TECHNOLOGY OVERVIEW

PHYTOTECHNOLOGIES

August 2010

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ITRC (Interstate Technology & Regulatory Council). 2010. *Phytotechnologies.* Washington, D.C.: Interstate Technology & Regulatory Council, Mining Waste Team. www.itrcweb.org.

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1. INTRODUCTION

Phytotechnologies use plants to remediate various media impacted with different types of contaminants. Phytotechnologies can be applied to address certain issues associated with mining solid wastes and mining-impacted waters. Phytotechnologies can also stabilize tailings and act as a hydraulic control for drainage, thereby decreasing exposure of contaminants to humans and the ecological environment. Implementation of phytotechnologies is a common component of mining reclamation and restoration projects by the establishment of a plant cover as a final remedy. However, in certain cases, application of phytotechnologies can be used for removal of metals from contaminated media. Establishing phytotechnologies requires careful plant species selection and soil amendments, which equates to an investment of time up-front; however, these systems, once established, can be maintained with minimal effort. This document provides an overview of the ITRC document *Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised* (ITRC 2009), highlighting the key concepts relevant to using phytotechnologies specifically for mining solid waste and mining-impacted waters. Please refer to the full document for more thorough guidance on the use of phytotechnologies.

2. APPLICABILITY

There are six basic phytoremediation mechanisms that can be used to clean up mining-contaminated sites: phytosequestration, rhizodegradation, phytohydraulics, phytoextraction, phytodegradation, and phytovolatilization (Table 1-1). The particular phytotechnology mechanisms used to address contaminants depend not only on the type of contaminant and the media affected, but also on the cleanup goals. Typical goals include containment through stabilization or sequestration; remediation through assimilation, reduction, detoxification, degradation, metabolization, or mineralization; or both. To achieve these goals, the proper phytotechnology system must be selected, designed, developed, implemented, and operated using detailed knowledge of the site layout, soil characteristics, hydrology, climate conditions, analytical needs, operation and maintenance (O&M) requirements, economics, public perspective, and regulatory protection of the environment.

Table 1-1 Summary of phytotechnology mechanisms (ITRC 2009)

Mechanism	Description	Cleanup goal
Phytosequestration	The ability of plants to sequester certain contaminants in the rhizosphere through exudation of phytochemicals and on the root through transport proteins and cellular processes.	Containment
Rhizodegradation	Exuded phytochemicals can enhance microbial biodegradation of contaminants in the rhizosphere.	Remediation by destruction

Mechanism	Description	Cleanup goal
Phytohydraulics	The ability of plants to capture and evaporate water off the plant and take up and transpire water through the plant.	Containment by controlling hydrology
Phytoextraction	The ability of plants to take up contaminants into the plant with the transpiration stream.	Remediation by removal of plants
Phytodegradation	The ability of plants to take up and break down contaminants in the transpiration stream through internal enzymatic activity and photosynthetic oxidation/reduction.	Remediation by destruction
Phytovolatilization	The ability of plants to take up, translocate, and subsequently transpire volatile contaminants in the transpiration stream.	Remediation by removal through plants

Phytotechnologies are applicable to the following:

- mining solid waste or mining-impacted water
- high or low volumes of material
- remote, rural, or urban areas
- applies to many contaminants of concern (COC)
- solo technology or in conjunction with others

Phytotechnologies are applicable where the following cleanup goals are required:

- containment of solid material
- containment by controlling hydrology
- remediation by neutralization or volatilization of COCs
- remediation by removal of plants
- mitigation of human/ecological risk
- polishing step (for low-level COCs)
- restoration for end use

Due to the complexity of contaminants associated with the mining waste process, potentially all of the above phytotechnology mechanisms could be applied as sole remediation technology or as part of suite of remediation technologies. However, the phytotechnologies that may be most useful for mining wastes are likely those that relate to remediation of inorganic contaminants and hydraulic control: phytosequestration, phytohydraulics, and phytoextraction. More details on the types of applications are provided in the following sections. All tests have been conducted at pilot scale or smaller.

2.1 Phytosequestration

Phytosequestration reduces the mobility of the contaminant and prevents migration to soil, water, and air are as follows:

- Phytochemical complexation in the root zone. Phytochemicals can be exuded into the rhizosphere, leading to the precipitation or immobilization of target contaminants in the root zone. This mechanism of phytosequestration may reduce the fraction of the contaminant that is bioavailable.

- Transport protein inhibition on the root membrane. Transport proteins associated with the exterior root membrane can irreversibly bind and stabilize contaminants on the root surfaces, preventing contaminants from entering the plant.

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

Case studies using phytosequestration include the following:

- The Ely Copper Mine in Vermont is using a vegetative cover for mitigation of ecological risk and reducing bioavailable metals. As a means to neutralize acids in copper mine tailings, greenhouse studies found that mixing tailings from an active OMYA limestone mining operation can be used, together with compost, to neutralize and improve soil.

