Phytoremediation – Green for Environmental Clean

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ABSTRACT

Amorphous industrial activities, sewage sludge disposal, metal processing, and energy production units regularly discharge a huge amount of contaminants on soils. The remediation of contaminated soil is expensive and intrusive to the ecosystem. Phytoremediation is the use of plants and plant processes to remove, degrade, or render harmless hazardous materials present in the soil or water. This emerging technology may offer a cost-effective, non-intrusive, and safe alternative to conventional soil cleanup techniques by using the ability of certain tree, shrub, and grass species to remove, degrade, or immobilize harmful chemicals from the soil. The science of phytoremediation arose from the study of heavy metal tolerance in plants in the late 1980s. The discovery of hyperaccumulator plants, which contain high levels of heavy metals that would be highly toxic to other plants, prompted the idea of using certain plant species to extract metals from the soil and, in the process, clean up soil for other less tolerant plants. Certain plants could degrade organic contaminants by absorbing them from the soil and metabolizing them into less harmful chemicals. In addition to plants, microorganisms that live in the rhizosphere (the actively growing root zone of the soil) play a major role in degrading organic chemicals, often using these chemicals as a carbon source in their metabolism. Different types of phytoremediation have different potential results, such as accumulation of heavy metals in specific plant organs, volatilization from leaf surfaces, alteration of the form or availability of an organic chemical in the soil or within the plant, or actively excluding chemicals from plant tissues and keeping them out of the food chain. The result depends on site-specific research and this approach is not generally appropriate for grossly contaminated soils that are an immediate ecological health risk. The major challenge to using phytoremediation effectively remains gaining an understanding of these various plant-chemical interactions and learning how to apply them safely in remediation programs. Phytoremediation can occur through a series of complex interactions between plants, microbes, and the soil, including accumulation, hyperaccumulation, exclusion, volatilization, and degradation. Plants also stabilize mobile contaminated sediments by forming dense root mats under the surface.

INTRODUCTION

Phytoremediation is a set of processes that uses plants to remove, transfer, stabilize and destroy organic/inorganic contamination in ground water, surface water, and soil. The plants can be used for the phytoremediation, these mechanisms include enhanced rhizosphere biodegradation, hydraulic control, phyto-degradation and phyto-volatilization. Phytoremediation is the use of plants to partially or substantially remediate selected contaminants in contaminated soil, sludge, sediment, ground water, surface water, and waste water. It utilizes a variety of plant biological processes and the physical characteristics of plants to aid in site remediation. Phytoremediation is a continuum of processes, with the different processes, however, it must be realized that the various processes described by these terms all tend to overlap to some degree and occur in varying proportions during phytoremediation. This process encompasses a number of different methods that can lead to contaminant degradation, removal (through accumulation or dissipation), or immobilization. Phytoremediation is potentially applicable to a variety of contaminants, including some of the most significant contaminants, such as petroleum hydrocarbons, chlorinated solvents, metals, radionuclides, nutrients, pentachlorophenol (PCP), and polycyclic aromatic hydrocarbons (PAHs). Phytoremediation requires more effort than simply planting vegetation and, with minimal maintenance, assuming that the contaminant will disappear. It requires an understanding of the processes that need to occur, the plants selected, and what needs to be done to ensure plant growth. The screening studies will be important in selecting the most useful plants. Extrapolation of results from hydroponic or greenhouse studies to actual field situations will require further field studies. Verification of the applicability and efficacy of phytoremediation is likely to be required on a site-specific basis, at least until the technology becomes firmly proven and established. Phytoremediation requires a commitment of resources and time, but has the potential to provide a lower-cost, environmentally acceptable alternative to conventional remedial technologies at appropriate sites.
Why use of Phytoremediation?
A. Plants control 80% of the energy in most ecosystems and do not need external energy sources.
   i) Photosystem I make NADPH
   ii) Reduce CO₂ and make large biomass
   iii) Can reduce toxic metal ions
B. Plants grow extensive root systems (100 million/acre/yr)
   i) Plants mine 16 metals for normal growth
   ii) Some plants hyperaccumulate heavy metals
   iii) Some plants degrade toxic organic chemicals
C. Phytoremediation is a sound support to bacterial remediation methods.
D. Phytoremediation is affordable on grand scale needed for marginal land reclamation and cleaning the water in lakes, streams and marshes.
E. Phytoremediation is a rapid gaining support by the public as “Green” solution to our environmental problems.

