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REVIEW ARTICLE

Plantations as a tool for mine spoil restoration

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Because of large-scale destruction of natural areas due to mining operations, a restoration strategy is needed as a part of the overall mining management plan. In restoration, emphasis is given first to build soil organic matter, nutrients and vegetation cover to accelerate natural recovery process. Tree plantations can be used as a tool for mine spoil restoration as they have ability to restore soil fertility and ameliorate microclimatic conditions. We discuss here various approaches of ecosystem restoration on mine spoil, criteria for the selection of plantation species and future research needs in this regard.

VAST areas of land all over the world have been rendered unproductive by human activities[1]. The situation is particularly alarming in tropical areas where forest loss and degradation, as well as degradation of land that earlier supported forest, are proceeding at unprecedented rates[2,3]. Ecosystem destruction by mining for coal, quarrying for minerals, and other processes to meet demands of industries, is an inevitable part of civilization[4]. The increasing human need for these resources will certainly accelerate further degradation of natural habitats, as most of the mining areas are on the land which was previously occupied by forests. All these will lead to acceleration of erosion of biological diversity and creation of several other environmental problems.

The mine environment

As a result of mining and coal combustion, significant areas of land are degraded and existing ecosystems are replaced by undesirable waste materials in the form of dumps, tailing dams and ash dams[5]. The mineral extraction process drastically alters the physical and biological nature of a mined area. Strip-mining, commonly practiced to recover coal reserves, destroys vegetation, causes extensive soil damage and destruction and alters microbial communities[6]. In the process of removing desired mineral material, the original vegetation is inevitably destroyed and soil is lost or buried by waste[7]. We are usually confronted with a complete absence of soil, in either a pedological or a biological sense, and what is left is just a skeleton full of limiting factors[4]. Strip-mining can cause compaction, changes in soil texture[8], loss of soil structure[9] and reduced water infiltration. In addition, steep-sided soil piles are prone to erosion[8].

Establishment of vegetation on abandoned mined lands is hindered by physical factors such as high temperature,

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low availability of soil moisture[10], uncertain structure and unstable slopes due to hilly terrain[11,12], and compactation[13,14]. Particularly, in arid and semi-arid areas, limited rainfall during the growing season and high surface temperatures often limit plant establishment and growth[15]. Sparse vegetation growth on abandoned mine soils also results from low organic matter; low levels of plant nutrients, particularly P[16,17] and N[18,19], K concentration[20]; and high levels of metals (Al and Mn)[21,22]. In certain areas, the main factor in preventing vegetation from becoming established is acidity[22]. During strip-mining, strata in the overburden are exposed, that may contain iron disulfide (FeS_2, pyrite) minerals[23]. These minerals, when exposed to air and moisture, oxidize to produce acid and soluble salts[24]. The final pH is affected by the amount and type of pyrite present[25] and the acidity of the various potential buffering systems[26]. Pyrite oxidation and hydrolysis give rise to large amounts of H^+ ions which, by decomposition and exchange reactions with other spoil minerals, can give rise to high concentration of Al, Mn, Fe, Zn and Cu[27,28]. Therefore, toxic concentrations of Al, Mn and Fe may occur where pH is low[29,30].

Unreclaimed or poorly reclaimed lands are often barren, because problematic soil material left on the surface after mining would not support plant growth[22]. This creates problems, as waste dumps can be unsightly and subject to erosion and leaching if left unvegetated. In such circumstances, extreme degradation can easily spread beyond the disposal site[31]. This necessitates initiation of restoration of the degraded environment.

Ecological restoration

Widespread loss of production and conservation values of natural habitats due to mining operations make large-scale ecosystem restoration an increasingly urgent task[32]. Ecological restoration is the process of repairing damage caused by humans to the diversity and dynamics of indigenous ecosystems[33]. There has been a tremendous upsurge in restoration as a technique for reversing habitat degradation worldwide[34,35]. Ecological restoration implies that we wish to restore organisms and their interactions with one another and with the physical environment[33]. Ecological restoration concentrates on processes such as persistence of species through natural recruitment and survival, functioning food webs, system-wide nutrient conservation via relationships among plants, animals and the detrivore community[33]. The goal of restoration is usually to develop a long-term sustainable ecosystem native to the area where mining occurred[36]. Restoration (= rehabilitation) aims to return the degraded system to some form of cover that is protective, productive, aesthetically pleasing, or valuable in the sense of conservation[32]. Key processes in restoration include identifying and dealing with the processes leading to degradation in the first place, determining realistic goals and measures of success, developing methods for implementing the goals and incorporating them into land management and planning strategies, and monitoring the restoration and assessing its success[32]. Dobson and coworkers[37] feel that ecological restoration will continue to provide important insight into the way that ecological communities are assembled and ecosystems function.

