took intiative. This is completed phase I project; phase II would include an industrial site in FL and 120 residential/ garden/ playground sites. |
| **Citation** | Michael Blaylock, Edenspace, (703) 961-8700, blaylock@edenspace.com |
| **Site Name** | Phytoextraction of CCA-derived As: EPA SBIR Phase 2 Application |

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|---|---|
| **Site Name** | Bayonne, NJ |
| **Site Location** | Bayonne, NJ |
| **Contaminant** | Heavy metals |
| **Vegetation Type** | Indian mustard (Brassica juncea) |
| **Planting Descriptions** | Planted from seeds |
| **Media Type** | Soil (sandy loam) |
| **Site Characterizations** | Soil contaminated to 15 cm below ground surface |
| **ET Rates** | |
| **Climate** | Temperature Range: -8 to 105 F; Elevation: 7 ft; Mean annual precipitation: 43.9"; Growing season: 4/18 to 10/19 |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Fertilization, harvesting, EDTA and acetic acid amendments |
| **Project Scale** | Demonstration/ Pilot (1000 sq ft) |
| **Project Status** | Completed (1996) |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | Pb: 1000-6500 (avg. 2,055) mg/kg surface soil; 780-2100 (avg. 1,280) mg/kg subsurface soil (15-30 cm depth); 280-8800 mg/kg (30-45 cm depth) |
| **Final Concentrations** | Pb: 420-2300 (avg. 960) mg/kg surface soil; 992 mg/kg (15-30 cm); no change (30-45 cm) |
| **Lessons Learned** | Lead concentrations in shoots attained 0.4%. Decrease of total site area with concentration exceeding 1000 mg/kg, from 73% to 32%. No leaching of lead nor EDTA observed as a result of EDTA addition. |
| **Comments** | |
| **Primary Contact** | Michael Blaylock, Phytotech (now Edenspace), (703) 961-8700, blaylock@edenspace.com |
| **Citation** | http://www.edenspace.com |

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|---|---|
| **Site Name** | Big River Mine Tailings |
| **Site Location** | Desloge, MO |
| **Contaminant** | Cadmium, lead, zinc |
| **Vegetation Type** | tall fescue (Festuca aerundinacea Schreb., cv.Kentucky 31) |
| **Planting Descriptions** | 40 plots (4 rows, each row with one of three amendments or control, with 10 plots per row); seeded |
| **Media Type** | Soil (fine-grained tailings from froth/chemical flotation process for concentrating metals in milled ore) |
| **Site Characterizations** | Initial bulk density of tailings material ranged between 1.52 to 1.66 grams per cubic centimeter (average 1.59 g/cm3) |
| **ET Rates** | |
| **Climate** | Temperature range: -18 to 107 F; Mean low temperature: 43 F; Mean high temperature: 65 F; Elevation: 564 ft; Mean annual precipitation: 3.6'; Growing season: 4/30 to 1/8 |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Fertilization, weeding, irrigation, harvesting, addition of three organic soil amendments (milorganite, ormiorganics compost, St. Peters compost) |
| **Project Scale** | Demonstration/ pilot (7704 square feet) |
| **Project Status** | Completed (2000-2002), but monitoring may be extended |
| **Cost** | Demonstration cost: $17,200 per acre; full scale estimate: $5000-$15,000 per acre (variation due to cost of compost) |
| **Funding Source** | US EPA Mine Waste Technology Program |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | The overall evidence indicates that the Ormiorganics high application rate and St. Peters Compost high application rate treatments are most promising for reclaiming the BRMTS. However, a more vigorous comparison of the respective treatments should be performed before committing to use either amendment for full-scale reclamation of the BRMTS. Therefore, larger scale testing of these two treatments should be performed. |
| **Comments** | |
| **Primary Contact** | Darcy Byrne-Kelly, MSE Technology, (406) 494-7419, dbyrne@mse-ta.com |
| **Citation** | MSE Technology Applications, Inc., *Interim Report for the Revegetation of Mining Waste Using Organic Amendments and the Potential for Creating Attractive Nuisances for Wildlife Demonstration Project*, MWTP-189, July 2001 and Final Report MWTP-239, March 2004 |

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|---|---|
| **Site Name** | Bunker Hill |
| **Site Location** | Couer d' Alene, ID |
| **Contaminant** | Lead, Zinc |
| **Vegetation Type** | Mix of herbaceous species: Western wheat grass |
| **Planting Descriptions** | |
| **Media Type** | Soil |
| **Site Characterizations** | Steep slopes, some greater than 100% |
| **ET Rates** | |
| **Climate** | Temperature Range:-25 to 108 F; Elevation: 1922 ft; Mean annual precipitation: 16.5"; Growing season: 5/20 to 9/19 |
| **Mechanism** | Phytostabilization |
| **OM Requirements** | |
| **Project Scale** | Full-scale (1,050 acres) |
| **Project Status** | Completed (1998-2001) |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | Zn: 6000-14700 mg/kg; Pb: 2100-27,000 mg/kg; Cd: 9-28 mg/kg |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Biosolids (56 and 112 Mg/ha) combined with wood ash (157 Mg/ha) and log yard waste |
| **Primary Contact** | Rufus Chaney, USDA, (301) 504-8324, chaneyr@ba.ars.usda.gov |
| **Citation** | Brown, S.L. and R.L. Chaney. 2000. Combining residuals to achieve specific soil amendment objectives. pp. 343-360. *In* J. Bartels (ed.) Land Application of Agricultural, Industrial and Municipal By-Products. Soil Science Society of America, Madison, WI. |

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|---|---|
| **Site Name** | Cooperative Farm |
| **Site Location** | Bytom, Poland |
| **Contaminant** | Cadmium, lead, zinc |
| **Vegetation Type** | Brassica sp, Sinapis alba, Helianthus sp, Ricinus communis, Zea mays |
| **Planting Descriptions** | Herbicide applied, weeds removed, plowing, and fertilization prior to planting. Seeding followed Phytotech, Inc. recommendations on depth, density, seeds/hole. |
| **Media Type** | Soil (Sandy clay) |
| **Site Characterizations** | Depth to groundwater > 11 ft. Site topography ranges from moderately flat to significant sloping (2-20% slope) |
| **ET Rates** | |
| **Climate** | |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Fertilization (N, S, P, K), irrigation, chelation (EDTA amendment), harvesting, weed control |
| **Project Scale** | Full-scale (0.5 ha) |
| **Project Status** | Ongoing (planted Spring `97) |
| **Cost** | US $11 per square meter |
| **Funding Source** | |
| **Initial concentrations** | Pb: 391.4-11.96 mg/kg soil; Cd: 637.5-11.96 mg/kg |
| **Final Concentrations** | |
| **Lessons Learned** | The most efficient plant species in phytoextraction of lead in field experiments was indian mustard (Brassica juncea) provided by Phytotech. Brachinia (Brassica ol-eracea var. capitata x Brassica napus), provided by IETU, was less effective in com-parison with indian mustard. However Brachinia is less susceptible to environmental conditions compared to indian mustard and can grow well on variety of soil types. The highest concentrations of lead and cadmium in plants shoots was observed 2 weeks after treatment II (IETU) application. This treatment was especially effective for mature form of indian mustard. |
| **Comments** | Harvested materials were deposited in hazardous waste dumps.Weather (temperature, rainfall, wind speed, direction, humidity, light, deposition), soil chemistry, and plant monitoring occurred at site. |
| **Primary Contact** | Rafal Kucharski, Institute from Ecology of Industrial Areas, +48 32 254 00 29, sas@ietu.katowice.pl |
| **Citation** | Institute for Ecology of Industrial Areas, Katowice. 1998. Final Report for Bytom, Poland laboratory and site phytoremediation project. |

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|---|---|
| **Site Name** | Caslano |
| **Site Location** | Caslano, Switzerland |
| **Contaminant** | Cadmium, copper, zinc |
| **Vegetation Type** | Basket willow (Salix viminalis) |
| **Planting Descriptions** | From cuttings, 4 cuttings per subplot (~1 sq m area subplots) |
| **Media Type** | Soil (acidic soil, pH 5.2) |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Fertilization (120 kg P/ha, 200 kg K/ha, 40 kg N/ha), chelator amendments (Fe-rich Sequestren rapid, 24 kg Fe/ha), harvesting |
| **Project Scale** | Demonstration/ Pilot (four 1.0 x 1.0 m plots) |
| **Project Status** | Completed (1997-2001) |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | Cd: 2.8 mg/kg; Cu: 264 mg/kg; Zn: 1158 mg/kg (concentrations extractable with 2M nitric acid) |
| **Final Concentrations** | Total plant uptake: Cd: 47 g/ha; Zn: 14.5 kg/ha |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Catherine Keller, Swiss Federal Institute of Technology, catherine.keller@eplf.ch |
| **Citation** | Hammer, D; Kayser, A; Keller, C. 2003. Phytoextraction of Cd and Zn with Salix viminalis in field trials. Soil Use and Management. 19(2003): 187-192. |

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|---|---|
| **Site Name** | Central Louisiana Wood Treatment Facility |
| **Site Location** | Louisiana |
| **Contaminant** | arsenic, chromium, PAH's, CCA, creosote |
| **Vegetation Type** | Loblolly pines |
| **Planting Descriptions** | all native vegetation removed and non-natives planted, hand planted, density of 500 per acre, |
| **Media Type** | soil, groundwater |
| **Site Characterizations** | groundwater contaminated with As, Cr, and PAHs up to 40 feet bgs; CCA and cresote mostly in 0-4 feet below ground surface |
| **ET Rates** | |
| **Climate** | |
| **Mechanism** | |
| **OM Requirements** | |
| **Project Scale** | Field demonstration (30 acres) |
| **Project Status** | Began Nov 1999 |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | As: 1900 mg/kg, Cr: 2300 mg/kg, PAHs: 930 mg/kg |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Timothy Goist, Premier Environmental Services, Inc.; togoist@premiercorp-usa.com |
| **Citation** | 2003 Phytotechnologies Conference Abstract |

