

## Forestry Abstracts

### Review Article

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#### Rehabilitation of Mined Lands

J.E.D. Fox B.Sc.,M.F.S.,M.Sc.,Ph.D.  
School of Biology,  
Western Australian Institute of Technology,  
Kent Street, Bentley 6102  
Western Australia

#### Abstract

Problems involved in the treatment of land and surfaces disturbed by mining activities are reviewed. Land-use is closely related to pre-existing patterns, with highest values in more closely populated regions. Historical disaster areas provide the onus for avoiding future difficulties, with most problems stemming from slimes and toxic residues. In many cases pre-planning of mining procedures can provide favourable physical media for plant growth. Increased environmental awareness has resulted in more attention being paid to alleviating problems through careful planning. Where prior planning involves trials on potential species for post-mining growth, the time for successful rehabilitation is likely to be considerably shortened.

A wide range of techniques have been developed drawing on traditional agronomic, silvicultural and rangeland management. Species are available for many forms of disturbance whether post-mining land use is for agriculture, forestry or merely surface stabilisation. Species suitable for afforestation are mainly drawn from those used in conventional forestry, from the group of pioneer species or species able to fix nitrogen.

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### I. Introduction

In many senses the subject is an artificial one in that it embraces aspects of a number of traditional disciplines. Our concern with the land and its productive use is becoming more necessary as the supply of arable land is finite and as populations that must be fed continue to increase. The problems of land disturbance are affecting more of us as time goes by. I must at the outset declare my personal interests - firstly, in West Africa some of my colleagues lived in Government housing in the diamond fields and, secondly, my present residence lies in a bauxite lease. Diamonds among the okra seem more satisfying than attempting to cultivate tomatoes on lateritic cap rock.

The notion of 'rehabilitation' requires careful consideration. In general terms the word is used to indicate establishment of conditions such that the land can be used. 'Reclamation' is used to describe a return to use from a state of waste, whereas 'restoration' is more specific, referring to a return to a previous condition. Standard definitions have been developed in

the United States and these are elaborated by Box (1979). Restoration is rarely possible as it is difficult to replicate the pre-existing conditions. Reclamation implies that the site will be suitable for those species originally present, in similar composition and density after treatments. Thus the original native species should be used in post-mining but it is acceptable if the site is rendered suitable for organisms that closely resemble the original species. Rehabilitation is a broader term which may include restoration or reclamation. Box (1979) suggests rehabilitation means that the disturbed site will be returned to a form and productivity where a stable condition is established, consistent with adjoining aesthetic values. Rehabilitation allows alternative land uses to the pre-existing one.

Much of the world's wealth is derived from mining activities. Land surfaces are inevitably disturbed in seeking to win ores from the earth. In past ages the use of slave labour and restriction of mining to near-surface highgrade ores for precious metals, gemstones and armoury suggest that persistent visual effects would have been slight. Many mines could have been readily back-filled with rubble (Smith 1972). During the last century and a half the pattern has changed. Industrialisation has necessitated the winning of large quantities of material from the earth. In addition, ores not formerly workable have become important. The economic grade has declined as all rich easily worked ores have been exhausted. Mechanisation and improved

technology have brought increasingly large tracts of land into states of disturbance. It is only in comparatively recent times that economic effort has been put into rehabilitation of mined lands.

Mine wastes may be generated away from the minesite when exported in world trade or used in reduction near ports, markets, or sites of 'cheap' electricity. Another class of wastes are byproducts of industrial activity e.g. fly ash from power stations (Rees & Sidrak 1956).

Mining and forestry come together with rehabilitation. Köpp (1978) notes that rehabilitation was an early dominant force in the development of forestry. Foresters have been involved in rehabilitation of waste dumps on a formal scale from the turn of this century (Sheail 1974). Opinions differ on the relative roles of silviculture and agronomy. It has been suggested that early reports show the main approach to revegetation was through reafforestation (Hunter & Whiteman 1974) but, alternatively, that trees have been neglected, with most schemes designed to establish herbaceous vegetation or to develop agricultural systems (Sheldon 1974).

