Revegetation of Metalliferous Wastes and Land After Metal Mining

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1 Introduction

There has been a progressive worldwide increase in metalliferous mining in recent years underpinned by social, economic, and technological demand.[1] The ever-increasing need for metals, and the ability of modern mining and processing methods to develop low grade ore-bodies economically, has placed increased strain on the environment at a time when the demands for high environmental standards are also increasing.[2] Since mining is, by its very nature, a destructive industry, attention has become focused on ways in which the environmental impact may be reduced or rendered temporary in nature.

An effective decommissioning plan for eventual mine closure which provides for the reclamation of disused workings, waste-rock dumps, and tailings impoundments, is an increasingly important factor when decisions are being taken as to whether to grant planning consent for a new mine.[3] This concern is underpinned by the legacy of past mining in many parts of the world. Continuing environmental damage arising from polluted waters and dispersal of contaminated solid waste is a feature of old mines in North America, Australia, Europe, and elsewhere.[4,5] It is, therefore, becoming standard practice for reclamation measures to be considered as an integral part of mine planning and operations, even to the extent that financial provisions are made during the operational life of a mine to effect such reclamation measures upon closure.[1] The higher environmental profile attached to modern mining is linked not only to social acceptability but also to legal requirements in many countries. This requires attention to be paid to the prevention of environmental damage from mining operations, waste production, and site closure.

[1] United Nations, 'Environmental Aspects of Selected Non-ferrous Metals Ore Mining', Technical Report Series No. 5, United Nations Environment Programme/Industry and Environment Activity Centre, UNEP, Paris, 1991, p. 116.

[2] United Nations, 'Mining and the Environment: The Berlin Guidelines', United Nations Department for Technical Co-operation and German Foundation for International Development, Mining Journal Books, London, 1992, p. 180.

[3] Ontario Ministry of Mines and Northern Development, 'Rehabilitation of Mines: Guidelines for Proponents', Ministry of Mines, Sudbury, Ontario, Canada, 1991, p. 137.

[4] G. M. Ritcey, 'Tailings Management: Problems and Solutions in the Mining Industry', Elsevier, New York, 1989, p. 970.

[5] N. J. Coppin, M. G. Staff, and M. S. Johnson, in 'Minerals, Metals and the Environment', Institute of Mining and Metallurgy, London, 1992, p. 104.

2 Constraints Upon Revegetation

Although chemical and physical techniques exist for dust control and stabilization against water erosion,[4] such objectives can only be realistically achieved in the long-term by the use of vegetation as a basis for landscaping, stabilization, and pollution control. However, it is widely recognized that wastes from metalliferous mines, especially acidic ones, are very difficult materials upon which to establish vegetation.[6]

The reasons that metal mine wastes present difficulties for plant growth derive from a combination of their physical, chemical, and biological properties. The major physical constraint of mine tailings is their small and uniform particle size distribution which is dominated by material of silt and clay dimensions. Physical properties vary both horizontally and vertically within any tailings impoundment due to stratification during deposition, and also to the particle sizing objectives set for optimum recovery of metals in the prior ore milling and flotation process. Tailings also possess unfavourable porosity, aeration, water infiltration, and percolation properties, along with a high bulk density and an absence of structural aggregates. The result is that water and wind erosion of unprotected disused tailings surfaces is a common hazard.[7]

In the case of old mines, often long abandoned, the processing technology deployed to recover the target metals was elementary and inefficient as compared with contemporary magnetic, gravity, and flotation processes. The consequence is that waste materials representing past eras of mining contain high residual quantities of toxic metals, often in excess of 1% by weight of elements such as lead, zinc, and/or copper (Table 1). These high metal values are frequently accompanied by elevated levels of non-target elements such as arsenic and cadmium from the original crude ore.[8]

Some metals (*e.g.* copper, zinc) are essential trace elements at low concentrations but toxic to plants at high levels. It is not possible to state specific concentrations for normal metabolism as opposed to toxicity as the threshold varies with other soil variables and the species concerned. Also, some combinations of metals act antagonistically or even synergistically in solution. Nickel and zinc, copper and zinc, and copper and cadmium are more toxic than their individual toxicities would suggest.[9] The presence of phosphate or calcium can reduce the toxicity of lead, zinc, and copper through precipitation and ion competition reactions. Other non-essential elements (*e.g.* lead, mercury) are less toxic to vegetation but hazardous to livestock that may graze vegetation which has accumulated such metals either via the roots or as surface dusts.[10]

The suite of problems described is compounded, in many instances, by what is

[6] M. S. Johnson and A. M. Mortimer, in 'Environmental Aspects of Metalliferous Mining: A Select Bibliography', Technical Communications, Letchworth, UK, 1987, p. 212.

[7] J. M. Ringe and D. H. Graves, *Reclam. Reveg. Res.*, 1987, **6**, 121.

[8] N. A. Williamson, M. S. Johnson, and A. D. Bradshaw, in 'Mine Waste Rehabilitation: the Establishment of Vegetation on Metal Mine Waste', Mining Journal Books, London, 1982, p. 103.

[9] C. G. Down and J. Stocks, 'Environmental Impact of Mining', Applied Science, London, 1977, p. 371.

[10] Department of Environment, 'Notes on the Restoration and Aftercare of Metalliferous Mine Sites for Pasture and Grazing', ICRCL Guidance Note 70/90, Department of Environment, UK Government, London, 1990, p. 15.