- The Boston Mill site in Cochise County, Arizona used phytostabilization to jump-start native plant establishment on a barren section of the Boston Mill site approximately 1.5 acres containing high concentrations of heavy metals (Pb, As, Hg, Zn, Cu, Fe, Mn, Cd, and Al). The study describes greenhouse feasibility trials and outlines process to establish plants, through seeding.

2.2 Phytohydraulics

Plants significantly affect local hydrology. Phytohydraulics is the ability of vegetation to transpire sources of surface water and groundwater. The vertical migration of water from the surface downward can be limited by the water interception capacity of the aboveground canopy and subsequent evapotranspiration through the root system. If water infiltrating from the surface is able to percolate below the root zone, it can recharge groundwater. However, the rate of recharge depends not only on the rooting depth of the species, but on the soil characteristics as well (ITRC 2009). The horizontal migration of groundwater can be contained or controlled (USEPA 2000) using deep-rooted species such as prairie plants and trees to intercept, take up, and transpire the water. One class of trees that has been widely studied in phytotechnologies are the phreatophytes, which are deep-rooted, high-transpiring, water-loving trees that send their roots into regions of high moisture and that can survive in conditions of temporary saturation (Gatliff 1994). Typical phreatophytes include species within the *Salicaceae* family, such as cottonwoods, poplars, and willows.

Case study using phytohydraulics:

- Kerramerican NPL in Maine uses phytohydraulics (revegetation) as part of a multi-component geosynthetic cover system as part of an effort to repair soil cover and provide drainage diversion.

2.3 Phytoextraction

Phytoextraction refers to the ability of plants to take up contaminants into the roots and translocate them to the aboveground shoots or leaves. For contaminants to be extracted by plants, the constituent must be dissolved in the soil water and come into contact with the plant roots through the transpiration stream. Once a chemical is taken up, the plant may store the chemical and/or its by-products in the plant biomass via lignification (covalent bonding of the chemical or its by-products into the lignin of the plant) or sequester it into the cell vacuoles of aboveground tissues (as opposed to in root cells as part of phytosequestration, see above). Alternatively, the contaminant may be neutralized through phytochemical reactions and/or phytovolatilized in the transpiration stream exiting the plant. Specifically, tobacco plants have been modified to be able to take up the highly toxic methyl-mercury, alter the chemical speciation, and phytovolatilize relatively safe levels of the less toxic elemental mercury into the atmosphere (Heaton et al. 1998).

2.4 Applying Phytotechnologies

Applying phytotechnologies to environmentally impacted sites entails selecting, designing, installing, operating, maintaining, and monitoring planted systems that use the various mechanisms described above. The goal of the system can be broadly based on the remedial objectives of containment, remediation, or both. Furthermore, the target media can be soil/sediment, surface water, or groundwater, and these can be either clean or impacted. In some cases, groundwater transitioning to surface water (daylighting seep) can be addressed as a riparian situation where target media are combined. The possible combinations of treatment goal, target media, and applicable mechanisms are summarized in Tables 2-1 and 2-3 for each application. However, specific applications can be designed such that a particular mechanism is emphasized as the primary means of treatment either through plant selection, engineering and design, or method of installation or construction.

Table 2-1. Summary of phytotechnology applications and potential mechanisms for containment treatment goals (applications covered in ITRC 2009 in bold)

Media	Application	Potential mechanisms	Comments
Soil/sediment (impacted)	**Phytostabilization Cover** (soil/sediment stabilization)	Phytosequestration Phytoextraction (no harvesting) Adsorption (abiotic) Precipitation (abiotic) Settling/Sedimentation (abiotic)	Also controls soil erosion by wind/water ITRC WTLND-1 (2003) for sediment aspects

Surface water (clean)	**Phytostabilization Cover** (infiltration control)	Phytohydraulics (evapotranspiration) Runoff (abiotic)	Vertical infiltration control ITRC ALT-1 (2003), ALT-2 (2003), ALT-3 (2006), ALT-4 (2006) for alternative (evapotranspiration) covers
Surface water (impacted)	Pond/Lagoon/Basin **Riparian Buffer**	Phytosequestration Phytohydraulics (evapotranspiration) Phytoextraction (no harvesting) Evaporation (abiotic) Infiltration (abiotic)	See ITRC WTLND-1 (2003) Includes wastewater Also controls soil erosion by water run off
Groundwater (clean)	**Tree Hydraulic Barrier** **Riparian Buffer**	Phytohydraulics (evapotranspiration)	Lateral migration control
Groundwater (impacted)	**Tree Hydraulic Barrier** **Riparian Buffer**	Phytosequestration Phytohydraulics (evapotranspiration) Phytoextraction (no harvesting)	Lateral migration control

Adapted from ITRC 2009, Tables 1-5a and 1-5b.