The type of end use reported is a reflection of relative land scarcity combined with the climatic climax vegetation of the areas concerned. For example in Britain much of the literature is concerned with herbage on difficult sites or agricultural cropping on better sites; in much of the U.S. work forest or

range, with extremes of alpine and desert.

'The course of a gold mine is clear. There is so much gold in a mine. .... When the gold is exhausted the mine is finished. With forests the position is different. Here we have a mine of wealth, but, unlike a gold mine, it is inexhaustible so long as it is worked properly'

R.T. Robinson, Attorney-General and Minister for Woods and Forests, introducing the second reading of the Forest Bill, 17 September 1918, for the Western Australian Forests Act of 1918 (quoted by Beggs 1972)

Robinson's clear distinction between renewable and non-renewable resources is not so clear-cut in practice. As economic conditions change abandoned mines and dumps become re-workable. Long term forest land use requires that reworking for low grade ores is not a likely possibility. Rehabilitation to a stable state often entails reshaping of spoil, application of topsoil, soil amendments, planting or seeding and vegetation maintenance. Reworking possibilities may lead to economic loss where rehabilitation is undertaken or prevent its initiation. Gold slimes and tin tailings are examples where changes in metal prices result in reworking at the present time.

Following cessation of mining the land uses available are not unlimited. Many past mined areas of dereliction have remained unvegetated - a condition which has come to be known as

'orphaned' (Davidson 1979). Unused land in itself may lead to other values - recreational, historical or aesthetic. The land may be returned to its prior use or to a new use. In conversion to a new use the highest value is inevitably for urban usage, whether as housing, or for some commercial or industrial development. Worked out tin mining areas in S.E. Asia provide good examples of urban usage (Suwanasing 1981). Hazardous residues and remoteness both work against conversion to urban use such that this option has limited value.

Perhaps the next most valuable use would be for cropping, with waterbodies used for aquaculture or water supplies. Then range or pastoral livestock follow, with forestry production generally considered to be last in the productive sequence. Protection of the area, whether to minimise damage to other productive areas down from the site or simply to hold the new soil-scapes in place, rarely generates any monetary values directly to which costs of rehabilitation can be compared. Cosmetic work, often at considerable expense, may be undertaken at particularly sensitive sites. Here appearance is all important and criteria may include the degree to which the site blends visually with the landscape (e.g. Gemmell 1976). Recreation is often discussed as a use, but devotion of large areas to recreation alone will rarely produce any returns in an economic sense.

#### **Bibliographic Sources**

Activity in rehabilitation research has developed rapidly yielding a voluminous literature (Czapowskyj 1976). Aspects of

the subject have been covered in recent years in straightforward bibliographies, major reviews and in several texts. In addition to the items mentioned here it will be noted that a number of articles referred to elsewhere are papers from collected works derived from symposia of direct relevance (see for example Bennett 1979).

J.V. Thirgood at the University of British Columbia produced 10 issues of 'Reclamation Research Newsletter and Bibliography' (cyclostyled) between August 1971 and December 1975. This was under the auspices of Working Group S1.02-4 'Reclamation of Drastically Disturbed Sites' of the International Union of Forestry Research Organisations. This sterling effort was a direct forerunner of the journal 'Reclamation Review'.

The bibliography of Knabe (1958) gave 206 items published between 1950-57. Lists are given geographically, with the largest number relating to Germany. There is a tabulated analysis by type of waste land, country and ten separate aspects of the subject. The texts edited by Hutnik & Davis (1973) contain 66 papers. About half are of interest to forestry and include information on natural and artificial afforestation of wastelands resulting from mining in Europe and North America. The text edited by Thomasius (1973) includes several papers on reclamation of mine spoils in the German Democratic Republic. Hunter & Whiteman (1974) is a good source for several Australian bibliographies as well as a useful review of early reported revegetation work in different

parts of the world.