There are many approaches to land and vegetation rehabilitation[38]. These depend on severity of damage to the land resource, the goals of rehabilitation and the availability of resources for repairing the damage. The most intensive rehabilitation is sometimes termed reclamation, because the damage to sites is so severe that soils have to be replaced and landscapes may have to be reshaped[39,40]. Reclamation is the process by which derelict or highly degraded lands are returned to productivity, and by which some measure of biotic function and productivity is restored[38]. Long-term mine spoil reclamation requires the establishment of stable nutrient cycles from plant growth and microbial processes[41]. However, the reclamation process often becomes arrested because of severe limitations in the site or the biota[38]. In summary, rehabilitation, reclamation and restoration can be thought of as a continuum of outcomes from the least to the most similar to the predisturbance ecosystem[33].

Restoration of mine sites

The large-scale land disturbances associated with mining operations and related concerns about the environmental effects have triggered an increasing number of rehabilitation programmes which aim for the restoration of natural ecosystems disturbed by mining. Restoration of mine sites often entails amelioration of physical and chemical characteristics of substrate and ensuring the return of vegetation cover[39,42]. If specific problems hindering ecosystem redevelopment can be identified, a cure can be designed using or mimicking natural processes. According to Dobson *et al.*[37], this process of identification and intervention is the essence of ecological restoration.

The most common response to land degradation has been abandonment or reliance on natural succession to restore lost soil fertility, species richness and biomass productivity[2,3]. However, the process of natural succession on surface-mined soils is slow due to the removal of topsoil, resulting in elimination of soil seed bank and root stocks and due to soil profile disturbances[3]. As many as 50 or 100 years can elapse before a satisfactory vegetation cover develops on mine waste[7]. Redevelopment of advanced communities may take a millennium or more[37].

An important goal of ecological rehabilitation is to accelerate natural successional processes so as to increase biological productivity, reduce rates of soil erosion, increase soil fertility and increase biotic control over biogeochemical fluxes within the recovering ecosystems[43]. Analysis of different natural successions on natural and artificial substrates suggests that one of the important factors limiting the rate of development is the process of immigration of taxa[44,45]. There are genuine difficulties in appropriate species reaching a particular site, especially if they have heavy seeds, unless they already occur in the immediate vicinity[7]. Artificial revegetation is often used to facilitate the generally slow natural rehabilitation process[4,46]. Artificial seeding of grasses and legumes or both has been a commonly used method to stabilize unconsolidated mine tailings and to encourage natural invasion of tree and shrub seedlings. This ultimately improves site fertility and moisture retention capacity[47]. Once the abandoned mine lands have vegetation growing on the surface, the regeneration of these areas for productive use has begun and offsite damages are minimized. In addition, establishment of the vegetation on an abandoned mine land also improves the aesthetics of the area.

Overburden is the geologic material above coal seams and below the developed soil horizons[48]. Buried seeds and rhizomes are normally absent in overburden[49]. This fact makes seed reserves in the topsoil an important resource that, if handled correctly, can be used successfully to recover disturbed areas by natural vegetation[50–52]. Since most of the soil seed reserves are found in the surface 5 to 10 cm (refs 50, 53 and 54), upper 5–10 cm topsoil is recommended to be removed and replaced on the top of overburden material. However, the collection, storage and use of topsoil for restoration of mine areas are limited in many parts of the world[55]. Therefore, recent reclamation strategies have centred on creating soil that will support short-term establishment of native plant species and will sustain long-term successional development[56].

Harrington[57] describes plantation-related activities used in restoration of damaged sites. According to him, the first step should be stabilization of soil surface by contours, debris dams, mulch, etc. Compaction of soil also needs to be reduced by mechanical disruption. If needed, macroporosity of the soil can be improved by incorporation of wood and shale. Soil toxicity in terms of pH, metals and salts has to be reduced by suitable amendments and plantation of resistant species and cultivars. Vegetation establishment and mulching with organic matter will increase soil organic matter. Nutrient limitations imposed for the growth and establishment of vegetation can be minimized by fertilization and other soil amendments. One aspect in vegetation plantation is to improve microsite condition which can be done by scalping, microsite preparation or by clump planting. Once suitable vegetation starts growing, herbivory and physical damage can be reduced by controlled access, fencing and trapping[57].