Phytoremediation takes advantage of the natural processes of plants (Meager, 1996). These processes include water and chemical uptake, metabolism within the plant, exudate release into the soil that leads to contaminant loss and the physical and biochemical impacts of plant roots. Growth of plants depends on photosynthesis, in which water and carbon dioxide are converted into carbohydrates and oxygen, using the energy from sunlight. Roots are effective in extracting water held in soil, even water held at relatively high geometric and osmotic negative water potentials; extraction is followed by upward transport through the xylem. Transpiration (water vapor loss from plants to the atmosphere) occurs primarily at the stomata (openings in leaves and stems where gas exchange occurs), with additional transpiration at the lenticels (gas exchange sites on stem and root surfaces). Carbon dioxide uptake from the atmosphere occurs through the stomata, along with release of oxygen. Respiration of the carbohydrates produced during photosynthesis, and production of ATP, necessary for the active transport of nutrients by roots, requires oxygen. Diffusion and advection of oxygen into the soil are necessary for continued plant survival; and high or saturated soil water content will greatly slow oxygen transport. Plants do not transport oxygen into roots (or into the surrounding water or soil), except for a relatively small number of plants (mostly aquatic, flood-adapted, or wetland plants) using specialized structures or mechanisms such as aerenchyma, lacunae, or pneumatophores. Few woody species can transport oxygen to the root zone; flood tolerance of some trees, such as poplar, is likely due to coping mechanisms other than transport of oxygen. Plants require macronutrients (N, P, K, Ca, Mg, S) and micronutrients (B, Cl, Cu, Fe, Mn, Mo, Zn and possibly Co, Ni, Se, Si, V, and maybe others). Lack of chlorophyll due to stresses on the plant, such as lack of nutrients, can result in chlorosis (the yellowing of normally green plant leaves). Nutrient uptake pathways can take up contaminants that are similar in chemical forms or behavior to the nutrients. Cadmium can be subject to plant uptake due to its similarity to the plant nutrients calcium and zinc, although poplar leaves in a field study did not accumulate significant amounts of cadmium (Pierzynski et al., 1994). Arsenic (as arsenate) might be taken up by the plants due to similarities to the plant nutrient phosphate; however, poplars growing in soil containing an average of 1250 mg/kg arsenic did not accumulate significant amounts of arsenic in their leaves (Pierzynski et al., 1994). Selenium replaces the nutrient sulfur in compounds taken up by a plant, but does not serve the same physiological functions (Brooks, 1998b). For uptake by plants, a chemical must be in solution, either in ground water or in the soil solution (i.e., the water in the unsaturated soil zone). Water is absorbed from the soil solution into the outer tissue of the root. Contaminants in the water can move through the epidermis to and through the Casparian strip, and then through the endodermis, where they can be sorbed, bound, or metabolized. Chemicals or metabolites passing through the endodermis and reaching the xylem are then transported in the transpiration stream or sap. The compounds might react with or partition into plant tissue, be metabolized, or be released to the atmosphere through stomatal pores (Paterson et al., 1990; Shimp et al., 1993). The uptake and translocation of organic compounds is dependent on their hydrophobicity (lipophilicity), solubility, polarity, and molecular weight (Briggs et al., 1982; Bell, 1992; Schnoor, 1997). Briggs et al. (1982) found that translocation of nonionized compounds to shoots was optimum for intermediate polarity compounds that were moderately hydrophobic, with less translocation for more polar compounds. A slightly wider range of log Kow values (approximately 1.0 to 3.5) was provided by Schnoor (1997) for prediction of translocation to the shoot. More hydrophobic compounds are more strongly bound to root surfaces or partition into root solids, resulting in less translocation within the plant (Briggs et al., 1982; Schnoor et al., 1995; Cunningham et al., 1997). Very soluble organic compounds (with low sorption) will not be sorbed onto roots as much as lower solubility compounds, or translocated within the plant (Schnoor et al., 1995). In contrast to the very soluble organic compounds, soluble inorganic compounds, such as nutrients, can be readily taken up by plants. Uptake of the inorganic compounds (which are generally in ionic or complexed form) is mediated...
by active or passive uptake mechanisms within the plant (Brady, 1974), whereas uptake of organic compounds is generally governed by log kow (hydrophobicity) and polarity. Ryan et al. (1988) provide more discussion of plant uptake of organic compounds. Plant uptake of organic compounds can also depend on the type of plant, age of the contaminant, and many other physical and chemical characteristics of the soil.

PHYTOREMEDIATION PROCESSES

There are a number of different forms of phytoremediation, defining these forms is useful to clarify and understand the different processes that occur to a contaminant, their remediation and what should be done for effective phytoremediation.