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|---|---|
| **Site Name** | C-H Plant Area: Texas City Chemicals |
| **Site Location** | Texas City, TX |
| **Contaminant** | Cadmium, Copper, Lead, other metals; high salinity (calcium, sodium, and magnesium chlorides) |
| **Vegetation Type** | Eucalyptus (Red River Gun, E. camadulensis), Salt Cedar |
| **Planting Descriptions** | From potted stock, whips |
| **Media Type** | Groundwater (red clay) |
| **Site Characterizations** | |
| **ET Rates** | 35 gpd per tree |
| **Climate** | Temp range: 7 to 107 F; Elevation: 102 ft; Mean annual precip: 47"; Growing season: 3/17 to 11/14 |
| **Mechanism** | Hydraulic Control |
| **OM Requirements** | |
| **Project Scale** | Demonstration/Pilot (27 acres) |
| **Project Status** | Ongoing |
| **Cost** | |
| **Funding Source** | BP; Texas Voluntary Cleanup Program |
| **Initial concentrations** | Salinity: approx 110 mmhos/cm |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Quarterly monitoring of groundwater required for site. Sap flow measurements, tissue sampling, and root excavations also done. |
| **Primary Contact** | David Tsao, BP/Amoco, (630)836-7169, tsaodt@bp.com |
| **Citation** | ITRC Technologies Workshop 2004 and personal communication |

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|---|---|
| **Site Name** | Firing Range, Chilliwack |
| **Site Location** | Chilliwack, BC |
| **Contaminant** | Lead, Copper |
| **Vegetation Type** | Garden Pea (Pisum sativum) and Indian Mustard (Brassica juncea) |
| **Planting Descriptions** | P. sativum was grown from seed, initially planted at a density of 200 seeds/ m^2 and were thinned to roughly 100 plants/m^2 shortly after germination. B. juncea was transplanted as a four week old seedling at a density of 25 plants/m2 |
| **Media Type** | Soil (sandy clay) |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | Temp Range: 0 to 24 C; Elevation: 11 m; Mean annual precipitation: 1680 mm; Growing season: 4/6 to 11/9 |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Fertilization, amendments (EDTA), |
| **Project Scale** | Demonstration/Pilot |
| **Project Status** | Completed (Summer 1999- Fall 2001) |
| **Cost** | |
| **Funding Source** | National Defence Canada, Environment Canada |
| **Initial concentrations** | Pb: Mean concentration 1018 mg/kg |
| **Final Concentrations** | Pb: Less than 500 ppm |
| **Lessons Learned** | Overall results suggest that *P. sativum* is a more effective phytoremediation tool than *B. juncea* for lead, and also that soil acidification has the potential to be as effective as low dose applications of EDTA in enhancing lead extraction. However, EDTA was still most effective in enhancing lead concentrations in shoot tissues. In most treatments throughout this study, metal concentrations ranging from <100 to 600 mg/kg were observed in shoot tissues. However, single dose applications of 1.7 mmol/kg EDTA resulted in shoot tissue concentrations exceeding 1000 mg/kg for both *B. juncea* and *P. sativum*. (EDTA applications ranged from 0.3 to 1.7 mmol/kg). |
| **Comments** | Phytoremediation compound was was equipped with a double-layer geomembrane liner, overflow trench, and perimeter fence. |
| **Primary Contact** | Peat moss added as a bulking agent, at a rate providing a 10% volume increase to the top eight inches of the experimental soil. Granular fertilizer (28-10-10) was distributed at a rate of 25 kg per hectare. Some treatments received EDTA at a rate of 0.03 mmol/kg soil 50 days after planting. |
| **Citation** | Phytoremediation of Lead Contaminated Rifle Range Soils, CFB Chilliwack, BC. RMC-CCE-ES-00-13. Environment Canada, 2000. |

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|---|---|
| **Site Name** | Cobalt |
| **Site Location** | Cobalt, ON |
| **Contaminant** | Arsenic |
| **Vegetation Type** | Ryegrass |
| **Planting Descriptions** | |
| **Media Type** | |
| **Site Characterizations** | Depth to groundwater varies, approximately 3 to 20 feet on average. |
| **ET Rates** | |
| **Climate** | Temp Range: -40 to 35.4 C; Elevation: 252 m; Mean annual precipitation: 855.6 mm; Growing season: 5/17 to 9/25 |
| **Mechanism** | Phytoaccumulation |
| **OM Requirements** | None |
| **Project Scale** | Demonstration/Pilot (0.5 acres) |
| **Project Status** | Completed |
| **Cost** | $12,000 CAN, approximately $9,120 US |
| **Funding Source** | |
| **Initial concentrations** | As: 10-100 mg/Kg in tailings |
| **Final Concentrations** | |
| **Lessons Learned** | Mine tailings would rapidly dry out and maintain high salt concentrations that did not promote vegetative growth. However, a successful pilot-scale operation may have resulted had the hydrological status been controlled and/or another species of grass wa |
| **Comments** | |
| **Primary Contact** | Robert Tossell, CH2M Hill, Bob.Tossell@ch2m.com |
| **Citation** | |

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|---|---|
| **Site Name** | Combustion Superfund |
| **Site Location** | Denham Springs, LA |
| **Contaminant** | 1,2-dichloroethane, polychlorinated biphenyls, benzene, lead, mercury, nickel, silver, toluenediisocyante, toluene diamine |
| **Vegetation Type** | Eucalyptus, Poplar, Native Willows |
| **Planting Descriptions** | Potted Stock |
| **Media Type** | Groundwater |
| **Site Characterizations** | 5-10' depth of impact |
| **ET Rates** | |
| **Climate** | Temperature Range: -8 to 102 F; Elevation: 59 ft; Mean annual precipitation: 60.8"; Growing season: 3/18 to 11/4 |
| **Mechanism** | Hydraulic control, rhizodegradation, phytovolatilization |
| **OM Requirements** | |
| **Project Scale** | Full-Scale |
| **Project Status** | planted 2002 |
| **Cost** | |
| **Funding Source** | Superfund |
| **Initial concentrations** | Combustion Superfund |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | 5-10 ft (depth of impact) |
| **Primary Contact** | Katrina Coltrain, US EPA (214) 665-8143<br>Todd Thibodeaux, LDEQ (225) 219-3225 |
| **Citation** | LDEQ, EPA6 |

| | |
|---|---|
| **Site Name** | Craney Island Fuel Terminal |
| **Site Location** | Portsmouth, VA |
| **Contaminant** | Diesel fuel, lead, other petroleum compounds (TPH) |
| **Vegetation Type** | Bermuda grass, rye grass, white clover, tall fescue |
| **Planting Descriptions** | Seeding |
| **Media Type** | Soil (21% silt, 19% clay, 2.5 meq/L sand) |
| **Site Characterizations** | Phytoremediation on biological treatment cell containing 12 - 18 inch (30.5 - 45.7 cm) layer of contaminated soil followed by a sand layer, followed by a polyethylene liner, another sand layer, a geogrid liner, and finally, a compacted clay base. |
| **ET Rates** | |
| **Climate** | Temperature Range: -3 to 104 F; Elevation: 26 ft; Mean annual precipitation: 44.6"; Growing season: 4/6 to 10/31 |
| **Mechanism** | Rhizodegradation |
| **OM Requirements** | Monthly basis: Wedding, mowing, fertilization (50 lbs N/acre, 25 lbs P/acre). TPH and nutrient sampling monthly or bimonthly. Tilling and irrigation when necessary. Reseeding of fescue and clover in 1996. |
| **Project Scale** | Demonstration/Pilot (120 ft x 180 ft) |
| **Project Status** | Completed (1995-1997) |
| **Cost** | |
| **Funding Source** | AATDF(Advanced Applied Technology Demonstration Facility) and DOD (Department of Defense) |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | Total TPH degradation in soils varied by vegetative treatment. November 1996 data: Bermuda=31% TPH reduction in soils; fescue=35%; clover=37%; unvegetated=25% |
| **Comments** | |
| **Primary Contact** | M. K. Banks, Purdue University (765) 496-3424, kbanks@ecn.purdue.edu |
| **Citation** | Banks, M. Katherine, A. Paul Schwab, and R.S. Govindaraju. Phytoremediation of Soil Contaminated with Hazardous Organic Chemicals (1997): 5 pg. Online. Internet. 1 July 1998. Available: http://www.ruf.rice.edu/~aatdf/pages/phyto.htm. |

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|---|---|
| **Site Name** | Danbury, CT brownfields site (Abandoned Hat Factory) |
| **Site Location** | Danbury, CT |
| **Contaminant** | Hg |
| **Vegetation Type** | Eastern Cottonwood |
| **Planting Descriptions** | Genetically modified cottonwoods |
| **Media Type** | Soil (primarily fill) |
| **Site Characterizations** | Groundwater 7 ft. bgs |
| **ET Rates** | |
| **Climate** | Temperature Range: -26 to 102 F; Elevation: 378 ft; Mean annual precipitation: 51.9"; Growing season: 5/15 to 9/22 |
| **Mechanism** | Phytovolatilization |
| **OM Requirements** | Irrigation, weeding, visual inspections and monitoring |
| **Project Scale** | Demonstration/Pilot (1/3 acre) |
| **Project Status** | Ongoing (7/2003-fall 2004) |
| **Cost** | |
| **Funding Source** | USEPA Grant, City of Danbury |
| **Initial concentrations** | Hg: up to 1500 ppm |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Pilot through 2004. If results are positive, then phytoremediation may be applied to whole site |
| **Primary Contact** | David Glass, Applied Phytogenetics, 617-653-9945, dglass@appliedphytogenetics.com; Jack Kozuchowski, Danbury Health Dept, 203-797-4625, J.Kozuchowski@ci.danbury.ct.us |
| **Citation** | Documents not yet available. Referenced in memo to US EPA. |

