Phytoremediation

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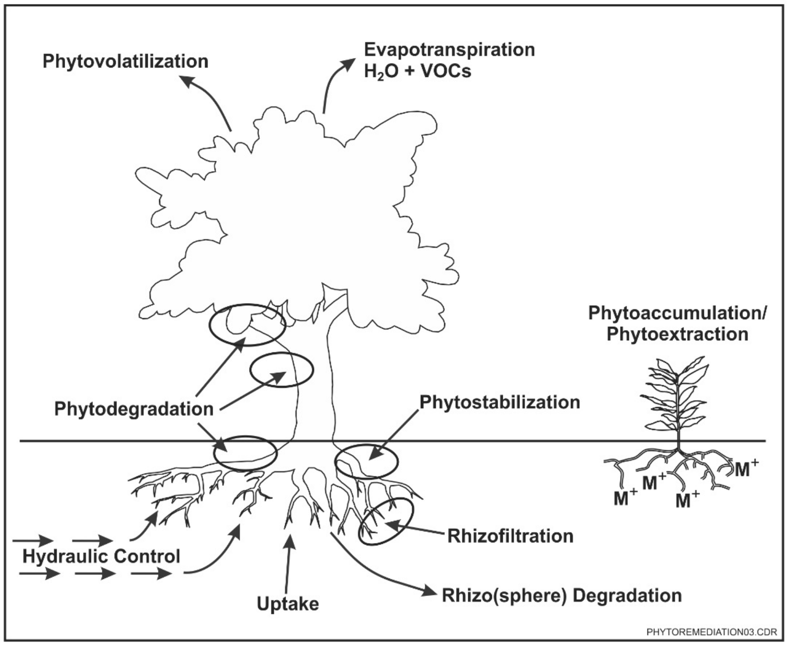
Schematic



Schematic of Phytoremediation Processes

Introduction

Phytoremediation is a treatment technology that uses vegetation and its associated microbiota, soil amendments, and agronomic techniques to remove, contain, or reduce the toxicity of environmental contaminants. Phytoremediation is most commonly applied to shallow soil and groundwater, but is also applicable to sludge, sediments, surface water, stormwater, and waste water. It is generally used as an in situ technology, but can also be used as an ex situ technology using hydroponics and/or constructed wetlands (see separate profile).

Other Technology Names

Phytotechnologies
Vegetation-enhanced Bioremediation
Dendroremediation (when trees are used)
Evapotranspiration/Botic/Phyto Cover (landfill applications for methane)

Description

Phytoremediation is implemented by establishing a plant or community of plants that have been selected to provide the required remediation mechanisms. The technology exploits the natural hydraulic and metabolic processes of plants, and thus is solar driven. The technology can be applied either in situ where the technology is passive or ex situ where contaminated groundwater is extracted and treated with engineered systems (hydroponics or constructed wetlands) to treat the groundwater utilizing natural plant processes. Since the ex situ phytoremediation applications are more expensive, have a narrower focus, and are less commonly used than the in situ applications, they are not covered further here. For more information, the reader is referred to the resource section and separate profile for constructed wetlands. The remainder of the technology description is focused on in situ applications of phytoremediation.

The phytoremediation mechanisms that are applicable to contaminated media are described in the paragraphs that follow.

Stabilization/Containment Mechanisms

- **Phytostabilization (phytosequestration):** Phytostabilization is the use of plants to increase sequestration of contaminants (usually metals) in the soil and/or the plant root. Soil sequestration occurs as plants alter water flux and reduce contaminant mobility. Plants and microbial enzymes bind contaminants into soil (humification). Plants also incorporate free contaminants into plant roots (lignification) and prevent wind and water erosion.
- **Hydraulic Control:** Hydraulic control is the use of plants, more specifically tree species with deep root systems (e.g., willows, poplars) which are capable of high groundwater uptake rates, to provide migration control for groundwater plumes. This hydraulic control acts in a similar manner as a pump and treat system in that the trees not only provide hydraulic control, but can also remove or degrade groundwater contaminants.

Removal/Degradation Mechanisms

- **Phytoaccumulation:** Phytoaccumulation is the use of specific species of plants to take up and accumulate metals through their inherent transpiration mechanisms. Metals must be dissolved in soil moisture or groundwater to be taken up by the plant roots and moved into the stem and leaves, where the metals are accumulated. Typically, the plants are harvested from the growing area. The biomass is composted to reduce the volume requiring landfilling off site or is incinerated and the ash is sent to a landfill. In some cases, the biomass can be sold for precious metals recovery. This approach has been used for remediation of metals-contaminated soils, sediments, and groundwater.