Table 2-2. Summary of phytotechnology applications and potential mechanisms for remediation treatment goals (applications covered in ITRC 2008 in bold)

Media	Application	Potential mechanisms	Comments
Soil/sediment (impacted)	**Phytoremediation** **Groundcover**	Rhizodegradation Phytoextraction (with harvesting) Phytodegradation Phytovolatilization Biodegradation (microbial) Oxidation/reduction (abiotic) Volatilization (abiotic)	Phytohydraulics (evapotranspiration) assumed for phytoextraction, phytodegradation, and phytovolatilization
Surface water (impacted)	Pond/Lagoon/Basin **Riparian Buffer** Constructed Treatment Wetland	Rhizodegradation Phytoextraction (with harvesting) Phytodegradation Phytovolatilization Biodegradation (microbial) Oxidation/reduction (abiotic) Volatilization (abiotic)	See ITRC WTLND-1 (2003) Includes wastewater and extracted groundwater Phytohydraulics (evapotranspiration) assumed for phytoextraction, phytodegradation, and phytovolatilization
Groundwater (impacted)	**Phytoremediation** **Tree Stand** **Riparian Buffer**	Rhizodegradation Phytoextraction (with harvesting) Phytodegradation Phytovolatilization Oxidation/reduction (abiotic) Biodegradation (microbial)	Phytohydraulics (evapotranspiration) assumed for phytoextraction, phytodegradation, and phytovolatilization

Adapted from ITRC 2009, Tables 1-5a and 1-5b.

3. ADVANTAGES

One of the main advantages of phytotechnologies, as compared to alternative cleanup technologies, is that most phytotechnologies can be applied to both organic and inorganic contaminants and to soil/sediment, surface water, and groundwater. Furthermore, in some cases, it can be applied to various combinations of contaminant types and impacted media simultaneously. In most other remedial approaches, these combinations would have to be addressed using a treatment train. Other advantages are listed below:

- Considered a sustainable and green technology
  - system is solar-powered and does not require supplemental energy, although monitoring equipment may be required
  - improves air quality and sequesters greenhouse gases
  - minimal air emissions, water discharge, and secondary waste generation
  - lower maintenance, resilient, and self repairing
- Inherently controls erosion, runoff, infiltration, and fugitive dust emissions.
- Can be designed as passive and in situ technology.
- Favorable public perception, which includes educational opportunity.
- Improves aesthetics, including reduction of noise.
- Applicable to remote locations, potentially without utility access source of irrigation.
- Can be used to supplement other remediation approaches or as a polishing step.
- Can be used to identify and map contamination.
- Can be installed as a preventative measure, possibly as a leak-detection system.
- Creates habitat. This can also be a disadvantage since it may attract nuisance animals.
- Provides restoration and land reclamation during cleanup and upon completion of project.
- Can be cost-competitive.

4. LIMITATIONS

Phytotechnologies are appropriate only under certain conditions. The major limitations are depth, area, and time. The physical constraints of depth and area depend on the plant species suitable to the site (i.e., root penetration) as well as the site layout and soil characteristics. Phytotechnologies typically require larger tracts of land than many alternatives. Time can be a constraint since phytotechnologies generally take longer than other alternatives and are susceptible to seasonal and diurnal changes. These limitations should be considered along with several other decision factors when evaluating a phytotechnology as a potential remedy (ITRC 2009).

Other limitations include the following:

- plant tolerance to contaminant of concern or site conditions
- availability of water as irrigation source
- climate (difficult for plant establishment in areas short growing season or in arid environments)
- pests, infestations or attractive nuisances

Many of the limitations can be overcome by proper plant selection. All plant selections must be made based on site-specific conditions. Climate, altitude, soil salinity, nutrient content, fertility, location, depth, concentration of contaminant, commercial availability, plantability, and plant hardiness are some of the determining elements. A variety of approaches and information resources can be used, including databases, site-specific vegetation surveys, and specifically designed tests to evaluate species (ITRC 2009). In addition to selecting species for the remediation, end-use considerations can be included in the initial plant selection. Typically, 10%–15% climax species might be included in the initial design.

5. PERFORMANCE

In some cases, the application of phytotechnologies can have an immediate effect on contaminant concentrations upon planting. In other cases, it may require several seasons before the plant can interact with a contaminated zone at depth. Furthermore, it may depend on whether the plant itself is directly or indirectly involved with remediating the contaminant.

The time it takes for cleanup to be achieved depends on the criteria set forth in defining the cleanup objectives for the site. Furthermore, it depends on the type, extent, and concentration of contamination, continuing sources, obstructions, soil conditions, hydrologic/groundwater conditions, and other site characteristics, the plant species, growth rate, and climate conditions. Complete restoration will depend on the type of phytotechnology applied at the site (ITRC 2009).