PHYTOEXTRACTION

Phytoextraction is contaminant uptake by roots with subsequent accumulation in the above ground portion of a plant, generally to be followed by harvest and ultimate disposal of the plant biomass. It is a contaminant removal process. Phytoextraction applies to metals (e.g., Ag, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Zn), metalloids (e.g., As, Se), radionuclides (e.g., 90Sr, 137Cs, 234U, 238U), and non-metals (e.g., B) (Salt et al., 1995; Kumar et al., 1995; Cornish et al., 1995; Bañuelos et al., 1999), as these are generally not further degraded or changed in form within the plant. Phytoextraction has generally not been considered for organic or nutrient contaminants taken up by a plant, as they can be metabolized, changed, or volatilized by the plant, thus preventing accumulation of the contaminant. Soluble metals in surface water or extracted ground water could conceivably be cleaned using phytoextraction, perhaps in conjunction with rhizofiltration. Phytoextraction is also known as phytoaccumulation, phytosorption, and phytosequestration (which can also apply to contaminant accumulation within the roots). Some practitioners define the term phytoremediation as extraction of metals by plants; however, as discussed in this paper, there are many types of phytoremediation. Hence phytoremediation should remain broad the term. Phytoextraction has also been referred to as phytomining or biomining. A narrower definition of phytomining is the use of plants to obtain an economic return from metals extracted by a plant, either from contaminated soils or from soils having naturally high concentrations of metals (Brooks, 1998a);

PHYTOSTABILIZATION

Phytostabilization is the use of vegetation to contain soil contaminants in situ, through modification of the chemical, biological, and physical conditions in the soil. Contaminant transport in soil, sediments, or sludges can be reduced through absorption and accumulation by roots; adsorption onto roots; precipitation, complexation, or metal valence reduction in soil within the root zone; or binding into humic (organic) matter through the process of humification. In addition, vegetation can reduce wind and water erosion of soil, thus preventing dispersal of the contaminant in runoff or fugitive dust emissions, and may reduce or prevent leachate generation. Phytostabilization is also known as in-place inactivation / hyperaccumulation of other metals if present; for example, copper or cobalt hyperaccumulators will hyperaccumulate both (Brooks, 1998c). Other hyperaccumulators will take up only a specific metal even if others are present. Plant roots generally contain higher metal concentrations than the shoots despite the translocation mechanisms. An upper limit to the metal concentration within the root can occur. Root uptake of lead by hydroponically-grown plants reached a maximum concentration and did not increase further as the lead concentration of the solution increased (Kumar et al., 1995).

RHIZOFILTRATION

Rhizofiltration (also known as phytofiltration) is the removal of the contaminants by plant roots in surface water, waste water, or extracted ground water, through adsorption or precipitation onto phytomobilization. It has generally focused on metals contamination, with lead, chromium, and mercury being identified as the top potential candidates for phytostabilization (U.S. EPA, 1997). However, there may be potential for phytostabilization of organic contaminants, since some organic contaminants or metabolic byproducts of these contaminants can be attached to or incorporated into plant components such as lignin (Harms and Langebartels, 1986). This form of phytostabilization has been called phytolignification (Cunningham et al., 1995). One difference, however, is that phytostabilization of metals is generally intended to occur in the soil, whereas phytostabilization of organic contaminants through phytolignification can occur aboveground. Lead, which is generally toxic to plants, is usually not accumulated in plants under natural conditions, possibly due to precipitation of lead as sulfate at the plant roots (Reeves and Brooks, 1983). Soil pH can be changed by the production of CO₂ by microbes degrading the plant root exudates, possibly changing metal solubility and mobility or impacting the
dissociation of organic compounds. Effective phytostabilization requires a thorough understanding of the chemistry of the root zone, root exudates, contaminants, and fertilizers or soil amendments, to prevent unintended effects that might increase contaminant solubility and leaching. Cunningham et al. (1995) indicate that phytostabilization might be most appropriate for heavy-textured soils and soils with high organic matter contents.

RHIZODEGRADATION

Rhizodegradation is the enhancement of naturally-occurring biodegradation in soil through the influence of plant roots, and ideally will lead to destruction or detoxification of an organic contaminant. Other terms have been used by some authors as synonyms for rhizodegradation, such as enhanced rhizosphere biodegradation. Organic contaminants in soil can often be broken down into daughter products or completely mineralized to inorganic products such as carbon dioxide and water by naturally occurring bacteria, fungi, and actinomycetes. The presence of plant roots will often increase the size and variety of microbial populations in the soil surrounding roots (the rhizosphere) or in mycorrhizae (associations of fungi and plant roots). Significantly higher populations of total heterotrophs, denitrifiers, pseudomonads, BTX (benzene, toluene, xylenes) degraders, and atrazine degraders were found in rhizosphere soil around hybrid poplar trees in a field plot (Populus deltoides × nigra DN-34, Imperial Carolina) than in non-rhizosphere soil (Jordahl et al., 1997). The increased microbial populations are due to stimulation by plant exudates, compounds produced by plants and released from plant roots. Plant exudates include sugars, amino acids, organic acids, fatty acids, sterols, growth factors, nucleotides, flavanones, enzymes, and other compounds (Shimp et al., 1993). The increased microbial populations and activity in the rhizosphere can result in increased contaminant biodegradation in the soil, and degradation of the exudates can stimulate cometabolism of contaminants in the rhizosphere.