- **Phytoextraction:** In phytoextraction, contaminants other than metals (e.g., volatile organic compounds [VOCs]) are taken up by plant roots â€“ either chemicals dissolved in soil moisture or groundwater, or chemicals in soil vapor that adsorb to the roots. Chemicals are moved into the stem and roots through transpiration and either accumulated (phytoaccumulation), metabolized, or transpired into the atmosphere.
- **Rhizofiltration:** Rhizofiltration is similar to phytoextraction; however, plant root systems usually are first developed to maturity in an aqueous environment within a greenhouse. When the root system is developed, contaminated site water (generally with metal contamination) is brought to the plants and circulated through their water supply to acclimate the plants to the contaminants. After a period of acclimation, the plants are then planted on site in contaminated water until the roots are saturated with the contaminant, at which point the plants are harvested for disposal.
- **Phytodegradation:** Phytodegradation is a process where plant enzymes completely mineralize or partially break down contaminant compounds through metabolic action within the plant.
- **Rhizo(sphere)degradation:** Rhizo(sphere)degradation is the symbiotic relationship that occurs between plant root systems and microorganisms in the root zone. Plant roots excrete sugars, acids, and alcohols that contain organic carbon used by microorganisms as a food source. This provision enhances microbial activity in the root zone, resulting in a microbial contribution to soil contaminant degradation.
- **Phytovolatilization:** Phytovolatilization is the use of plants to remove contaminants from the subsurface and evaporate or volatilize the contaminants from the leaf surface of the plant once the contaminant has traveled through the plant's system.

Development Status and Availability

The following checklist provides a summary of the development and implementation status of phytoremediation:

☐ At the laboratory/bench scale and shows promise

☐ In pilot studies

- ☒ At full scale
- ☒ To remediate an entire site (source and plume)
- ☐ To remediate a source only
- ☒ As part of a technology train
- ☐ As the final remedy at multiple sites
- ☐ To successfully attain cleanup goals in multiple sites

Phytoremediation is available through the following vendors:

- ☒ Commercially available nationwide
- ☐ Commercially available through limited vendors because of licensing or specialized equipment
- ☐ Research organizations and academia

Applicability

Contaminant Class Applicability Rating for Phytoremediation

(Rating codes: ● Demonstrated Effectiveness, ◐ Limited Effectiveness, ○ No Demonstrated Effectiveness,
◊ Level of Effectiveness dependent upon specific contaminant and its application/design, I/D Insufficient Data)

Nonhalogenated VOC	Halogenated VOC	Nonhalogenated SVOC	Halogenated SVOC	Fuels	Inorganics	Radionuclides	Munitions	Emerging Contaminants
	●		●	●			●	

◐ ◒ ◐ ◒ ◒ ◐ ◐ ◒ ◊

Phytoremediation can be used to treat a wide range of inorganic and organic contaminants in shallow groundwater and soil, and is applicable to sites where water uptake is desirable for hydraulic/migration control or treatment. Contaminant classes for which phytoremediation has been applied include nonhalogenated and halogenated VOCs, fuels, inorganics, radionuclides, munitions, polychlorinated biphenyls (PCBs), and pesticides (ITRC, 2009). Full-scale implementation has been documented for phytoremediation for all of these contaminant classes (ITRC, 2009).

Phytoremediation is typically selected when a longer treatment time can be tolerated, and when starting concentrations are relatively low or as part of a treatment train as a polishing step. For groundwater, phytoremediation can be used to provide hydraulic/migration control in lieu of pump and treat. Willow and poplar trees with deep root systems are commonly used for shallow water table groundwater units.

