Mine Site Rehabilitation and Ecosystem Reconstruction for Biodiversity Gain

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Abstract

The rehabilitation of mined land can largely be considered as ecosystem reconstruction — the re-establishment of the capability of the land to capture and retain fundamental resources. In rehabilitation planning, it is imperative that goals, objectives, and success criteria are clearly established to allow the task to be undertaken in a systematic way, while realizing that these may require some modification later in light of the direction of the rehabilitation succession. Biodiversity gains are a realistic objective within rehabilitation planning models whether topsoil is, or is not, available as an ecological tool. Where mines are located in populated areas, community requirements also need be taken into account when selecting the most appropriate rehabilitation goals

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Introduction

The scale of human activities has become such that most of the ecosystems of the earth have been disturbed in some way (Ehrlich 1993). More than 40% of the terrestrial vegetated surface has been directly disturbed (Daily 1995) and its natural productive capacity diverted, reduced, or destroyed (Vitousek et al. 1986). The area of land directly altered by mining industries is still relatively low in terms of the global inventory of degradation, but can represent considerable quantities on an individual country basis. Further, the scale of mining is increasing and the impacts are generally more severe than most other kinds of disturbance (Walker and Willig 1999). In this context of increasing land degradation, both the ecological and economic imperatives demand that rehabilitation of land be prioritized even if 'restoration ecologists' are “doomed to fight an uphill battle” (Ehrlich 1993). This paper discusses some of the main issues, both theoretical and practical, concerning ecological rehabilitation of land in the particular context of maximising biodiversity gains within the land reclamation objectives and chosen land use patterns.

The direct impacts of mining disturbance to land surfaces are usually severe, with the likelihood of the destruction of biodiversity within natural ecosystems through the removal of natural soils, plants, and animals. However, mining is a temporary land use because the mineral deposit is finite and eventually exhausted. The social and legislative context of mining in many parts of the world today means that some form of land rehabilitation goals will have been set for the post-closure situation, and nowadays these are often determined prior to the granting of planning and operating permits for a new mine. Rehabilitation considerations are now incorporated into mine planning such that it becomes a major governing factor in mining operations, waste disposal and site closure (Johnson et al. 1994). However, there is a considerable past legacy of poor reclamation practice that, at best, has not provided any successful ecosystem development, and certainly no consideration of biodiversity losses and gains *per se*. Nonetheless, it is an indisputable fact that the reclaimed land surface remains indefinitely, post-mining, and must be able to meet the major goal of 'sustainability', which is the maintenance of the land use options of future generations (Haigh 1993). In this context, ecological rehabilitation of mined land represents one of, if not the, best approach to promote both sustainability and the safeguarding of biodiversity.

Mine closure and rehabilitation also need to take into consideration the long-term effects of acid mine drainage, and the need to rehabilitate in such a manner that AMD generation is reduced to acceptable levels. In conditions where the long-term risks of AMD are significant, design of rehabilitated profiles may need to be modified to minimize water or air ingress. For those mines in relatively heavily populated areas, community needs must also be taken into account in determining the final land rehabilitation objectives.

What is ecological restoration and how does it relate to biodiversity?

There is currently no agreed terminology in the rehabilitation of mined land. The term 'reclamation' describes the general process whereby the land surface is returned to some form of beneficial use. Where reclamation is guided by ecological principles and promotes the recovery of ecological integrity (SER 1996) the term 'restoration' is used. Hereunder, restoration refers to reinstatement of the original (pre-mining) ecosystem in all its structural and functional aspects, 'rehabilitation' is the term used for the progression towards the reinstatement of the original ecosystem, and 'replacement' is the creation of an alternative ecosystem to the original (Bradshaw 1984, 1990).

Ecological restoration is about a broad set of activities (enhancing, repairing, or reconstructing degraded ecosystems (Fig. 1), and optimising biodiversity returns. In essence, the restoration of mined land is based around ecosystem reconstruction. It is usually a question of the re-establishment of the capability of the land to capture and retain fundamental resources (energy, water, nutrients, and species). The question then arises as to what to restore. Should it be an exact replica of the biodiversity of the immediate pre-mining ecosystem, an ecologically superior (more pristine?) and perhaps historical standard, or even a future state, which is the condition that natural succession may have produced if no disturbance had occurred? (Cairns 1991; Westman 1991; Clewell 2000).

