Phytoextraction of Cadmium: the advantages, limitations, cost and potential improvements of this remediation technique.

Becky Meyerholt

Abstract

Throughout the United States there are multiple sites where the soil has been contaminated with heavy metals such as zinc, cadmium, lead, and arsenic. Due of the risk that these metals pose to humans and the local ecosystem, these contaminated sites are not fit for food production until the contamination is remediated. Because of the cost and perceived invasiveness of traditional ex-situ remediation techniques, there has been an increase in the number of sites that are remediated using in-situ techniques such as phytoremediation. Phytoremediation uses plants to reduce the concentration of a contaminant and/or reduce the risk of exposure from a contaminant in the environment. Phytoextraction uses plants to remove a soil contaminate by sequestering it in the plant tissues, which are then harvested and removed. As with all remediation techniques, phytoextraction has a limited effectiveness. Its two main limitations are: metal toxicity to plants at high concentrations and the cost to dispose of the plant tissues. Recent studies have proposed different methods to overcome these limitations through the use of genetic engineering and coupling the disposal of harvested biomass with the production of energy, biofuels or as a source for the mining of valuable metals.

1. Introduction:

The land area of our planet is finite and as the world population grows, it is important that degraded lands are restored for productive uses such as food and sustainable energy production. Land degradation, or the loss of productive value from a given area of land, can occur due to multiple reasons including chemical contamination from both natural and anthropogenic sources. According to the Joint Research Center European Soil Data Centre (2016), soil contamination is defined as “the occurrence of pollution above a threshold value that results in the loss of a soil function, or causes some other type of land degradation”.

Chemical contamination of soils can occur when inorganic contaminants (lead, arsenic, and cadmium), organic contaminants (petroleum products, pesticides, and polycyclic aromatic hydrocarbons), or radioactive materials (plutonium and uranium) are present in the soil above a threshold concentration and pose a risk to members of the local community or ecosystem. Soil contamination can lead to an unacceptable exposure risk though dermal contact, ingestion, or inhalation of soil particles containing contaminants. This review paper focuses on how phytoextraction can be used as a remediation technique for soils contaminated with cadmium.

1.1 Cadmium contaminated soils

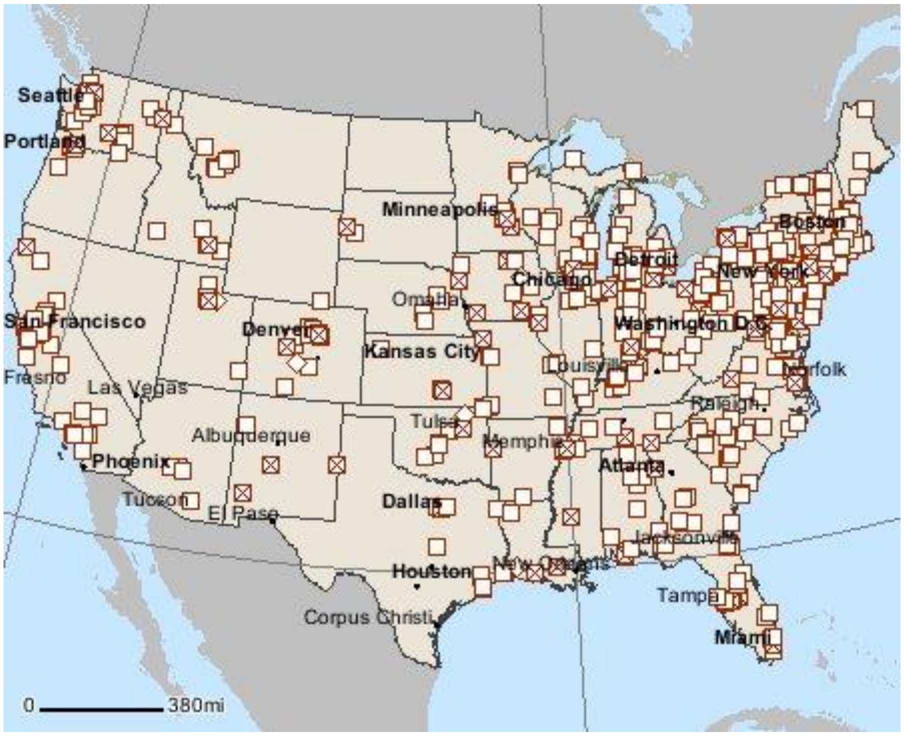

Figure 1: Locations of the 661 NPL sites in the U.S. with soils contaminated with cadmium. Image taken from http://toxmap-classic.nlm.nih.gov/toxmap/search/select.do, 2016. Map Key: Empty diamond- proposed NPL site. Empty square- listed NPL site. Square with red x- delisted NPL sites.