Table 1 Copper, lead, and zinc in spoil from abandoned mines in Britain*

Mining region	*Counties*	*Number of sites surveyed*	*Principal base metals*		
			Cu	*Pb*	*Zn*
S.W. England	Devon and Cornwall	16	65–6140	48–2070	26–1090
W. and N.W. England	Shropshire and Cheshire	12	15–7260	840–26 000	980–21 000
N. Pennines	N. Yorkshire and Durham	8	20–140	605–13 000	470–28 000
S. Pennines	Derbyshire	17	23–97	10 800–76 500	12 700–42 000
Lake District	Cumbria	7	77–3800	2070–7630	4690–7370
Mid-Wales	Powys and Dyfed	10	67–195	1670–54 000	475–8000
N. Wales	Clwyd and Gwynedd	19	30–5750	6400–76 000	11 300–12 700
S. Scotland	Dumfries and Galloway	6	125–657	4730–28 300	1600–31 400
Normal agricultural soil			2–100	2–200	10–300

*All values in $mg\,kg^{-1}$ air dried substrate

probably the most intransigent revegetation problems faced by the mining industry. The presence of significant quantities of iron pyrites (FeS_2), which may not be removed during ore beneficiation, often leads to very acid waste as the mineral is comminuted during processing and then undergoes weathering to generate sulfuric acid.[11] Pyrite-bearing wastes disposed of at neutral or slightly alkaline pH can degrade within months or years to produce extreme acidity.[12] Initial chemical processes are probably the result of natural weathering but this oxidation and hydrolysis is then assisted by ferrous ion oxidizing bacteria, *Thiobacillus ferrooxidans*, which thrive at pH 1.5–3.0.[13,14]

The rate of oxidation of pyrite is influenced by the surface area of the material available for weathering.[15] Other factors also influence the rate of production of acid, namely the native carbonate content of the material, and the size, morphology, and type of the pyrite present. If the wastes contain only small quantities of native carbonates, acid regeneration may exceed the neutralizing potential, resulting in a significant decline in pH. The pH values of mine tailings and waste-rock range from below 2 to more than 8, depending on the gangue material, the pyrite content, and, in the case of tailings, the chemicals added in the mill. Gold mining wastes in South Africa have pH values as low as 1.5, and

[11] M. U. Ahmed, in 'Extraction of Minerals and Energy: Today's Dilemmas', ed. R. A. Deju, Ann Arbor Science, Ann Arbor, Michigan, 1974, p. 49.

[12] A. C. Hartley, *Aust. J. Soil Res.*, 1979, **17**, 355.

[13] N. V. Blesing, J. A. Lackey, and A. H. Spry, in 'Minerals and the Environment', ed. M. J. Jones, Institute of Mining and Metallurgy, London, 1975, p. 341.

[14] J. R. Hawley, 'The Problem of Acid Mine in the Province of Ontario', Ministry of the Environment, Ontario, 1977, p. 32.

[15] M. Kalin, Proceedings of the 4th Annual General Meeting of Biominet, Sudbury, Canada, Special Publication, CANMET No. SP, 87-10, 1988.

uranium tailings in Colorado have been reported with pH values of 8.0.[16]

A further consistent feature of metalliferous waste, whether rock or tailings, is the low concentration of essential plant nutrients. Nitrogen levels are invariably inadequate for plant growth, phosphorus levels are generally very low, and deficiencies of potassium, calcium, and magnesium also may occur.[17] In warmer climates than temperate Britain, salinity of tailings can also prove troublesome.[18] It results from: (1) the interaction of the products of pyrite weathering with native carbonates; (2) the concentration of naturally occurring salts in tailings due to recycling of water; (3) the additions made to tailings by mill personnel in order to adjust effluent pH; and (4) excessive evaporation from the surface. The resulting salinity levels can be high enough to prevent plant growth. Tailings generally are more complex chemically than waste-rock, due to the addition of reagents and pH modifiers during the metal extraction process.[19]

The basic combination of adverse physical and chemical characteristics produces an environment in mine wastes that is hostile to plants. This is accentuated by the absence of the organic fraction that comprises 3–5% of the surface horizons of most natural soils. Organic matter contributes to soil structure, provides a reservoir of essential macronutrients, and a resource for invertebrates and micro-organisms that support the decay processes which underpin energy and nutrient cycling. The sterile nature of mine wastes has to be rectified before adequate and sustainable growth of plants can be achieved.

3 Revegetation Objectives

Essentially, the objectives of vegetation establishment are: long-term stability of the land surface which ensures that there is no surface erosion by water or wind; reduction of leaching throughputs, lessening the amounts of potentially toxic elements released into local watercourses and to groundwaters; development of a vegetated landscape or ecosystem in harmony with the surrounding environment; and with some positive value in an aesthetic, productivity, or nature conservation context.

The first objective is achievable by a continuous vegetation cover, especially where the cover is at least 100% and of relatively low growth. With lower cover values erosion may begin to occur.[20] The degree to which the second objective is met by a vegetation cover depends on the ambient climate. Vegetation will intercept and return rainfall to the atmosphere by evapotranspiration. In temperate climates the amount intercepted and returned will be up to 50% of the total, in the wet tropics less than 25%, and in the dry tropics more than 75%. However, these values are also affected by the distribution of the rainfall and the

[16] H. B. Peterson and R. F. Nielson, in 'Ecology and Reclamation of Devastated Land', Gordon and Breach, New York, 1973, Vol. 1, p. 15.

[17] A.D. Bradshaw and M.S. Johnson, in 'Minerals, Metals and the Environment', Institute of Mining and Metallurgy, London, 1992, p. 481.

[18] K.L. Ludeke and A.D. Day, *Trans. Soc. Min. Eng. AIME*, 1985, **278**, 1807.

[19] L.C. Bell and M. Evans, *Reclam. Rev.*, 1980, **3**, 113.

