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Review

Mining waste contaminated lands: an uphill battle for improving crop productivity

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Abstract: Mining drastically alters the physico-chemical and biological environment of the landscape. Low organic matter content, unfavourable pH, low water holding capacity, salinity, coarse texture, compaction, siltation of water bodies due to wash off of mineral overburden dumps, inadequate supply of plant nutrients, accelerated erosion, acid generating materials, and mobilization of contaminated sediments into the aquatic environment are the principal constraints experienced in mining contaminated sites. A variety of approaches have been considered for reclaiming mine wastes including direct revegetation of amended waste materials, top soiling, and the use of capillary barriers. The simplest technology to improve crop productivity is the addition of organic amendments. Biosolids and animal manure can support revegetation, but its rapid decomposition especially in the wet tropics, necessitates repeated applications. Recalcitrant materials such as "biochars", which improve soil properties on a long term basis as well as promote soil carbon sequestration, hold enormous promise. An eco-friendly and cost-effective Microbe Assisted Phytoremediation system has been proposed to increase biological productivity and fertility of mine spoil dumps. Agroforestry practices may enhance the nutrient status of degraded mine spoil lands (facilitation). N-fixing trees are important in this respect. Metal tolerant ecotypes of grasses and calcium-loving plants help restore lead, zinc, and copper mine tailings and gypsum mine spoils, respectively. Overall, an integrated strategy of introduction of metal tolerant plants, genetic engineering for enhanced synthesis and exudation of natural chelators into the rhizosphere, improvement of rhizosphere, and integrated management including agroforestry will be appropriate for reclaiming mining contaminated lands.

***Keywords**: agroforestry, biochars, mining sites, organic amendments, phytoremediation, revegetation*

Introduction

Mining generates considerable waste materials and tailings, which are deposited on the surface as mine-spoil dumps. Removal of fertile topsoil, formation of unstable slopes prone to sliding and erosion, and siltation of water bodies due to wash off of mineral overburden dumps are also major negative effects of mining. The metals released from mining, smelting, forging, and other sources would accumulate in the soil (Khan et al., 2009), altering its chemistry. Metal contamination is not restricted to the mining site only because considerable release of metals occurs through acid mine drainage and erosion of waste dumps and tailing deposits (Salomons, 1995). Land use conflicts owing to operations close to the dwellings and farmlands as well as disposal of mine wastes on land intended for other uses, air and noise pollution, siltation of rivers by leachate and runoff from waste dumps, and degradation of land are also commonly associated with mining (Banda, 1995). Mining conflicts related to discharges of suspended solids rich in mercury, and cyanide from the artisanal gold mining areas into rivers are a major concern in Africa and South America. In the Ecuadorian artisanal gold mine environment, for instance it has been noticed that, when the river overflows, the mercury reaches the downstream banana plantations and shrimp ponds (UNIDO, 2007). The hazards of surface and groundwater pollution increases significantly when the mine waste materials contain reactive sulphide minerals such as pyrite (Liao et al., 2007). Pyrite-bearing mine tailings disposed at neutral or slightly alkaline conditions also can weather within a relatively short period of time to produce extreme acidity and lead to acid mine drainage (Robb and Robinson, 1995). Acid mine drainage usually contains a high load of heavy metals, in addition to having a low pH, which poses a major risk to surrounding water and soil systems (Achterberg et al., 2003; Braungardt et al., 2003). Chemical problems associated with surface mining, such as acid generating materials, are thus significant (Darmody et al., 2002) and in mine spoils, the geomorphic system is in disequilibrium (Dutta and Agarwal, 2001). Unfavourable soil chemistry and poor structure also deprive soil microbe and plant growth (Pederson et al., 1988).

Although mining-contaminated lands constitute a relatively small proportion of the total extent of degraded lands in the world, the scale of mining is increasing and the impacts are generally more severe than most other kinds of disturbances (Walker and Willig, 1999). Surface mined areas and mine spoil dumps are also nutritionally deprived habitats characterized by infertile soils having extreme pH values, low cation exchange capacity, low water holding capacity, low nutrient availability, and poor organic matter status (Gonzalez-Sangregorio et al., 1991).

Given the growing food insecure populations of the world (835.2 million undernourished people in the developing world according to FAO 2010), it is important to raise agricultural productivity on all types of lands including the mine-contaminated ones. In this paper, I will address the issues related to mine contaminated sites from the perspective of sustaining agricultural productivity.