Remediation of sites contaminated with inorganic contaminants has been tested using phytoremediation, phytoaccumulation/extraction, or phytostabilization mechanisms (ITRC, 2009). Hyperaccumulators are plants that absorb unusually large amounts of metals in comparison to other plants. For example, metals can accumulate to levels of 1% copper and cobalt and 3% zinc, nickel, and manganese on a dry weight basis (Missouri Botanical Garden Phytoremediation Web Page, 2012). These hyperaccumulators have been tested to remediate shallow soils, however few hyperaccumulators have been found that take up significant metals contamination, or that can reduce concentrations to target levels. The plant root zones are also very shallow and can only reach surface and near surface soils. Examples of this type of plant include sunflowers, dandelions, and hops. One consideration for hyperaccumulation of inorganics in certain plants is the potential to poison wildlife. At sites known to be high in inorganics and where wildlife use is likely, plants should be tested for high metals concentrations and the risks to wildlife assessed. Plants with dense root systems are the best for phytostabilization, most easily absorbing metals such as lead, cadmium, zinc, arsenic, copper, chromium, selenium and uranium. Phytoremediation has also been effective for the removal of nitrates and ammonium from groundwater. All plants require a nitrogen source to grow. Some nitrogen-containing contaminants can be directly used by the plants for plant growth.

Phytoextraction, phytodegradation, and rhizodegration can operate together to treat nonhalogenated and halogenated VOCs, fuels, pesticides, and munitions in soils and groundwater (ITRC, 2009). These organic compounds have been shown by some studies to be degraded via enzymes that are produced in the plant's natural growth cycle. The enzymes break down complex organic contaminant molecules into simpler molecules, which aid in tree growth. As the complex compounds are broken down, the simple molecules are added to plant tissue. In contaminated soils, enzymes and proteins can initiate chemical reactions to degrade chlorinated solvents, as well as herbicides and cyanide. Projects that target organic contaminants, such as trichloroethylene (TCE) and trinitrotoluene (TNT) in the water phase (ITRC, 2009), have shown to be effective; however, more research is needed for the less mobile contaminants, such as PCBs and carcinogenic polynuclear aromatic hydrocarbons (PAHs). Alfalfa and prairie grasses have been used to treat petroleum contamination (with the exception of carcinogenic PAHs).

Phytoremediation is applicable to sites with sufficient land area for planting and shallow contamination. Phytoremediation mechanisms rely on the transpiration and metabolic processes of plants, as driven by sunlight. Maximizing the solar radiation captured by the remedy is a key design component. For example, phytoremediation using tree stands is typically designed with tree spacing that results in a closed canopy at maturity, which maximizes sunlight capture and provides overlap of the root systems for more effective groundwater capture. Cold climates, which typically also are characterized by short growing seasons, are less amenable to phytoremediation because fewer plant species are tolerant of these conditions, and the plants are active for a shorter period of the year.

Cost

In situ phytoremediation is a passive technology that typically requires little equipment installation (except in some cases where elaborate irrigation systems are required), and the implementation cost is typically low compared to other more aggressive technologies. Phytoremediation is typically selected when a longer treatment time can be tolerated, and when starting concentrations are relatively low or as part of a treatment train as a polishing step. Grid planting of a large number of tree stands is a typical approach for using phytoremediation to provide groundwater hydraulic/migration control. As with all in situ technologies, application costs vary according to site conditions and contaminants. The labor and equipment associated with site preparation and planting represent the primary capital costs for phytoremediation. The cost of the plants themselves can also be a cost driver, although not in all cases. For instance, when planting 9-inch hardwood cuttings of hybrid poplars, the cost of the cuttings themselves is typically just a few hundred dollars. Major cost drivers include:

Upfront Costs

- Degree to which existing infrastructure (e.g., buildings, pavement, and utilities) must be removed in order to plant
- Need for pilot studies or bench-scale tests to demonstrate effectiveness at a particular site
- Need for, and complexity of, irrigation and monitoring systems
- Site climate
- Selected species of plant and growth stage (e.g., hardwood cuttings versus whips)
- Size of treatment area, topography, soil type, and drainage requirements
- Degree of growing media amendments and support materials required

Operation and Maintenance Costs

- Level of plant maintenance, including irrigation, fertilization, pest control, pruning and thinning
- Need for harvesting and disposal (for phytoaccumulation)
- Need to replace plants lost to disease or damage
- Treatment timeframe, which may require plant/tree replacement, which is mostly applicable to hydraulic/migration control applications.

The list above highlights those cost dependencies specific to phytoremediation and does not consider the dependencies that are general to most in situ remediation technologies. Click here for a general discussion on costing which includes definitions and repetitive costs for remediation technologies. A project-specific cost estimate can be obtained using an integrated cost-estimating application such as RACER® or consulting with a subject matter expert.