[20] A.D. Bradshaw and M.J. Chadwick, 'The Restoration of Land', Blackwell Scientific Publishers Ltd., Oxford, 1980, p. 297.

type of rain event; it is more difficult for vegetation to intercept and re-evaporate precipitation if it falls in the form of intermittent, heavy storms. The third, and ultimately most demanding, objective represents the successful integration of all the factors that can influence a revegetation scheme and as such it is the ultimate test of the approach or the philosophy of the programme in practice.

4 Philosophies of Revegetation

The approaches to revegetation can be described in terms of three different basic philosophies: (1) ameliorative, (2) adaptive, and (3) agricultural.

(1) *The ameliorative approach* relies on achieving optimum conditions for plant growth by improving the physical and chemical nature of mine wastes using organic matter, fertilizer, and/or lime. Alternatively, mixing or cover materials may be deployed. The most suitable species available commercially are sown on to the wastes whose edaphic properties have been modified in accordance with the land use objectives and type of vegetation to be introduced. This approach is commonly used in preference to the adaptive because it is quicker, requires less forward planning, and is less labour-intensive.

(2) *The adaptive approach* emphasizes selection of the most suitable species, sub-species, cultivars, and ecotypes to meet the rigours of the extreme conditions. In addition, but not necessarily, the mine wastes may be improved using amendments to achieve optimum establishment and long-term growth. This approach is simple but is constrained by the availability of suitable propagules in some areas and by the long lead-time in producing commercial seed from promising natural or artificially selected plant material.

(3) *The agricultural and forestry approach* has been used directly on less toxic media such as ironstone and bauxite wastes, and on wastes covered over with deep layers of soil or overburden. Agricultural crops or livestock or woodland and/or scrub species are established using conventional or specialized techniques.

In practice, it is combinations of the above approaches based on site-specific considerations that produce the final revegetation strategy. An extension to the above philosophies, and their combination, is the 'ecological approach' which places emphasis on the importance of establishing biological processes such as nitrogen fixation, decomposition, nutrient cycling and retention, and important biotic interactions (*e.g.* pollination). It is these that indicate proper ecosystem functioning, which is as important as the careful selection of plant species in providing the primary vegetation structure.[21] Whether the reclamation goals are to restore the original natural ecosystem or to produce an acceptable alternative, ecological principles should underlie all good reclamation schemes.

[21] A. D. Bradshaw, in 'Restoration Ecology', ed. W. R. Jordan, M. E. Gilpin, and J. D. Aber, Cambridge University Press, Cambridge, 1990, p. 53.

5 Revegetation Techniques and Land Use

Identification and treatment of the problems preventing plant growth, coupled with careful selection of species and appropriate long-term management, is the basis of successful revegetation. Various techniques have been developed to suit particular waste problems, ranging from cultivation with conventional agricultural machinery followed by fertilization and direct seeding for innocuous wastes, to specialist procedures such as placement of a barrier layer or deep coverings of non-toxic material for very toxic sites. The range of specific revegetation options together with their limitations are outlined in Table 2, and are based upon the degree of toxicity, salinity, and acidity of the waste material or site.

Many factors have to be considered in the choice of plant materials, and their method of establishment, in particular the nature of the spoil, the prevailing climate, and the eventual land use (Table 3). Examples of other local factors to be considered, including pest and disease incidence and availability, are given in (Table 4).

6 Direct Seeding

Normal Species

Unfortunately, straightforward direct seeding with conventional species and fertilizers is often unsuccessful as a revegetation measure, at least on older mine tailings, because of the toxic residual levels of metals—often with an acidity problem as well. Under these circumstances grass and other seedlings persist for only a few weeks. However, it remains an attractive option in principle because direct seeding is much cheaper than any other method. In situations where the waste has little residual metal, or where the metal is not available to plants, normal species can be established directly with the assistance of fertilizer.[22] Because the long-term growth of vegetation depends on an adequate supply of nitrogen, legumes such as white clover (*Trifolium repens*) or birdsfoot trefoil (*Lotus corniculatus*) are an important component of the seed mixture, since they have the capacity to supply nitrogen by fixation of atmospheric sources.[8]

Metal Tolerance

A close examination of even the most toxic waste from old metal mines representing eras when processing technology was crude and inefficient, nearly always reveals a sparse natural vegetation cover. Sometimes this is limited to only a few plants but of a characteristic and narrow range of species. Supplied with fertilizer, these plants are apparently able to tolerate and indeed thrive under conditions where non-tolerant plant material dies in a short time (see Figure 1). It is now known that these natural colonizers are special metal-tolerant populations of normal species that have become genetically adapted to thrive on metal-contaminated sites.

Metal tolerance is a widely recognized phenomenon in higher plants and has

[22] M.S. Johnson, A.D. Bradshaw, and J.F. Handley, *Trans. Inst. Min. Metall.*, 1976, **81**, A32.