Cadmium (Cd) is a naturally occurring metal, which according to the U.S. Department of Health and Human Services [U.S.HHS], is highly toxic to humans through the consumption of contaminated food supplies (U.S.HHS, 2012a). While the highest levels of Cd have been detected in leafy vegetables such as lettuce (*Lactuca sativa*) and spinach (*Spinacia oleracea*) (U.S. HHS, 2012b), the average concentration of Cd in an agricultural soil is within the background concentration. Throughout the United States, typical background concentrations of Cd range from 0.06 ppm to 1.1 ppm (U.S. HHS, 2012b). Some soils, due to the rocks and minerals that are present, will contain concentrations of Cd above this level but are still not considered to be contaminated. For example, a soil in the State of Michigan can have concentrations of Cd as high as 2.5 ppm before it is considered contaminated (Michigan Department of Environmental Quality [MDEQ], 2005).

To show how wide spread soil contamination is from the presence of cadmium, the Toxmap from the U.S. HHS is utilized (Figure 1). According to the U.S. HHS database (2016), 661 out of 1,673 sites (40% of sites) on the National Priorities List are soils contaminated with Cd.

1.2 How contaminated soils are addressed

Traditionally, remediation of contaminated soils occurred by digging up the areas of greatest contamination and landfilling the excavated material in a designated landfill or by treating the excavated soil in such a fashion that the contamination was removed (i.e., incineration of soil to volatilize any organic contamination). While dig and treat methods of soil clean up are useful for small areas of contamination, they can lead to increased exposure risks through the generation of dust particles and can be cost prohibitive for areas of widespread contamination. *In-situ* remediation occurs at the contaminated site, which offers an alternative to traditional *ex-situ* (cleanup that occurs off site) methods because it lowers the amount of soils that can potentially become airborne and there by lowers the risk of potential exposure. According to the U.S. Environmental Protection Agency [USEPA], the number of sites using *in-situ* remediation techniques increased from 35% to 53% for all remediation projects that occurred during the mid-1990’s (2001).

Just as there are a variety of soil contaminants there are a variety of *in-situ* remediation methods that can be used to address soil contamination. Chemical amendments (e.g., lime and acid) can be added to the soil to alter the mobility of the contaminant by increasing or decreasing the pH of the soil solution. Physical collection systems such as permeable reactive barriers can be installed to retain and prevent the contamination from moving off site. Biological organisms such as plants and bacteria can be added to the soil or to the collection system to facilitate the degradation of the contamination. The use of biological organisms to address contamination is known as bioremediation.

Phytoremediation, a type of bioremediation, uses plants to clean up soils, including phytovolatilization, phytostabilization, phytoextraction, rhizofiltration, phytodegradation and rhizodegradation (USEPA, 1999). Of the different phytoremediation techniques, phytoextraction is one of the most commonly used for heavy metal contamination (USEPA, 2010). In comparison to traditional remedial techniques, phytoremediation offers a lower cost and is a more socially-acceptable alternative (Ali et. al, 2013; and Hadi et. al, 2015). However, there are limitations to the use of phytoremediation, especially for heavy metal contamination. From the perspective of heavy metal contamination, phytoextraction is faced with biological, soil, and disposal cost limitations. This review will focus on the recent studies to address these limitations.

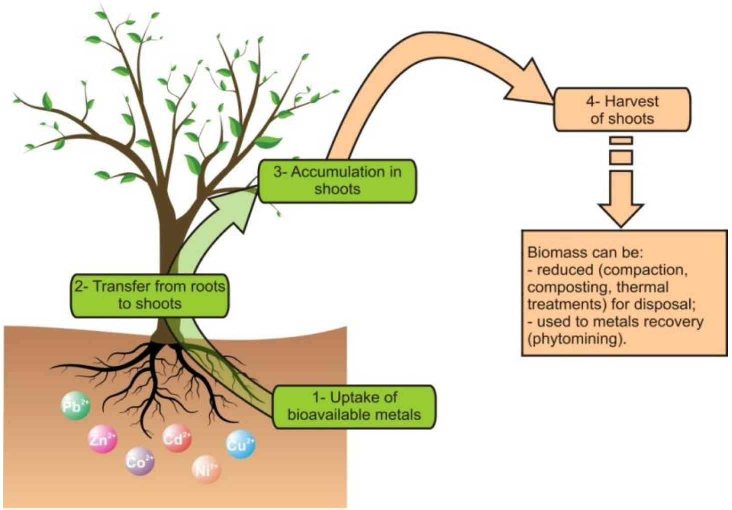

Figure 2: The process of phytoextrcation. Taken from Favas et. al, 2014.

2. Biological and soil limitations

Phytoextraction uses plants to reduce soil contamination through contaminant uptake and translocation (Figure 2), which is often portrayed as an environmentally friendly and relatively novel remediation technique (Ahmadpour et. al, 2012; Ali et. al, 2013; Gupta et al., 2013; Hadi et. al, 2015; and Zheng et. al, 2013). However, because phytoextraction involves biological organisms there are some limitations to this remediation technique when compared to traditional methods such as soil excavation (Table 1). Some of the natural limitations that impact the effectiveness of phytoextraction include: metal toxicity, metal bioavailability (how mobile the metal is), and/or biomass production. For example, in order for plants to establish from a seed, grow, and remove the metal contaminant from a soil the concentration of metals that is available in the soil solution for uptake must not be high enough to be toxic to the plants. If the metal is toxic to the plant, there is a reduction in the effectiveness of the plant to perform the desired phytoremediation. Hadi et al. (2015) showed that plants respond to the stress of metal toxicity by reducing their overall biomass production but the amount of biomass that is produced is a critical parameter of phytoextraction.

