Chapter 7
Phytoremediation: The Wave of the Future

Jerry S. Succuro, Steven S. McDonald, and Casey R. Lu

Abstract As the industrial age developed, societies have allowed large amounts of contaminants to enter the environment unchecked. As a result of this neglect, the incidence of heavy-metal contaminated sites has been on the rise. These sites are polluted with toxic hydrocarbons and radionuclides, as well as heavy metals, such as cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), and zinc (Zn). The result is unsightly areas left untreated, undeveloped and are accurately referred to as "Brown Fields." Heavy metals in the soil can create a contaminated and possibly toxic top layer ranging 2–5 cm deep in addition to the possibility of entering the food chain. The typical and most common method of removing contaminants is to excavate the soil by mechanical means and store it at off-site locations.

Phytoremediation is an innovative, emerging technology that utilizes plant species to remove contaminants from the environment using a distinct set of plant-based technologies. Four types of remediation technologies have been employed: (1) *phytostabilization* is the use of a plant's root system to stabilize the metal-contaminated soil thus preventing the spread of the contaminant; (2) *phytodegradation* is the process of using plants to convert toxic contaminants into less toxic forms; (3) *rhizofiltration* is the process of using plants to clean aquatic environments; and finally, (4) *phytoextraction* is the practice of using plants to take up metals from the soil and translocate them to the above-ground tissues which can then be harvested. By utilizing phytoremediation techniques, the environmental disruption is minimized, soil fertility is maintained, secondary air- and water-borne wastes are reduced, and these techniques are well received by the public as in situ methods. This chapter will discuss the use of multiple plant species in each of the listed remediation techniques for the goal of rejuvenating Earth's ecosystems.

J.S. Succuro (✉)
Department of Biological Sciences, Humboldt State University, Arcata, CA 95521, USA
e-mail: jssemail38@yahoo.com

A. Kirakosyan, P.B. Kaufman, *Recent Advances in Plant Biotechnology*,
DOI 10.1007/978-1-4419-0194-1_7,

7.1 Introduction

During the industrial age, humans have allowed large amounts of contaminants to enter the environment unchecked. As a result of this neglect, many toxins have been permitted to accumulate in our soils and water systems. Since this neglect was allowed to continue for so long, the incidence of heavy-metal contaminated sites has been on the rise. The public is made aware of this issue through the media. In most cases, the media have a tendency to paint a very grim picture of how these contaminated sites will affect humans and animals alike (Environmental Protection Agency, 2007). For the most part, their interpretation of the situation is correct. Contaminated sites do exist and are polluted with toxic hydrocarbons and radionuclides, as well as heavy metals, such as cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), and zinc (Zn) (Amaya-Chavez et al., 2006). This heavy-metal contamination is a result of anthropogenic activities such as metal mining and smelting, agriculture, sewage sludge, fossil fuel combustion, and chemical manufacturing (Alloway, 1995). In addition to manufacturing types of activities, recreational sports such as the use of shooting ranges and improper storage techniques add to the list of sources (Alloway, 1995; Ebbs and Kochian, 1997). Often these sites of contamination become unsightly reminders of the lackadaisical attitude people take toward the environment.

These large, unsightly areas are often left untreated, undeveloped and are accurately referred to as “Brown Fields.” Brown fields, or any other smaller toxic sites, are subject to wind-blown dispersion if the soil is disturbed and the heavy metal is set free. As the wind blows across the disturbed soil, soil particles and associated contaminants can be blown into the upper atmosphere and travel rather large distances, thus contaminating locations, such as playgrounds, parks, and yards thousands of miles from the original site (Xei et al., 1999). In addition to wind dispersal, when a heavy metal such as lead contacts the soil, it becomes tightly adsorbed to the soil particles. This can create a contaminated and possibly toxic top layer of soil that ranges 2–5 cm deep (Sharma and Dubey, 2005), where, in playgrounds or backyards, it becomes a threat to human health. Another concern for heavy-metal contaminated sites is the possibility of it entering the food chain. Although animals, plants, and microbes have no biological need for certain specific heavy metals, they can be taken up and sequestered in the cells of living organisms. Furthermore, these heavy metals can be moved from plants to animals as they graze on contaminated sites. Once the heavy metal enters the food chain, secondary and tertiary predators can be adversely affected by the quantities of metal present (Taylor and Crowder, 1983a). As these organisms in the higher trophic levels continue to consume heavy-metal contaminated foods, the toxic level within these organisms also increases (Taylor and Crowder, 1983a,b). This process is known as *bioaccumulation*.

In response to public outcry, the US Environmental Protection Agency (EPA) has spent billions of dollars on Superfund site cleanup projects across the nation (Bouchier and Lu, 2002; USEPA, 1993). As public awareness increases, so have the questions concerning how safe areas such as playgrounds, homes, and gardens, are for plants and animals (including humans). The largest concern regarding the toxicity or accumulation of heavy metals, such as lead, is directed toward small children. Their bodies and central nervous systems are developing rapidly and any exposure to lead, even blood levels as low as 10 μg dL^{-1}, can cause long-term health problems within many organ systems. Examples of affected systems include, but are not limited to, gastrointestinal tract, cardiovascular system, nervous system, kidneys, immune, reproductive, and mental and physical impairment (www.epa.gov/iaq/lead.html, 2007; ATSDR, 2007; Pyatt and Gratten, 2001). Potential areas of concern for children are the ingestion of soil particles in playgrounds, and most importantly, the consumption of small lead-based paint chips in homes built before 1960, and the inhalation of lead dust from painted friction surfaces.

In an attempt to reduce exposure to heavy-metal contamination in soils, several methods of disposal have been developed. The typical and most common method is to excavate the soil by mechanical means using tractors and bulldozers, and then to transport the soil to another location where it is stored (Memon et al., 2001; Cunningham et al., 1995). Even though these storage facilities are lined with material to prevent the spread of contamination, the sites themselves become areas that are uninhabitable. In some cases, these sites become problems as heavy metals escape the confines of the protective barriers such as native claystone soils (ATSDR, 2005) and leach into the surrounding area and possibly nearby sources of groundwater. In addition to excavation of contaminated sites, some sites are remediated by the process of covering the soil with large quantities of concrete, asphalt, and/or clean, uncontaminated soil (Berti and Cunningham, 2000), which temporarily fixes the problem right where it lays by covering it to reduce contact. When these types of remediation techniques are used, they only satisfy an immediate and temporary fix to a long-term problem. In addition, these options can be very costly. Depending on the type of management strategy, remediation of a site by traditional means can cost between \$10 and \$3,000 m^{-3} per year (Cunningham et al., 1995). No one really knows what the long-term ramifications will be if these types of management techniques are allowed to continue. In light of this problem, a developing new technology has begun to focus on utilizing plants to decontaminate areas of high concentrations of heavy metals and organic contamination. This new technology is termed phytoremediation.