Table 2 Approaches to revegetation

Waste characteristics	*Revegetation technique*	*Problems encountered*
Low metal toxicity. No major acidity or alkalinity problems.	(1) *Amelioration and Direct Seeding with Agricultural or Amenity Grasses and Legumes* Apply lime if pH < 6. Add organic matter if physical amelioration required. Otherwise apply nutrients as granular compound fertilizers. Seed using agricultural or hydraulic techniques (*e.g.* Pb/Zn/CaF_2 tailings, Derbyshire, UK).[22]	Probable commitment to long-term maintenance. Grazing must be strictly monitored and controlled in some situations due to movement of toxic metals into vegetation.
Low metal toxicity and climatic limitations. No major acidity or alkalinity problems. Extremes of temperature, rainfall, *etc*.	(2) *Amelioration and Direct Seeding with Native species* Seed or transplant adapted native species using amelioration treatments (*e.g.* lime, fertilizer) where appropriate (*e.g.* Cu tailings, Arizona, USA).[23] Use thin layer of native soil as seed inoculum.	Irrigation often necessary during establishment in arid climates. Expertise required on the selection of native flora. Labour intensive.
Medium to high metal toxicity. High salinity.	(3) *Amelioration and Direct Seeding with Tolerant Ecotypes* Sow metal and/or salt and/or acid tolerant seed. Apply lime, fertilizer, and organic matter, as necessary, before seeding (*e.g.* Pb/Zn waste Wales, UK).[24]	Possible commitment to regular fertilizer applications. Relatively few species have evolved tolerant populations. Grazing inadvisable. Very few species are available commercially as tolerant varieties.
	(4) *Surface Treatment and Seeding with Agricultural or Amenity Grasses and Legumes* Amelioration with 10–50 cm of innocuous mineral waste (*e.g.* overburden). Apply lime, fertilizer and organic matter as necessary (*e.g.* Pb/Zn waste, Wales, UK).[25]	Regression will occur if shallow depths of amendment are applied or if upward movement of metals occurs. Availability and transport costs of surface amendments may be limiting.
Extreme toxicity. Very high toxic metal content. Intense salinity or acidity.	(5) *Barrier Layer* Surface treatment with 30–100 cm of innocuous barrier material (*e.g.* unmineralized rock) and surface covering with a suitable rooting medium (*e.g.* subsoil). Apply lime and fertilizer as necessary (*e.g.* Pb/Zn/Cu wastes, New South Wales, Australia).[26]	Susceptibility to drought according to the nature and depth of the surface covering. High cost and potential limitation of availability of barrier material. Integrity of barrier layer may be affected by root penetration.

23 K. L. Ludeke, in 'Tailings Disposal Today', ed. C. L. Aplin and G. O. Argall, Miller Freeman, San Francisco, 1973, p. 606.
24 R. A. H. Smith and A. D. Bradshaw, *J. Appl. Ecol.*, 1979, **16**, 595.
25 M. S. Johnson, T. McNeilly, and P. D. Putwain, *Environ. Pollut.*, 1977, **12**, 261.
26 B. Craze, *J. Soil Conserv. Serv.*, 1977, **33(2)**, 98.

Table 3 Primary considerations in selection of plants

Primary considerations	*Plant types selected*
Nature of Spoil	
Toxic metals at high concentrations	Metal-tolerant cultivars Natural invaders of mineralized outcrops
Toxic metals moving into herbage	Unpalatable species Spiny shrubs around site perimeter
Extreme acidity/alkalinity	Natural invaders of acidic or alkaline conditions
High levels of salts	Salt-tolerant species Natural invaders of salty areas
Drought conditions	Drought-tolerant species Certain metal-tolerant cultivars
Poor nutrient status	Legumes or other nitrogen-fixers Species that grow in nutrient poor areas
Climate	
Extreme cold with short growing season	Native or naturalized species Species that grow and develop rapidly
Arid or semi-arid	Native or naturalized species Transplants or cuttings of slow growing species
Temperate	Agricultural, forestry, or other commercial species depending on land use
Eventual Land Use	
For rapid stabilizing cover and high productivity	Agricultural species
For wildlife	Variety of native and naturalized species that provide seeds, fruits, palatable herbage, nesting sites, *etc.*
For aboriginal or tribal use	Native species Timber, medicinal, or food crops Species that regenerate after practices such as burning of forests
For amenity and recreation	Wear-tolerant cultivars as developed for sportsground turf Low productivity

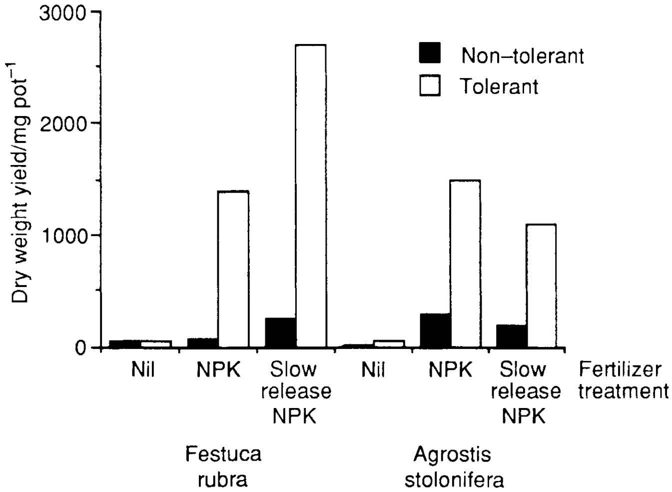
Table 4 Other considerations in selection of plants