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|---|---|
| **Site Name** | Dearing, KS Phytostabilization Demonstration |
| **Site Location** | Dearing, KS |
| **Contaminant** | Pb, Zn, Cd |
| **Vegetation Type** | Hybrid poplars (4 Ecolotree varieties including D01, PC1, OP367, and Imperial Carolina ) |
| **Planting Descriptions** | First planted June 1994 (93% did not survive), replanted March 1995 (after removing all previously planted trees). Planted as 120 cm whips, deep-trenched (15 cm wide x 1 m deep). Trenches amended with N (11 g/m trench), P (23 g/m), K (11 g/m), and limestone (1 kg/m). Half of plots were amended with cattle manure. Each plot consisted of 24 trees planted in three adjacent rows of eight trees. Trees planted one meter apart within rows and rows were 1.5 mapart. Three replications used for a total of 24 plots. |
| **Media Type** | Soil (smelter slag residue, finer than soils at Galena) |
| **Site Characterizations** | Contaminant concentrations highly stratified |
| **ET Rates** | D01: 26.69 mmol/(m2-s); PC1: 25.85 mmol/(m2-s); OP367: 20.93 mmol/(m2-s); Imperial Carolina: 23.51 mmol/(m2-s) |
| **Climate** | Temperature Range: -13 to 111 F; Elevation: 770 ft; Mean annual precipitation: 43.7"; Growing season: 4/26 to 10/13 |
| **Mechanism** | Phytostabilization, phytoextraction |
| **OM Requirements** | Manure amendments. After tree establishment, no management needed. |
| **Project Scale** | Demonstration/Pilot (1 acre) |
| **Project Status** | Completed (1994-1998) |
| **Cost** | |
| **Funding Source** | Great Plains/ Rocky Mtn Hazardous Substance Research Center |
| **Initial concentrations** | Zn: 47,223 mg/kg (top 15 cm of soil), decreasing down to 2828 mg/kg (75-90 cm); Pb: Ranged between 40 and 14134 mg/kg (declining with depth); Cd: 4.6-108 mg/kg (declining with depth) |
| **Final Concentrations** | |
| **Lessons Learned** | Overall poplar survival rate ranged between 18-53%, possibly attributed to Zn phytotoxicity. There were higher concentrations of contaminants than in Galena study and contaminants highly stratified. Manure amendments generally increased poplar survivability. Transpiration rates were higher for manure-treated trees. Imperial Carolina hybrids have twice rate of photosynthesis of other varieties and highest water use efficiency and are recommended species for site remediation. Metal concentrations in plants decreased in order of leaves>bark>twigs>wood for Zn and Cd, and bark>wood>twig=leaves for Pb (see Pierzynski, 2002 for details). |
| **Comments** | |
| **Primary Contact** | G. Pierzynski, Kansas State University, 785-532-7209, gmp@ksu.edu |
| **Citation** | Pierzynski, GM; Schnoor, JL; Youngman, A; Licht, L; Erickson, LE. 2002. Poplar Trees for Phytostabilization of Abandoned Zinc-Lead Smelter. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management. 6(3):177-183<br>Phytostabilization Demonstration, One Acre Test Plot Abandoned Smelter, Barren Land, Phytoremediation: Technology Evaluation Report. GWRTAC TE-98-01 (p 8) |

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|---|---|
| **Site Name** | Dorchester, MA |
| **Site Location** | Dorchester, MA |
| **Contaminant** | Lead |
| **Vegetation Type** | Indian mustard, sunflower |
| **Planting Descriptions** | Planted from seeds |
| **Media Type** | Soil (sandy loam) |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | Temperature Range: -7 to 102 F; Elevation: 30 ft; Mean annual precipitation: 41.5"; Growing season: 5/3 to 10/5 |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Irrigation, fertilization, liming, harvesting, pesticides, EDTA amendment |
| **Project Scale** | Demonstration/ Pilot (1200 sq ft) |
| **Project Status** | Completed (1996-1998) |
| **Cost** | |
| **Funding Source** | Phytotech |
| **Initial concentrations** | Pb: varied less than 400 to greater than 1000 ppb |
| **Final Concentrations** | Pb: less than 800 ppb |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Michael Blaylock, Edenspace, (703) 961-8700, blaylock@edenspace.com |
| **Citation** | Blaylock, MJ. 2000. Field Demo of Phytoextraction of Lead Contaminated Soils. Phytoremediation of Contaminated Soil and Water. Ed: Terry, Norman and Banuelos, GS.  CRC Press. |

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|---|---|
| **Site Name** | Dornach |
| **Site Location** | Dornach, Switzerland |
| **Contaminant** | Cadmium, copper, zinc |
| **Vegetation Type** | Basket willow (Salix viminalis) |
| **Planting Descriptions** | From cuttings, 2-4 cuttings per subplot (~1 sq meter area subplots) |
| **Media Type** | Soil (calcerous, pH 7.3) |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Fertilization (120 kg P/ha, 200 kg K/ha, 40 kg N/ha), chelator amendments (Fe-rich Sequestren rapid, 24 kg Fe/ha), sulfur (36 mol/m2), harvesting |
| **Project Scale** | Demonstration/ Pilot (four 1.1 x 1.1 m plots) |
| **Project Status** | Completed (1997-2001) |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | Cd: 2.3 mg/kg; Cu: 550 mg/kg; Zn: 650 mg/kg (concentrations extractable with 2M nitric acid) |
| **Final Concentrations** | Total plant uptake: Cd: 170-194 g/ha; Zn: 13.4-17 kg/ha |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Catherine Keller, Swiss Federal Institute of Technology, catherine.keller@eplf.ch |
| **Citation** | Hammer, D; Kayser, A; Keller, C. 2003. Phytoextraction of Cd and Zn with Salix viminalis in field trials. Soil Use and Management. 19(2003): 187-192. |

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|---|---|
| **Site Name** | East Palo Alto |
| **Site Location** | East Palo Alto, CA |
| **Contaminant** | Arsenic, sodium |
| **Vegetation Type** | Eucalyptus, Tamarisk |
| **Planting Descriptions** | Planted as 5 gal trees with 4-5 foot centers, some shoots and cuttings. Tight planting density. |
| **Media Type** | Soil (clayey soil on top, over more porous sand layer) |
| **Site Characterizations** | Groundwater containment inside slurry wall. Groundwater 4-5 ft bgs. |
| **ET Rates** | |
| **Climate** | Temperature Range: 27 to 105 F; Elevation: 39 ft; Mean annual precipitation: 13.8"; Growing season: 1/24 to 12/28 |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Soil treatment prior to planting, fertilization (N and K), irrigation (during 1st 6 months, then ceased), Mulching (wood chips), Pest control (ladybugs released to control psyllids), replanting after 1st year but then unnecessary |
| **Project Scale** | Full-Scale (1 acre) |
| **Project Status** | Operational (began 1981) |
| **Cost** | $4000/ yr; < 50,000 plant installation |
| **Funding Source** | Private |
| **Initial concentrations** | Arsenic: 0.05-200 mg/l; sodium: 5000mg/l |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | Mike Rafferty, SS Papadopulous and Associates, 415-896-9000 ext. 202, mrafferty@sspa.com |
| **Citation** | Five Year Status Report: 1990 Bay Road Site, East Palo Alto, CA. March 31, 2004. Prepared by Geomatrix Consultants, Inc. in association with S.S. Papadopulos & Associates, Inc. |

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|---|---|
| **Site Name** | Ecological Experimental Station of Red Soil, China |
| **Site Location** | Yingtan, Jangxi Province, China |
| **Contaminant** | Cadmium, lead, zinc |
| **Vegetation Type** | Vetiver grass |
| **Planting Descriptions** | |
| **Media Type** | Soil (red soil-oxisoil) |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Fertilization |
| **Project Scale** | Demonstraton/ Pilot |
| **Project Status** | Completed |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | HM Chen, Chinese Academy of Sciences, PO Box 821, Nanjing, 210008, China |
| **Citation** | |
| **Site Name** | Chen, HM; et al. 2000. Chemical methods and phytoremediation of soil contaminated with heavy metals. Chemosphere. 41(2000): 229-234 |

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|---|---|
| **Site Name** | Ensign-Bickford Company |
| **Site Location** | Simsbury, CT |
| **Contaminant** | Lead |
| **Vegetation Type** | Indian mustard (Brassica juncea) and sunflower (Helianthus annus) |
| **Planting Descriptions** | Seeded with three treatment crops |
| **Media Type** | Soil (silty loam) |
| **Site Characterizations** | Water table 2-4 ft bgs. Poor site drainage. Soil saturated throughout growing seasons (April-October) |
| **ET Rates** | |
| **Climate** | Temperature Range: -26 to 102 F; Elevation: 174 ft; Mean annual precipitation: 44.1"; Growing season: 5/12 to 9/23 |
| **Mechanism** | Phytoextraction, phytostablilization |
| **OM Requirements** | Irrigation; fertilization with N, P, K (tilled to 15-20 cm depth) and foliar fertilizers via irrigation system; dolomite lime added to adjust pH (tilled to 15-20 cm depth); stabilizing amendments added to Area 5. |
| **Project Scale** | Full scale (2.35 acres) |
| **Project Status** | Completed (April-Oct 1998) |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | Pb concentrations for Area 1: 500-5000 mg/kg; Area 2: 125-1250 mg/kg; Area 3: 500-2000 mg/kg; Area 4: 750-1000 mg/kg; Area 5: 6.5-7.5 mg/kg. Average Pb concentration: 635 mg/kg. |
| **Final Concentrations** | Average Pb concentration: 478 mg/kg (Area 1-4). |
| **Lessons Learned** | Lead uptake ranged from 342 mg/kg in Indian mustard in treatment crop 1 to 3252 mg/kg in Indian mustard in treatment crop 3. Average lead uptake in sunflower similar, approximately 1000 mg/kg. |
| **Comments** | Plant growth for treatment crops generally good, although some areas remained saturated and thus exhibited poor plant growth and reduced biomass yields. |
| **Primary Contact** | Michael Blaylock, Edenspace Systems Corp, (703) 390-1100, SoilRx@aol.com |
| **Citation** | FRTR. 2000. Phytoremediation at the Open Burn and Open Detonating Area, Ensign-Bickford Company, Simsbury, CT. Abstracts of Remediation Case Studies, Volume 4. EPA 542-R-00-006. June 2000 |

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|---|---|
| **Site Name** | Fort Dix, NJ |
| **Site Location** | Fort Dix, NJ |
| **Contaminant** | Lead |
| **Vegetation Type** | Indian mustard, sunflower, mixed grasses |
| **Planting Descriptions** | Seeding |
| **Media Type** | Soil (predominantly sand) |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | Temperature Range: -4 to 102 F; Elevation: 130 ft; Mean annual precipitation: 44"; Growing season: 4/15 to 10/23 |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Irrigation (with leachate containing EDTA, lead) |
| **Project Scale** | Demonstration/ Pilot (1.25 acres) |
| **Project Status** | Completed 1997- 10/2002 |
| **Cost** | |
| **Funding Source** | Superfund |
| **Initial concentrations** | Pb: 515 mg/kg (range: 160-10,000 mg/kg) |
| **Final Concentrations** | Pb: 290 mg/kg |
| **Lessons Learned** | Project goals (reduction of Pb below 400 mg/kg) were met. However, the amount of phytoextracted lead did not account for the difference in initial and final lead concentrations |
| **Comments** | Excavated lead fragments prior to planting. 3500 tons of soil placed in 12 inch deep phytocells. 111,000 gallons of recicrulated drainage water remained at end of demonstration with soil lead concentration of 30 mg/kg |
| **Primary Contact** | Steve Rock, USEPA, 513-569-7149, rock.steven@epa.gov |
| **Citation** | Rock, Steve. 2003. Field Evaluations of Phytotechnologies. Phytoremediation: Transformation and Control of Contaminants. Ed: Steven C. McCutcheon and Jerald. L. Schnoor. 2003 John Wiley and Sons, Inc. |