7.2 What Is Phytoremediation?

Phytoremediation is an innovative, emerging technology that utilizes plant species to remove contaminants from the environment (Tian et al., 2007; Amaya-Chavez et al., 2006). Much research has been conducted in this field and is gaining global acceptance because of the possibility of adapting this technology to many different types of ecosystems in both developed and developing countries. The term phytoremediation stems from the words "phyto," meaning plant, and the Latin suffix "remedium," meaning to clean or restore. *Phytoremediation* refers to a distinct set of plant-based technologies utilizing naturally occurring and/or genetically modified plants to remove contaminants, such as metals and hydrocarbons from soil, sediments, or water systems (Padmavathiamma and Li, 2007; Amaya-Chavez et al., 2006). Plants accomplish this task by removal, transfer, stabilization, or decomposition of these contaminants in the environments listed above (Hughes et al., 1997). Heavy metals contaminate the major environmental systems of our planet: air, water, and soil; therefore, biogeochemical cycles can be severely disrupted (Tian et al., 2007). Heavy-metal pollution in soil differs from that of air- and water-based systems because heavy metals have a tendency to remain in the soil for very long periods of time. There are two major categories of contaminants that should be considered, elemental pollutants and organic pollutants, each of which has its own set of remediation strategies (Meagher, 2000). These will be discussed later in this chapter. Based on the type of contaminant, site conditions, quantity of contaminant to be removed, and the species of plants to be used for the process, four types of remediation technologies have been employed. They are classified based on the containment of metals (phytostabilization and phytodegradation) or the extraction of metals (phytofiltration and phytoextraction) (Padmavathiamma and Li, 2007). A brief description of these processes is as follows: (1) *phytostabilization* is the use of a plant's root system to stabilize the metal-contaminated soil thus preventing the spread of the contaminant; (2) *phytodegradation* is the process of using plants to convert toxic contaminants into less toxic forms; (3) *rhizofiltration* is the process of using plants to clean aquatic environments; and finally, (4) *phytoextraction* is the practice of using plants to take up metals from the soil and translocate them to the above-ground tissues which can then be harvested. In order for a plant to be listed as a good candidate for phytoremediation, several factors should be met. A plant must be tolerant to the environmental conditions of the contaminated site as well as be fast-growing and produce high quantities of biomass in harvestable tissue (Yang et al., 2005). With these conditions met, the phytoremediation process can begin.

7.2.1 Why Is Phytoremediation Important?

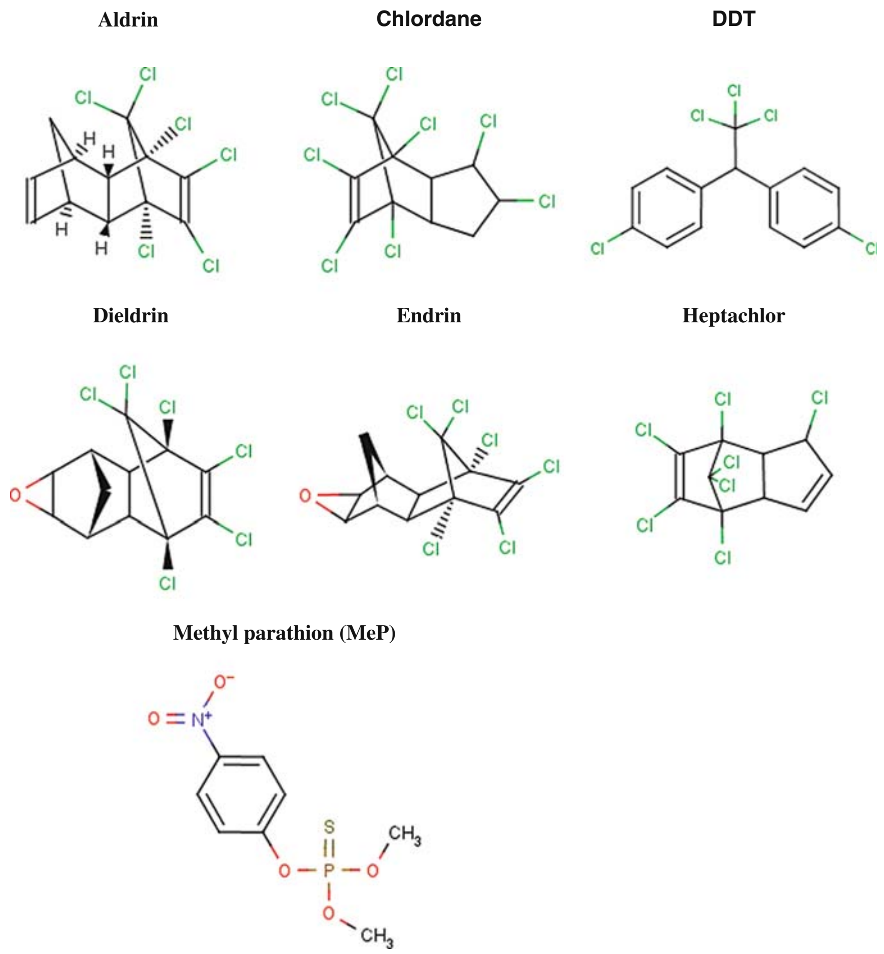
Taking into account the above-listed remediation techniques, the first thoughts that come to mind are cost and how environmentally sound the phytoremediation practices are at removing the contaminant from the environment. Traditionally, contaminated sites are remediated by physical, chemical, or biological processes (McEldowney et al., 1993). In the aftermath of the destructive treatments, irreversible effects may occur to soil properties. The destruction of biodiversity can render soils useless for the growth of plants that could potentially remove remaining contamination (Padmavathiamma and Li, 2007). By utilizing phytoremediation techniques, the environmental disruption is minimized, soil fertility is maintained, secondary air- and water-borne wastes are reduced, and these techniques are well received by the public as in situ methods (Tian et al., 2007; Amaya-Chavez et al., 2006; Padmavathiamma and Li, 2007). In some cases, phytoremediation may be the only solution for reducing contaminated soil and water systems that cover hundreds of thousands of square kilometers as a result of human activity (Meagher, 2000). The harvesting of plants that have accumulated large quantities of usable metals in their tissues, such as nickel, zinc, and copper, could be recycled and used for other purposes, thus producing an economic incentive for using phytoremediation (Ow, 1996). In addition to being environmentally friendly, the phytoremediation process may also be cost-effective (Padmavathiamma and Li, 2007; Zhuang et al., 2007a,b; Yang et al., 2005). In the recent past, the cost to handle contaminated waste was approximately \$100 m^{-3} for incineration, \$60–\$300 m^{-3} for landfill, \$200–\$700 m^{-3} for special landfill requirements, and \$1,000–\$3,000 m^{-3} to dispose of radionuclides per year (Cunningham et al., 1995). Using the techniques of phytoremediation, these costs are reduced remarkably to levels of only \$5–\$40 t^{-1} and \$0.02–\$1.00 m^{-3} per year (Padmavathiamma and Li, 2007; Cunningham et al., 1995).