(1) *Insect resistance* River red gum (*Eucalyptus camaldulensis*) has proven to be a most promising reclamation tree worldwide. Its performance at Groote Eylandt manganese mine in Northern Territory, Australia, has also been promising but its lack of resistance to termites could impose considerable limitations on its timber value, a prime consideration in this reclamation scheme.[27]	(2) *Disease resistance* Disease resistance is becoming an important factor in selection of species for reclamation of bauxite-mined lands in the Jarrah forests of the Darling Range, Australia, where *Phytophthora cinnamomi*, a soil borne fungal pathogen, is causing large-scale dieback of vegetation.[28]
(3) *Intrusion by man* Thickets of spiny shrubs such as Arnot Bristly Locust (*Robinia fertilis*), an acid-tolerant, nitrogen-fixing shrub, may be effectively positioned around perimeters of open pits and radioactive or hazardous wastes to restrict public access.	(4) *Landscape planting* Trees with rapid growth such as Black Locust (*Robinia pseudoacacia*) can be effective in visual screen plantations for tailings ponds, waste heaps, and mine buildings.
(5) *Growth habit* Ideally, material should be easily propagated, quick to establish, be mat-forming with fibrous root systems or rhizomes. Selection of deep rooted plants such as alfalfas and trefoils may be of value in breaking up a compacted soil. Herbaceous or perennial plants should be favoured rather than annuals, which suffer problems with re-establishment.	(6) *Competition* Species should be chosen that grow favourably with other components of the mixture; for example, establishment of young trees in a lush ground cover vegetation may be adversely affected by competition. (7) *Availability* If possible, species should be selected that are available commercially. If companies can foresee requirements, and order from reputable commercial nurseries giving at least a year's notice, unusual requirements can often be met. If full reinstatement of a diverse native flora is to be carried out, then the company should consider establishing its own nursery facilities.

[27] P. Langkamp and M. Dalling, *BHP J.*, 1977, **1**, 42.

[28] J.R. Bartle and S.R. Shea, Proceedings of the Australian Mining Industry Council (1979), Environmental Workshop, Bunbury, Australia, 1979.

Figure 1 Growth of lead/zinc tolerant and non-tolerant populations on lead/zinc mine waste after seven months growth



been reported in respect of cadmium,[29] arsenic,[30] and nickel[31] as well as in the more widely publicized cases of copper, lead, and zinc.[32] Recognizing the revegetation potential of these plants, a breeding programme was initiated in the 1970s in order to produce commercial cultivars of certain grasses bearing the same genetic characteristics as the 'natural' plant material. As a result of this, three cultivars of temperate grasses are now available commercially enabling direct seeding of toxic areas. These three, and their associated tolerances, are: *Festuca rubra* cv. 'Merlin' (lead–zinc), *Agrostis capillaris* cv. 'Parys' (copper), and *Agrostis capillaris* cv. 'Goginan' (lead–zinc). The value of these cultivars for seeding unstable and toxic tips is considerable since revegetation can be achieved by direct sowing and treatment with simple inorganic fertilizers.[24] They are particularly useful for revegetation of older sites, though may prove to be less essential on newer waste materials as the improved mineral processing technologies of today leave less residual metal in the tailings. Under these circumstances, normal plant material is able to thrive (see Figure 2).

Overall, revegetation costs are low using the tolerance route but there are limitations. For example, the tolerance mechanism is specific and though cross-tolerance exists between related metals,[32] this is at a low level so a particular cultivar is unlikely to thrive on mine waste containing toxic quantities of metals other than those to which it has evolved an adaptation. Furthermore, grazing of the sward for agricultural purposes is not usually possible and the recreational or trampling resistance of the ground cover comprising tolerant plant material is low. Also, long-term fertilizer input is usually required and from an ecological viewpoint it is important that such schemes using metal-tolerant plants can lead eventually to the site becoming available for colonization by other tolerant but also non-tolerant species.

[29] P.J. Coughtrey and M.H. Martin, *New Phytol.*, 1978, **81**, 147.
[30] J.R.C. Hill, *Trans. Inst. Min. Metall.*, 1977, **86A**, 98.
[31] R.R. Brooks, J. Lee, R.D. Reeves, and T. Jaffre, *J. Geochem. Explor.*, 1977, **7**, 49.
[32] A. Baker, *New Phytol.*, 1987, **106**, 93.

Figure 2 Growth of lead/zinc tolerant (T) and non-tolerant (NT) *Festuca rubra* with (+) and without (−) NPK fertilizer on $Pb/Zn/CaF_2$ tailings of different ages, in Derbyshire, UK

Considering the usefulness of tolerant temperate grasses in revegetation work it is surprising that equivalent commercial breeding programmes have not so far taken place for some of the more promising tropical species, including *Chloris gayana* and *Eragrostis curvula*. These could possibly be developed for mine waste revegetation.

7 Surface Improvement and Covering Systems

Principles

The selection of methods for improving growing conditions should be based on: (1) alleviating toxicity and acidity; (2) augmenting supplies of essential plant nutrients; (3) improving the physical properties; and (4) achieving maximum benefit from the materials available on site or nearby. Fertilizer application to tailings is always necessary and use of organic matter is advisable if it can be obtained locally. Correction of acidity or alkalinity not only enables a wider range of plants to be established, but also alleviates metal toxicity and increases availability of nutrients for plants.

The principle behind addition of materials to tailings or covering over of the surface is to **dilute** or **avoid** toxicity problems rathern than **counter** them by direct seeding of tolerant populations. The covering of mine waste to isolate it from the establishing vegetation is a common approach to reclamation and can succeed if a suitable depth of material can be introduced into which the chosen vegetation can root and develop satisfactorily. Usually the cover material is topsoil, subsoil, or overburden. However, it is rarely feasible, for economic reasons, to provide depths of cover greater than 300 mm, and in the case of some modern tailings the load-bearing capacity precludes the use of most forms of civil engineering equipment required to apply the cover. On wastes of low to medium toxicity, covering layers can provide a cheap method of improvement, whilst very toxic materials require barrier layers or isolating materials between the waste and growing medium to reduce upward movement of metals. In some cases, especially where toxicity is marginal, simple dilution of the waste with innocuous material may suffice.