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|---|---|
| **Site Name** | Galena, KS field study |
| **Site Location** | Galena, KS |
| **Contaminant** | Cadmium, Lead, Zinc from "chat" waste |
| **Vegetation Type** | tall fescue |
| **Planting Descriptions** | Planted via seeding |
| **Media Type** | Soil (coarse, sandy loam) |
| **Site Characterizations** | 5% graded slope; chat primarily chert, and on average composed of 81% sand-sized, 13% silt-sized, and 6% clay-sized particles by weight. |
| **ET Rates** | |
| **Climate** | Temperature Range: -13 to 111 F; Elevation: 941 ft; Mean annual precipitation: 44.5"; Growing season: 4/26 to 10/13 |
| **Mechanism** | Phytostabilization, phytoextraction |
| **OM Requirements** | Amendments (inoculation with mycorrhiza, treatment with Benomyl fungicide, manure amendment), reseeding (1996) |
| **Project Scale** | Demonstration/Pilot |
| **Project Status** | Completed (seeded in Fall 1995, 5 years) |
| **Cost** | |
| **Funding Source** | Great Plains/ Rocky Mtn Hazardous Substance Research Center |
| **Initial concentrations** | Cd: 53 mg/kg; Pb: 2050 mg/kg; Zn: 22690 mg/kg |
| **Final Concentrations** | Cd: 81 mg/kg (higher due to anaytical error?); Pb: 2079 mg/kg; Zn: 20680 mg/kg |
| **Lessons Learned** | Concentrations of Cd, Pb, Zn in fescue uninfluenced by treatments. No indication that inoculation of mycorrhizal fungi was successful. Vegetative cover decreased over time, despite intial promotion of growth by manure, perhaps due to Zn phytotoxicity. Manure applications generally decreased exchangeable forms of metals and increased organic forms. Exchangeable forms of Pb and Zn generally increased while residual forms decreased during 1st and 3rd years of study, probably due to soil acidification over the same period. |
| **Comments** | Fescue selected after result of greenhouse studies. Three different seeded treatments: manure-amended and seeded control; manure amended, seeded, and mycorrhizal-inoculated treatment; and manure-amended, seeded treatment with Benomyl fungicide. |
| **Primary Contact** | G. Pierzynski, Kansas State University, 785-532-7209, gmp@ksu.edu |
| **Citation** | Pierzynski, GM; Lambert, M; Hetrick, BAD; Sweeney, DW; Erickson, LE. 2002. Phytostabilization of Metal Mine Tailings Using Tall Fescue. Practice Periodical of Hazardous, Toxic, and Radioactive  Waste Management. 6(4): 212-217. Also see US EPA STAR Grant R825549C047. |

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|---|---|
| **Site Name** | Unnamed Gary, IN site |
| **Site Location** | Gary, IN |
| **Contaminant** | Arsenic, lead |
| **Vegetation Type** | bulrush, sedges, cattails, arrowhead |
| **Planting Descriptions** | Native species used |
| **Media Type** | Soil (sandy loam, submerged) |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | Lake Michigan/ Harbor area climate. Temperature Range: ; Elevation: ft; Mean annual precipitation: "; Growing season: |
| **Mechanism** | Phytostabilization (As, Pb), Phytoextraction (As) |
| **OM Requirements** | Irrigation, fertilization |
| **Project Scale** | Demonstration/ pilot (3 acres) |
| **Project Status** | Ongoing (began 5/2002) |
| **Cost** | unfunded |
| **Funding Source** | not applicable |
| **Initial concentrations** | As: approx. 2000 mg/kg; Pb: approx. 2000 mg/kg |
| **Final Concentrations** | |
| **Lessons Learned** | Results are still somewhat premature because this is in progress. However, it was immediately recognized that high phosphate applications released As from the sediments and into the water. It increases As bioavailability but also increased mobility. |
| **Comments** | |
| **Primary Contact** | Paul Schwab, Purdue University, (765)-496-3602, pschwab@purdue.edu |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Jones Island Confined Disposal Facility |
| **Site Location** | Milwaukee, WI |
| **Contaminant** | Anthracene, PCBs, heavy metals |
| **Vegetation Type** | Populus deltoides (tree)  Tripsacum dactyloides (grass)  Sesbania exultata (vetch)  Carex microptera (sedge) or Andropogon gerardii (grass)  Juncusus effusus (rush) or Helianthus grosserratus (sunflower)  potentially Morus rubra or Morus alba (trees) |
| **Planting Descriptions** | From seeds, hand planted |
| **Media Type** | Sediment, silty loam |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | Mostly sunny during the day. Temp range: -26 to 103 F; Elevation: 672 ft; Mean annual precip: 32.9"; Growing season: 5/20-9/26 |
| **Mechanism** | Rhizodegradation |
| **OM Requirements** | Fertilization, Harvesting |
| **Project Scale** | Demonstration/Pilot (2744 cu ft) |
| **Project Status** | Ongoing |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | Concentration results available Fall '04 |
| **Final Concentrations** | Concentration results available Fall '04 |
| **Lessons Learned** | |
| **Comments** | The project has just started so the total cost can not be estimated as their are probably more expenses to come. We are not yet sure what fraction of the plants will have to be replanted but are quite sure that we will need to seed again. |
| **Primary Contact** | Katy Euliss, Purdue University, 765-496-2211, keuliss@purdue.edu |
| **Citation** | |

| | |
|---|---|
| **Site Name** | Leadwood Chat Tailings |
| **Site Location** | Desloge, MO |
| **Contaminant** | Cadmium, lead, zinc |
| **Vegetation Type** | Tall fescue |
| **Planting Descriptions** | 40 plots (4 rows, each row with one of three amendments or control, with 10 plots per row); seeded |
| **Media Type** | Soil (coarse tailings from coarse milling and gravity separation of metals from ore) |
| **Site Characterizations** | Bulk density of tailings intially 1.77 to 1.90 grams per cubic centimeter (average 1.82 g/cm3) |
| **ET Rates** | |
| **Climate** | Temperature Range: -18 to 107 F; Elevation: 805 ft; Mean annual precipitation: 37.5"; Growing season: 4/30 to 10/8 |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Fertilization, weeding, irrigation, harvesting, addition of organic soil amendements (milorganite, ormiorganics compost, St. Peters compose) |
| **Project Scale** | Demonstration/Pilot (7704 square feet) |
| **Project Status** | Completed (2000-2002) but monitoring may be extended |
| **Cost** | Demonstration cost: $17,200 per acre; full scale estimate: $5000-$15,000 per acre (variation due to cost of compost) |
| **Funding Source** | US EPA Mine Waste Technology Program |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | None of the soil amendments evaluated exhibited long-term compliance with the three plant performance objectives. However, the St. Peters Compost high application rate treatment came closest as it. |
| **Comments** | MSE recommends the following: that the amendment rates used were insufficient for meeting the study objectives. Acid-extractable metals levels in rooting zone soils were generally 1.5- to 2-fold greater than those observed at BRMTS, which may translate to higher plant available metal concentrations as well (up to their respective solubility limits). Thus, it is hypothesized that at application rates of greater than 2-fold, the St. Peters Compost high application rate treatment rate may be necessary to meet the present objectives for successful site reclamation. Furthermore, the Ormiorganics high application rate treatment results at BRMTS were sufficiently encouraging to justify elevated rates of applying this amendment at LCTS as well |
| **Primary Contact** | Darcy Byrne-Kelly, MSE Technology, (406) 494-7419, dbyrne@mse-ta.com |
| **Citation** | Revegetation of Mining Waste Using Organic Soil Amendments and Evaluation of the Potential for Creating Attractive Nusiances for Wildlife. Abstract. 2001. Proceedings of the 2001 Conference on Environmental Research. |

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|---|---|
| **Site Name** | Lechang Pb/Zn mine tailings |
| **Site Location** | Lechang City, Guangdong Province, China |
| **Contaminant** | Cadmiu, copper, lead, zinc |
| **Vegetation Type** | Vetiver grass (V. zizanioides), Sesbiana species (S. sesban, S. rostrata) |
| **Planting Descriptions** | Planted as seedlings |
| **Media Type** | Soil |
| **Site Characterizations** | tailings pond (dry surface) |
| **ET Rates** | |
| **Climate** | Subtropical climate. Mean annual precipitation: 1500 mm |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Fertilization, harvesting, irrigation |
| **Project Scale** | Field trial |
| **Project Status** | Completed |
| **Cost** | |
| **Funding Source** | |
| **Initial concentrations** | Zn: 4388 mg/kg, Pb: 4164 mg/kg; Cu: 35 mg/kg; Cd: 32 mg/kg |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | MH Wong, Hong Kong Baptist University, +852-3411-7743, mhwong@hkbu.edu.hk |
| **Citation** | Yang, B, et. al. 2003. Growth and metal accumulation in vertiver and two Sesbania species on lead/ zinc mine tailings. Chemosphere. 52(2003): 1593-1600 |

