Ecological restoration of mine degraded soils, with emphasis on metal contaminated soils

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Abstract

This paper reviews the ecological aspects of mined soil restoration, with special emphasis on maintaining a long-term sustainable vegetation on toxic metal mine sites. The metal mined soils are man-made habitats which are very unstable and will become sources of air and water pollution. Establishment of a vegetation cover is essential to stabilize the bare area and to minimize the pollution problem. In addition to remediate the adverse physical and chemical properties of the sites, the choice of appropriate vegetation will be important. Phytostabilization and phytoextraction are two common phytoremediation techniques in treating metal-contaminated soils, for stabilizing toxic mine spoils, and the removal of toxic metals from the spoils respectively. Soil amendments should be added to aid stabilizing mine spoils, and to enhance metal uptake accordingly.

2. Physical and chemical constraints of mined degraded soils

Mined degraded soils are man-made habitat which experience a wide range of problems for establishing and maintaining vegetation, depending on the types of mines such as metal mines, coal mines and quarries. The physico-chemical properties of the metal-contaminated soils tend to inhibit soil-forming processes and plant growth. In addition to elevated metal concentrations, other adverse factors included absence of topsoil; periodic sheet erosion; drought; surface mobility; compaction; wide temperature fluctuations; absence of soil-forming fine materials; and shortage of essential nutrients (Wong et al., 1999a,b).

The original soil of mine degraded lands is usually lost or damaged, with only skeletal materials. There is commonly a lack of organic matter and its associated nutrients such as nitrogen (N) in most degraded land materials. Organic matter provides a continuous source of nutrients, e.g., it provides most of the N reserve in...
soils and comprises typically 5% N which is mineralized at about 2% per year (Harris et al., 1996).

For soils contaminated by heavy metals such as copper (Cu), lead (Pb), nickel (Ni) and zinc (Zn), metal toxicity would restrict the growth of all but the most tolerant plants. Toxic metals can also adversely affect the number, diversity and activity of soil organisms, inhibiting soil organic matter decomposition and N mineralization processes. However, toxicity is not a simple matter of particular concentrations of substances being toxic to a plant. The chemical form of the potential toxic metal, the presence of other chemicals which may aggravate or ameliorate metal toxicity, the prevailing pH and nutrient status of the contaminated soil will affect the way plants respond to the toxic metal. Substrate pH affects plant growth mainly through its effect on the solubility of chemicals, including toxic metals and nutrients. It is commonly recognized that at pH 6.5 nutrient availability to plants is at a maximum and toxicity at a minimum (Harris et al., 1996). Table 1 lists the factors that may affect the bioavailability of metals (Adriano et al., 1997).

The bioavailability of heavy metals to plants and soil biota including fauna and microorganisms is controlled by their total concentration in the soil and their chemical forms. As to plants, the bioavailability is governed by the factors that control the activity of soluble metal species in the soil solution that is preferentially taken up (Thornton, 1999). Methods for determining the soluble and thus bioavailable fractions of metals in soils have been extensively studied for the past 20 years. For the soil-plant/microorganisms pathway, these included the use of (a) single chemical extractants of varying concentrations, such as EDTA, DTPA, acetic acid and 0.01 M CaCl2 (Allen, 1989) and (b) operationally defined sequential extraction procedures (Tessier et al., 1979) in which increasing strong extractants are used to release metals associated with different soil fractions.

### Table 1
Factors that may affect the bioavailability of metals (from Adriano et al., 1997)

<table>
<thead>
<tr>
<th>Soil capacity</th>
<th>Plant capacity</th>
<th>Environmental and other factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>Plant species</td>
<td>Climatic conditions</td>
</tr>
<tr>
<td>Cation exchange capacity</td>
<td>Plant cultivars</td>
<td>Management practices</td>
</tr>
<tr>
<td>Organic matter</td>
<td>Plant part and age</td>
<td>Irrigation water/salinity</td>
</tr>
<tr>
<td>Amount and type of clay</td>
<td>Ion interactions</td>
<td></td>
</tr>
<tr>
<td>Oxides of Fe and Mn</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Redox potential</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. Treatment of physical and chemical problems

Techniques such as crushing, compacting, ripping, grading, and drainage are employed to improve physical conditions of mine degraded soils. Terracing planting, use of run-off channels and stabilization ponds, and mulches should be practiced. Erosion control could be achieved once an overall plant cover has been established.