Dilution

The simplest approach to revegetation using amendments is to incorporate suitable material into the mine waste surface on the principle of diluting the influence of the residual metal values below phytotoxic thresholds. Organic matter, in particular, is used in this connection because it has important beneficial effects both on the physical characteristics and the nutrient status of mine wastes.[33] It increases the water and nutrient-holding capacity, improves surface stability, aeration, and water penetration by alteration of the soil structure, whilst decreasing surface run-off, and improving the seed bed. In addition, heavy metals can be temporarily complexed or chelated by organic material which binds them in an innocuous form until natural decay of the organic matrix causes remobilization. Organic materials also provide a source of micro-organisms. Amendments such as farmyard or poultry manure or sewage sludge, are usually incorporated into the waste surface to 150 mm depth by discing. The aim is to achieve about 3–6% organic matter content, which is the level expected in a normal soil.[34]

Modern high-analysis, compound fertilizers are used in association with the dilution and cover approaches to revegetation. They are formulated from compatible chemicals, and are easy and clean to handle whilst occupying less storage and transport space than the more bulky organic sources of nutrients. Compound fertilizers are available to cover most needs, *e.g.* NPK fertilizer 17.17.17, which supplies 17% N, 17% P_2O_5 (7.5% P), and 17% K_2O (14% K) by weight. Slow-release commercial fertilizers, which release their nutrients in a time-graded pattern over months and even years, are more expensive but can produce good results and reduce labour costs.[20]

Fluorspar–lead–zinc mine tailings in the Peak District National Park in the UK, represents a successful example of the dilution approach to reclamation. Residual levels of metals and fluorides proved not to be toxic and a hydroseeding technique was used to establish a commercial grass–legume seed mix, with the use of air-dried, digested sewage sludge and phosphate fertilizer applied directly to the dewatered tailings surface.[22] The establishment of the grassland together with subsequent planting of trees and shrubs has been very successful and led to extensive colonization by wildlife.

Surface leaching, using overhead sprinkler systems as the basis for dilution of acidity, has been used successfully along the Witwatersrand near Johannesburg in South Africa for controlling acid–sulfate levels in the surface layers of gold mine tailings. Regular mist-spraying regulates the acidity in surface layers at a sufficiently low level to permit the establishment of grasses (*e.g. Chloris gayana*, *Cynodon dactylon*, *Eragrostis curvula*) and legumes (*e.g. Medicago sativa*) after treatment of the tailings with lime and fertilizer.[35] The technique, though

[33] S.J. Stokowski, Jr., Proceedings of the Annual Meeting of the Society of Mining, Phoenix, Arizona, 1988.

[34] G.W. Cooke, 'The Control of Soil Fertility', Crosby Lockwood, London, 1967, p. 526.

successful, is expensive in equipment and labour, reflecting the intransigence of highly pyritic metalliferous wastes to long-term reclamation.

Simple Coverings

Some form of soil or surface cover has been extensively used in past revegetation schemes to avoid toxicity and to improve the texture and stability of waste surfaces so that vegetation can be established. Many of these schemes have worked well but failures have also resulted because of: (1) lack of penetration of roots into the underlying material leading to poor binding at the soil/waste interface; (2) contamination of the covering through upward migration and accumulation of toxic metals, salts, and acidity; or (3) penetration of plant roots into toxic material beneath, with subsequent regression of the vegetation. Experience suggests that the minimum depth of such surface coverings should be 300 mm.[36] With less, erosion of the covering is a real risk.

Coastal dune mining for heavy minerals at Richards Bay on the east coast of S. Africa illustrates the possibilities of reinstating the former vegetation using a shallow layer of topsoil directly on to non-toxic tailings. Topsoil, recovered in advance of the opencast dredgers, is returned to the reformed dunes because it contains a viable seed bank. After 8–12 years, 9 m high *Acacia karoo* woodland has established, which in most respects is comparable to natural stands of this age. There is evidence that normal succession will lead eventually to dune forest typical of the area.[37]

Barrier or Isolating Layers

The use of barrier layers, though less common than the simpler methods on the grounds of the higher cost, is nowadays popular for wastes that present a particular hazard to local communities through toxic metal pollution, and also where there is a pressing need to develop a specific land use (*e.g.* sports fields, grazing land), or where vegetative stabilization cannot otherwise be considered due to extremes of toxicity and acidity. If simple covering layers such as soil are used on toxic waste, then even with deep layers (>300 mm) upward migration of contaminants may in time cause regression of vegetation. In these cases it is necessary to use barrier layers of material designed to inhibit the upward movement of solutes.

The main requirement is that the barrier layer should disrupt the capillary water columns established within the waste. Usually this means at least a 300 mm deep layer of a coarse textured material such as screened gravel, with no fines,[38] rock waste, or coarse non-toxic mine spoil. A column study in Canada, investigating the use of a barrier material, showed that a 50 mm layer of coarse

[35] Chamber of Mines, 'Handbook of Guidelines for Environmental Protection', Chamber of Mines of S. Africa, 1979, p. 5.

[36] M. A. Norem and A. D. Day, *Reclam. Reveg. Res.*, 1985, **4**, 83.

[37] P. Camp and P. J. Weisser, in 'Dune Forest Dynamics in Relation to Land-use Practices', ed. D. A. Everard and G. P. von Maltitz, Foundation for Development, S. Africa, 1991, p. 106.

[38] S. Ames, Proceedings of the 3rd Annual British Columbia Mine Reclamation Symposium, Vernon, British Columbia, Canada, 1979.