PHYTOVOLATILIZATION

Phyto-volatilization occurs as plants take up water containing organic contaminants and release the contaminants into the air through their leaves. Plants can also break down organic contaminants and release breakdown products into air through leaves. Phytovolatilization is the uptake of a contaminant by a plant, and the subsequent release of a volatile contaminant, a volatile degradation product of a contaminant, or a volatile form of an initially non-volatile contaminant. For effective phyto-remediation, the degradation product or modified volatile form should be less toxic than the initial contaminant. The reduction of highly toxic mercury species to less toxic elemental mercury, or transformation of toxic selenium (as selenate) to the less toxic dimethyl selenide gas. (Adler, 1996). In some cases, contaminant transfer to the atmosphere allows much more effective or rapid natural degradation processes to occur, such as photodegradation. Because phytovolatilization involves transfer of contaminants to the atmosphere, a risk analysis of the impact of this transfer on the ecosystem and on human health may be necessary. At a phyto remediation site, combinations of the phytoremediation processes discussed above may occur simultaneously or in sequence for a particular contaminant, or different processes may act on different contaminants or at different exposure concentrations. For example, TCE in soil can be subjected to biodegradation in the root zone (rhizodegradation) and metabolism within the plant (phytodestruction), with loss of some contaminant or metabolite through volatilization from the 11 plant (phytovolatilization). Some metals or radionuclides in water can be accumulated on or within roots (rhizofiltration) while other metals or radionuclides are simultaneously taken up into the aerial portion of the plant (phytoextraction). Some undisturbed contaminated sites, such as inactive land treatment
units, will naturally revegetate. Vegetation may become established after the phytotoxic contamination has been reduced through naturally-occurring biodegradation, abiotic processes such as volatilization, or through intentional traditional remedial technologies. In these cases, the vegetation would indicate that the contaminants are no longer bioavailable or toxic to the established plant species. Alternatively, a plant that can withstand the contaminant might preferentially become established, and perhaps then contribute to additional contaminant loss through the phytoremediation processes.

ADVANTAGES

(i) Phytoremediation is a lower-cost technology, although actual costs of routine application of phytoremediation is still unclear.
(ii) Phytoremediation has been perceived to be a more environmentally friendly “green” and low-tech alternative to more active and intrusive remedial methods.
(iii) Phytoremediation can be applied in situ to remediate shallow soil and ground water, and can be used in surface water bodies.
(iv) Phytoremediation does not have the destructive impact on soil fertility and structure. The presence of plants is likely to improve the overall condition of the soil, regardless of the degree of contaminant reduction.
(v) Vegetation can also reduce or prevent erosion and fugitive dust emissions.

DISADVANTAGES

There are a number of limitations to phytoremediation
i) It is limited to shallow soils, streams, and ground water.
ii) High concentrations of hazardous materials can be toxic to plants.
iii) It involves the same mass transfer limitations as other biotreatments.
iv) Climatic or seasonal conditions may interfere or inhibit plant growth, slow remediation efforts, or increase the length of the treatment period.
v) It can transfer contamination across media, e.g., from soil to air.
vi) It is not effective for strongly sorbed (e.g., PCBs) and weakly sorbed contaminants.
(vii) Phytoremediation will likely require a large surface area of land.
(viii) The toxicity and bioavailability of biodegradation products is not always known. Products may be mobilized into ground water or bioaccumulated in animals.

ix) A longer time period is likely to be required for phytoremediation.

x) High initial contaminant concentrations can be phytotoxic, and prevent plant growth. Preliminary phytotoxicity studies are likely to be necessary to screen candidate plants.

SOCIAL ASPECTS OF PHYTOREMEDIATION ACCEPTABILITY

Phytoremediation comprises a suite of promising cleanup technologies that use plants to remove or contain contaminants in soil and water. Phytoremediation must be both technically and socially acceptable Amy K. Wolfe (2002). This article explores the potential social acceptability of phytoremediation options proposed for use at specific sites and describes the conceptual framework that guides our exploration. The framework, called PACT (Public Acceptability of Controversial Technologies), consists of Dialog, Technology, Constituent, and Context dimensions. It reveals that remediation decision making is a social process informed by scientific and technical information, rather than a science- or technology-driven process. Although empirical data are scarce, applying PACT shows that a number of issues have the potential to impose conditions on the social acceptability of phytoremediation, and that some issues could lead to outright rejection. Further, because many of these issues concern values and goals, they cannot be resolved simply by providing better or more detailed technical information about phytoremediation. PACT is instructive in showing how even seemingly benign or desirable technologies such as phytoremediation have the potential to generate public controversy, delineating issues in ways that can help lead to their resolution.

REFERENCES