An overview of ecological restoration planning

Ecological restoration with biodiversity benefits in mind must involve an orderly set of considerations that promote successful procedures and practices. Often these practices, although based on similar general considerations, will need to be innovative because of the unique set of circumstances each area and ecosystem to be restored represents. Restoration planning models recognize that, for most mine reclamation programmes over the last 30 years, an over-riding consideration has been whether the topsoil has been retained or lost (Johnson and Bradshaw 1979; Bradshaw 1984, 1990). This will, in all probability, determine how quickly a pre-mining ecosystem can be restored with its biodiversity regained, and whether such a restoration goal is actually realistic and sustainable.

Fig. 1. The continuum of general ecological restoration effort from enhancement to reconstruction (adapted from Hobbs and Norton (1996)).

Enhancing Conservation Value in Disturbed Landscapes

e.g. tackling overgrazing, alien species invasion, pollution, and decreasing landscape fragmentation; the introduction of semi-natural areas (patches and corridors) within agricultural or commercial forestry landscapes

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Repairing Degraded Land

e.g. improving the productivity and biodiversity of land with soil erosion or salinization problems

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Reconstruction of Highly Degraded Sites

e.g. amelioration of substrates where the original soil is lost and introducing vegetation where it is absent

The restoration objectives must be formulated from a detailed knowledge of the basic structural and functional characteristics of natural ecosystems (Table 1). Ecological restoration may implicitly want all attributes to be achieved (e.g., to claim close correspondence to the pre-mining ecosystem), but the practical context of any site restoration demands that the following are considered: speed of attainment, economics (or cost-benefit), achievability, and long-term stability with on-going management at reasonable (low) cost (Bradshaw 1990).

It is also necessary to consider the potential for acid mine drainage (in metal sulphide mining) and the need to provide appropriate covers to minimize the ingress of water or air into reactive residues. The socio-economic situation will also play a significant role in determining final land use for those mine sites in populated areas. Such practical considerations are necessary for without them unrealistic objectives can be set both in ecological/biodiversity and economic terms.

The development of measurable criteria for judging restoration success has proved difficult but they are usually derived from the particular community and ecosystem characteristics desired as restoration objectives (Johnson and Putwain 1981; Hobbs and Norton 1996). Cairns (1993) provides three general success guidelines that the restored ecosystem should attain: (i) self-regulation for some set period of time, where self-regulation means the structural and functional attributes persist in the absence of whatever "subsidies" (fertilizer, seeding etc.) may have been necessary during the initial phases of implementation; (ii) the design criteria (restoration goal and objectives) established before restoration was undertaken; (iii) no observable adverse effects in the larger ecological landscape.

From these criteria, it can be seen that it is absolutely necessary to have restoration objectives that have unambiguous operational definitions (technically feasible), which are ecologically sound (scientifically valid) and socially relevant, and that are receptive to measurement and prediction (Cairns 2000). The ecosystem characteristics measured are usually those related to the composition, structure, and pattern of the vegetation as a key component of the biodiversity pool (Allen 1992). It is notable that some important structural measurements of biodiversity are usually omitted (Chambers et al. 1994). In particular, measurements concerning the soil biotic community and animal species numbers are not usually made, even though they can often provide important indications of long-term productivity and successional pathways (Chambers and Wade 1992).

Table 1. Ecosystem characteristics for consideration as ecological restoration objectives (adapted from Hobbs (1999)).