Duration

Operation and maintenance duration for phytoremediation will range from 1 to 30+ years. In contrast to active mechanical treatment systems, selection and operation and maintenance activities require expertise in agriculture and silviculture. The duration of operation and maintenance is dependent on the following conditions:

- Cleanup goals
- Volume of in situ media requiring treatment
- Contaminant concentrations and distribution
- Growth rate and characteristics of remediation plantings
- Climate (i.e., temperature, winds, and rain).

Implementability Considerations

The following are key considerations associated with implementing phytoremediation:

- Employing specific plant species to target particular contaminants at a site can be difficult because of species adaptability problems.
- Climatic or seasonal conditions may interfere with or inhibit plant growth, slow remediation efforts, or increase the length of the treatment period.
- In addition to climate, site soil type, lithology, and hydrogeology characteristics may not be conducive to needed plant/tree species (e.g., insufficient groundwater yield or transmissivity for tree root systems).
- The transpiration mechanisms of phytoremediation function almost entirely during the active growing season, and during daylight hours when solar radiation drives transpiration. Choosing a mix of species can somewhat accommodate the variation in treatment efficiency resulting from daily and seasonal variation. The daily and seasonal variation in treatment efficiency can also be accommodated by proportionally increasing the planted area such that any plume migration during the dormant period does not move beyond the planted area.
- Phytoremediation will likely require a large area of land surface for remediation, and may require removal of anthropogenic structures and land surface preparation prior to planting.
- Generally, phytoremediation can only be employed in areas with lower levels of contamination due to plant toxicity effects.
- For vadose zone treatment, phytoremediation is limited to contaminants located in shallow soils within the root zone of the plants (typically 3 to 10 feet). For groundwater, hydraulic/migration control is limited to shallow water table groundwater units where root systems can reach 30 to 40 feet. Deeper

contamination, however, may not be adequately addressed by phytoremediation affecting only the upper portion of the aquifer.

- Mass transfer limitation is similar to other remediation technologies.
- Phytoremediation can take significantly longer than other technologies to reach cleanup objectives.
- Hydraulic/migration control capabilities may be minimal during winter conditions when trees are dormant and uptake capacities are much lower.
- Phytoremediation is ranked as having low reliability and high maintenance.

Resources

EPA. Phytotechnologies Web Page (2016)
Provides an overview of phytoremediation along with links to guidance, application, training, and additional resources.

EPA. Phytotechnology Project Profiles (2016)
This Web page summarizes timely information about selected full-, field- and large greenhouse-scale applications of phytotechnology. Includes information on approximately 180 phytotechnology projects documenting the use of phytotechnology for various contaminants, such as chlorinated solvents, metals, explosives and propellants, pesticides, PAHs, radionuclides, and petroleum hydrocarbon compounds.

EPA. A Citizen's Guide to Phytoremediation (September 2012)
A summary fact sheet on basic concepts of phytoremediation.

EPA. Phytoremediation Resource Guide (June 1999)
This document provides abstracts of over 100 phytoremediation overviews, field studies and demonstrations, research articles, and Internet resources.

Hazardous Substance Research Center (HSRC) Phytoremediation
Information on the internet relating to phytoremediation — an innovative technology for remediating sites contaminated with hazardous substances. Includes a listserv, bibliography, and links.

International Phytotechnology Society Web Site (2017)
Information on conferences, bibliography, directory of members, and links to other resources.

Interstate Technology and Regulatory Council (ITRC) Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised (February

2009)
ITRC guidance document providing the process and protocol for selecting and applying phytotechnologies.

Missouri Botanical Garden Phytoremediation Web Page (2012)
Links to phytoremediation sites, information on conferences, and articles about the remediation process.

NAVFAC Phytoremediation Tool
This tool explores the use of plants as a sustainable remedial option for sites contaminated with organic and/or inorganic constituents. A decision tree is reviewed that can assist Remedial Project Managers (RPMs) in deciding whether or not phytoremediation is applicable for their site.

U.S. Army Corps of Engineers (USACE) Phytoremediation Research (2016)
USACE news article describing a research project where the ERDC's Cold Regions Research and Engineering Laboratory is using transgenic switchgrass to remediate munitions constituents in soil.

U.S. Geological Survey (USGS) Phytoremediation (2016)
Description of a phytoremediation textbook by USGS scientist Dr. James E. Landmeyer, with links to other phytoremediation resources.