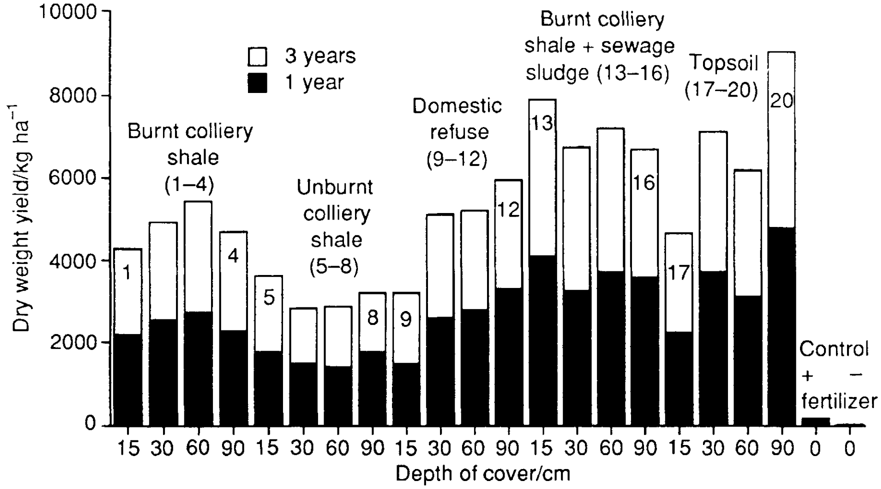


Figure 3 Dry weight yields of a grass–legume mixture on different types and depths of cover material on Pb/Zn waste after one and three years growth at Y Fan mine, Powys, West Wales

gravel placed between acidic iron tailings and a 450 mm layer of overburden, was effective in preventing the upward movement of salts, acids, and toxic metals.[38] On a field scale, however, there would be serious technical problems in spreading a 50 mm layer; 300 mm would be a more practical minimum as regards the use of large machinery. In practice therefore, a 300 mm layer of porous, coarse material covered with a minimum 300 mm depth of rooting medium is usually recommended. In order to be effective, the barrier layer must be free of soil or organic matter and allow free lateral and downward drainage of infiltrating water. The rooting medium allows establishment and growth of stabilizing vegetation and storage of soil moisture. In warm climates, adequate storage of moisture cannot be achieved without deep surface layers.

Faced with the problems of achieving a permanent vegetation cover on as shallow a layer of imported material as possible, extensive trials were undertaken at Y Fan lead–zinc mine in west Wales between 1975 and 1982 (Figure 3). The objective was to develop treatment systems that would prevent root accumulation of toxic metals, eliminate vertical migration of soluble metal salts and provide a vegetation cover that would survive, independently of regular maintenance, because of the high management costs the latter incurs. The field experiments at Y Fan compared plant growth on various inorganic waste materials placed over highly toxic lead–zinc wastes. Figure 3 shows that burnt colliery spoil with sewage sludge was effective in achieving good plant growth and it also prevented movement of lead and zinc, in fact much better than more usual covering materials.[25] The colliery spoil in question was non-toxic, non-pyritic, and of a suitable texture to disrupt water columns in the tailings.

A covering approach has been used at the copper tailings dam of the old Avoca mine in Co. Wicklow, Republic of Ireland. This 30 ha dam was subject to serious erosion problems before the enactment of a revegetation scheme in 1984. The erosion problem was so serious that direct seeding using tolerant seed presented too great a risk in view of the relative slowness of sward establishment by this method. Accordingly, a two-layered cover approach was adopted in which a layer of shale, 200–300 mm deep, was placed on the tailings surface to isolate the material and then overlaid with a skim of 75–100 mm of topsoil and subsoil to provide the supportive medium for cover vegetation. The surface was then treated with conventional limestone and fertilizers before being sown with a traditional agricultural seed mixture.

With careful management, the results were outstanding in the first two years. A crop of hay was taken from the reclaimed surface in the summer following the year of reclamation. The quality of the product was such that there were no constraints upon feeding the product to livestock. In recent years, the management of the site has changed and the sward has been permitted, quite deliberately, to deteriorate and become invaded by other species. The grass surface now supports gorse (*Ulex europaeus*) and broom (*Sarothamnus scoparius*), plus a wide range of herbaceous species, and is now carrying a significant complement of wildlife. In particular, it provides excellent cover for pheasant which have been bred for decades in local woodlands.

A long-standing example of revegetation based on a combination of the use of a shallow covering layer and tolerant plants together is that of Parc Mine, Nr. Llanwrst in north Wales. This old, abandoned lead–zinc mine had a tailings dam of 6 ha that, until 1977, was undergoing severe erosion caused by the steep, angular shape of the dam and the absence of a proper retaining wall. The dam was re-contoured and 200 mm cover of quarry shale placed as a single layer, before seeding with a mixture based on *F. rubra* cv. 'Merlin' with accompanying white clover (*Trifolium repens*). The advantage of including this tolerant fescue in the final product was that the shallow layer of cover was adequate for the clover but the fescue roots penetrated into the tailing beneath keying the cover to the tailings and increasing the physical stability and thus the persistence of the sward. The specification proved successful and an effective cover has been maintained to the present day.

The same broad style of revegetation has been used in the Mediterranean region, particularly in Spain, for decommissioning tailings dams where wind erosion and the residual copper levels are just too high to enable the simpler direct seeding systems described earlier to succeed. In this instance infertile but weathered surface rock and shale was stripped from the base slopes of pine woodland adjacent to the tailings area, and placed upon the tailings surface as a shallow, 200 mm, layer. Trials showed that native buried seed from the natural seed bank (particularly *Pinus pinaster* and *P. pinea*) provided sufficient viable propagules for re-establishment of woodland without any further effort or expenditure apart from the use of limestone and conventional fertilizers as aids to establishment (Figure 4).