1. Composition: species presence and their relative abundance
2. Structure: vertical arrangement of vegetation and soil components
3. Pattern: horizontal arrangement of system components
4. Heterogeneity: a variable composing of characteristics 1–3
5. Function: performance of basic ecosystem processes (energy capture, water retention, nutrient cycling)
6. Species Interactions, e.g., pollination, seed dispersal etc.
7. Dynamics and resilience: succession and state-transition processes, ability to recover from normal episodic disturbance events (e.g., floods, drought, fire)

The ecological considerations needed for practical restoration planning must be considered in some detail in relation to situations where topsoil has been lost or retained within the mining and waste disposal operations. In the restoration of sites where the topsoil has been lost, the major ecological challenges are still concerned with plant species–substrate interactions, i.e., revegetation. Restoration practice where topsoil has been retained focuses less on vegetation establishment and more on the spatial and temporal factors affecting species colonization and establishment, the criteria for monitoring and assessing success, particularly in the longer term, and the restoration of natural indigenous ecosystems and biodiversity values.

Social factors also need to be considered in practical restoration planning for those situations where the mine is not isolated from surrounding communities. In such situations the rehabilitation objectives need to be defined in close consultation with the local communities, as they will have to utilize the rehabilitated land in perpetuity after the mining company has departed.

Restoration in practice: where topsoil has been lost

Mining substrates

Mining substrates do vary considerably in their physical and chemical properties, but their tendency is towards the inhibition of natural colonization by most plant species for many years. However, a few plant species (which may be particularly tolerant or have tolerant ecotypes or populations) may form an open natural vegetation cover representing an arrested succession prevented from further development because of the toxicity of the metalliferous mine spoils, their infertility, or extreme acidity. Old mining areas have often developed plant communities through natural colonization by distinctive and unique metallophyte species (Antonovics et al. 1971). Such communities are recognised 'biodiversity hotspots' and include the well-described floras of the copper–cobalt areas of south-central Africa (Brooks and Malaisse 1985) and western Europe (Simon 1978).

Many old mining sites have become of high biodiversity and conservation value both because of endemic plant species or populations, and because they serve as refugia for both rare plant and animal species whose natural habitats have been considerably reduced through a range of human activities (Johnson 1978; Box 1992). Such genuine, but unplanned, biodiversity gains provide natural models that can be used in planning restoration work in modern day mines.

Recovery

At its simplest, ecological restoration may equate with primary succession or the recovery of mined land when it is largely left to natural processes after disturbance (Cairns, 1991). Studies of abandoned mining areas have enabled investigation of the issues concerning the development of ecosystems without intervention (Bradshaw 1999) and so have helped inform the practice of modern ecosystem restoration.

The presence of populations of plant species in a particular site will depend on the ability of propagules to be transported to the site and to germinate, and of the young plants to survive and reproduce. The timescales involved are often long and the initial colonization phase, in particular, can show a considerable lag depending on substrate conditions (Ash et al. 1994). On metalliferous sites plant colonization success depends upon avoidance of the high soil metal areas where substrate heterogeneity exists, or on metal tolerance either through natural selection and survival of tolerant populations, or because it is constitutional to a particular species, e.g., a metallophyte (Baker and Proctor 1990). Slow natural succession has sometimes been promoted as a reclamation option but is conceptually difficult and usually politically unacceptable in an era when “closure planning”, an active process, is becoming an everyday expectation. Moreover, natural recovery on bare mine waste and tailings will usually yield a biodiversity pool very different from the original or surrounding vegetation, again because of the physical and chemical properties of the substrates being so different from those of the original soils.

In countries with high rainfall intensities, use of natural succession to achieve reclamation may result in excessive erosion. In such situations, use of a “nurse” crop is of value in ensuring that that the plant growth substrate remains in place.

Ameliorative and adaptive approaches

Despite the wide ranging constraints of mining sites and substrates there have been some important success stories in the direct restoration of metal mining wastes yielding significant biodiversity benefits. However, where the original topsoil has been lost, faithful restoration of original ecosystems is rare. An overview of the range of approaches shows the drivers to be the degree of toxicity, salinity, and acidity of the waste material or site. The principal restoration options, on a site-specific basis, are the **ameliorative** approach (improving the physical and chemical nature of the site) and the **adaptive** approach (the careful selection of species, cultivars, or ecotypes) both used in a way which seeks to achieve the ecological restoration goal of establishing ecosystem structure and function and thus biodiversity (Johnson et al. 1994).