7.2.2 Remediation of Organic Contaminants

Over many decades, humans have added large volumes of contaminants to the soil, water, and atmosphere as a result of industrial manufacturing such as petroleum and chemical operations and private independent operations such as dry-cleaning. In addition to these processes, burning wood, coal, and fossil fuels, add a wide range of organic chemicals to the environment, potentially causing negative health effects for humans as well as wildlife. Further anthropogenic causes include car emissions, waste incineration, service stations, solvent use, cigarette smoking, and the use of pesticides.

Organic contaminants are carbon-containing compounds that are resistant to environmental degradation through chemical, biological, and photolytic processes. These compounds can be transported great distances, bioaccumulate in both human and other animal tissues, as well as biomagnify in food chains. Health agencies have identified several compounds as being extremely toxic to humans, wildlife, and the environment. This list is by no means complete, but it includes aldrin, chlordane, DDT, dieldrin, endrin, heptachlor, PCBs, and toxaphene (Fig. 7.1).

Some chemical properties of these organic toxins include decreased water solubility, increased lipid solubility, semi-volatility, and higher molecular weights. With their higher molecular weights and the addition of chlorine (Cl) substituents, the compounds are increasingly difficult to break down and remain persistent in the environment. Finally, their lipid solubility results in the ability of these molecules to pass through biological phospholipid membranes and bioaccumulate in fatty tissues. Humans may experience contamination through exposure from diet, environment, and accidental discharges into the atmosphere or spills into the soil. Deleterious health effects include damage to the endocrine system, the reproductive system, the immune system, neurological disorders, cancer, and ultimately, death. In contrast, compounds with lower molecular weights, less than 236 g mol^{-1}, are usually less toxic, thus reducing the health issues and environmental problems as a result of being less persistent (http://en.wikipedia.org/wiki/persistent_organic_pollutant, 2007).



Aldrin **Chlordane** **DDT**

Dieldrin **Endrin** **Heptachlor**

Methyl parathion (MeP)

Fig. 7.1 Chemical structures of organic contaminates that are environmental risks to humans and wildlife

Current research suggests that there are two different ways by which organic contaminants can be removed from soil- and water-based systems, namely, phytodegradation and rhizofiltration. First we look at *phytodegradation* (Fig. 7.2), the process that utilizes plants and their associated microflora to convert hydrocarbons to non-toxic forms (Cunningham et al., 1995).

The conversion of contaminants by plants takes place in the following manner: First the plant releases root exudates that include organic and inorganic substances into the *rhizosphere* (soil–root–microorganism interface zone) during metabolism. These root exudates act as substrates for soil microorganisms, thus enhancing the uptake and degradation of toxic organic compounds by the plants. This principle has been used to remediate crude oil, motor oil, and diesel fuel from soils (Chaineau

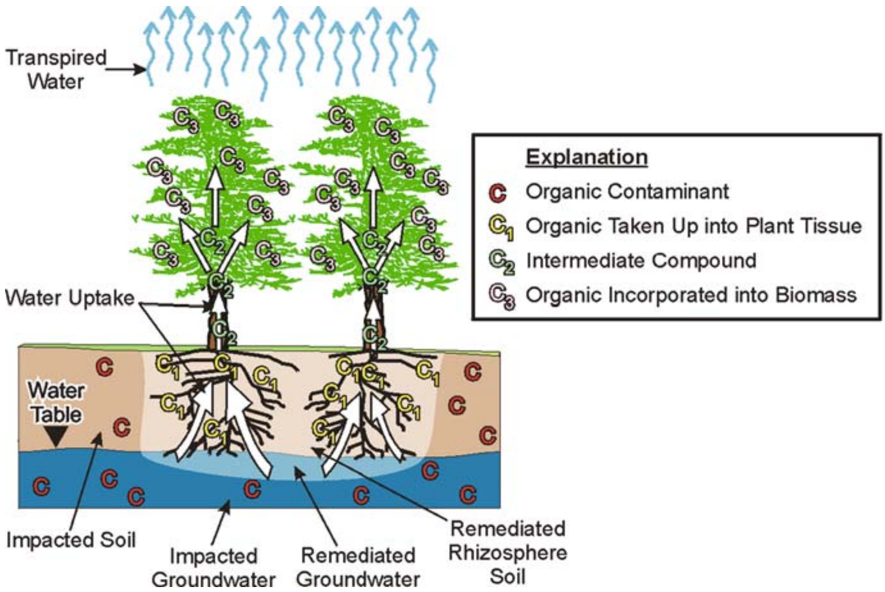


Fig. 7.2 Phytodegradation of organic contaminants. (Used with permission from Mueller et al., 2001)

et al., 2000). In a field study conducted by Palmroth et al. (2006) over a 39-month growth period, the initial soil concentration of contaminants was 11,400 mg kg^{-1} hydrocarbons in soil (dry weight). This soil contaminant component consisted of two-thirds lubricating oil, and the remaining one-third, diesel fuel. The field area was divided into four plots with two being fertilized with municipal biowaste, one plot with NPK fertilizer (16.6:4:25.3), and in the remaining plot, no fertilizer was used. The target concentration of phytoremediation was set at a level of 1,500 mg kg^{-1} hydrocarbons in dry soil, which translates to a reduction of hydrocarbons by 87% (Palmroth et al., 2006). Initially the hydrocarbon concentration did not decrease significantly in non-amended soil; however, there was a 30% decrease in the original concentration during the last 4 months of the experiment. In soil amended with either NPK fertilizer or biowaste compost, 65 and 60% of the hydrocarbons were removed, respectively, using a mixture of grasses (red fescue, *Festuca rubra*; meadowgrass, *Poa pratensis*; and ryegrass, *Lolium perenne*), Dutch white clover (*Trifolium repens*), Scots pine (*Pinus sylvestris*), and poplar seedlings (*Populus deltoides* x *Wettsteinii*). Ultimately, 57% of the hydrocarbons were removed in the plots amended with biowaste, clover, and grasses. Approximately 60% of the hydrocarbons were removed in the plot with grasses, clover, and trees. For the plot using NPK fertilizer, increased hydrocarbon removal was recorded compared to the biowaste plots, but during the last 4 months of the study there was no significant difference between the two amendments (Palmroth et al., 2006). This study shows positive potential for phytodegradation with approximately 50% or more of the hydrocarbons being removed by plants and associated microflora from contaminated soil. The length of time for remediation can take several years to achieve treatment goals. It should be noted that in this study, the goal of achieving the 1,500 mg kg^{-1} hydrocarbons in dry soil weight was not achieved. This, however, does not mean that the process of phytodegradation is a non-viable technique; it does confirm the need for further research into optimizing the phytoremediation process and possibly using genetically modified (GM) plants.