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|---|---|
| **Site Name** | Magic Marker |
| **Site Location** | Trenton, NJ |
| **Contaminant** | Lead |
| **Vegetation Type** | Indian Mustard (Brassica juncea) and sunflower |
| **Planting Descriptions** | Planted from seeds |
| **Media Type** | Soil (shallow, loamy sand) |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | Temperature Range: -4 to 102 F; Elevation: 190 ft; Mean annual precipitation: 42"; Growing season: 4/15 to 10/23 |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | amended with EDTA, harvested, replanted |
| **Project Scale** | Full-Scale (0.25 acres, 1 acre, 4500 sq ft) |
| **Project Status** | Operational (planted 1996) |
| **Cost** | $200,000 (EPA); $109,408 (NJ preliminary investigation) |
| **Funding Source** | EPA brownfield grant; NJ State Hazardous Discharge Site Remediation Fund |
| **Initial concentrations** | Pb: 500 to 1000 ppm, 200 to 1800 mg/kg |
| **Final Concentrations** | Pb: 51 grams removed from treatment plot |
| **Lessons Learned** | Indian mustard uptake was 830 mg/kg (1st crop) and 2300 mg/kg (2nd crop); sunflower uptake around 400 mg/kg. However, uptake did not account for total soil reduction, which estimated to be around 4%. |
| **Comments** | |
| **Primary Contact** | Michael Blaylock, Edenspace, (703) 961-8700, blaylock@edenspace.com |
| **Citation** | US EPA. 2001. Phytoextraction of lead in soils at Magic Marker and Ft. Dix. Innovative Technology Evaluation Report, US EPA. National Risk Management Research Laboratory, Cincinatti, OH |

| | |
|---|---|
| **Site Name** | Metal Plating Facility |
| **Site Location** | Findlay, OH |
| **Contaminant** | Chromium, cadmium, nickel, zinc, lead, trichloroethylene |
| **Vegetation Type** | Hybrid Poplar, Ryegrass; Indian mustard |
| **Planting Descriptions** | 30 trees, deep rooted and planted when 10-16 ft tall |
| **Media Type** | Soil (silt loam) |
| **Site Characterizations** | GW 10-15' bgs |
| **ET Rates** | |
| **Climate** | Temp range: -19 to 104 F; Elevation: 804 ft; Mean annual precip: 34.5"; Growing season: 5/19 to 9/24 |
| **Mechanism** | Phytoextraction, Hydraulic Control |
| **OM Requirements** | sampling groundwater |
| **Project Scale** | Full-Scale (10,000 sq ft) |
| **Project Status** | Operational/In Progress. Planted 1997 |
| **Cost** | |
| **Funding Source** | State, voluntary |
| **Initial concentrations** | TCE: up to 150 mg/L |
| **Final Concentrations** | |
| **Lessons Learned** | Dramatic drop, on average, of 30 ppm to less than 5 ppm. However, the source area continues to supply site with contaminants |
| **Comments** | SITE Program. Trees have grown at a rate of 4-8 ft/year. Results of the first 3 years indicated significant reduction of TCE concentrations in the aquifer in addition to demonstration of hydraulic effects on groundwater flow |
| **Primary Contact** | Michael Blaylock, Edenspace, (703) 961-8700, blaylock@edenspace.com or Edd Gatliff, Applied Natural Sciences, (513) 895-6061 ans@fuse.net |
| **Citation** | Phytoremediation of TCE in Groundwater using Populus. http://www.clu-in.org/products/phytotce.htm |

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|---|---|
| **Site Name** | Former Orchard Site |
| **Site Location** | Picatinny Arsenal, New Jersey |
| **Contaminant** | Arsenic (from arsenical pesticides) |
| **Vegetation Type** | Brake Fern (Pteris: mayil, parkeril, vittata) |
| **Planting Descriptions** | Transplanted from pots, 12 and 6 inch planting density |
| **Media Type** | Soil (loam soil) |
| **Site Characterizations** | Groundwater >20 feet below ground surface |
| **ET Rates** | |
| **Climate** | Temperature Range: -4 to 102 F; Elevation: 171 ft; Mean annual precipitation: 45.9"; Growing season: 4/15-10/26 |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Irrigation, lime amendments, harvesting, and fertilizer |
| **Project Scale** | Demonstration plots (10,000 sq ft) |
| **Project Status** | Ongoing (2001) |
| **Cost** | |
| **Funding Source** | US Army |
| **Initial concentrations** | As: 10 ppm to 60-70 ppm |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | Original turf grass was removed. A greenhouse was constructed on site for overwintering ferns |
| **Primary Contact** | Michael Blaylock, Edenspace, (703) 961-8700, blaylock@edenspace.com |
| **Citation** | Report available Fall '04 from Edenspace |

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|---|---|
| **Site Name** | Palmerton Zinc Pile Demo (Blue Mountain) |
| **Site Location** | Palmerton (Carbon County), PA |
| **Contaminant** | Zinc, cadmium |
| **Vegetation Type** | Alpine Pennycress, Bladder Campion |
| **Planting Descriptions** | Hydroseeding |
| **Media Type** | Soil; manufactured soil (blend of treated municipal solids, power plant fly ash, and agricultural limestone) |
| **Site Characterizations** | Very steep slopes, mountainous topography. Zinc pile is cinder bank, 2.5 miles long, 200 feet high and 500-1000 ft wide. Drains to Aquashicola Creek and eventually Lehigh River. |
| **ET Rates** | |
| **Climate** | Temperature Range: -12 to 105 F; Elevation: 1500 ft; Mean annual precipitation: 43.5"; Growing season: 5/5 to 10/2 |
| **Mechanism** | Phytostabilization, Phytoextraction |
| **OM Requirements** | Amendment application using spreader trucks |
| **Project Scale** | Demonstration/Pilot (25 sq meters) |
| **Project Status** | Completed (1986) |
| **Cost** | Estimated as $100,000 feasibility study |
| **Funding Source** | PRP |
| **Initial concentrations** | Zinc: 35000-80000 mg/kg |
| **Final Concentrations** | N/A |
| **Lessons Learned** | Determined manufactured soil performed best when not overly blended. Site could withstand storms as great as 2.9"/hr in 2 hours, or 8.5" rain/hr in 20 hrs. Manufactured soil would be surface-applied, containing limestone and seed, and unmulched. Best ratio for woody plants 3:1 (biosolids: flyash). Best ratio for grass/legumes is 1:1 (biosolids: flyash). Ratio selected for full scale is 2:1 (biosolids:flyash). Dominant grass species for mixed seed is 'Oahu' intermediate wheatgrass. |
| **Comments** | |
| **Primary Contact** | S. L. Brown; Rufus Chaney USDA, (301) 504-6511, chaneyr@ba.ars.usda.gov |
| **Citation** | Oyler, J. Blue Mountain Superfund Remediation Project, Palmerton, PA. Powerpoint presentation. June 10, 2004. ITRC Phytotechnologies conference. |

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|---|---|
| **Site Name** | Palmerton Zinc Pile (Blue Mountain) |
| **Site Location** | Palmerton (Carbon County), PA |
| **Contaminant** | Zinc, cadmium |
| **Vegetation Type** | Oahe intermediate wheatgrass, Pennfine perennial ryegrass, empire birdsfoot trefoil, ruebans Canada bluegrass, and Streeker redtop |
| **Planting Descriptions** | Manufactured soils contained seeds already in it and was spread uniformly using trucks on terraced roads |
| **Media Type** | Soil; manufactured soil (blend of treated municipal solids, power plant fly ash, and agricultural limestone) |
| **Site Characterizations** | Very steep slopes, mountainous topography. Zinc pile is cinder bank, 2.5 miles long, 200 feet high and 500-1000 ft wide. Drains to Aquashicola Creek and eventually Lehigh River. |
| **ET Rates** | |
| **Climate** | Temperature Range: -12 to 105 F; Elevation: 1500 ft; Mean annual precipitation: 43.5"; Growing season: 5/5 to 10/2 |
| **Mechanism** | Phytostabilzation, phytoextraction |
| **OM Requirements** | 2:1 biosolids:flyash amendments |
| **Project Scale** | Full Scale (1000 acres; 1000 more acres proposed) |
| **Project Status** | Completed (1991-1995) |
| **Cost** | $1,249,262 (EPA, OU1) |
| **Funding Source** | PRP |
| **Initial concentrations** | Zinc: 35000-80000 mg/kg |
| **Final Concentrations** | |
| **Lessons Learned** | All water leaving treated areas of mountain is in compliance with NPDES Limits for pH, zinc, cadmium, lead, TDS, TSS and no further treatment is required to discharge |
| **Comments** | This is a reclamation site using biosolids and vegetative cover. Not really phytoremediation site although phytoremediation processes are taking place. |
| **Primary Contact** | John Oyler, oylers@ptd.net |
| **Citation** | Oyler, J. Blue Mountain Superfund Remediation Project, Palmerton, PA. Powerpoint presentation. June 10, 2004. ITRC Phytotechnologies conference. |

| | |
|---|---|
| **Site Name** | Port Colborne |
| **Site Location** | Port Colborne, ON |
| **Contaminant** | Arsenic, cobalt, copper, and nickel are contaminants of concern (Site of former Ni refinery) |
| **Vegetation Type** | Corn, soybeans, radish, oats, alyssum |
| **Planting Descriptions** | From seeds, hand planted |
| **Media Type** | Soil (4 types used in demonstration: sandy, high & low clay, high organic peaty) |
| **Site Characterizations** | 7 to 11 feet (depth to groundwater) |
| **ET Rates** | |
| **Climate** | Temperature Range: -26 to 33.5 C; Elevation: 175 m; Mean annual precipitation: 854.1 mm; Growing season: 5/20-9/23 |
| **Mechanism** | Phytostabilization |
| **OM Requirements** | Amendment of dolimitic limestone (80-100 tons per hectare) |
| **Project Scale** | Demonstration/Pilot (4 field sites, 30x50 m) |
| **Project Status** | Ongoing (2001-2003) |
| **Cost** | Several million $ |
| **Funding Source** | |
| **Initial concentrations** | n/a |
| **Final Concentrations** | n/a |
| **Lessons Learned** | |
| **Comments** | Purpose of the phytostabilization part of the project is determine levels of the liming agent that will mitigate any adverse effects of the CoCs. 20 metals are being evaluated in very great detail. Four crop plants (corn, soybeans, radish and oats) are involved in the phytostabilization testing though there has been some nickel phytoextraction testing carried out with alyssum in conjunction with it. |
| **Primary Contact** | James Higgins, Jacques Whitford Environment, 905-469-2475, jhiggins@jacqueswhitford.com |
| **Citation** | |