For assessing results, phytotechnology systems should be monitored using the same primary lines of evidence as any other alternative (i.e., concentration trends, hydrology, soil effects, etc.). That information may need to be supported by secondary lines of evidence, which generally entail analyzing the plants in some manner (ITRC 2009).

6. COSTS

The benefits of using the phytotechnology-based techniques are the relative lower costs, labor requirements, and safer operations compared to the more intensive and invasive conventional techniques. Establishment of phytotechnology systems include various expenditures, such as earthwork, labor, planting stock, planting method, field equipment, heavy machinery (typically farming or forestry equipment), soil amendments, permits, water control infrastructure, utility infrastructure, fencing, security, etc.

Phytotechnologies require significant operation, maintenance, and monitoring for several years after planting. Costs can include labor, sampling, analytical, materials, field equipment, utilities, waste handling, and disposal. Once the plantation becomes established, however, the operation and maintenance (O&M) costs tend to diminish. Furthermore, additional sampling and monitoring will typically be required during the initial phases compared to subsequent years. Phytotechnologies are generally long-term remedial solutions.

In addition, phytotechnology plantations may require irrigation, fertilization, weed control (mowing, mulching, or spraying), and pest control. At the onset of a planting, which too may be a reoccurring O&M event, some percentage of replanting may be required due to the lack of establishment. As a general rule of thumb, 10%–15% of the initial capital costs should be added as a contingency for replanting.

7. REGULATORY CONSIDERATIONS

When selecting a phytotechnology as the remedy for the site, one of the absolute requirements is to demonstrate to regulators that the contaminants of concern (COCs) can be contained and/or remediated using the phytotechnology. This is often demonstrated in feasibility studies conducted specifically for the site or extrapolated from literature results that are sufficiently similar to the site conditions. Furthermore, the proposed remedy must ensure that the fate and transport of the contaminant(s) and/or by-products are acceptable through all potential exposure pathways.

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

Because phytotechnology systems use plants at a contaminated site, the potential ecological exposures posed by the species planted need to be considered. EPA guidance for the preparation of ecological risk assessments (USEPA 1999) should be used to evaluate any potential exposure pathways created or enhanced by using phytotechnologies. The level of detail required is site specific and varies with the application. Factors that should be incorporated into the risk assessment may include species-specific considerations of bioavailability (USEPA 2008), ecological exposures, and the transformation of the chemical composition or physical state.

Depending on the plant species chosen (e.g., invasive, or genetically modified organism [GMO]), other regulations may apply. On February 3, 1999, an Executive Order was signed that specifically addresses invasive species. It requires federal agencies to prevent the introduction of invasive species and to detect and respond rapidly to control established populations of invasive nonnative species. At this time, regulations on GMOs are unclear in the United States (possibly covered under a variety of statues). While EPA does not currently regulate GMO plants used for commercial bioremediation, it may have given them authority to do so under the Toxic Substances Control Act (TSCA). This authority could be invoked to regulate these plants if EPA believed such regulation necessary to prevent unreasonable risk to human health and the environment.

8. STAKEHOLDER CONSIDERATIONS

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

9. LESSONS LEARNED

Establishment of vegetation can be enhanced by using native soil or other amendments to offset the often poor growing conditions offered by the tailings material. Some suggestions follow:

- Waste streams from other operations may be suitable as an amendment to tailings material. At the Ely Copper Mine in Vermont, limestone mining tailings are being explored to neutralize copper mine tailings for vegetative cover. Gribbons Basin, MI used sewage and paper mill sludge to establish vegetation on iron mine waste materials. Bark Camp, PA uses municipal solid waste and coal fly ash to restore contour of mining area, followed by cover with manufactured soil before replanting. In some cases, because waste streams may introduce additional organic or inorganic contaminants, additional permits may be required.
- During land movement operations, stockpile soil for later replanting to avoid having to use soil from undisturbed locations (Magmont Mine, MO).

10. CASE STUDIES

Table 10-1. Case studies including phytotechnologies

Ely Copper Mine, VT, phytosequestration
Kerramerican NPL, ME, phytohydraulics
Magmont Mine, MO, phytosequestration
Black Butte Mercury Mine, OR, phytosequestration
Gribbons Basin, MI, phytosequestration, phytohydraulics
Valzinco Mine, VA, phytosequestration
Copper Basin, TN, phytosequestration
Sequatchie Valley Coal Mine, TN, phytosequestration, phytohydraulics
Bark Camp, PA, phytosequestration, phytohydraulics
Annapolis Lead Mine Site, MO, phytosequestration
UP Mines, MI, phytosequestration
Boston Mill, AZ

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