Ecological restoration without topsoil usually depends on careful selection of suitable substrates for plant growth from the overburden materials left behind after mining, adapted species and includes consideration of their suitability for ground stabilization, the value of the species as wildlife habitat (and as forage for domestic animals), and then also for achieving aesthetic value. Indigenous species available as propagules do not always satisfy these criteria, in which case native, but not locally indigenous, species can be sown as a supplement, usually in a way that provides a rapid solution to short-term problems such as erosion, but one which enables colonization by local volunteer species and thus facilitates succession to eventually restore the native ecosystem and biodiversity. This reasonable compromise has been the approach used for copper tailings berms and surfaces in the arid and testing conditions of southern Arizona (Bengson 1995).

The use of metal tolerant ecotypes, in particular of the temperate grasses *Agrostis capillaris* and *Festuca rubra*, is a proven reclamation technology of 20 years standing for lead, zinc, and copper mine tailings (Tordoff et al. 2000). These ecotypes have metal tolerance as a genetically heritable character, and some have been bred on to cultivar status (e.g. *F.rubra* cv. “Merlin”). Direct seeding of tolerant cultivars is a promising area of further development, with candidate species from tropical areas including *Chloris gayana*, *Eragrostis curvula* and *Cynodon dactylon*. Exploiting biodiversity for dealing with difficult man-made substrates is surely a legitimate strategy.

More recently, a technology has been promoted whereby the tolerance to metals of some plants is used in a different way. Some species, (e.g., *Minuartia verna*), are described as “hyperaccumulators” in recognition of their ability to accumulate elements that are usually present in trace concentrations in plants. For highly toxic metal mine wastes, it has been suggested that such species could be manipulated to clean-up or 'bioremediate' soils and at the same time both stabilize and reclaim land for other purposes(Salt et al. 1998). Long term trials are also underway in the U.S.A. (Nicks and Chambers 1995) and Chile (Ginocchio 1998). However, before this approach, which may combine restoration with land remediation, can be considered viable, major problems of species rarity, low productivity, gene manipulation into more productive species, suitable harvesting methods and final disposal of the biomass as 'green' waste must be addressed.

Restoration in practice: where topsoil has been retained

Topsoil as the strategic restoration resource

The modern context of restoration as part of the total mining process involves carefully planned decommissioning rather than the common past practice of simple abandonment. Topsoil is today viewed as a strategic resource that should be conserved if at all possible. Thus its removal, storage, and replacement have received much technical research in recent times. The main reason for this is to protect the physical and chemical properties and biological processes of this valuable natural resource (Harris et al. 1996).

On the north-east coast of South Africa in Zululand near Richards Bay, dredge mining for heavy minerals in coastal dunes has taken place since 1977 (Camp 1990). Ecosystem restoration is a fundamental part of the mining operation. Mining entails the removal of the dune forest in a prescribed mining path through the dunes. Topsoil is then stored to be used in the restoration process that relies heavily on the initiating of succession and then leaving the ecosystem to develop naturally. The success of the approach was thought to be likely as, over ecological and evolutionary timescales, the dunes have been built, vegetated, and destroyed many times along the African coast (Mentis and Ellery 1998). Aerial photographs taken in 1937 showed that highly degraded coastal dune vegetation had, because of subsequent human depopulation, seemingly recovered through natural succession. This indicated that a minimal interventionist approach could be successful. Over 400 ha have been reclaimed in this way since 1978, providing a chronosequence of restored mined dunes.

Bauxite mining in the northern Jarrah forest in Western Australia currently requires the restoration of 450 ha of forest per year (Baker et al. 1995) and, as it is currently practiced, provides some interesting contrasts in the approach to restoration of the South African dune forests. In particular, a much more clearly defined set of success criteria has been combined with a greater interventionist approach to reach the desired restoration objectives within specific time limits. This has required a considerable knowledge of the ecosystem structure and function before mining commenced. However, this knowledge has been acquired over 30 years as a result of " trial and error, planned research, lucky discovery, standardisation, and fine tuning" (Baker et al. 1995).