Topsoil is used to cover poor substrates and to provide improved growing conditions for plants. To maintain a good topsoil quality is a must for any revegetation scheme. In addition to a suitable physical property, application of appropriate fertilizers, and inoculation of nitrogen-fixing bacteria and mycorrhiza would facilitate reconstruction of self-sustained ecosystems. The role of other soil organisms, e.g. earthworms in maintaining soil fertility should not be overlooked (Ma et al., in press).

Organic wastes such as sewage sludge and refuse or manure compost can be used as soil amendment and to certain extent as a slow release nutrient source. Table 2 shows the organic matter and nutrient content of some common organic materials which could be used to lower metal availability, in addition to remediating the physical and chemical properties of the spoils, and the provision of plant nutrients (Bradshaw and Chadwick, 1980). Plant residues (e.g. rice and barley straw) can be used as a mulch to insulate the surface from temperature extremes, permits the soil to absorb moisture and reduce water erosion. In addition to organic amendments, inorganic amendments are used to improve substrate characteristics. These included quarry waste, pulverized refuse, pulverized fuel ash, etc. Inert materials including colliery spoils and steel slag are very often necessary to serve as an insulation layer, to avoid upward migration of toxic elements to the topsoil. It is a common practice to apply liming materials to overcome some of the problems associated with acidic condition.

### Table 2
Nutrient and organic matter contents of some organic soil amendments (from Bradshaw and Chadwick, 1980) (% dry solids)

<table>
<thead>
<tr>
<th>Material</th>
<th>Nitrogen</th>
<th>Phosphorus</th>
<th>Potassium</th>
<th>Organic matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmyard manure</td>
<td>0.6</td>
<td>0.1</td>
<td>0.5</td>
<td>26</td>
</tr>
<tr>
<td>Poultry manure</td>
<td>2.3</td>
<td>0.9</td>
<td>1.6</td>
<td>68</td>
</tr>
<tr>
<td>Sewage sludge</td>
<td>2.0</td>
<td>0.3</td>
<td>0.2</td>
<td>45</td>
</tr>
<tr>
<td>Domestic refuse</td>
<td>0.5</td>
<td>0.2</td>
<td>0.3</td>
<td>65</td>
</tr>
<tr>
<td>Straw</td>
<td>0.5</td>
<td>0.1</td>
<td>0.8</td>
<td>95</td>
</tr>
</tbody>
</table>
4. Phytoremediation of metal-mined soils

Selection of appropriate plant species would be very important to ensure a self-sustainable vegetation cover. Phytoremediation refers to the use of green plants and their associated microbiota, soil amendments, and agronomic techniques to remove, contain, or render harmless environmental contaminants (Cunningham and Ow, 1996). Phytoremediation of heavy metal-contaminated soils basically includes phytostabilization and phytoextraction.

4.1. Containment of toxic metals by plants

4.1.1. Phytostabilization

Some soils are so heavily contaminated that removal of metals using plants would take an unrealistic amount of time. The normal practice is to choose drought-resistant, fast-growing crops or fodder which can grow in metal-contaminated and nutrient deficient soils. Phytostabilization is the use of metal-tolerant plant species to immobilize heavy metals through absorption and accumulation by roots, adsorption onto roots, or precipitation within the rhizosphere. This process reduces metal mobility and also reduces bioavailability for entry into the food chain. By using metal-tolerant plant species for stabilizing mine spoils, it could also provide improved conditions for natural attenuation.