Table 1: Pro and con comparison of two remediation methods for soil contamination

Remediation method	**Pros**	**Cons**
Excavation	Quick (months)	Generates dust particles
	Doesn't care about concentration	Disposes of high volume of waste
	Works on all soil types and depths	High cost
phytoextraction	Limits dust generation	Slower process (years)
	Smaller amount of waste to dispose	Concentration is important
	Low cost	Depth of contamination is important

2.1 Metal Toxicity

As with all living things, plants need both the proper type and the correct amount of nutrients to grow. Some nutrients such as carbon, nitrogen, phosphorus, and calcium are needed in large amounts (macronutrients), while other nutrients such as copper, and cobalt are needed in smaller amounts (micronutrients). These nutrients are taken up from the soil solution and moved throughout the plant tissues as they are needed for growth. Some of the micronutrients needed for plant growth include heavy metals like zinc, which can become toxic to the plant if the concentration of that metal is too high. Symptoms of heavy metal toxicity include: reduction of growth, discoloration of leaves, and ultimately plant death.

For the purposes of soil remediation, plants can utilize this naturally occurring process of nutrient uptake and translocation to allow otherwise toxic heavy metals such as Cd to be transferred from the soil solution into plant tissues. These toxic metals are taken up by plants due in part to their chemical similarity to the metallic nutrients. For example, Cd is a divalent cation (carries a 2+ charge) and is similar in size to calcium (Ca^{2+}), so it is possible that the Cd uses the same mechanisms as calcium to enter the plant (Krauskopk and Bird, 1995). Because Cd is not a nutrient (i.e., it does not serve a purpose in the plant) the plant must be able to tolerate the presence of the metal or isolate the metal from the critical metabolic pathways in order to prevent the negative consequences of toxic metal uptake. The impacts of Cd toxicity, typically a reduction in biomass production, are seen when the total soil Cd concentration ranges from 0.55 ppm to 8 ppm depending on the individual plant species (He et. al, 2015).

There are two main methods that plants can use in order to address the negative impacts of heavy metal toxicity and these methods can be exploited for remediation purposes by either the phytoextraction or phytostabilization process. The first method that plants can utilize to tolerate an increased soil concentration of heavy metals, is the ability to hyperaccumulate those metals (He et al., 2015; Nwoko, 2009; Peuke and Rennenberg, 2005). Hyperaccumulators are members of various plant families that have a genetic disposition to store higher than normal concentrations (> 0.1 % dry weight) of heavy metals in their tissues (seeds, leaves, steams, shoots, and roots) (Ali et. al, 2013) without displaying the physical symptoms of Cd toxicity.

While the ability of plant species to hyperaccumulate metals was first seen in plants native to metal rich soils that resulted from the mineral weathering of ultramafic deposits (Sheoran et al., 2009); current research is finding Cd hyperaccumulators that are native to heavily contaminated soils. Since 2006, over 360 studies have been published on the topic of Cd phytoextraction. Of these studies, the majority were pot studies designed to look at the applicability of a plant species or genotype to be used in phytoextraction. Some of the plant families that contain known hyperaccumulators for Cd include: Amaranthaceae, Asteraceae, Brassicaceae, and Chenopodiaceae (He et. al, 2015). Members of the Brassicaceae family (which includes crop plants like kale, broccoli, cauliflower, and cabbage) have been shown to tolerate concentrations of cadmium as high as 6,100 ppm (He et. al, 2015) inside their plant tissues (Table 2). While this finding initially appears to contradict the information from the U.S. HHS that lettuce (a member of the Asteraceae family) and spinach (a member of the

Table 2: Select cadmium hyperaccumulator plant families and the range of Cd concentrations (in ppm) tolerated in plant tissues. Data taken from He et. al, (2015).

Plant family (common name)	**Lowest concentration (ppm)**	**Highest concentration (ppm)**
Amaranthaceae	212	260
Asteraceae (Sunflower family)	27.9	1,109
Brassicaceae (Mustard family)	150	6,100
Chenopodiaceae	70	2,075

Amaranthaceae family) often contain the highest concentration of cadmium in food supply crops (2012b), there are differences in how the foods where sampled for Cd. In the U.S. HHS study Cd concentrations were based on wet weight, while the study by He et. al (2015) concentrations were based on dry weight.