7.3 Rhizofiltration

Rhizofiltration (Fig. 7.3) is the adsorption or precipitation of contaminants onto plant roots or the absorption into the roots of contaminants that are in solution surrounding the root zone due to biotic or abiotic processes.

The uptake, concentration, and translocation of contaminants by the plants may occur and will depend on the contaminant and the type of plant. Exudates from the plant roots may cause precipitation of some organics. Rhizofiltration first results in decontamination, a process by which the contaminants are immobilized or accumulated on or within the plant. Contaminants are then removed via plant harvesting (www.gsd.harvard.edu/users/yauanian/phyto_processes_main.html). Work done by Amaya-Chavez et al. (2006) has shown that cattails (*Typha latifolia* L.) have been successful in removing methyl parathion (MeP) (Fig. 7.1), an organophosphorus (OP) pesticide, from water systems and sediments. The cattails were subjected to various levels of MeP in the following concentrations: 0, 25, 50, 100, 150, and 200 mg L^{-1}. Photosynthetic potential, based on chlorophyll a and chlorophyll b concentration ratios, were used to determine the overall health of the plants. The basal mean total chlorophyll content was determined to be 32.9 mg ml^{-1} and the

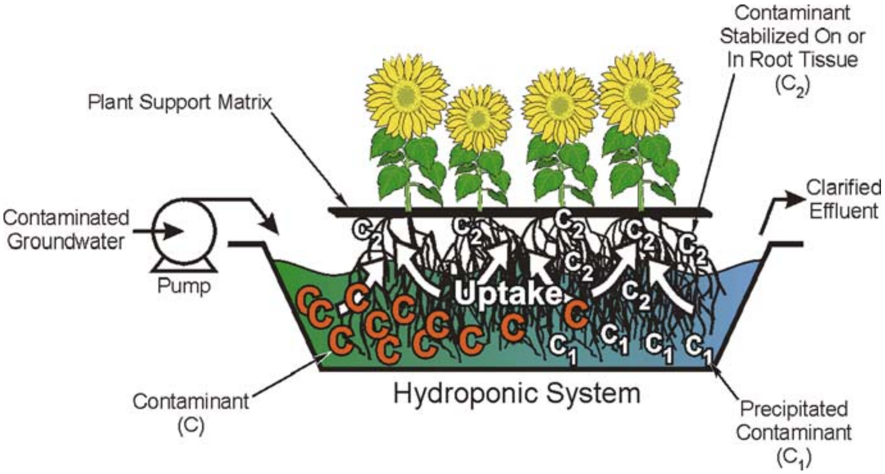


Fig. 7.3 Rhizofiltration of organic or inorganic contaminants. (Used with permission from Mueller et al., 2001)

chlorophyll a/b ratio was 2.8. After 10 days of exposure to MeP, no significant differences were shown in either total chlorophyll content or chlorophyll a/b ratio at the different MeP exposure levels (Amaya-Chavez et al., 2006). As a result, *T. latifolia* shows a low level of toxicity as a result of MeP uptake and a higher level of tolerance than other macrophytes tested to date. This higher tolerance could be due to *T. latifolia*'s ability to produce higher biomass with its rhizomatous/fibrous root system. As a result of these studies, *T. latifolia* has been determined to be quite efficient at removing MeP from water and sediment systems. Glick (2003) surmises that this efficiency could be due, in part, to a rhizosphere root/microorganism association that aids in the organic contaminant degradation with *T. latifolia*'s extensive rhizomatous/fibrous root system. Finally, given *T. latifolia*'s ability to tolerate a range of MeP concentrations without any loss of removal efficiency and minimal toxic effects to the plant, it should be seriously considered for remediation practices.

7.3.1 Remediation of Inorganic Contaminates

Inorganic contaminants (heavy metals or trace metals) compose much of the contamination at sites throughout the world. These higher atomic weight elements and some lower-weight elements can be called heavy metals as a group. Certain heavy metals or trace metals are required for the metabolic processes in organisms. Some of these trace metals, including iron, cobalt, copper, manganese, and zinc, however, become toxic at elevated levels (Alloway, 1995). As discussed in the Introduction section, some heavy metals have no biological use: these include mercury, lead, and cadmium. The question arises, then, as to how we can safely and effectively remove metals from our environment with as little destruction as possible, thus reducing or removing the threat to environmental health? This is where the utilization of phytoremediation techniques becomes important, particularly since they can be more cost-effective, less destructive, and at the same time, be more appealing to the public. There are a number of different ways in which phytoremediation can work. As discussed in the above section on rhizofiltration of organic types of contamination, *phytofiltration* is used in this section as a means to remove heavy metals from an aquatic environment. The processes are essentially the same.

Plants can also be used for *phytoextraction* (Fig. 7.4). This occurs when metal contaminants in the soil are taken up by roots and translocated to the above-ground tissues. The plants can then be removed from the site, or if removal of the entire plant is not practical, then the above-ground tissues can be removed for continual remediation of the soil. Removal of these tissues can occur multiple times during the growing season, thus increasing the rate of contamination removal. The harvested tissues can then be incinerated and the ash can be stored in a hazardous waste landfill. The volume of ash stored would be significantly less than excavating the soil and storing it in the same hazardous waste landfill.

Since there is no single plant species that can remove all contaminants at one site, several different species must be used for multiple contaminants. As these plants grow, they can accumulate high quantities of heavy metals such as lead. The normal

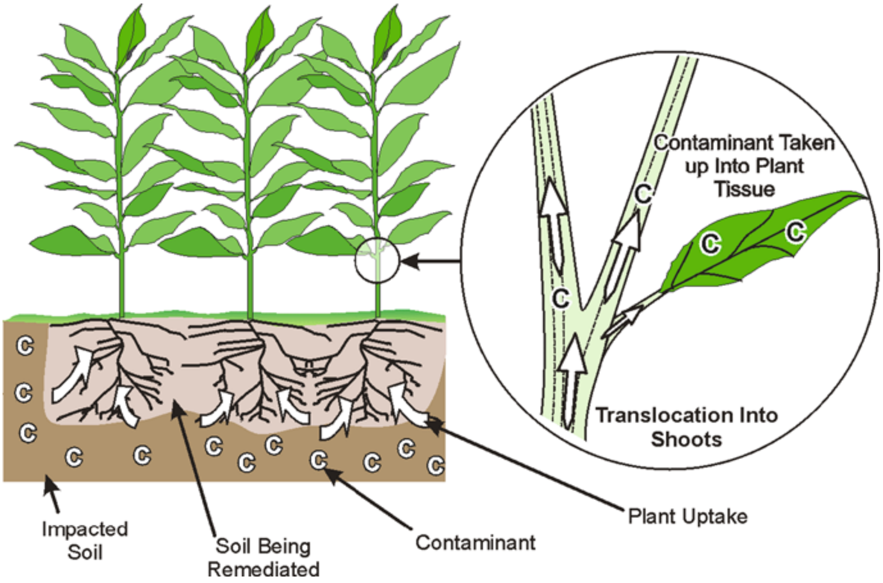


Fig. 7.4 Phytoextraction of inorganic contaminants. (Used with permission from Mueller et al., 2001)