The basic mineral extraction is technically simple. The forest is cleared with some timber kept to provide animal habitat on the restored area. The top 5–15 cm of topsoil is stripped separately to maintain the seed bank (350–1500 viable seeds per metre square). Overburden above the cap rock (about 40 cm depth) is then removed and stockpiled. The cap rock is blasted and the ore removed. As in the South African dune forest restoration, the topsoil seed bank is the major source of seed for the developing ecosystem, with an estimated 75% of the native species becoming established from the soil seed bank. However, in the restoration of the Jarrah forest this is now augmented by a seed mix that is sown by hand. This mix includes more than 60 different native species, including the important understorey legumes. In a fire-regulated system such as the Jarrah forest, the main restoration objective is to establish as many of the most common plant species as soon as possible. This includes having a minimum success criterion for plant establishment of 2000 eucalypt seedlings per hectare and two legume understorey species per square metre after 9 months.

Future challenges and sustainable development

Future challenges in ecological restoration in the mining and mineral industries leading to the maximising and/or return of biodiversity 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, such as high altitude forest; tall canopy forest in tropics, and in the tundra; and even possibly Antarctica eventually. These developments will require considerable research and ecological knowledge if biodiversity losses are to be avoided. Most of the world's large mining companies now know that environmentally sound practices including restoration do not add significantly to the costs of new mining projects, and innovation in environmental technologies can even provide income by being commercially exploited (Warhurst 1994).

The great majority of new mining ventures entered into by the multinational mining corporations are the subject of detailed pre-mining Environmental Impact Assessments and Social Impact Assessments. These should be of sufficient quality to ensure that biodiversity impacts that may be caused by the operation are fully appreciated prior to the operation commencing, and that the socio-economic framework within which the mine will function is also understood. Current international best practice requires that mining operations define their rehabilitation and closure objectives prior to commencement of mining, and that these be reviewed in association with the communities and organizations that will be affected by these activities. In those developing nations where legislative requirements may be less developed than in the first world, mining companies remain obliged to use currently available technology to achieve satisfactory solutions to biodiversity issues.

The situation is not as clear-cut in the case of existing operations, as these were established in many cases prior to the understanding of the requirements for effective rehabilitation. Despite this, mining corporations continually upgrade their biodiversity and social impact assessments in an effort to minimize the long-term negative impacts, and to maximize the long-term positive impacts of their activities.

Artisanal and small-scale mining represents the other end of the spectrum. It is large in terms of the people directly involved in it: Indonesia 350 000 (Hollaway 1997), Brazil 300 000 “garimpeiros” (Cleary and Thornton 1994), and 200 000 in both Tanzania and Zimbabwe. It is a growing sector particularly in southern Africa, Latin America, and southeast Asia. There are an estimated 10 million people dependent on small-scale mining for gold, chrome, tin, and gemstones in southern Africa alone and possibly 80 million worldwide.

This mining sector provides for some of the poorest people in the world, working small-scale, often low grade ore deposits that are not economic to large-scale mining. This sector is characterized by technological backwardness and lack of economic and environmental knowledge. It is clear that ecological restoration and biodiversity will have to "take their turn" and contribute to solutions for this sector that takes a holistic view of sustainable development and creating sustainable livelihoods. Problems of this sector include deforestation and removal of biodiversity through thousands of small workings with many open pits, unplanned growth of villages and towns without clean water and sanitation, and alluvial workings which can cause extensive disturbance and damage to river systems. The social agenda as part of sustainable development will become increasingly important to environmental management in the mining sector in general and to ecological restoration and biodiversity issues in particular.

Finally, a further challenge to sustainable development is the continuing social and environmental problems associated with the enormous number of abandoned and "orphaned" mine sites. Although the case for ecological restoration of most of these sites is the same as for active mines, the assignment of responsibilities is different. Non-action is usual because of non-identification of the responsible body. National approaches such as the "Superfund" arrangement in U.S.A. or national contaminated land policies elsewhere seem to be a possible answer. Again, however, it is unlikely that even strategic intervention by national governments can succeed in relatively poor developing countries without significant financial support of the private mining industry providing for the costs of restoration of past mining degradation.

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