Mine-spoil reclamation: problems and approaches

Reclamation of mine dumps and abandoned mine lands (AML) is a complex multi-step process. The first step in transforming the mine contaminated lands into productive agricultural lands is restoring its ecological integrity (Sheoran and Sheoran, 2009; Juwarkar and Singh, 2010). Most AML sites and many active mining or re-mining sites, however, lack any true topsoil and it consists primarily of mine spoil or overburden whose properties can range from loose, coarse textured material with many rock fragments, to highly compacted clay material. Broadly two types of effects are plausible: **excesses** (supra-optimal levels of chemical elements including metal ions) and **deficiencies** (suboptimal concentrations of essential elements).

Mine contaminated soils thus represent a very harsh environment for crop production (e.g., phytotoxicity and high acid production potentials of waste materials, low fertility, and limited topsoil availability). The principal restoration options are, therefore, **ameliorative** (improving the physical and chemical nature of the site) and **adaptive** (careful selection of species, cultivars, or ecotypes), both to be used in juxtaposition with one another (Johnson et al., 1994).

Amelioration

Topsoiling

Although a variety of approaches has been employed for reclaiming acid mine wastes including direct revegetation (no soil cover) of amended waste materials, application of topsoil is often the most effective method. Experimental studies have shown that topsoiling improved the water holding capacity and nutrient status of the mine wastes (e.g., Trlica et al., 1995), and provided a source of propagules and soil microorganisms (Schuman and Power 1980). Bowen et al. (2002) assessed the long-term (after 24 years) effects of different topsoil replacement depths (0, 20, 40, and 60 cm) on plant community cover, production, and diversity in south-central Wyoming, USA. Plant species richness was highest (7.5) at the zero topsoil depth and lowest (5.6) at the 60 cm topsoil depth. Total canopy cover was greatest (average 26.7%) at 40 and 60 cm of topsoil and least (21.5%) at the zero topsoil depth. Merril et al. (1998) noted that the productivity of soil reconstructed by topsoil-subsoil placement on sodic mine spoil), however, would be influenced by the subsoil characteristics. Redente and Sydnor (2005) evaluated long-term plant community development on study plots in which 60 cm of retorted oil shale was covered by various depths of topsoil. Data over 20 years showed that native species were as productive as introduced species on deeper topsoil depths, implying the need for thick topsoiling. Excavated sediment of ponds and tanks is an effective indigenous soil amendment practice in India. Pond silt, rich in organic material, has been used for preparation of a topsoil layer of about 30–50 cm over the mine waste and levelled pits in some case studies (Singh et al., 2000; Wong, 2003). Silt layer also increased the productivity of the land and helped ground water recharge.

Capillary barriers

Despite potential benefits of amending mine waste and/or topsoiling, problems may arise such as acidification (or reacidification) of surface layers (Boon, 1986), excessive plant uptake of trace elements (Paschke et al., 2000), and/or capillary rise of soluble salts (McFarland et al., 1994). Therefore, some researchers have investigated the use of capillary barriers between overlying topsoil and underlying wastes as a reclamation option to reduce capillary rise of salts and trace elements and direct contact of plant roots with untreated waste materials. For instance, Molson et al. (2008) used *covers with capillary barrier effects* (CCBEs) for reducing acid mine drainage (AMD) from sulphidic mine tailings and found that capillary barrier covers significantly reduced sulphide oxidation and AMD. A CCBE basically involves the placement of a relatively fine-grained soil, which acts as a water-retention layer, over a coarser capillary break material. Aubertin et al. (2009) showed that increasing the thickness of the cover may improve efficiency, but only up to a certain maximum beyond which the gain becomes minimal. One promising option is to combine different types of soil to create a layered CCBE.