range of lead a plant can accumulate is between 6.3 and 9.9 mg kg^{-1} (Outridge and Noller, 1991). Lead becomes toxic to the plants at levels above 27 mg kg^{-1} (Beckett and Davis, 1978). In addition to lead uptake, some plants are tolerant to increased levels of zinc, an essential mineral element. The mean level is 66 mg kg^{-1} and becomes toxic at levels of 230 mg kg^{-1} and higher (Borkert et al., 1998; Long et al., 2003). In some cases, plants can be classified as *hyperaccumulators* because of their ability to accumulate extremely high levels of the metal contaminant into their tissues. Hyperaccumulator status is achieved when a plant accumulates more than 1,000 mg kg^{-1} or 0.1% of the metal by dry weight for lead and 10,000 mg kg^{-1} or 1.0% of the metal by dry weight for zinc (Brooks et al., 1977). One example of a hyperaccumulator plant is *Brassica juncea* (L.) Czern. or Indian Mustard. *B. juncea* has been known to accumulate 1.5% Pb (lead) by dry weight with the addition of ethylenediaminetetraacetic acid (EDTA), a synthetic chelating agent used to increase the solubility of lead when grown in media that had a large quantity of lead available (Blaylock et al., 1997; Bouchier, 2003). Another plant that receives much attention as a hyperaccumulator of zinc (Zn) and cadmium (Cd) is *Thlaspi caerulescens* J. & C. Presl. or alpine penny cress. Research conducted by Baker et al. (1994, as cited in Brown et al., 1994) has shown that field samples collected at sites contaminated with cadmium (Cd) and zinc (Zn) had shoot concentrations as high as 164 and 21,000 mg kg^{-1} dry weight, respectively. Additionally, Brown et al. (1995) showed that when grown hydroponically in solutions containing 650 mg L^{-1} Zn and 22 mg L^{-1} Cd, *T. caerulescens* could accumulate Zn and Cd in shoots up to 33,600 and 1,140 mg kg^{-1} dry weight, respectively. These heavy-metal concentrations far exceed the concentrations typically found in plant tissues.

In addition to *B. juncea* and *T. caerulescens* achieving hyperaccumulator status, *Typha latifolia* (the broadleaf cattail) is receiving attention due to its ability to grow in many different types of semi-aquatic and aquatic environments and tolerate high levels of contamination (Amaya-Chavez et al., 2006; Doucette et al., 2005). A greenhouse study of 12 weeks duration conducted by McDonald (2006), consisting of growing cattails in mason jars with lead levels of 0, 1,000, 2,000, and 4,000 mg kg^{-1}, has shown that there was no apparent reduction in growth caused by the different lead levels. It should be noted that any reduction in growth was attributed to the cattails being confined to a small growth area (McDonald, 2006). In addition, the only visible signs of exposure to consistently increasing levels of lead was the yellowing and burning of shoot tips subsequent to the addition of EDTA. To determine if *T. latifolia* could achieve hyperaccumulator status, ethylenediaminetetraacetic acid (EDTA) was added to the soil at the 10th week of the 12-week growth period.

Over the 12-week period, the cattails that were exposed to the varying levels of lead without the addition of EDTA revealed that the roots and rhizomes of the 4,000 mg kg^{-1} exposed cattails accumulated large quantities of lead rather than translocating lead to the above-ground tissues (McDonald, 2006). In this particular case, the cattails accumulated 1,515.2 mg kg^{-1} in root/rhizome tissue, showing that in the absence of a chelating agent, lead movement is significantly confined to a greater extent to the rhizomes and roots. On the other hand, with the addition of EDTA, the most promising results were obtained, as large quantities of lead accumulated in the cattail shoots that were exposed to the 4,000 mg kg^{-1} lead level. The roots were able to absorb 2,483.5 mg kg^{-1}, in which 2,418.5 mg kg^{-1} was transported into the shoots (McDonald, 2006), indicating that the chelating agent facilitated the translocation of lead to aerial portions of the plant. Based on these results, it was determined that *T. latifolia* can reach hyperaccumulator status with the assistance of a chelating agent that allows for the translocation of contaminates (lead in this case) from rhizomes and roots to the shoots.

Plants can also be used for *phytostabilization* which refers to use of plants to immobilize contaminants in the soil and/or ground water through absorption and accumulation by roots, adsorption onto roots, or the precipitation of contaminants within the rhizosphere (Fig. 7.5) (Phytoremediation Resource Guide, EPA, 1999; Brookhaven National Laboratory, 2000).

Additionally, this technique reduces the mobility of the contaminant(s) and prevents migration to groundwater, as well as reducing the bioavailability for entering the food chain. Using plants that are metal-tolerant can restore vegetation on contaminated sites where the threat of contaminant migration from soil erosion is high due to wind and water. Once a plant cover is established, the threat of direct contact with humans and animals is significantly reduced. The vegetative cover can provide a barrier between the contaminant(s) in the soil and the surrounding environment. This technique works in the following way: a study of the nature of the

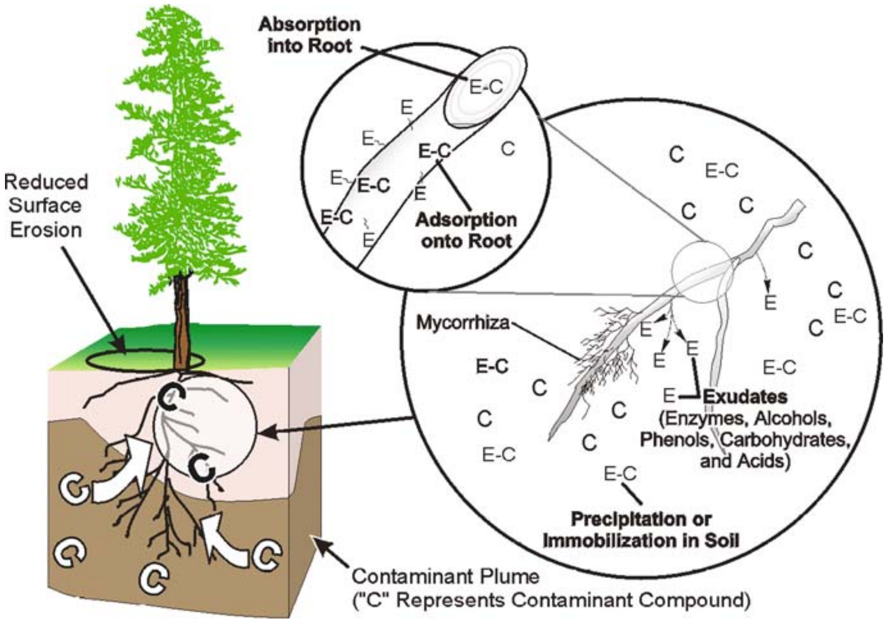


Fig. 7.5 Phytostabilization of inorganic or organic contaminants. (Used with permission from Mueller et al., 2001)