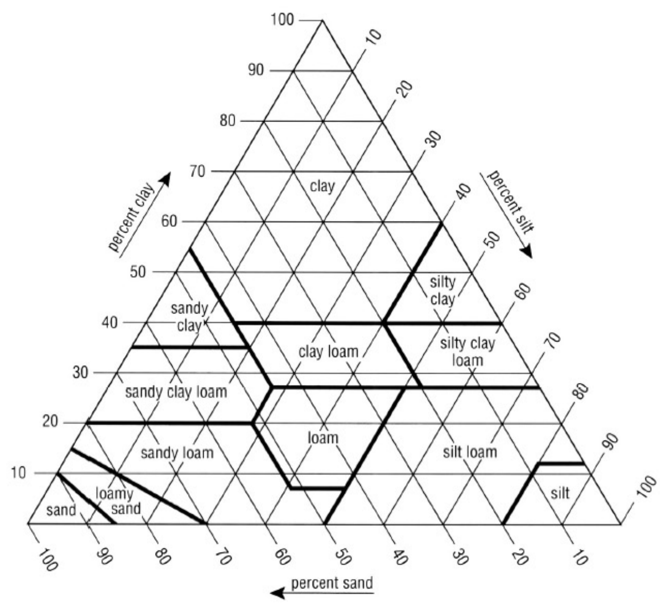
| | |
|---|---|
| **Site Name** | Savannah River, SC |
| **Site Location** | Aiken, SC |
| **Contaminant** | Cadmium, Chromium, Vanadium |
| **Vegetation Type** | Bush beans (Phaseolus vulgaris ) |
| **Planting Descriptions** | Planted in three consecutive years (1, 15, and 27 months after metals treatment to soils). Final spacing of 76 cm between rows and 10 cm between plants |
| **Media Type** | Soil (fine loamy and loamy siliceous sands) |
| **Site Characterizations** | |
| **ET Rates** | |
| **Climate** | Abundant rainfall. Warm, humid conditions prevail. Temp range: -1 to 108; Elevation: 134 ft; Mean annual precip: 44.6"; Growing season: 4/15 to 10/23 |
| **Mechanism** | Phytoextraction |
| **OM Requirements** | Mowing, fertilization, irrigation, weeding, lime amendments (pH adjustment), tilling |
| **Project Scale** | Demonstration/ Pilot |
| **Project Status** | 1987-1992 |
| **Cost** | |
| **Funding Source** | US DOE |
| **Initial concentrations** | |
| **Final Concentrations** | |
| **Lessons Learned** | There was little vertical movement of Cd and V after 30 months, and somewhat greater movement of Tl. During the first 18 months, there were large reductions in extractable amounts of metals, with very little change detected in the subsuquent 12 months. Adter 18 months, the Cd, Tl, and V applied were probably transformed to forms less available for uptake. |
| **Comments** | Metals added to site five years prior to planting: 11.2 kg/ha Cd, 5.6 kg/ha Tl, and 5.6 kg/ha V. |
| **Primary Contact** | HW Martin, Savannah River Ecology Laboratory, University of Georgia, hawmartin@aol.com |
| **Citation** | Martin, H.W. and D.I. Kaplan. 1998. Temporal changes in cadmium, thallium, and vanadium mobility in soil and phytoavailability under field conditions. Water, Air, and Soil Pollution 101:399-410. See also 1996 *Plant and Soil* article |

| | |
|---|---|
| **Site Name** | Spring Valley (former Army ammunition site) |
| **Site Location** | Washington, DC |
| **Contaminant** | Arsenic |
| **Vegetation Type** | hyperaccumulating fern (Pteris) |
| **Planting Descriptions** | Ferns transplanted from pots |
| **Media Type** | Soil |
| **Site Characterizations** | Mixed clay loam and sandy loam |
| **ET Rates** | |
| **Climate** | |
| **Mechanism** | Temperature Range: -5 to 104 F; Elevation:16 ft; Mean annual precipitation: 38.6"; Growing season: 4/10-10/31 |
| **OM Requirements** | Phytoextraction |
| **Project Scale** | Irrigation, shade cloths installed, fertilization, lawn removed prior to installation |
| **Project Status** | Demonstration/Pilot (3 sites with total area = 2500 sq ft.) |
| **Cost** | Ongoing (began May 2004) |
| **Funding Source** | Army Corps of Engineers |
| **Initial concentrations** | As: 20-150 ppm |
| **Final Concentrations** | |
| **Lessons Learned** | |
| **Comments** | |
| **Primary Contact** | |
| **Citation** | Michael Blaylock, Edenspace, (703) 961-8700, blaylock@edenspace.com |
| **Site Name** | |

# Appendix E: USDA Soil Classification System
## (adopted from the 1993 USDA Soil Survey Manual)

For most sites, soil particles in the contaminated medium were less than 2 mm, and the following soil texture classification system was used. Sites containing a contaminated soil medium of larger particle sizes (i.e. rock fragments) or manufactured soils were described using language found in the site literature or documentation, or in reference to USDA manual.

Figure 1. Sand, clay, and silt percentages for soil texture classification




Prior to classifying soils, it is important to discuss the three mineral components of soils that are categorized based on particle size: sands, silts, and clays. Particles that range from about 0.05 mm to 2 mm in size are sands. Particles between 0.002 mm and 0.05 mm are classified as silts. Particles less than 0.002 mm are clays. Further breakdown based on soil textures is as follows:

**Sands:** Contain more than 85% sand, and the percentage of silt plus 1.5 times the percentage of clay is less than 15.

1. *Coarse sand*: Greater than or equal to 25% or more very coarse and coarse sand; less than 50% ay other single grade of sand.
2. *Sand*: Greater than or equal to 25% or more very coarse, coarse, and medium sand; less than 25% very coarse and coarse sand; less than 50% fine sand and/or very fine sand.
3. *Fine sand*: 50% or more fine sand; less than 25% very coarse, coarse, and medium sand; less than 50% very fine sand
4. *Very fine sand*: 50% or more very fine sand

**Loamy sands**: Between 70 and 91% sand and the percentage of silt plus 1.5 times the percentage of clay is 15 or greater; the percentage of silt plus twice the percentage of clay is less than 30.

1. *Loamy coarse sand:* Greater than or equal to 25% or more very coarse and coarse sand; less tha 50% any other single grade of sand
2. *Loamy sand:* Greater than or equal to 25% or more very coarse, coarse, and medium sand; less than 25% very coarse and coarse sand; less than 50% fine and/or very fine sand
3. *Loamy fine sand*: Greater than or equal to 50% fine sand; less than 50% very fine sand; less than 25% very coarse, coarse, and medium sand
4. *Loamy very fine sand*: 50% or more very fine sand.

**Sandy loams**: Between 7% and 20% clay, greater than 52% sand, and the percentage of silt plus twice the percentage of clay is 30 or more; or, less than 7% clay, less than 50% silt, and more than 43% sand.

1. *Coarse sandy loam*: Greater than or equal to 25% or more very coarse and coarse sand; less than 50% any other single grade of sand
2. *Sandy loam:* Greater than or equal to 30% very coarse, coarse, and medium sand; less than 25% very coarse and coarse sand; less than 30% fine and/or very fine sand. Or, less than or equal to 15% very coarse, coarse, and medium sand, less than 30% fine and/or very fine sand, and less than or equal to 40% fine or very fine sand.
3. *Fine sandy loam*: Greater than or equal to 30% fine sand, and less than 30% very fine sand. Or, between 15%-30% very coarse, coarse, and medium sand. Or, greater than or equal to 40% fine and very fine sand, one half of which is fine sand, and less than or equal to 15% very coarse, coarse, and medium sand.
4. *Very fine sandy loam*: Greater than or equal to 30% or more very fine sand and less than 15% very coarse, coarse, and medium sand. Or, greater than 40% fine and very fine sand, more than half of which is very fine sand, and less than 15% very coarse, coarse, and medium sand.

**Loam**: Between 7% and 27% clay, 28% and 50% silt, and 52% or less sand.

1. *Silt loam*: Greater than or equal to 50% or more silt and between 12% and 27% clay. Or, between 50% and 80% silt and less than 12% clay
2. *Silt*: greater than or equal to 80% or more silt, and less than 12% clay.
3. *Sandy clay loam*: Between 20% and 35% clay, less than 28% silt, and more than 45% sand.
4. *Clay loam*: Between 27% and 40% clay and more than 20%-46% sand.
5. *Silty clay loam*: Between 27% and 40% clay and less than or equal to 20% sand.
6. *Sandy clay*: Greater than or equal to 35% clay and greater of equal to than 45% sand
7. *Silty clay*: Greater than or equal to 40% clay and greater than or equal to 40% silt.

4*Clay*: Greater than or equal to 40% or more clay, less than 45% sand, and less than 40% silt.