Phytoremediation

Recently, the potential of bioremediation, particularly the role of higher terrestrial plants (phytoremediation) in reclamation of metal-polluted soils has been studied (Ghosh and Singh, 2005a), particularly for clean-up of diffusely polluted soils (Ginneken et al., 2007). Generally, decontamination of metal-contaminated soils requires the removal of toxic metals, as they cannot be degraded. Phytoextraction thus has emerged as a cost-effective, environment-friendly clean-up alternative. One of the directions in which research is currently evolving, is the use of oil-producing plant species, such as rape seed (*Brassica napus*) for phytoextraction purposes (Ginneken et al., 2007). Phytoremediation of metal contaminated soils thus is a 'win-win' situation: the biomass produced could be economically valorised in the form of bioenergy, e.g., *Brassica* spp. grown on metal contaminated sites can yield biodiesel, besides having the potential to accumulate high levels of heavy metals including Cd, Cr, Cu, Ni, Pb and Zn under certain conditions (Ebbs et al., 1997 and many others). A variety of factors, such as climatic conditions, soil properties, and site hydro-geology, however, may impact its efficiency (Lasat, 2000).

Short rotation coppice crops (SRC) consisting of fast growing trees such as willow (*Salix* spp.), poplar (*Populus* spp.), or black locust (*Robinia pseudoacacia*) are also promising as they can be used for bioenergy production and C sequestration (Quinkenstein et al., 2011), apart from phytoremediation. Experiments on reclamation sites have reported growth rates between 1 to 6 Mg/ha/ yr for poplar and willow (Bungart and Hüttl, 2004; Grünewald et al., 2007). For black locust plantations established on reclamation sites in the mining district of Lower Lusatia, Germany, average aboveground biomass production ranged from 0.04 to 9.5 Mg/ha/ yr for 1 to 14 years of growth (Quinkenstein et al., 2011).

Juwarkar and Singh (2010) suggested an eco-friendly and cost-effective *microbe-assisted phytoremediation (MAP)* approach for restoring zinc mine spoil dumps. This approach involves isolation and inoculation of site-specific specialised nitrogen-fixing strains of *Bradyrhizobium* and *Azotobacter*, nutrient mobilising vesicular arbuscular mycorrhizal spores of *Glomus* and *Gigaspora* sp., selection of suitable plant species (preferably multispecies), and the use of organic amendments. This approach restored the productivity, fertility, and stability of zinc mine spoil leading to the development of sustainable ecosystems (Juwarkar and Singh 2010). Other beneficial microbes, which accumulates heavy metals, and decrease crop uptake include *Piriformospora indica*, a root-colonizing endophytic fungus (Oelmüller et al., 2009). Rhizobacteria, besides their role in metal detoxification/removal, also promote plant growth through production of growth promoting substances and siderophores (Khan et al., 2009). Choice of appropriate plant varieties, which are tolerant to the specific metals, is another design criterion for reclaiming mine overburdens. Among the tree species evaluated, *Eucalyptus tereticornis, Acacia auriculiformis,* and *Casuarina equisetifolia* were the most suitable for modification of spoil characteristics during the revegetation process (Dutta and Agrawal, 2002). Juwarkar et al. (2009) reported that tree species such as *Tectona grandis*, *Senna siamea*, *Dalbergia sissoo*, *Dendrocalamus strictus* and *Acacia nilotica* generated large biomass and soil organic matter, implying the need for site-specific selection of the tree and crop components.

Mixed species stands and agroforestry

In recognition of the role of trees to improve soil fertility (Nair et al., 2010), agroforestry systems (growing trees and crops in an integrated manner) are believed to have a great potential to reclaim the mine contaminated sites. This conjecture is based on the notion that tree incorporation would result in greater export of pollutants, improve site fertility, and render the sites productive. Since nutrient availability especially nitrogen commonly limits site productivity of mine spoils, the development of systems with nitrogen-fixing species—the so-called 'fertilizer trees' and cover crops—are important. Leguminous cover crops (e.g., *Centrosema*, *Calapogonium*, and *Pueraria*) are particularly important in this respect. Kimaro and Salifu (2011) also screened several grass species to identify appropriate cover crops for nursing newly planted tree seedlings and reported better survival and growth for trees grown in association with cover crops. Kumar et al. (1998) reported that in intercropping trials with teak (*Tectona grandis*) + *Leucaena leucocephala*, teak growth increased linearly as the proportion of *Leucaena* in the mixture increased. At 44 months after planting, teak in the 1:3 teak-*Leucaena* mixture was 45% taller and 71% larger in diameter at breast height than those in pure stands. Likewise, Parrotta (1999) found that at harvest age of 4 years, total aboveground biomass ranged from 63 Mg/ha/yr in the *Eucalyptus* monoculture to 124 Mg/ha/y in the

Casuarina+Leucaena mixture (50:50). Kaye et al. (2000) compared N_2-fixers and non-N_2-fixers and found 20 to 100% more soil C under N_2fixers. Overall, species mixtures especially those involving fertilizer trees may be useful in the ecorestroration of contaminated mine sites, where the soils are low in nitrogen.