soil contaminant(s) is determined; next, traditional fertilizers or specific amendments are used to improve the soil conditions and render the contaminants immobile. Once this is achieved, a plant species is selected based on the conditions of the soil, the surrounding environment, the ability of the plant not to accumulate the contaminants into above-ground tissues, and the plant's tolerance to the specific site contaminants.

This technique can be thought of as a two-step process. First, a suitable soil amendment should be selected that is long-lasting if not permanent (Berti and Cunningham, 2000). This selection should be based on the following considerations: it must be inexpensive, easy to handle, safe for workers, be compatible and non-toxic with the plants selected, be available for use, and finally, not cause the environment further damage (Berti and Cunningham, 2000). In addition to the listed considerations, some amendments may have secondary benefits to the growth of plants by providing nutrients and by increasing soil water-holding capacity (i.e., phosphate fertilizers and organic materials). The most common amendments include phosphate fertilizers (e.g., superphosphate), organic matter or biosolids such as composts and manures, iron or manganese oxyhydroxides, clay minerals, or mixtures of these amendments (Cunningham and Berti, 2000; Berti and Cunningham, 2000). The second step is to determine a species of plant that is able to grow in the harsh environment of the contaminated site. These plants will be responsible for physically stabilizing the soil that they are growing on by having dense root systems that prevent soil erosion by protecting the soil from human contact and rain. In addition, the root systems should reduce the incidence of water percolation, thus immobilizing the contaminant(s). Further considerations include these plants being poor translocators of heavy metals to the above-ground tissues (to reduce risk of entering the food chain via herbivory), their rapid growth rates, and their high transpiration rates that allow for more effective removal of soil water (Berti and Cunningham, 2000).

A study by Tang and Fang (2001) was conducted to determine the usefulness of two perennial herbs from the Polygonaceae family, *Polygonum microcephalum* D. Don (Red Dragon) and *Rumex hastatus* D. Don (Curly Dock), as plants that could be used for phytostabilization. Plant and soil samples (from the root zone) were taken from three different heavily contaminated copper mines of the Yunnan Province in China for analysis. Results showed that *P. microcephalum* accumulated high concentrations of copper in roots, stems, and shoots, averaging 491, 110, and 133 mg kg^{-1}, respectively. On the other hand, *R. hastatus* accumulated lower concentrations of copper in roots, stems, and shoots, averaging 33, 42, and 45 mg kg^{-1}, respectively. This, however, does show that both species can accumulate copper into tissues when grown in a copper-contaminated soil (Tang and Fang, 2001). Since *P. microcephalum* accumulated more copper in its tissues than *R. hastatus*, this could indicate that *P. microcephalum* has a higher level of tolerance than *R. hastatus*. When considering the higher levels of copper accumulated by *P. microcephalum* and lower accumulation amounts in *R. hastatus*, one can infer from these data that *R. hastatus* is excluding copper from the shoots. The result of the soil analysis revealed that copper concentrations for *P. microcephalum* and *R. hastatus*, averaged 1,494 and 2,105 mg kg^{-1} dry weight, respectively, confirming that these species can grow in highly contaminated soil. It should also be noted that there was a lack of soil fertility as confirmed by low soil organic carbon (humus). In conclusion, *P. microcephalum* appears to be more of an accumulator with respect to copper-type contaminants, whereas *R. hastatus* is more of an excluder based on the comparison of shoot/root metal ratios (Tang and Fang, 2001). This evidence shows that two species can grow side by side even though they have different uptake and transport characteristics, thus providing the potential for phytostabilization (Tang and Fang, 2001).

7.4 Case Study: Phytoremediation of Contaminated Air

There is also the concern today about how plants respond to air pollution and how they might be used to help alleviate this problem. This occurs mainly in urban areas as a result of industrialization and the burning of fossil fuels (Park et al., 2006). A large contributor to this pollution is the automobile, causing roadside damage to both plants and the underlying soil (Park et al., 2006). As fossil fuels are burned in the engines of vehicles, many greenhouse gases are emitted, including sulfur dioxide (SO_2), carbon monoxide (CO), and particulate matter (Kulshreshtha et al., 2003).

Since plants provide a large leaf surface area that is in contact with the surrounding environment, absorption, adsorption, and accumulation of these air pollutants can occur, thus reducing pollution's negative effect on the environment (Kulshreshtha et al., 2003; Sharma et al., 2005). Research conducted by Kulshreshtha et al. (2003) evaluated 30 species of plants to determine the tolerance to air pollution in a roadside (heavily polluted) environment and a park/garden (non-polluted) environment. In order to determine the tolerance of the plants, several factors were investigated. These included chlorophyll and ascorbic acid contents, relative water content, and leaf extract pH. These tolerance measures were then converted to an Air Pollution Tolerance Index (APTI) (Kulshreshtha et al., 2003). Plants that had an APTI that was high were considered to have a tolerance to pollutants, whereas plants with an APTI that was low indicated plants were not as tolerant to the pollutants. Of the 30 plants that were investigated, species that had an APTI of 30 or greater included *Catharanthus roseus* (L.) G. Don or Madagascar periwinkle (37), *Ficus religiosa* L. or Sacred fig (35), *Bougainvillea spectabilis* Willd. or Bougainvillea (32), and *Ficus glomerata* Roxb. or Bonsai tree (32), while plants that showed less tolerance (an APTI of 5 or less) to air pollution included *Delbergia sissoo* Roxb., or Shisham tree (3) and *Cansa carendes* (3). Further research with the plants that had high APTI value should be considered for the reduction of roadside pollution in urban areas.