Plantations on mine spoil

Plantation is the oldest technology for the restoration of lands damaged by human activity[58]. A primary objective for achieving satisfactory rehabilitation of a mined landscape is to establish a permanent vegetation cover. There is an increasing evidence that forest plantations can play a key role in harmonizing long-term forest ecosystem rehabilitation or restoration goals with near-term socio-economic development objectives[2]. Plantations can play a critical role in restoring productivity, ecosystem stability and biological diversity to degraded areas[42]. Relative to unplanted sites, plantations have a marked catalytic effect on native forest development (succession) on severely degraded sites[2].

Numerous studies have demonstrated that land rehabilitation benefits from plantations because it allows to jump-start succession[40,59–61]. The catalytic effects of plantations are due to changes in understorey microclimatic conditions (increased soil moisture, reduced temperature, etc.), increased vegetational–structural complexity, and development of litter and humus layers that occur during the early years of plantation growth. The development of a plantation canopy can alter the understorey microclimate and the soil physical and chemical environment to facilitate recruitment, survival and growth of native forest species. Otherwise, native species would only very slowly, if ever, regenerate on degraded sites[62–64]. Thus, plantations may act as 'foster ecosystems', accelerating development of genetic and biochemical diversity on degraded sites[65].

Plantations have an important role in protecting the soil surface from erosion and allowing the accumulation of fine particles[7]. They can reverse degradation process by stabilizing soils through development of extensive root systems. Once they are established, plants increase soil organic matter[66–68], lower soil bulk density, moderate soil pH and bring mineral nutrients to the surface and accumulate them in available form[7,69–71]. Their root systems allow them to act as scavengers of nutrients not readily available. The plants accumulate these nutrients and re-deposit them on the soil surface in organic matter, from which nutrients are much more readily available by microbial breakdown. This is exhibited in the levels of available phosphorus and potassium in afforested colliery spots[72].

Most importantly, some species can fix and accumulate nitrogen rapidly in sufficient quantities to provide a nitrogen capital, where none previously existed, more than adequate for normal ecosystem functioning[7]. Once the soil characteristics have been restored, it is not difficult to restore a full suit of plant species to form the required vegetation[37]. According to Faulconer *et al.*[73], other advantages are that establishment of desirable tree species capable of maintaining the site will slow or prohibit invasion of less desirable weedy species, will provide economic returns in the long term, will aid in developing wildlife habitat and will promote hydrologic balance in the watershed.

Species selection for plantations

The choice of plantation species is likely to greatly influence both the rate and the trajectory of rehabilitation processes[43]. The establishment of a permanent cover of vegetation involves not only growing plants, but it necessitates bringing into being a plant community that will maintain itself indefinitely without attention or artificial aid, and support native fauna[74]. Such performance could be achieved by selecting species adapted to grow, spread and reproduce under severe conditions, provided both by the nature of the damp material and the exposed situation on the dump surface[74]. The presence of certain tree species in a productive system can result in better soil structure and increased soil nutrient availability[68,69,75,76]. Among species that may be considered suitable for a given degraded site, there may be considerable variations in their capacity to stabilize soils, increase soil organic matter and available soil nutrients[67,71] and facilitate understorey development[63,77]. These variables include susceptibility to pests and diseases, patterns of aboveground and root biomass accumulation[78], nutrient utilization and allocation, nutrient use efficiency, nutrient retranslocation, litter production and fine root turnover, and rates of litter decomposition[66,67] and the presence of secondary compounds that may inhibit the activity of decomposing organisms[79].

While most species appear to act as catalysts for ecosystem rehabilitation, broadleaf species seem to give better results than conifers[2]. Of these, fast-growing species that represent lower successional stages should have preference, particularly those known to establish and grow well on degraded sites. Where phytotoxicity is suspected, it is particularly important to include plant material from populations growing naturally on mine sites and other areas likely to contain similar toxic factors[5]. In addition to their potential effects on soil fertility, species choices must be guided by seed and seedling availability, local uses for the species and economic aspects[80].

Many studies document the positive role of grass cover as a nurse crop[47,81–85]. Helm[48] emphasized that grasses may have both positive and negative effects on restoration of mine lands. They are frequently needed to stabilize soils during the restoration process, but they may compete with woody regeneration[48]. On the positive side, grasses, particularly C_4 ones, can offer superior tolerance to drought, low soil nutrients and other climatic stresses[86]. Grasses have fibrous roots that can slow erosion and their sod-forming tendencies eventually produce a layer of organic soil. They are useful in restoration of mined land because they stabilize soil, conserve soil moisture, and may compete with weedy species[48]. This initial cover must allow the development of diverse, self-sustaining plant communities[48].