The second method that some plant species use to address the metal toxicity issue is by excluding the uptake, preventing the translocation, or precipitating metals in the rhizosphere (Nwoko, 2010) in a process known as phytostabilization. Phytostabilization might be selected over phytoextraction for remediation projects because some heavy metals are preferentially stored in the root tissues of plants rather than the aerial tissues. This preference, which limits the effectiveness of phytoextraction, depends on the translocation factor and relative bioavailability of that metal (Ali et. al, 2013).

2.2 Metal Bioavailability

The success of any phytoremediation technique is dependent upon the plant roots being able to reach the location of the contamination and the mobility of that contaminate. With the exception of tree roots, most plants will have a rooting depth that ranges from a couple of inches to about 10ft deep (Havlin et. al, 2005). This means that if the soil contamination is located beyond the rooting depth, the plants used in phytoextraction will not be able to access the pool of contaminant and remove it from the soil. The ability of plant roots to contact the contamination is also dependent upon physical soil properties such soil texture, soil porosity, soil bulk density, and soil aeration status (Zheng et al., 2013). These soil properties impact how easily plant roots can break through the soil clods. For example, if the soil texture is clay rich the plant roots could have a hard time penetrating through the soil aggregates to reach both nutrients and the contamination. This would restrict the amount of contaminates that can be remediated and the overall growth of the plant (i.e. biomass production).

The amount of Cd in the soil solution is the result of soil properties such as pH, soil texture, and the presence of various oxides, that alter the mobility of Cd. Although Cd is considered to be mobile and bioavailable (Akkajit & Tongcumpou, 2010; Ali et. al, 2013) under near neutral pH soils (He et. al., 2015), not all of the Cd in the soil will be available for plant uptake. Due to the heterogeneity of the soil, some Cd will remain bound to the soil organic matter or adsorbed to soil particles (clays and Iron oxides). In addition, the amount of bioavailable Cd can increase or decrease depending on the cation exchange capacity of the soil (which is a function of soil texture). The bioavailability of contaminates is also impacted by how long the contaminate has been present in the soil, such that the longer a contaminate is present in the soil less bioavailable it becomes (Alexander, 2000). This aspect of bioavailability is called aging. Cadmium can age in the soil by becoming tightly bound to the soil particles or incorporated into the soil minerals by isomorphic substitution. However, if the soil conditions are changed, namely the pH and presence of other cations, this remaining Cd may become available to plants or act as contamination hot spots and thus require further remediation.

Once the Cd is in the soil solution, it will move with the water towards the plant roots as required by transpiration (He et. al., 2015). After the Cd containing water has entered the plant roots, the translocation factor (TF) (concentration of Cd in shoots/concentration of Cd in roots) determines how much the plant can uptake and store. According to He et. al (2015), the best plants to use for phytoextraction are hyperaccumulator of Cd that have a TF value > 1. Having a TF value greater than 1 indicates that the plant is capable of moving and storing Cd in the aerial tissues of the plant. If the metal is stored predominantly in the root tissues, rather than the aerial tissues as indicated by having a TF value <1, the harvesting process becomes more difficult. Roots can break off and remain in the soil when harvested. Having a portion of the metal bearing tissues remain in the soil reduces the amount of metal that is removed with each harvest and the efficiency of the remediation process. However, it is possible that plants with lower TF values can still be used for phytoextraction (Hadi et. al, 2015) if they possess a greater growth rate.

2.2 Biomass Production

Similar to metal toxicity, there are two strategies that plants can adapt in order to survive. Which strategy is used can have an impact on the success of phytoremediation as they are the strategies of biomass production. The first strategy that plants can utilize is to develop more root tissue than aboveground tissue in order to effectively scavenge water and nutrients from an otherwise limiting environment. According to Brady and Weil (2008) the roots of plants in relatively limited rainfall regions extend deeper into the soil profile than those plants located in area where rain is more plentiful. An example of extended root depth was seen in corn grown in Iowa during the drought of 2012. During this drought, it was reported that corn roots grew to a depth of 9 feet (Fawcett, 2013), which is beyond the average depth of 3 - 5 feet (Figure 3). The second strategy that plants can use for their growth is to develop more aboveground tissue to facilitate the production of energy via photosynthesis. This strategy is seen in plants that either have a quicker

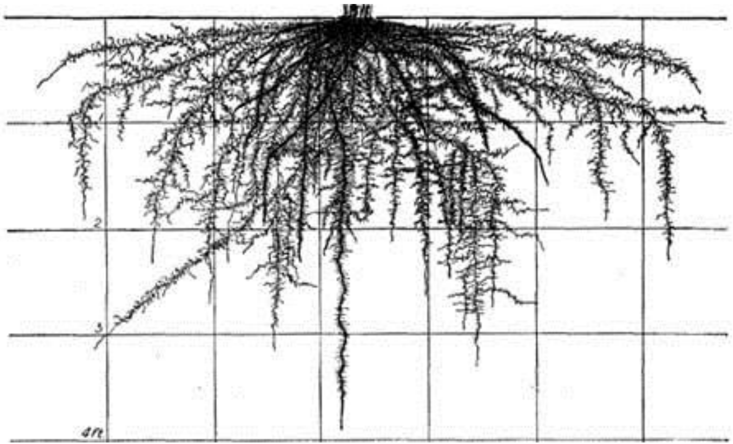

Figure 3: Drawing of Sweet Corn root development. Taken from Weaver and Bruner, 1927.

growth rate than other plant species (i.e., grasses vs. shrubs, Ali et. al, 2013) or are not nutrient limited (Agren & Franklin, 2003). Because both of these strategies provide the plant with things necessary for growth (nutrients, water and sunlight), the ratio of biomass is typically 50/50 aerial/root (Poorter et. al, 2012).