Sharma et al. (2005) compared the use of bougainvillea plants as a means of reducing air pollution along roadsides in both high- and low-traffic areas. Plants of 11 cultivars grown in pots were subjected to a low-traffic-density area (LTDA) represented by the NBRI Botanical Garden and a high-traffic-density area (HTDA) represented by a median dividing roads in a high-traffic area (Sharma et al., 2005). To determine the effectiveness of the bougainvilleas at removing pollutants from the air, several different foliar aspects of health were studied. These parameters included cuticle, stomata, subsidiary cells, and trichomes. In the LDTA the cuticle was smooth, granular, or striate having inconspicuous wax at certain locations while the stomata were globose and present at the same level as other cells. The subsidiary cell walls were clear but slightly raised and the trichomes were non-glandular, uniseriate, and multicellular with a bolbus base and globular tip (Sharma et al., 2005). The HTDA foliage showed that the cuticle was wrinkled and striations were not present, while the stomata were raised from the surface of other cells and present in larger numbers. Subsidiary cell walls had fused and were irregularly shaped, while the number of trichomes increased, their overall length had decreased, and the cuticle over the trichomes had become cracked (Sharma et al., 2005). It was determined that because of morphological, anatomical, and physiological changes within the foliage, absorption of toxic pollutants was confined to the cell sap which neutralized these toxins, thus forming a stable complex within certain cellular compartments, thus allowing greater tolerance to pollutants. The conclusion reached was that bougainvilleas with their relatively thick leaves of large surface area can trap more dust and pollutants in the surrounding area of high traffic, reducing pollution, while at the same time, presenting a pleasing environment since these plants provide a wide array of flower colors (Sharma et al., 2005).

7.5 Conclusions

Since the beginning of time, humans have left their mark (in some cases, irreversibly) on the environment. During the industrial revolution, no one stopped to think about the long-term ramifications of constantly polluting air, water, and soil. The thinking during this period was that Earth's environment is going to be around forever and that it can clean itself. In addition to the industrial age releasing huge amounts of contaminants into the environment, the consumption of fossil fuels also increased as motor vehicles continued to grow in size and number. When humans discovered that the oil used for the production of gasoline was in short supply, they began to realize that our resources are limited. The same chain of events can be said about the logging industry, fishing industry, and the mining industry, just to name a few. As the realization became transparently clear, new ways to save our natural resources and to help repair the environment began to be developed. One of the outcomes of this greening revolution was the field or technology of phytoremediation, whereby plants that are already here can be used to assist in the rejuvenation of Earth's ecosystems. Through phytoremediation techniques, the environment can be "cleaned" in less destructive and most cost-effective ways by the virtue of the ability of plants' adaptation to many different types of contamination across many different ecosystems. Although phytoremediation seems like it is the answer to many problems of pollution, it is subject to some limitations such as requiring supplemental nutrients, having extended time requirements for remediation to occur, and only removing contaminants within the root zone (rhizosphere). However, the picture is not bleak because current research (from many different fields of study) is now coming together as a multidisciplinary effort for the discovery of new ways to better the phytoremediation processes. As long as there is a need for remediation (and there may likely be from now on), scientists will continue to come together and to work diligently to solve the problems of contamination in an attempt to make the world a safer and more healthy place to live.

References

Agency for Toxic Substances and Disease Registry. 2005. Casmalia Resources Superfund Site, Casmalia, Santa Barbara County, CA. EPA Facility ID CAD020748125. September 2005. www.atsdr.cdc.gov/HAC/PHA/CasmaliaResources/CasmaliaResources092805PHA.pdf

Agency for Toxic Substances and Disease Registry (ATSDR). 2007. *Toxicological Profile for Lead (Update).* US Department of Health and Human Services, Public Health Service, Atlanta, GA. www.atsdr.cdc.gov/tfacts13.html#bookmark07

Alloway, B. J. 1995. The origin of heavy metals in soils. In *Heavy Metals in Soils,* Alloway, B. J., Ed., 2nd ed., pp. 38–57. Blackie Academic and Professional, New York.

Amaya-Chavez, A., Martinez-Tabche, L., Lopez-Lopez, E., Galar-Martinez, M. 2006. Methyl parathion toxicity to and removal efficiency by *Typha latifolia* in water and artificial sediments. Chemosphere 63: 1124–1129.

Baker, A. J. M., Reeves, R. D., Hajar, A. S. M. 1994. Heavy metal accumulation and tolerance in British populations of the metallophyte *Thlaspi caerulescens* J. & C. Presl (Brassicaceae). New Phytology 127: 61–68.

Beckett, P. H. T., Davis, R. D. 1978. The additivity of the toxic effects of Cu, Ni and Zn in young barley. New Phytology 81: 155–173.

Berti, W. R., Cunningham, S. D. 2000. Phytostabilization of metals. In *Phytoremediation of Toxic Metals – Using Plants to Clean Up the Environment,* Raskin, I., Ensley, B. D., Eds., pp. 71–88. Wiley, New York.

Blaylock, M., Salt, D. E., Dushenkov, S., Zakharova, O., Gussman, C., Kapulnik, Y., Ensley, B. D., Raskin, I. 1997. Enhanced accumulation of Pb in Indian mustard by soil-applied chelating agents. Environmental Science Technology 31: 860–865.

Borkert, C.M., Cox, F.R., Tucker, M., R. 1998. Zinc and copper toxicity in peanut, soybean, rice and corn in soil mixtures. Communications in Soil Science and Plant Analysis 29: 2991–3005.

Bouchier, T. 2003. Pb distribution and ultrastructural changes induced by Pb and EDTA in shoot tissue of *Brassica juncea* (Indian mustard). Master's Thesis, Humboldt State University.

Bouchier, T., Lu, C. R. 2002. *Cleaning by Greening. Creating a Sustainable Future; Living in Harmony with the Earth*, pp. 354–364. Science Technology Publishing LLC, Houston, TX.

Brookhaven National Laboratory. 2000. Technology fact sheet: Peconic River remedial alternatives, phytostabilization. Argonne National Laboratory, University of Chicago for the US Department of Energy, No. W-31-109-Eng-38.

Brooks, R. R., Lee, J., Reeves, R. D., Jaffre, T. 1977. Detection of nickeliferous rocks by analysis of herbarium specimens of indicator plants. Journal of Geochemical Exploration 7: 49–57.

Brown, S. L., Chaney, R. L., Angle, J. S., Baker, A. J. M. 1994. Phytoremediation potential of *Thlaspi caerulescens* and Bladder campion for zinc- and cadmium-contaminated soil. Journal of Environmental Quality 23: 1151–1157.

Brown, S. L., Chaney, R. L., Angle, J. S., Baker, A. J. M. 1995. Zinc and cadmium uptake by the hyperaccumulator *Thlaspi caerulescens* grown in nutrient solution. Soil Science Society American Journal 59: 125–133.

Chaineau, C. H., Morel, J. L., Oudot, J. 2000. Biodegradation of fuel oil hydrocarbons in the rhizosphere of maize. Journal of Environmental Quality 29: 569–578.

Cunningham, S. D., Berti, W. R. 2000. Phytoextraction and phytostabilization: technical, economic, and regulatory considerations of the soil-lead issue. In *Phytoremediation of Contaminated Soil and Water*. Terry, N., Banuelos, G., Eds., pp. 359–376. Lewis Publishers, New York.