Some plant cultivars tolerant to toxic metals are available commercially in some countries such as the UK and Australia (Lothenbach et al., 1998). The existence of these plant varieties is the result of evolution rather than innate physiological tolerance (Bradshaw, 1993). These included single (Cynodon dactylon) (Wong, 1982) and multiple (Festuca rubra, Typha latifolia and Phragmites australis) (Wong and Lau, 1985; Ye et al., 1997a,b, 1998a,b) tolerances to heavy metals.

There is literally growing evidence that phytostabilization can be achieved by selective planting in combination with a various soil amendments such as zeolites, beringite, steel shot and hydroxyapatite that immobilize metals in soil (Lothenbach et al., 1998). During the past few years we have demonstrated successful establishment and colonization of several pioneer plant species growing on Pb/Zn mine spoils in China. These included Vetiveria zizanioides, grass (Shu et al., 2000), Sesbania rostrata, herb legume (Yang et al., 1997), and Leucaena leucocephala, woody legume (Zhang et al., 2001). Therefore, selection of appropriate plant species which can establish, grow and colonize metal-contaminated soils is important for successful reclamation of these sites.

Vetiver grass (V. zizanioides) has a massive finely structured and deep root system capable of reaching 3–4 m in the first year. Due to its unique morphological and physiological characteristics, it has been commonly known for its effectiveness in erosion and sediment control, and has also been found to be highly tolerant to extreme soil conditions including prolonged drought, flood, submergence, extreme temperature (−10 to 48 °C), and a wide range of soil acidity and alkalinity (pH from 3 to 10.5). The plant is also highly tolerant to soil salinity, sodicity, acidity, Al, Mn and heavy metal (such as As, Cd, Cr, Ni, Pb, Zn, Hg, Se and Cu) toxicities in the soil (Dalton et al., 1996). Greenhouse and field trials in Queens land, Australia have shown that vetiver grass is suitable for the rehabilitation of metal contaminated soils, and for the treatment of landfill leachate (Truong and Baker, 1988). Recently, it has been found that vetiver grass was the best plant species (in terms of biomass production and coverage) when compared with other three grass species, namely Paspalum notatum, C. dactylon and Imperata cylindrica var. major used for revegetating Pb/Zn mine tailings in South China (Shu et al., 2000). In addition, oil products extracted from vetiver roots posses high values in biomedical utilization (Andersen, 1970). By planting vetiver grass in metal-contaminated soils, it will fulfill the dual purpose of stabilizing the site and modifying soil properties suitable for the colonization of other plants, and at the same time producing oils with a high commercial value. It is essential to investigate if there were higher metal concentrations taken up by the grass, and the subsequent effects on the quantity and quality of the oil products.

An annual legume native to Africa S. rostrata which possesses stem as well as root nodules can be used to modify properties of mine spoils, by supplying the much needed N and organic matter. The plant is able to complete its life cycle and produce seeds within four months after growing on bare Pb/Zn mine tailings. Apart from having a very high growth rate, it is also tolerant to toxic metals and low nutrient status, and therefore will be an ideal pioneer species to accelerate ecological succession of the man-made habitats. Table 3 shows that S. rostrata had higher biomass, and N accumulation when grown in Pb/Zn mine tailings amended with domestic refuse, which was possibly due to the higher biomass of both stem and root nodules. The N-fixing bacteria Azorhizobium caulinodans (AR57 and AR111) seemed to be rather tolerant to the stress imposed by Pb/Zn mine tailings, as they were able to fix N (Yang et al., 1997).

It is commonly observed that heavy metals will inhibit the growth of rhizobia (Obbard et al., 1993), and host legume, nodulation and N-fixation activity. This results in the failure of legume-rhizobia symbiotic associations (McGrath et al., 1995), which will in turn negatively affect the provision of organic matter by the legume, and the N cycle within mine wastes. Therefore, understanding the effects of metals on the host legume,
and the legume-rhizobia symbiotic association, is important for using legumes in the reclamation of metal-contaminated areas (Zhang et al., 1998).