In order for phytoextraction to be effective the plant must have a sufficient amount of metal bearing tissues that can be harvested at some frequency, which allows the metals to be removed rather than remaining in the soil (Jabeen et. al., 2009). As discussed above hyperaccumulators will store large quantities of metal in their aerial tissues (stems and leaves), which is beneficial for phytoextraction as aerial tissues are easier to harvest than root tissues. However, hyperaccumulators typically grow slower and have a lower biomass production than other less metal tolerant plant species (Gupta et al., 2013). This slower growth and lower overall biomass production is the result of accumulating and detoxifying the increased metal concentrations. Utilizing plants that grow slower and have a lower overall biomass production can potentially increase the duration of the remediation effort, as a longer growing season and multiple harvests might be required to reach the desired outcome.

2.3 Potential solutions

How plants are able to tolerate such high concentrations of toxic metals and the mechanisms that allow for hyperaccumulation to occur is an area of active research (Gupta et al., 2013; Stearns et. al, 2007; Zheng et al., 2013) that could lead to the development of more metal tolerant plant species for use in phytoremediation. Because the number of native hyperaccumulators is limited and their biomass production is lower than other plants, recent studies have tried to improve the concentration of metal that is bioavailable to plant species though the addition of synthetic chelates (Ghosh and Singh, 2005; Gupta et al., 2013; Zheng et al., 2013). This method of “inducible” phytoextraction however, is limited by the metal tolerance of the plant that is selected as the remedial material (i.e. plant might be killed by the concentrations that it takes up) and the increased risk of metal mobility. By increasing the mobility (bioavailability) of the metal, not only is the potential of the metal to be taken up by the plants greater but the potential for the metals to move out of the plant root zone and into the groundwater is greater as well (Jabeen et.al, 2009; Zheng et al., 2013). The use of synthetic chelates poses additional concern as the chelate might not be readily degraded in the soil environment (Zheng et al., 2013).

Some plant species and associated soil microbes have the capability of producing biological chelates such as phytochelatins (Zheng et al., 2013), siderophores, organic acids, and biosurfactants (Rajkumar et. al, 2012). Chelates whether they are biological or synthetic in nature, increase the bioavailability of the metal contaminant in the rooting zone and the ability of the metal to be translocated in the plant. This increase in bioavailability is the result of an increase in solubility. According to Peuke and Rennenberg (2005), biological chelates allow the heavy metals to be sequestered in the plant tissues as a means of detoxification, which would be ideal for the phytoextraction process. While the concept of using a biological compound to increase metal solubility is a promising idea, it needs additional research in order to limit the amount of metal that is leached from the rooting zone and into groundwater sources.

Under ideal conditions, the plants that are selected for phytoextraction will have a high aerial biomass production, be able to translocate the metal, and be tolerant of the increased metal concentration as the result of biological chelate production. Because it is not common to find a plant that will meet all these traits, other researchers have focused on creating genetically modified plants for the purpose of phytoextraction (Ghosh and Singh, 2005; Gupta et. al., 2013; Robinson and McIvor, 2013; Stearns et. al, 2007).

3. Disposal and cost limitations

As with all remediation techniques, there is a cost associated with the disposal of the material regardless of if it is the remedial material (in the case of phytoextraction, the plant tissue) or the material that is being remediated (the soil). The cost of remediation depends on the type of contaminate and the method used for remediation. For example, it might be cheaper to phytoremediate soils contaminated with organic contaminates rather than inorganic contaminates because these organic compounds can ideally be degraded by the plants and associated microorganisms to non-hazardous components that do not require disposal. Heavy metals, on the other hand cannot be degraded (Ali et. al, 2013; Nwoko, 2010) because they are elemental in nature and will require disposal. Disposal methods for the metal laden phytoremediation material can include: landfilling (Rajkumar et. al, 2012), composting (Robinson and McIvor, 2013), and incineration/combustion (Sas-Nowosielska et. al, 2004).

Table 3: Differences in cost of remediation methods for soil contamination. Taken from FRTR, 2016.