# Appendix F: Climate Table

| State | City | Spring Frost Date | Fall Frost Date | Elevation (ft) | Low Temperature (F) | High Temperature (F) | Precipitation (in) |
|---|---|---|---|---|---|---|---|
| AK | Barrow | 8/4 | 7/24 | 26 | -54 | 76 | 4.5 |
| AK | Bethel | 6/21 | 9/5 | 39 | -48 | 84 | 15 |
| AK | Fairbanks | 5/25 | 8/25 | 499 | -62 | 96 | 10.9 |
| AK | Gulkana | 6/23 | 8/9 | 1578 | -58 | 90 | 10.8 |
| AK | Juneau | 5/30 | 9/5 | 23 | -22 | 90 | 53.6 |
| AK | King Salmon | 6/8 | 8/27 | 49 | -48 | 85 | 19.8 |
| AK | Nome | 7/8 | 8/17 | 10 | -54 | 86 | 14.9 |
| AK | Sitka Airport | 5/7 | 10/11 | 66 | 0 | 88 | 85.9 |
| AL | Birmingham | 4/14 | 10/24 | 630 | -6 | 106 | 54.6 |
| AL | Mobile | 3/19 | 11/5 | 30 | 3 | 103 | 64 |
| AL | Montgomery | 3/28 | 10/29 | 200 | 0 | 104 | 53.4 |
| AL | Tuscaloosa | 4/8 | 10/20 | 187 | -1 | 105 | 55 |
| AR | Fayetteville (Airport) | 5/3 | 10/4 | 1250 | -15 | 106 | 43.8 |
| AR | Fort Smith | 4/14 | 10/18 | 446 | -10 | 110 | 40.9 |
| AR | Little Rock | 4/8 | 10/27 | 259 | -4 | 112 | 50.8 |
| AR | Pine Bluff | 4/4 | 10/26 | 207 | -2 | 107 | 47.7 |
| AR | Texarkana | 3/29 | 10/29 | 361 | 5 | 107 | 44.2 |
| AZ | Flagstaff | 6/26 | 9/9 | 7004 | -23 | 97 | 22.9 |
| AZ | Phoenix | 3/16 | 11/18 | 1112 | 19 | 122 | 7.7 |
| AZ | Tuscon | 3/27 | 11/7 | 2558 | 16 | 117 | 12 |
| AZ | Yuma | 2/19 | 12/14 | 207 | 24 | 122 | 3.2 |
| CA | Bakersfield | 3/3 | 11/20 | 492 | 19 | 114 | 5.7 |
| CA | Barstow | 4/15 | 10/29 | 1929 | 7 | 117 | 3.7 |
| CA | Berkeley | 1/19 | 12/26 | 6 | 26 | 104 | 18.2 |
| CA | Bishop | 5/25 | 9/26 | 4146 | -8 | 109 | 5.4 |
| CA | Blythe | 3/1 | 11/28 | 262 | 20 | 122 | 3.3 |
| CA | Eureka | 3/14 | 11/15 | 59 | 21 | 86 | 37.5 |
| CA | Fresno | 4/1 | 11/7 | 338 | 18 | 111 | 10.6 |
| CA | Los Angeles | 2/11 | 12/8 | 148 | 30 | 110 | 12.1 |
| CA | Sacramento | 3/23 | 11/14 | 69 | 18 | 115 | 17.5 |
| CA | San Diego | 3/30 | 11/12 | 42 | 32 | 108 | 9.1 |
| CA | San Francisco | 1/24 | 12/8 | 7 | 24 | 106 | 19.7 |
| CA | Santa Barbara | 2/26 | 12/4 | 16 | 20 | 109 | 16.2 |
| CO | Denver | 5/20 | 9/20 | 5333 | -25 | 103 | 15.4 |
| CO | Grand Junction | 6/1 | 9/16 | 4848 | -23 | 105 | 8.7 |
| CT | Hartford | 5/12 | 9/23 | 174 | -26 | 102 | 44.1 |
| DE | Dover | 4/19 | 10/15 | 36 | 0 | 101 | 36 |
| DE | Wilmington | 4/25 | 10/15 | 36 | -14 | 102 | 40.8 |
| FL | Gainesville | 3/29 | 11/5 | 157 | 10 | 102 | 51.4 |
| FL | Jacksonville | 3/14 | 11/16 | 30 | 7 | 103 | 51.3 |
| FL | Miami | none | none | 13 | 30 | 98 | 55.9 |
| FL | Orlando (Sanford) | 3/4 | 12/3 | 98 | 19 | 100 | 47.7 |

| State | City | Spring Frost Date | Fall Frost Date | Elevation (ft) | Low Temperature (F) | High Temperature (F) | Precipitation (in) |
|---|---|---|---|---|---|---|---|
| FL | Pensacola | 3/20 | 11/8 | 76 | 6 | 105 | 58.9 |
| FL | Tallahassee | 4/5 | 10/28 | 69 | 6 | 103 | 65.8 |
| FL | Tampa | 2/25 | 12/3 | 7 | 18 | 99 | 43.9 |
| GA | Albany | 3/31 | 10/26 | 208 | 7 | 101 | 48.3 |
| GA | Atlanta | 4/10 | 10/25 | 977 | -8 | 105 | 50.8 |
| GA | Augusta | 4/15 | 10/23 | 134 | -1 | 108 | 44.6 |
| GA | Brunswick | 3/18 | 11/15 | 10 | 13 | 99 | 53 |
| GA | Columbus | 4/8 | 10/27 | 387 | -2 | 104 | 51 |
| GA | Macon | 4/4 | 10/25 | 354 | -6 | 108 | 44.6 |
| GA | Savannah | 3/30 | 10/31 | 46 | 3 | 105 | 49.2 |
| HI | Hilo | none | none | 30 | 53 | 94 | 129.7 |
| HI | Honolulu | none | none | 39 | 52 | 94 | 22.1 |
| HI | Lihue | none | none | 103 | 50 | 90 | 43.1 |
| IA | Cedar Rapids | 5/13 | 9/25 | 902 | -28 | 104 | 33.4 |
| IA | Des Moines | 5/9 | 9/21 | 968 | -24 | 108 | 33.1 |
| IA | Mason City | 5/20 | 9/16 | 1174 | -30 | 104 | 32.7 |
| IA | Ottumwa | 5/2 | 10/5 | 840 | -23 | 105 | 33.8 |
| ID | Boise | 5/26 | 9/22 | 2706 | -25 | 110 | 12.1 |
| ID | Idaho Falls | 6/14 | 9/4 | 4728 | -38 | 102 | 10.9 |
| ID | Pocatello | 6/12 | 9/6 | 4477 | -33 | 104 | 12.1 |
| IL | Chicago | 4/25 | 10/22 | 658 | -27 | 104 | 35.8 |
| IL | Peoria | 5/8 | 10/6 | 653 | -25 | 105 | 36.2 |
| IL | Rockford | 5/13 | 9/25 | 725 | -27 | 104 | 37.1 |
| IL | Springfield | 5/1 | 10/6 | 617 | -22 | 106 | 35.3 |
| IN | Evansville | 4/23 | 10/12 | 430 | -21 | 104 | 43.1 |
| IN | Ft. Wayne | 5/15 | 9/25 | 856 | -22 | 106 | 34.7 |
| IN | Indianapolis | 5/9 | 10/7 | 807 | -23 | 103 | 39.9 |
| KS | Dodge City | 5/7 | 10/11 | 2593 | -21 | 109 | 21.5 |
| KS | Goodland | 5/16 | 9/23 | 3680 | -27 | 108 | 18.2 |
| KS | Salina | 5/4 | 10/9 | 1275 | -24 | 109 | 30.1 |
| KS | Topeka | 5/4 | 10/1 | 879 | -26 | 110 | 35.2 |
| KS | Wichita | 5/1 | 10/10 | 1321 | -21 | 112 | 29.3 |
| KY | Bowling Green | 4/28 | 10/7 | 538 | -21 | 107 | 51 |
| KY | Lexington | 5/3 | 10/10 | 1063 | -21 | 103 | 44.5 |
| KY | Padicah | 4/18 | 10/15 | 397 | -15 | 105 | 48.9 |
| LA | Alexandria | 3/26 | 10/31 | 77 | 5 | 104 | 53.1 |
| LA | Baton Rouge | 3/18 | 11/4 | 59 | -8 | 102 | 60.8 |
| LA | Lafayette | 3/17 | 11/6 | 36 | 9 | 102 | 58.6 |
| LA | Lake Charles | 3/18 | 11/5 | 9 | 11 | 103 | 55.3 |
| LA | New Orleans | 3/21 | 11/15 | 7 | 11 | 102 | 62.2 |
| LA | Shreveport | 4/2 | 10/27 | 174 | 3 | 107 | 46.1 |
| MA | Boston | 5/3 | 10/5 | 30 | -7 | 102 | 41.5 |
| MD | Baltimore | 4/11 | 10/29 | 148 | -7 | 105 | 40.7 |
| ME | Augusta | 5/12 | 9/22 | 354 | -19 | 97 | 42 |
| MI | Detroit | 5/12 | 10/9 | 619 | -13 | 103 | 26.6 |

| State | City | Spring Frost Date | Fall Frost Date | Elevation (ft) | Low Temperature (F) | High Temperature (F) | Precipitation (in) |
|---|---|---|---|---|---|---|---|
| MI | Lansing | 5/31 | 9/18 | 859 | -29 | 100 | 30.6 |
| MI | Marquette | 5/25 | 10/4 | 1414 | -34 | 99 | 36 |
| MI | Muskegon | 5/24 | 9/24 | 644 | -15 | 99 | 32.6 |
| MI | Traverse City | 6/9 | 9/17 | 625 | -37 | 101 | 29.8 |
| MN | Duluth | 6/4 | 9/10 | 1424 | -39 | 97 | 30 |
| MN | International Falls | 6/9 | 9/4 | 1118 | -46 | 98 | 24.3 |
| MN | Minneapolis | 5/21 | 9/15 | 833 | -34 | 105 | 28.4 |
| MO | Joplin | 4/26 | 10/13 | 987 | -15 | 108 | 43.2 |
| MO | Kansas City | 4/30 | 10/9 | 742 | -19 | 110 | 36.1 |
| MO | Springfield | 5/2 | 10/8 | 1364 | -17 | 108 | 43.2 |
| MO | St. Louis | 4/30 | 10/8 | 564 | -18 | 107 | 37.5 |
| MS | Columbus | 4/11 | 10/15 | 200 | -2 | 104 | 55 |
| MS | Jackson | 4/7 | 10/14 | 291 | 2 | 106 | 55.4 |
| MS | Meridian | 4/12 | 10/19 | 295 | 0 | 107 | 56.7 |
| MT | Billings | 5/29 | 9/6 | 3569 | -32 | 105 | 15.1 |
| MT | Bozeman | 6/19 | 8/31 | 4467 | -46 | 103 | 14.7 |
| MT | Butte | 7/1 | 8/23 | 5530 | -52 | 99 | 12.2 |
| MT | Helena | 6/2 | 9/2 | 3827 | -38 | 105 | 11.6 |
| NC | Asheville | 4/24 | 10/11 | 2239 | -7 | 95 | 38.8 |
| NC | Charlotte | 4/25 | 10/14 | 787 | -5 | 103 | 43.1 |
| NC | Greensboro | 4/22 | 10/14 | 902 | -8 | 103 | 42.6 |
| NC | Raleigh | 4/29 | 10/16 | 443 | -9 | 105 | 41.4 |
| ND | Bismark | 5/26 | 9/7 | 1673 | -43 | 109 | 15.5 |
| ND | Dickinson | 6/9 | 8/28 | 2542 | -35 | 109 | 16.1 |
| ND | Fargo | 5/25 | 9/12 | 895 | -35 | 106 | 19.5 |
| ND | Minot | 5/31 | 9/2 | 1722 | -36 | 106 | 18.7 |
| NE | Grand Island | 5/16 | 9/26 | 1853 | -28 | 110 | 24.9 |
| NE | Lincoln | 5/9 | 9/30 | 1181 | -33 | 108 | 28.8 |
| NE | North Platte | 5/25 | 9/10 | 2788 | -34 | 108 | 19.3 |
| NE | Omaha | 5/12 | 9/23 | 1027 | -23 | 110 | 29.9 |
| NE | Scottsbluff | 5/25 | 9/14 | 3854 | -42 | 109 | 15.3 |
| NH | Concord | 6/9 | 9/8 | 338 | -33 | 102 | 36.4 |
| NH | Mt. Washington | 7/29 | 8/2 | 6268 | -46 | 72 | 98.9 |
| NJ | Atlantic City | 5/15 | 9/28 | 52 | -2 | 102 | 36.7 |
| NJ | Millville | 4/29 | 10/10 | 72 | -10 | 102 | 42.1 |
| NJ | Newark | 4/15 | 10/26 | 7 | -8 | 105 | 43.9 |
| NJ | Trenton | 4/15 | 10/23 | 190 | -4 | 102 | 42 |
| NM | Albuquerque | 5/25 | 9/26 | 5104 | -17 | 105 | 8.9 |
| NM | Gallup | 6/14 | 9/15 | 6465 | -34 | 99 | 11.3 |
| NM | Las Vegas | 5/29 | 9/22 | 6501 | -26 | 99 | 16.1 |
| NV | Ely | 6/30 | 8/21 | 6262 | -30 | 100 | 10.1 |
| NV | Las Vagas | 4/3 | 11/7 | 2030 | 12 | 117 | 3.4 |
| NV | Reno | 6/19 | 8/23 | 4526 | -16 | 105 | 7.5 |
| NV | Winnemucca | 6/26 | 8/26 | 4300 | -37 | 108 | 8.2 |