4.2. Using plants to remediate metal-contaminated sites

4.2.1. Phytoextraction

Phytoextraction is also called phytoaccumulation. It involves the uptake and translocation of heavy metals by roots into the aboveground portions of "hyperaccumulator" plants. Some plants have a quite extraordinary ability to accumulate heavy metals, to the extent they are described as hyperaccumulators. Hyperaccumulators are able to accumulate Zn concentration higher than 1%, and Cu, Pb and Ni higher than 0.1% of the tissue dry weight (Baker et al., 1994).

Hyperaccumulators of Ni, Cd and Zn have been identified and characterized. There is sufficient evidence showing that plants including certain species and clones of trees (e.g. willows and poplars) can remove sufficient heavy metals from soils to clean-up at least low-level contaminated soils (Dickinson and Lepp, 1997). Table 4 compares the removal of Zn by different species of hyperaccumulator plants and non-accumulating plants growing in soils receiving 20 years of sludge application (Baker et al., 1994). The results indicated that the rate of removal of Zn *Thlaspi caerulescens* was greater than the allowed maximum annual addition of Zn to soils, the Belgian population (B) could remove twice amount. It was estimated that 13 cropings with this population would be required to extract the excess loading of Zn (374 kg/ha) in the experimental soil to bring the total soil Zn concentration down to below CEC limits, from 444 to 300 mg/kg (CEC, 1986), provided if the subsequent crops would remove metals at the same rates as the first crop. Therefore, metal-contaminated soils can be cleaned up by sowing hyperaccumulating plants, after several harvests of the plants along with the metals. Plants are harvested and either incinerated or composted to recycle the metals.

Recently, we have observed that there is a potential plant species, namely *Commelina communis* growing on the Cu mine spoils at Huangshi, Hubei Province, which have a high uptake of Cu, in the shoot, exceeding 1% of their total dry weight (Shu et al., unpublished data). Selective breeding, adding soil amendments to increase metal uptake and transfer of hyperaccumulator genes into genetically engineered crop plants are all real possibilities and huge advances in these areas have been made in the last few years (Chaney et al., 1998; Salt et al., 1998). In addition, synthetic metal chelates, such as EDTA and citric acid have been used as soil amendments to enhance metal uptake by these hyperaccumulators (Luo et al., 1999; Wong et al., 1999a,b). Recently, synthetic metal chelates have been used to artificially induce hyperaccumulation of toxic metals, e.g., Pb from the soil into plant shoots (Huang et al., 1997). Each cleanup situation may also require a different plant species or a number of plants in tandem. In general, phytoremediation is used in conjunction with other cleanup approaches (Asante-Duah, 1996).

### Table 3

Growth, nodulation, and nitrogen accumulation of *S. rostrata* grown in Pb/Zn mine tailings and tailings amended with sediment and domestic refuse (from Yang et al., 1997)

<table>
<thead>
<tr>
<th>Culture medium</th>
<th>Plant height</th>
<th>Biomass</th>
<th>Nitrogen accumulation (mg/plant)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Plant (DM g/plant)</td>
<td>Stem nodule (FM mg/plant)</td>
</tr>
<tr>
<td>100% tailings</td>
<td>49a</td>
<td>8.1a</td>
<td>207</td>
</tr>
<tr>
<td>85% tailings + 15% sediment</td>
<td>55a</td>
<td>12.1a</td>
<td>272</td>
</tr>
<tr>
<td>85% tailings + 15% refuse</td>
<td>65b</td>
<td>15.9b</td>
<td>301</td>
</tr>
</tbody>
</table>

DM—dry matter; FM—fresh matter.
Different letters of the same vertical row indicate significant difference at \( p < 0.05 \) level based on LSD test.