Cunningham, S. D., Berti, W. R., Huang, J. W. 1995. Phytoremediation of contaminated soils. TIBTECH 13: 393–397.

Doucette, W. J., Chard, J. K., Moore, B. J., Staudt, W. J., Headly, J. V. 2005. Uptake of sulfolane and diisopropanolamine (DIPA) by cattails (*Typha latifolia*). Microchemical Journal 81: 41–49.

Ebbs, S. D., Kochian, L. V. 1997. Toxicity of zinc and copper to *Brassica* species: implications for phytoremediation. Journal of Environmental Quality 26: 776–781.

Glick, B. R. 2003. Phytoremediation: synergic use of plants and bacteria to clean up the environment. Biotechnology Advances 21: 383–393.

Hughes, J. B., Shanks, J., Vanderford, M, Lauritzen, J., Bhadra, R. 1997. Transformation of TNT by aquatic plants and plant tissue cultures. Environmental Science & Technology 31: 266–271.

Kulshreshtha, A., Dixit, C. K., Kant, S., Verma, V., Kulshreshtha, A., Jain, K., Kumar, A. 2003. Evaluation of some air pollution tolerant plants in Agra City. Indian Journal of Environmental Protection 23(7): 805–808.

Long, X. X., Yang, X. E., Ye, Z. Q., Ni, W. Z., Shi, W. Y. 2003. Difference of uptake and accumulation of zinc in four species of *Sedum*. Acta Botanica Sinica 44: 152–157.

McDonald, S. 2006. Phytoremediation of lead-contaminated soil using *Typha latifolia* (Broadleaf Cattail). Master's Thesis, Humboldt State University, Arcata, CA.

McEldowney, S., Hardman, D. J., Waite, S. 1993. Treatment technologies. In *Pollution, Ecology and Biotreatment*. McEldowney, S., Hardman, D. J., Waite, S., Eds., pp. 48–58. Longman Singapore Publishers Pvt. Ltd, Singapore.

Meagher, R. B. 2000. Phytoremediation of toxic elemental and organic pollutants. Current Opinion in Plant Biology 3: 153–162.

Memon, A. R., Digdem, A., Aylin, O., Vertii, A. 2001. Heavy metal accumulation and detoxification mechanisms in plants. Turkish Journal of Botany 25(3): 111–121.

Mueller, B., Rock, S., Tsao, D., Geller, K., Thuraisingham, R., Greene, K. A., Kornuc, J., Strauss, M., Coia, K., Hoddinott, L., Newman, B., Berti, T., Douglas, M., Lasat, D., Easley, P., Hall, T., Compton, H., Olson, K., Gatchett, A., Foote, E. 2001. Interstate Technology Regulatory Cooperation (ITRC): Technical/Regulatory Guidelines; Phytotechnology Technical and Regulatory Guidance Document (cited 2007 December 15). Available from: http://www.itrcweb.org/Documents/PHYTO-2.pdf

Outridge, P.M., Noller, B.N. 1991. Accumulation of toxic trace elements by freshwater vascular plants. Reviews of Environmental Contamination and Toxicology, 121: 1–63.

Ow, D. W. 1996. Heavy metal tolerance genes: prospective tools for bioremediation. Resources, Conservation and Recycling 18: 135–149.

Padmavathiamma, P. K., Li, L. Y. 2007. Phytoremediation technology: hyper-accumulation metals in plants. Water, Air and Soil Pollution 184: 105–126.

Palmroth, M. R. T., Koskinen, P. E. P., Pichtel, J., Vaajasaari, K., Joutti, A., Tuhkanen, T. A., Puhakka, J. A. 2006. Field-scale assessment of phytotreatment of soil contaminated with weathered hydrocarbons and heavy metals. Journal of Soils and Sediments 6(3): 128–136.

Park, G. S., Kim, D. H., Lim, J. G., Ohga, S. 2006. Heavy metal concentration and identification of microorganisms in soil under roadside trees of Daejeon City, Korea. J. Fac. Agr., Kyushu Univ., Journal of the Faculty of Agriculture Kyushu University 51(1): 53–56.

Pyatt, F. B., Gratten, J. P. 2001. Some consequences of ancient mining activities on the health of ancient and modern human populations. Journal of Public Medicine 23: 235–236.

Sharma, P., Dubey, R. S. 2005. Lead toxicity in plants. Brazilian Journal of Plant Physiology 17: 35–52.

Sharma, S. C., Srivastava, R., Roy, R. K. 2005. Role of bougainvilleas in mitigation of environmental pollution. Journal of Environmental Science and Engineering 47(2): 131–134.

Tang, S., Fang, Y. 2001. Copper accumulation by *Polygonum microcephalum* D. Don and *Rumex hastatus* D. Don from copper mining spoils in Yunnan Province, P.R. China. Environmental Geology 40: 902–907.

Taylor, G. J., Crowder, A. A. 1983a. Uptake and accumulation of heavy metals by *Typha latifolia* in wetlands of the Sudbury, Ontario Region. Canadian Journal of Botany 61: 63–73.

Taylor, G. J., Crowder, A. A. 1983b. Uptake and accumulation of copper, nickel, and iron by *Typha latifolia* grown in solution culture. Canadian Journal of Botany 61: 1825–1830.

Tian, D., Xiang, W., Yan, W., Kang, W., Deng, X., Fan, Z. 2007. Biological cycles of mineral elements in a young mixed stand in abandoned mining soils. Journal of Integrative Plant Biology 49(9): 1284–1293.

USEPA. 1993. Cleaning up the nation's waste sites: market and technology trends. Office of solid waste and emergency response, technology innovative office (OS-110 W), Washington, DC, EPA 542-R-92-012.

USEPA. 1999. Phytoremediation Resources Guide. Solid waste and emergency response (5102G). EPA 542-B-99-003. www.epa.gov/tio/download/remed/phytoresgude.pdf

USEPA. 2007. www.epa.gov/iaq/lead.html

Xei, K., Waguespace, Y. Y., McPherson, G. 1999. The comparison of lead content of soil and plants in urban and rural areas. Unpublished report. Department of Natural Sciences, University of Maryland.

Yang, X., Jin, X., Feng, Y., Islam, E. 2005. Molecular mechanisms and genetic basis of heavy metal tolerance/hyperaccumulation in plants. Journal of Integrative Plant Biology 47: 1025–1035.

Zhuang, X., Chen, J., Shim, H., Bai, Z. 2007a. New advances in plant growth-promoting rhizobacteria for bioremediation. Environmental International 33: 406–413.

Zhuang, P., Yang, Q. W., Wang, H. B., Shu, W. S. 2007b. Phytoextraction of heavy metals by eight plant species in the field. Water, Air and Soil Pollution 184: 235–242.