Soil Enhancement Applications

Organic matter and synthetic amerliorants

Many studies have illustrated numerous benefits of adding organic matter (OM), in addition to lime and fertilizer, to acidic mine wastes (Bellitto et al., 1999). Mine reclamation research and practices have also demonstrated that organic amendments such as biosolids can support revegetation of mine spoil materials (Stehouwer, 1997). Most surface-mining reclamation operations also stockpile the A horizon and then redistribute these materials over the tailings and overburden to offset the problems of low water-holding capacity and compaction. Constructing an A horizon from tailing materials, however, requires additions of organic matter. By extension, productivity can be increased by adding various natural amendments such as saw dust, wood residues, sewage sludge, animal manures, and organic carbon to soil, which stimulates the microbial activity and augments nutrient (N, P) availability.

Synthetic and natural zeolites have been used as chelators for rapid mobility and uptake of metals from contaminated soils by plants (Prasad and Freitas, 1999). Use of synthetic chelators significantly increased Pb and Cd uptake and translocation from roots to shoots facilitating phytoextraction of the metals from low grade ores. Cross-linked polyacrylates, hydrogels, to metal-contaminated soils are used extensively (Prasad and Freitas, 1999) to increase the nutrient efficiency and alleviate the detrimental effects of the heavy metals (Prasad and Hagemeyer, 1999).

Hyper-accumulation can be induced in some plant species by soil amendment using EDTA on an insoluble target metal complex such as lead ore, rendering insoluble elements soluble (Anderson et al., 1998). Contrastingly, synthetic cross linked polyacrylates (hydrogels) have protected plant roots from heavy metal toxicity and prevented the entry of metals into roots (Prasad and Hagemeyer, 1999). However, large scale application of such synthetics may not be cost effective.

Organic matter inputs have the potential to improve the properties of mine tailings and spoils by increasing water-holding capacity, cation exchange capacity, buffering capacity, and by promoting soil structure and reducing bulk density (Smith et al., 1987). Incorporation of organic matter significantly increased aboveground biomass, with mushroom compost being more effective than biosolids (Redente and Sydnor, 2005). Various sources of organic resources and by-products are used as mine-spoil amendments. Recent research on these aspects is summarised below.

- Surface applications of municipal sewage sludge (Oyler 1988), fly ash (Moffat et al., 2001) and press mud (Juwarkar et al., 1992) were successful in promoting plant growth.
- Mine tailings amended with yardwaste compost (i.e., the end product of decomposing leaves and grass clippings) showed greater porosity, water-holding capacity (WHC), and saturated hydraulic conductivity of soil (K_{Sat}) and lower mechanical resistance, and bulk density than un-amended tailings (Stolt et al., 2001).
- Because of the dominance of silt-size particles, fly ash may often be substituted for topsoil in surface mine lands, thereby enhancing physical conditions of soil, especially WHC (Adriano and Weber, 2001). Certain fly ashes are able to provide essential nutrients for plant nutrition.
- 'Wastes' from mining and mineral-related industries are useful for low-input agriculture. Examples include: waste from incomplete calcining in lime operations, calcium carbonate wastes from cement and other industries using $CaCO_3$, wastes from 'black granite' operations, phosphate mining / processing, steel production (e.g., basic slag, and calcium silicate slag), coal burning operations (fly ash, bottom ash, the by-products of fluidized bed combustion), and materials from flue gas desulphurization scrubbers are rich in micronutrients, with potential for application to the crop fields (van Straaten, 2002).
- Mine tailings containing biotite has the potential to be used as a slow-release K fertilizer and has been evaluated on pasture lands in Norway (Bakken et al., 2000). Likewise, calcium silicate slags increased sugarcane yield, specifically on low Si soils (Anderson et al., 1991).
- Phosphogypsum as a soil amendment on sodic soils and for groundnut fertilization has been tested (van Straaten, 2002). Pyrites and pyritic mill tailings with low to heavy metal contents have also been tested as inexpensive Fe-sources for sodic and Fe-deficient soils.
- Particle size and shape, alkalinity, and availability of several micronutrients in coal combustion by-products (CCBs) have been used to amend soil texture for increased water infiltration and acidity, and to supply some of the nutrient needs of the agricultural soils (Chugh et al., 2000). Alfalfa yields increased

significantly by application of the CCB to the soil compared to the untreated control.