Trees can potentially improve soils through numerous processes, including maintenance or increase of soil organic matter, biological nitrogen fixation, uptake of nutrients from below the reach of roots of understorey herbaceous vegetation, increase water infiltration and storage, reduce loss of nutrients by erosion and leaching, improve soil physical properties, reduce soil acidity and improve soil biological activity[58]. Given time, new self-sustaining topsoils are created by trees[58]. However, impact of trees on soil fertility depends on their nutrient-cycling characteristics such as litter chemistry and decomposition[80]. In addition to the nutrient sink function due to mass accumulation, some plantation species exhibit high nutrient use efficiency and may be more effective nutrient sink than the other species[87]. In temperate environment, slower-growing, broad-leaved native trees are regarded as better for amenity, but less efficient for timber production[58].

The role of exotic or native species in rehabilitation, needs careful consideration, because we may have to use species combinations (native, exotic or combination thereof) that are capable of surviving into new conditions[88,89]. Careful selection of species is needed, as newly introduced exotics may also become pests in other situations. Exotic species are believed to negatively impact site conditions, escape into pristine habitats and displace native species[90]. Therefore, candidate plantation species should be screened for their potential to become problematic weeds in relation to local and regional floristics[2]. As a part of revegetation efforts, selection of desirable species adapted to the local environment has been emphasized. For artificial introduction, use of species that are well adapted to the local environment should be emphasized[34,37,91,92]. Indigenous species are preferable to exotics because they are most likely to fit into a fully functional ecosystem and to be climatically adapted[5]. According to Harrington[57], if there are native species available that are suited to the current soil and site conditions, the regeneration methods have been worked out for the desired species, and the resources are available to cover the cost, then clearly the reestablishment of native species rather than exotics should be preferred.

On mine spoils, nitrogen is a major limiting nutrient and regular addition of fertilizer nitrogen may be required to maintain healthy growth and persistence of vegetation[93]. An alternative approach might be to introduce legumes and other nitrogen-fixing species. Dobson *et al.*[37] emphasized that the use of nitrogen-fixing species requires good knowledge of their biology, both their soil preferences and their interactions with other species. Nitrogen-fixing species can have a dramatic effect on soil fertility through the production of readily decomposable, nutrient-rich litter and turnover of fine roots and nodules[68,94]. Mineralization of N-rich litter from these species will allow substantial transfer to companion species and subsequent cycling, thus enabling the development of a self-sustaining ecosystem[95]. Again, here it should be emphasized that leguminous species also differ in their soil enrichment capabilities. In a study done for restoration of damaged coal mine areas in India, Singh *et al.*[49] reported that compared to native non-leguminous species, native leguminous species show greater improvement in soil fertility parameters. Also, native legumes are more efficient in bringing out differences in soil properties than exotic legumes in the short term[49].

In summary, a desired species for planting on mine spoils should possess the ability to (i) grow on poor and dry soils, (ii) develop the vegetation cover in a short time and to accumulate biomass rapidly, (iii) bind soil for arresting soil erosion and checking nutrient loss, and (iv) to improve the soil organic matter status and soil microbial biomass, thereby enhancing the supply of plant available nutrients[96]. In addition, if possible, the species should be also of economic importance.

The research need

Strategic and applied research is needed to develop and design management options to facilitate restoration of mined habitats. However, these options need to be developed in full recognition of socio-economic realities, developmental priorities and conservation goals[2,3]. Rehabilitation of degraded landscape needs research for identification of stress-tolerant plant species having a positive influence on soil fertility and design of management systems for maximizing ecosystem productivity under a wide range of degraded site conditions. In recent years, interest in rehabilitating land disturbed by mining activity has grown from species selection and site preparation to include research on ecological aspects of reclaimed areas, such as role of organic matter in productivity and nutrient relationships[97].

The questions that are raised against the use of tree plantations in rehabilitation usually centre on the negative effects of monoculture such as low stability, low resource use efficiency and a low level of biodiversity[90]. Studies are needed to establish biodiversity restoration potential of individual plantation species and of combinations thereof. The pure tree stands offer a unique opportunity to evaluate the nutrient-cycling characteristics of several species that could be useful for their future utilization in land rehabilitation[80]. Lugo[87] feels that plantations are an ideal subject for ecological studies at the ecosystem level. First, their age and species composition are known and controlled from the time the forest is planted. Second, plantations are simple ecosystems from a structural perspective, and thus provide contrast to the inherent structural complexity of native forests. Finally, understanding the ecological characteristics is also important because high rates of forest destruction, energy shortages and the need to restore degraded lands to forest production have forced an increase in the rate of plantation establishment in the tropics[87].

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