This approach, simple covering with a shallow layer of local seed-rich soil and application of NPK fertilizer at 400 kg ha^{-1}, has been outstandingly successful on a large scale tailings facility of 60 ha. In northern Spain, where the climate is sub-Mediterranean, the cover approach has been employed successfully using non-toxic mine overburden. Following trials, direct seedings of tree and shrub seed on to a 500 mm layer of overburden was undertaken on two areas of tailings at a disused copper mine. Slow-release NPK fertilizers were used together with a

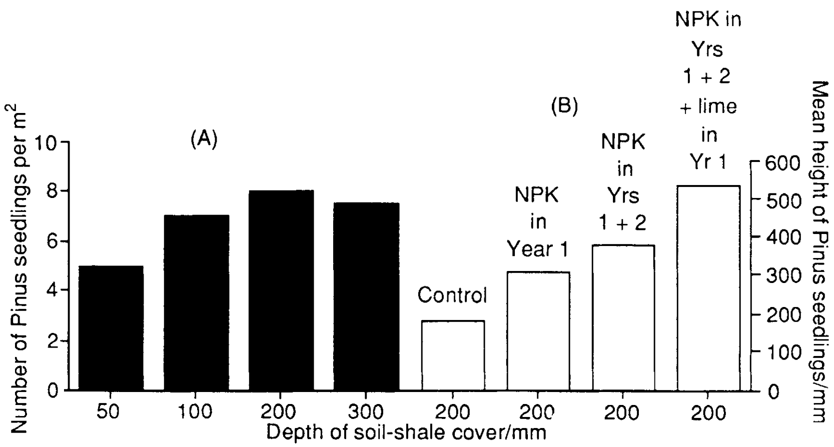


Figure 4 (A) Establishment of *Pinus* seedlings from buried seed banks of soil/shale cover in relation to depth of cover applied. (B) Mean height of *Pinus* seedlings 2 years after seeding and in relation to fertilizer treatment

seed mixture dominated by *Eucalyptus globulus* and *E. camaldulensis*, along with *Acacia retinoides*, *Pinus* spp., and *Betula* spp. as nurse species. The dual reclamation objectives of erosion control and amenity improvement were met less than three years after seeding.

8 Management and Aftercare

Where toxic wastes are reclaimed, regression of a well-established sward can occur. Regression may be due to one or more of the following: (1) weathering of pyritic wastes producing acidity, which in turn alters the availability of plant nutrients and toxic metals; (2) gradual decomposition of organic amendments releasing metals previously held in stable organic complexes; (3) depletion of nutrients required for growth; (4) extreme weather conditions; or (5) upward migration of acidity, heavy metals, or salts into the surface layers of amendment.[39] Long-term management should therefore be considered as an integral part of any reclamation scheme and should be planned at an early stage.

The programme of long-term management will depend ultimately upon the species sown and the land use objective. Refertilization and/or management of a legume component, cutting/grazing, pruning and tying of trees, and fencing maintenance may all figure as components of a management programme for a reclamation site. It is necessary to build up soil fertility, in particular with respect to nitrogen, and then to maintain plant growth through the establishment of leguminous species and the decomposition of organic matter. Legumes are encouraged by maintaining a suitable pH (>5.5) and by application of phosphate fertilizer. In the period directly following reclamation, re-treatment with inorganic fertilizers is necessary, and on acidic wastes maintenance dressings of lime may also be required. Fertilizer applications are based on assessments of the extent of ground cover, colour of the vegetation, seeding potential, productivity, and the results of nutrient analyses and possibly small-scale field

[39] J.R. Harris and A.I.M. Ritchie, *Environ. Geochem. Health*, 1987, **9(2)**, 27.

experiments. Generally, fertilizer inputs are necessary for 4–6 years. These annual applications should be in the order of 35–70 kg ha^{-1} each of N, P_2O_5, and K_2O,[20] depending on vegetation type and land use objective, *etc.*

Grasslands, especially more productive swards comprising forage species, require cutting, grazing, or burning to prevent their gradual deterioration. These practices thicken the sward by encouraging tillering. The timing and frequency of cutting and grazing influence the species that establish, those that persist over time, and the natural seeding that takes place. One of the main problems of aftercare on metal mine wastes results from mobilization of toxic metals, leading to uptake by plants, and potential toxicity problems to grazing livestock. Regular monitoring of metals in vegetation is necessary, and prompt attention to any increase in metal content should enable potential problems to be avoided.

9 Conclusions

Standards of environmental care within the mining industry have increased greatly in the last decade, and derive from the recognition of the socio–environmental demands of society, as well as the need to comply with statutes and regulations that are extending worldwide in order to improve performance and accountability. In the last two decades, techniques have been developed that enable revegetation of metalliferous mine wastes to be undertaken to a necessarily high standard, thus improving the prospects for creating a new, substitute landscape that, whilst not the restoration of the original, may be viewed as a satisfactory and sometimes even more valuable replacement.

The essential ingredients of success are commitment, careful development of a specification, specific objectives, practical implementation methods—sometimes deploying innovative ideas and equipment—and a properly formulated management and aftercare plan (Figure 5). Different endpoints are achievable according to the waste, location, and climate. A wide range of land uses is available, including various grasslands, woodland, and wildlife habitat. On occasions it is even possible to regard some form of crop or livestock production as a part of the long-term revegetation plan. However, there remain some doubts as to the sustainability of certain specifications in the long-term. The so-called 'walk-away' option has been promoted at some sites but remains an elusive target. What is certain, however, despite the challenges that remain, is that with modern reclamation techniques it is no longer appropriate to argue against mining in its totality based upon the inevitability of irreversible damage to the landscape, loss of amenity, or nature conservation values.

Figure 5 Flow chart of the stages in achieving successful revegetation of mine waste or tailings