### Table 4

The extraction efficiency of Zn by different hyperaccumulator and non-accumulator plants (from Baker et al., 1994)

<table>
<thead>
<tr>
<th>Plant species</th>
<th>Plant uptake (kg/ha)</th>
<th>Removal as % of annual permitted addition rate</th>
<th>Number of cropings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyperaccumulator species</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>T. caerulescens</em> (population B)</td>
<td>30.1</td>
<td>201</td>
<td>13</td>
</tr>
<tr>
<td><em>T. caerulescens</em> (population A)</td>
<td>27.6</td>
<td>184</td>
<td>14</td>
</tr>
<tr>
<td><em>Cardaminopsis halleri</em></td>
<td>10.3</td>
<td>69</td>
<td>37</td>
</tr>
<tr>
<td><em>Alyssum tenium</em></td>
<td>4.3</td>
<td>29</td>
<td>88</td>
</tr>
<tr>
<td><em>Alyssum lesbiacum</em></td>
<td>3.9</td>
<td>6</td>
<td>96</td>
</tr>
<tr>
<td><em>Alyssum murale</em></td>
<td>3.6</td>
<td>24</td>
<td>105</td>
</tr>
<tr>
<td><em>Thlaspi ochroleucum</em></td>
<td>1.5</td>
<td>10</td>
<td>254</td>
</tr>
<tr>
<td>Non-accumulator</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Cochlearia pyrenaica</em></td>
<td>0.6</td>
<td>4</td>
<td>622</td>
</tr>
<tr>
<td><em>Brassica napus</em></td>
<td>0.5</td>
<td>3</td>
<td>832</td>
</tr>
<tr>
<td><em>Raphanus sativus</em></td>
<td>0.2</td>
<td>1</td>
<td>2046</td>
</tr>
</tbody>
</table>
4.2.2. Phytofiltration

Rhizofiltration is the removal of contaminants from flowing water; this can be achieved by the plant itself or the microorganisms associated with the rhizosphere. Floating plants such as water hyacinth and duckweed have been used in a large scale for the treatment of municipal wastewater in Asia (Negri and Hinchman, 1996).

Certain varieties of sunflowers have been identified as having the highest metal removal capacity after screening hundreds of plant species. It has been observed that within several hours, small amounts of roots of hydroponically grown sunflower plants were able to remove various metals (Pb, Cu, Sr, Cs, Co and Zn) from water to reach concentrations meeting accepted water standards. Several other terrestrial plants have been shown to accumulate Pb in their roots when grown hydroponically, e.g., Indian mustard, Brassica juncea where Pb removal was based on tissue absorption and on root-mediated Pb precipitation in the form of insoluble inorganic compounds (lead phosphate) (Raskin, 1997).

Emerging wetland species such as reeds and bulrush have been investigated and applied more recently for the removal of nutrients and/or heavy metals (Sundaravadivel and Vigneswaran, 2001). A combined treatment system which includes an aquatic treatment pond with Typha latifolia as the dominant species and a stabilization pond, to treat the wastewater from a Pb/Zn mine at Shaoguan, Guangdong Province, China. The wastewater contained high concentrations of Pb (1.6 mg/l) and Zn (1.9 mg/l), as well as total suspended solids (4635 mg/l), and chemical oxygen demand (14.5 mg/l). The results of the effluent after treatment showed that concentrations of Pb, Zn, total suspended solids and chemical oxygen demand had been reduced by 95%, 80%, 99% and 55% respectively (Lan et al., 1992).

5. Maintenance of biodiversity and environmental health

Special attention should be given to restore wildlife communities. Diversified crops and fruit trees should be planted, and agriculture should be integrated with forestry and animal husbandry, appropriate to local conditions. Assessment and monitoring should be made in order to ensure toxic substances are not transferred and accumulated through food chains, if the sites are used for agriculture and animal husbandry purposes.

6. Conclusion

In order to achieve a self-sustainable vegetation on toxic-metal mined lands, it is essential to choose plant materials which are tolerant to the specific metals, as well as tolerant to drought and the lack of nutrients. Adding organic amendment is essential to facilitate the establishment and colonization of these “pioneer plants”. They can eventually modify the man-made habitat and render it more suitable for subsequent plant communities. Planting of different grass species, rotating with legumes and native species will be able to restore soil fertility and accelerate ecological succession. The use of hyperaccumulator plants seems to be only effective for cleaning up soils containing light to moderate toxic metal concentrations.

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References


Wong, M.H., 1982. Metal co-tolerance to copper, lead and zinc in Festuca rubra. Environ. Res. 29, 42–47.