- Magnesium-containing fluidized bed combustion by-products have proved to be effective liming materials with a high effectiveness to ameliorate subsoil Al phytotoxicity (Stehouwer et al., 1999).
- Use of effluent treatment plant sludge, as an organic amendment, biofertilizers, and mycorrihzal fungi along with suitable plant species improved the physico-chemical properties of coal mine spoil (Juwarkar and Jambhulkar 2008).

Charcoal and biochar application

Considering the fact that soil organic matter in degraded land is very low, the simplest technology to improve soil productivity and stabilize crop yield is the addition of organic amendments, as outlined in the preceding section. The main limitation of organic matter addition, especially in the wet tropical condition, however, is its rapid decomposition, necessitating repeated additions during every planting season, which is impractical in view of the difficulty to source enough organic manures.

Some workers have therefore evaluated recalcitrant organic materials such as "biochars" for their ability to improve soil properties, carbon sequestration (e.g. Glaser et al., 2002; Lehman et al., 2003; Liang et al., 2006), and to increase crop yields (Yamato et al., 2006; Chan et al., 2008). Islami et al. (2011) tested the hypothesis that the beneficial effects of biochar as organic amendments in cassava based cropping system would last longer compared to that of the conventional organic manure such as farm yard manure and would promote soil carbon sequestration. The beneficial effects of biochar on soil properties also have been reported by many and includes chemical (Yamato et al., 2006), physical (Chan et al., 2008), and biological changes in the soil (Rondon et al., 2007). By extension, incorporation of biochar in mine contaminated sites may improve its nutrient retention power and productivity.

Metal tolerant cultivars

The use of metal tolerant ecotypes is a proven reclamation technology for lead, zinc, and copper mine tailings (Tordoff et al., 2000). Metal tolerance is a genetically heritable character, and some cultivars too have been bred incorporating this trait (e.g., *Festuca rubra* cv. "Merlin") (Johnson et al., 1994). Direct seeding of tolerant cultivars is a promising area of further development. Results of some long term trials for exploiting biodiversity for dealing with difficult man-made substrates are available (e.g., Nicks and Chambers, 1995; Ginocchio, 1998). Introduction of metal tolerant wild plants to metalliferous soils, genetic engineering of plants for enhanced synthesis and exudation of natural chelators into the rhizosphere, improvement of the rhizosphere with the help of mycorrhiza and integrated management of the metalliferous ecosystem following the principles of phytoremediation are important. The efficiency of phytoremediation can be enhanced by the judicious and careful application of appropriate heavy-metal tolerant, plant growth promoting rhizobacteria including symbiotic nitrogen-fixing organisms.

Conclusions

Future challenges in crop productivity of the mining and mineral industries include the increasing scale of operations with large mining companies seeking to exploit large reserves in more remote wilderness environments, greater innovation in new technologies such as the *in situ* extraction of metals through leaching, the increasing need to regulate and develop environmental management in the artisanal and small mining sector, and the imperative to incorporate policies of sustainable development as far as possible. Most of the new mining initiatives currently are in developing countries, and this will extend to mining ore deposits in more remote and fragile ecosystems. The time has arrived for a rethinking on the way mine contaminated site development programs are planned and implemented around the world.

We need to encourage the "remarriage of trees, tolerant crops and microbes" on these landscapes and exploit the time-tested benefits of such practices to address some of the major threats of increasing extent of mine spoils and contamination. If we are to meet society's needs and aspirations, we must find novel ways of utilizing mine contaminated lands.

While it is creditable that considerable progress has been achieved during the past three decades in transforming mine-contaminated lands into agriculturally productive sites, several knowledge gaps exist even in areas that have received research attention in the past. There are also several potentially promising areas that have not yet been explored. For example, substantial efforts are needed to domesticate metal tolerant species and breed new cultivars with higher yield potential. In our obsession with "grain crops" in modern agriculture, we have ignored the tree component which has considerable potential for "phytoremediation".

The exploitation of these species, and the agroforestry practices involving their use, has wide implications in food security and environmental protection, as well as conservation and use of genetic resources.

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