Phytoremediation	**Includes**	**Excludes**
	Labor	Disposal at Resource Conservation and Recovery Act (RCRA) facility
	Monitoring	Fees
		Transportation of material to disposal facility
Excavation	Disposal at RCRA facility	Labor
	Transportation of material to disposal facility	Fees
		Monitoring

The traditional remediation method of soils contaminated with heavy metals (i.e. excavation) can cost $193 - $329 per cubic yard of soil removed, while phytoremediation can cost $479 - $1,775 per cubic yard (Federal Remediation Technologies Roundtable [FRTR], 2016). The main difference in the costs between these two remediation methods, steams from the inclusion of different work processes (Table 3). Furthermore, there are two additional factors that play into the final determination of how much the phytoextraction project will cost. These two factors are the concentration of metal and the amount of biomass to be disposed of. As discussed above, the amount of biomass produced during the phytoextraction project depends on the plant that is selected and its proper growth through the growing season. Assuming that the plant is effective at translocating the metal from the plant roots to the aerial tissues, the concentration of the metal determines where the waste is disposed of. For example, if the metal concentration is high enough the material may be considered a hazardous waste (Gerhardt et. al, 2009; Narodoslasky and Obernberger, 1996).

Table 4: RCRA Hazardous waste concentration for select heavy metals. Taken from Crouth, (2012).

Metal	concentration (ppm)
Arsenic	100
Cadmium	20
Lead	100
Mercury	4
Silver	100

A soil or plant material would be considered Resource Conservation and Recovery Act (RCRA) hazardous waste if the concentration of metals is greater than those listed in Table 4. According to the U.S. EPA, a hazardous waste is “a waste that is dangerous or potentially harmful to our health or the environment” (EPA, 2016). The cost to dispose of RCRA hazardous waste depends on how the waste is disposed of and if there was any treatment of the waste prior to its disposal. For example, if the plant material containing the metal is first incinerated (i.e. treatment) the ash from the incinerator would still be classified as RCRA hazardous, but the volume of waste needing to be disposed of would be lower. Because there are a variety of treatment and disposal options there is also a range in the cost to dispose of RCRA hazardous waste. In the State of California the cost to dispose of material at a RCRA hazardous waste land fill ranges from $4.09 to $184.92 per cubic yard (California Department of Toxic Substances Control, 2013).

An additional cost that any remediation project faces is the cost associated with the duration of the project. The typical goal of remediation is to restore the previously contaminated land to a state that will allow for cost recuperation in the shortest amount of time. According to He et al. (2015) one of the greatest limitations that phytoremediation faces is that the time it takes to address the soil contamination is double that of traditional methods. As mentioned in the above sections, there are studies that are looking into how to improve the phytoextraction processes by increasing the metal tolerance and sequestration of metals in the aerial tissues of plants.

By using plants to remove metal contamination there are some additional risks that are associated with the disposal of the biomass. When Cd is accumulated in plant tissues, it will remain in the tissues until the tissues are degraded (and the metal returned to the soil) or incinerated (at which point the Cd would remain in the ash). When Cd containing tissues are reapplied to the land as nutrient compost (because their concentration does not meet the definition of a RCRA hazardous waste) the metal will be transferred to surface of the soil where they pose a greater risk to children whom come in contact with the dirt (Robinson and McIvor, 2013). If the biomass is considered a RCRA hazardous waste the biomass could be directly landfilled (which again would return the contamination to a new location) or incinerated and then landfilled. While incineration would lower the total volume of material to be landfilled, the smaller ash particles could pose an inhalation hazard.

3.1 Alternatives to the disposal of metal bearing plant tissues

As with any remediation project, the largest contributor to the total cost of the project is associated with the disposal of the project's waste. It would be more cost effective to link the use of biomass generated during phytoextraction to some industrial process such that the former waste becomes a raw material. Examples of where phytoremediation could be linked with industry include: paper product production and timber production (Peuke and Rennenberg, 2005; Robinson and McIvor, 2013). However, prior to introducing these commercial products into the public, studies should be conducted in order to prove that the metals are not leached out causing exposure to the consumers. An alternative to using the biomass for consumer goods is the idea that the incineration/combustion of remedial material can be coupled with energy generation, biofuels production (Lievens et al., 2009; Stals et al., 2010), or used for phytomining (Li et. al., 2003; Sheoran et. al, 2009; Witters et. al, 2012).

According to Stals et al (2010), when heavy metal laden biomass undergoes pyrolysis the metal is concentrated in the ash (solid) portion leaving the bio-oils that are generated relatively free of metal contamination. By concentrating the metals in the ash component (Narodoslawsky et. al., 1996), it would be possible to recover the metals for further re-use in industrial processes such as electroplating or smelting. The concentrated ash can serve as a source of metal similar to that of a traditional low grade ore, in a process known as phytomining. According to Sheoran et al (2009) it would be possible to phytomine valuable metals (Zinc, Gold, and Silver) from low grade ores (such as the incinerator fly ash) and mine tailings at a cost that would be comparable to traditional mining methods. An additional benefit of incinerating the biomass from phytoextraction is that the volume of the biomass is reduced and can be stored until the value of the metal increases, assuming proper precautions are taken to limit the amount of airborne particles. By using the harvested plant tissue as a source of metals for mining purposes, it would lower the cost of phytoremediation even further and provide incentive for owners of the degraded land to address the contamination throughout the entire length of the remediation project.