| State | City | Spring Frost Date | Fall Frost Date | Elevation (ft) | Low Temperature (F) | High Temperature (F) | Precipitation (in) |
|---|---|---|---|---|---|---|---|
| NY | Albany | 5/24 | 9/19 | 292 | -28 | 99 | 36.1 |
| NY | Buffalo | 5/20 | 9/23 | 705 | -20 | 97 | 38.6 |
| NY | New York City | 4/13 | 10/27 | 98 | -2 | 104 | 47.2 |
| NY | Rochester | 5/18 | 9/29 | 544 | -19 | 98 | 31.9 |
| NY | Syracuse | 5/14 | 10/3 | 426 | -26 | 97 | 38.9 |
| OH | Akron | 5/21 | 10/2 | 1214 | -24 | 101 | 36.6 |
| OH | Cincinnati | 4/29 | 10/13 | 760 | -15 | 101 | 39.7 |
| OH | Cleveland | 5/18 | 10/5 | 804 | -19 | 104 | 36.6 |
| OH | Columbus | 5/9 | 10/3 | 833 | -19 | 101 | 38.1 |
| OH | Dayton | 4/27 | 10/16 | 1004 | -24 | 102 | 36.6 |
| OH | Toledo | 5/16 | 9/29 | 669 | -20 | 104 | 32.9 |
| OH | Youngstown | 5/24 | 9/29 | 1178 | -20 | 100 | 37.4 |
| OK | Okalahoma City | 4/15 | 10/16 | 1280 | -8 | 110 | 33.3 |
| OK | Tulsa | 4/13 | 10/21 | 676 | -8 | 110 | 40.6 |
| OR | Baker City Airport | 6/29 | 8/26 | 3372 | -39 | 106 | 10.6 |
| OR | Eugene | 5/22 | 10/1 | 430 | -7 | 108 | 49.4 |
| OR | Klamath | 6/28 | 8/31 | 4099 | -25 | 100 | 12.6 |
| OR | Pendleton | 5/3 | 10/5 | 1200 | -19 | 113 | 12 |
| OR | Portland | 4/26 | 10/18 | 33 | 6 | 107 | 36.3 |
| OR | Redmond | 7/17 | 8/20 | 3050 | -28 | 108 | 8.6 |
| OR | Salem | 5/22 | 9/28 | 180 | -5 | 108 | 39.2 |
| PA | Allentown | 5/5 | 10/2 | 380 | -12 | 105 | 43.5 |
| PA | Harrisburg | 5/4 | 10/4 | 340 | -9 | 107 | 40.5 |
| PA | Philadelphia | 4/14 | 10/28 | 27 | -7 | 104 | 41.5 |
| PA | Pittsburg | 5/26 | 9/20 | 1223 | -18 | 103 | 36.8 |
| PA | Williamsport | 5/16 | 9/30 | 522 | -17 | 103 | 40.7 |
| SC | Beaufort | 3/28 | 11/1 | 21 | 10 | 104 | 51.2 |
| SC | Charleston | 4/6 | 10/30 | 49 | 6 | 104 | 51.5 |
| SC | Columbia | 4/17 | 10/16 | 226 | -1 | 107 | 49.9 |
| SC | Greenville | 5/5 | 10/8 | 956 | -6 | 103 | 50.6 |
| SD | Huron | 5/27 | 9/15 | 1282 | -39 | 112 | 20.1 |
| SD | Pierre | 6/2 | 9/8 | 1469 | -33 | 114 | 18.7 |
| SD | Rapid City | 5/26 | 9/14 | 3247 | -23 | 109 | 18.6 |
| SD | Sioux Falls | 5/24 | 9/17 | 1440 | -36 | 110 | 23.8 |
| TN | Chattanooga | 4/18 | 10/19 | 689 | -10 | 105 | 53.5 |
| TN | Knoxville | 4/9 | 10/23 | 981 | -24 | 102 | 47.1 |
| TN | Memphis | 4/8 | 10/27 | 510 | -14 | 106 | 50.9 |
| TN | Nashville | 4/16 | 10/14 | 600 | -17 | 105 | 47.3 |
| TX | Amarillo | 4/30 | 10/14 | 3615 | -12 | 108 | 19.5 |
| TX | Austin | 3/21 | 11/5 | 617 | 4 | 106 | 31.9 |
| TX | Brownsville | 2/15 | 12/17 | 20 | 16 | 106 | 26.6 |
| TX | Dalhart | 5/9 | 10/11 | 3995 | -18 | 107 | 17.5 |
| TX | Dallas/ Ft Worth | 4/8 | 10/24 | 574 | -1 | 113 | 33.7 |
| TX | El Paso | 4/14 | 10/28 | 3913 | -8 | 112 | 8.8 |

| State | City | Spring Frost Date | Fall Frost Date | Elevation (ft) | Low Temperature (F) | High Temperature (F) | Precipitation (in) |
|---|---|---|---|---|---|---|---|
| TX | Houston | 3/17 | 11/14 | 102 | 7 | 107 | 47 |
| TX | Midland | 4/11 | 10/21 | 2857 | -11 | 112 | 15 |
| TX | San Antonio | 3/23 | 11/6 | 581 | 6 | 108 | 31 |
| TX | Wichita Falls | 4/13 | 10/24 | 1027 | -8 | 117 | 28.9 |
| UT | Cedar City | 6/8 | 9/14 | 5852 | -24 | 105 | 11.5 |
| UT | Logan | 5/22 | 9/27 | 4300 | -13 | 104 | 18.9 |
| UT | Salt Lake City | 5/18 | 9/29 | 4225 | -18 | 104 | 16.2 |
| UT | Wendover | 5/8 | 10/10 | 4241 | -10 | 102 | 5.4 |
| VA | Norfolk | 4/6 | 10/31 | 26 | -3 | 104 | 44.6 |
| VA | Richmond | 4/27 | 10/13 | 164 | -8 | 105 | 43.1 |
| VA | Roanoake | 4/29 | 10/5 | 1174 | -11 | 105 | 41.1 |
| VT | Burlington | 5/25 | 9/19 | 335 | -30 | 99 | 34.4 |
| VT | Montpelier | 6/3 | 9/8 | 1099 | -34 | 97 | 34.6 |
| WA | Bellingham | 5/6 | 10/1 | 59 | -1 | 94 | 13.7 |
| WA | Olympia | 5/17 | 9/30 | 36 | -8 | 104 | 50.5 |
| WA | Seattle | 4/20 | 10/27 | 125 | 9 | 96 | 37.1 |
| WA | Spokane | 5/20 | 9/19 | 1922 | -25 | 108 | 16.5 |
| WA | Walla Walla | 4/19 | 10/20 | 1166 | -24 | 114 | 19.5 |
| WA | Yakima | 5/20 | 9/21 | 1135 | -17 | 110 | 8 |
| WI | Eau Claire | 5/26 | 9/15 | 892 | -39 | 104 | 31.6 |
| WI | Green Bay | 5/26 | 9/18 | 699 | -29 | 99 | 28.8 |
| WI | Lacrosse | 5/15 | 9/29 | 672 | -36 | 105 | 30.6 |
| WI | Madison | 5/13 | 9/25 | 872 | -30 | 104 | 30.9 |
| WI | Milwaukee | 5/20 | 9/26 | 672 | -26 | 103 | 32.9 |
| WI | Wausau | 5/22 | 9/6 | 1191 | -36 | 99 | 33 |
| WV | Charleston | 5/9 | 10/5 | 951 | -15 | 104 | 42.5 |
| WV | Parkersburg | 5/9 | 10/2 | 840 | -20 | 102 | 41.4 |
| WY | Casper | 6/8 | 9/7 | 5320 | -41 | 102 | 12.5 |
| WY | Cheyenne | 6/8 | 9/9 | 6143 | -29 | 98 | 14.4 |
| WY | Laramie | 6/26 | 8/26 | 7186 | -50 | 94 | 10.6 |
| WY | Rock Springs | 6/11 | 9/1 | 6370 | -37 | 96 | 9.5 |
| WY | Sheridan | 6/6 | 9/7 | 3952 | -37 | 106 | 14.5 |

# Appendix G

# Resources

Internet Resources:

1. RTDF Phytoremediation Profiles website
   http://rtdf.org/public/phyto/siteprof/index.cfm

2. EPA REACH IT website
   http://www.epareachit.org/

3. CLU-IN Innovative Remediation Technologies: Field Scale Demonstration Project Database and Report
   http://clu-in.org/products/nairt/

4. EPA Superfund Innovative Technology Evaluation (SITE) Project Status Information
   http://www.epa.gov/ORD/SITE/projectstatus.htm

5. Federal Remediation Technologies Roundtable (FRTR)
   http://www.frtr.gov/

6. NIST Chemistry Webbook
   http://webbook.nist.gov/chemistry/

Database resources:

- Science Direct
- LexisNexis
- EBSCOhost
- MEDLINE
- BIOSIS
- National Technical Information Service (NTIS)
- Energy Science and Technology
- General Science Abstracts
- Waternet
- Agricola
- CAB Abstracts
- Science.gov
- USDA PLANTS database

# Appendix H

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