4. Conclusion

Land around the world has been degraded by different types of chemical contamination, including heavy metals. The cost and invasiveness of traditional remedial methods have led to the idea that phytoremediation can be used as a lower cost and more environmentally friendly remediation technology. Phytoextraction is a type of phytoremediation that uses plants natural capabilities to remove metals from the soil solution and store them in the above ground tissues. These tissues then can be harvested, removing the contamination from the soil one harvest at a time.

However, as with all remediation strategies there are limitations to the application of phytoextraction. These limitations include metal toxicity, metal bioavailability, contamination location (both in the soil and in the plant tissue), and the cost of disposal. Multiple studies over the past decade or so have proposed different methods that could address these limitations.

As a way to reduce the impact that metal bioavailability has on phytoextraction, recent studies have proposed the use of biological chelates to increase the metal's solubility and mobility within the soil and the plant tissues. Other studies have proposed the use of genetically developed plants, which would produce these biological chelates. An additional benefit of using genetically modifying plants is that the plant can store (i.e. be more tolerant) higher concentrations of metals in their aerial tissues (leaves and stems). Because how the plant biomass is disposed of once it contains the metal is a cost limitation, some studies have focused on using the plant biomass as a raw material. Examples of areas where phytoremediation produced biomass might be used as a raw material includes: electroplating and smelting processes, biofuels production, paper products and timber. Regardless of rather the material is used in consumer good production or not, the cost of the disposal can be avoided because the metal laden material is no longer considered a waste but a raw material. However, there is still further study needed in order to develop the technology that will facilitate the recovery of metals from the incineration/pyrolysis ash and to make those products using this recovered metal safe and marketable.

Literature Cited:

Agren, G. I., & Franklin, O. (2003). Root:shoot ratios, optimization and nitrogen productivity. Annals of Botany, 92, 795-800.

Ahmadpour, P., Ahmadpour, F., Mahmud, T. M. M., Abdu, A., Soleimani, M., & Tayefeh, F.H. (2012). Phytoremedation of heavy metals: A green technology [Review]. African Journal of Biotechnology, 11 (76), 14036-14043.

Akkajit, P., & Tongcumpou, C. (2010). Fractionation of metals in cadmium contaminated soil: relation and effect on bioavailable cadmium. Geoderma, 156 126-132.

Alexander, M. (2000). Aging, bioavailability, and overestimation of risk from environmental pollutants. Journal of Environmental Science and Technology, 34 (20), 4259-4265.

Ali, H., Khan, E., &. Sajad, M. A. (2013). Phytoremediation of heavy metals- Concepts and applications [Review]. Chemosphere, 91, 869-881.

Brady, N. C., & Weil, R. R. (2008). The Nature and Properties of Soils. (14th ed.). Upper Saddle River: Pearson Education.

California Department of Toxic Substance Control. (2013). Department of Toxic Substances Control Fee Summary.

Crouth, G. (2012). How to recognize a hazardous waste (even if it's wearing dark glasses). (12th Ed.) OLAP World Press.

Fawcett, J. (2013). How deep can corn roots go? Wallaces Farmer. January 2013.

Favas, P. J.C., Pratas, J., Varun, M., D'Souza, R., & Paul, M.S. (2014). Phytoremediation of soils contaminated with metals and metalloids at mining areas: potential of native flora, Ch. 17 in Environmental Risk Assessment of Soil Contamination.

Federal Remediation Technologies Roundtable. (2016). Remediation Technologies Screening Matrix and Reference Guide, Version 4.0. https://frtr.gov/matrix2/top_page.html

Gerhardt, K. E., Huang, X. D., Glick, B. R., & Greenberg, B. M. Phytoremediation and rhizoremediation of organic soil contaminants: Potential and challenges [Review]. Plant Science, 176, 20-30.

Ghosh, M. &. Singh, S.P. (2005). A review of phytoremediation of heavy metals and utilization of it's by products. Asian Journal on Energy and Environment, 6, (4), 214-231.

Gupta, D. K., Huang, H. G., & Corpas, F. J. (2013). Lead tolerance in plants: strategies for phytoremediation [Review article]. Journal of Environmental Science Pollution Res, January 22, 2150-2161.

Hadi, F., Arifeen, M. Z. U., Aziz, T., Nawab, S., & Nabi, G. (2015). Phytoremediation of cadmium by *Ricinus communis* L. in hydrophonic condition. American-Eurasian Journal of Agric & Environ. Sci, 15,(6), 1155-1162.

Havlin, J. L., Beaton, J.D., Tisdale, S. L., & Nelson, W. L. (2005). Soil Fertility and Fertilizers. (7th ed.). Upper Saddle River: Pearson Education.

He, S., He, Z., Yang, X., Stoffella, P. J., & Baligar, V. C. (2015). Soil biogeochemistry, plant physiology, and phytoremediation of cadmium-contaminated soils. Advances in Agronomy. (1st ed.). 135-225.

Jabeen, R., Ahmad, A., and Iqbal, M. (2009). Phytoremediation of heavy metals: physiological and molecular mechanisms. Bot. Rev, 75, 339-364.

Joint Research Center European Soil Data Centre (ESDAC). (2016, January). Soil Contamination. Retrieved January 29th, 2016 from the world wide web: esdac.jrc.ec.europa.eu/themes/soil-contamination

Krauskopf, K. B., & Bird, D. K. (1995). Introduction to geochemistry (3rd ed.): McGaw-Hill.

Li, Y. M., Chaney, R., Brewer, E., Roseberg, R., Angle, J.S., Baker, A., Reeves, R., & Nelkin, J. (2003). Development of a technology for commercial phytoextraction of nickel: economic and technical considerations. Plant and soil, (249), 107-115.

Lievens, C., Carleer, R., Cornelissen, T., & Yperman, J.. (2009). Fast pyrolysis of heavy metal contaminated willow: Influence of the plant part. Fuel, 88, 1417-1425.

Michigan Department of Environmental Quality. (2005). Michigan background soil survey 2005.

Narodoslawsky, M., & Obernberger, I. (1996). From waste to raw material- the route from biomass to wood ash for cadmium and other heavy metals. Journal of Hazardous Materials, 50, 157-168.

Nwoko, Chris O. (2010). Trends in phytoremediation of toxic elemental and organic pollutants. African Journal of Biotechnology, 9, (37), 6010-6016.

Peuke, A. D., & Rennenberg, H. (2005). Phytoremediation. European molecular biology organization reports, 6, (6), 497-501.

Poorter, H., Niklas, K.J., Reich, P.B., Oleksyn, J., Poot, P., & Mommer, L. (2012). Biomass allocation to leaves, stems, and roots: meta-analyses of intraspecific variation and environmental control. New Phytologist, 193, 30-50.

Rajkumar, M., Sandhya, S., Prasad, M.N.V., & Freitas, H. Perspectives of plant-associated microbes in heavy metal phytoremediation. (2012). Biotechnology Advances, 30, 1562 -1574.

Robinson, B., & McIvor, I. (2013). Phytomanagement of Contaminated Sites using Poplars and willow. In Recent Advances Towards Improved Phytoremediation of Heavy Metal Pollution (pp. 119-133). Bentham Science Publishers.

Sas-Nowosielska, A., Kucharski, R., Malkowski, E., Porgrzeba, M., Kuperberg, J.M., & Krynski, K. (2004). Phytoextraction crop disposal- an unsolved problem. Environmental Pollution, 128, 373-379.

Sheoran, V., Sheoran, A.S., & Poonia, P. (2009). Phytomining: A review. Minerals Engineering, (22), 1007-1019.

Stals, M., Thijssen, E., Vangronsveld, J., Carleer, R., Schreurs, S., & Yperman, J. (2010). Flash pyrolysis of heavy metal contaminated biomass from phytoremediation: Influence of temperature, entrained flow and wood/leaves blended pyrolysis on the behavior of heavy metals. Journal of Analytical and Applied Pyrolysis, 87, 1-7.

Stearns, J. C., Shah, S., & Glick, B. R. (2007). Increasing Plant Tolerance to Metals in the Environment. In Methods in Biotechnology, 23: Phytoremediation: Methods and Reviews (pp. 15-26). Totowa: Humana Press Inc.

U.S. Department of Health and Human Services. 2012. Toxicological profile for cadmium.

U.S. Department of Health and Human Services. 2012. ToxGuide™ for cadmium Cd.

U.S. Department of Health and Human Services. 2016. Toxmap classic search. http://toxmap-classic.nlm.nih.gov/toxmap/search/select.do

U.S. Environmental Protection Agency. 1999. Phytoremediation Resource Guide.

U.S. Environmental Protection Agency. 2001. Use of bioremediation at superfund sites.

U.S. Environmental Protection Agency. 2010. Phytotechnology for site clean up.

U.S. Environmental Protection Agency. 2016. Definitions. www.epa.gov

Weaver, J.E. & Bruner, W. E. (1927) Root development of vegetable crops. Ch. 2. Sweet Corn. (1st Ed.). MacGraw-Hill Book Company, New York.

Witters, N., Mendelsohn, R., Van Passel, S., Van Slycken, S., Weyens, N., Schreurs, E., Meers, E., Tack, F., Vanheusden, B., & Vangronsveld, J. (2012) Phytoremediation, a sustainable remediation technology? II: Economic assessment of CO2 abatement through the use of phytoremediation crops for renewable energy production. Biomass and Bioenergy, 39, 470-477.

Zheng, L., Lutz-Meindl, U., & Peer, T. (2013). Chelate-Assisted Phytoremediation of Lead. In Recent Advances Towards Improved Phytoremediation of Heavy Metal Pollution (pp. 40-54). Bentham Science Publishers.