Albrecht & Smith (1976) list 270 English language items from 1923-1976, with 24 dealing with the environmental effects of copper-nickel mining in Minnesota. Albrecht (1978) lists a further 168 items of which 100 were published in 1976 or later, with a further 24 specifically related to Minnesota, mainly post 1975. Czapowskyj (1976) presents an annotated bibliography using 591 references mainly to mining effects and reclamation in the U.S. coal mining areas. There are geographical, material and subject indices: the latter in 8 major and 35 minor categories - 'revegetation' includes 185 references. The bibliography of Kampfer (1976) contains 304 references, mainly related to open-cast lignite mining. The text by Down & Stocks (1977) includes a chapter on reclamation with 130 references. Gemmell (1977) deals specifically in text form with the colonization of industrial wasteland in the U.K. Ralston et al (1977) is also specific, but a bibliography, in this case to the ecological effects of strip mining in the Western U.S. It includes a substantial key word index (156 pp) to the references, many of which are given with abstracts. Thames (1977) is a text of 33 chapters dealing with reclamation and land use in the southwestern U.S.

The text by Bradshaw & Chadwick (1980) is a very useful handbook summarising the problems presented by mining worldwide, and of the various solutions currently available to restore different types of surface materials to use. It is not bibliographically arranged in the strict sense, but each chapter is provided with a



list of key references for 'further reading'. The annotated bibliography of Follett (1980) deals with agricultural research over the period 1972-1980 undertaken on areas surface mined for coal in the U.S. A total of 106 publications are dealt with. Richardson & Pratt (1980) deal with minerals other than coal won by surface mining techniques. They include 797 separate entries - 94 of which are bibliographies, mainly from the 1970's and including all the U.S. sources given above. Also included are 160 listed comments on significant environmental problems (mainly relating to rehabilitation) for which more research is required.

Despite the large scale of mining activities, particularly that of surface stripping for coal, the extent of gross land disturbance should be taken in perspective. The area involved in open-cast mining is generally small in comparison with that used for agriculture and is usually less than that used for roads (Coaldrake 1973). Although lignite mining in West Germany disturbs some 3 km<sup>2</sup> of farm and forest land annually, this should be contrasted with permanent loss of productive land of 1 km<sup>2</sup> per day for city growth, highway construction and industrial expansion (Bradley 1981). Areas disturbed by mining are often a function of the roading required. Roading left in situ on abandonment, though useful for the mechanics of rehabilitation also increases human pressure on the land for recreation, hunting and other uses.

The present review will concentrate firstly on a delimitation of

types of disturbance due to mining, then a consideration of planning to achieve successful rehabilitation and an account of techniques developed to fit the special problems. The review concludes with a consideration of the role of succession and of species found useful in rehabilitation.

## II. Types of Disturbance

The disturbance of land surfaces clearly alters the potential for vegetative growth such that it is not possible for the pre-existing plant community to be replaced exactly as it was previously. This obvious fact has not prevented the promulgation of institutional measures to seek such an outcome. Should mankind wish to preserve examples of naturally occurring vegetation then mining is one activity which should not intrude into designated areas. Nevertheless mining is generally considered the 'highest' form of land use.

The significance of mining disturbance is correlated with surface effects and the economic costs associated with restoration. Mining which disturbs large tracts of land is clearly of much greater significance than smaller localized sites. Fortunately much surface mining involves relatively innocuous materials being exposed. Activities which generate downstream effects or impinge in other ways on mans total environment entail greater consideration being given to mitigation. In this section some land use considerations are presented, followed by characterization of dumps and slimes dams. The section concludes with a summary of adverse soil conditions, with particular emphasis given to compaction, heavy metal contamination and acidity.

### Land Use Considerations

The greatest impact on landscapes in terms of disturbance comes from stripping or open-cut operations. Stripped areas are

theoretically simpler to restore than other types of mine as the overburden can be temporarily placed in sequences for later return. In practice very large operations have often been unsatisfactorily planned. Typical U.S. strip mining for coal is described by Muir (1979) - a narrow lane of overburden is removed leaving a trench. The trench is then partially filled with overburden from a parallel strip. Strips are progressively exposed, mined and filled across the landscape. On exhaustion the landscape is a series of ridges of mixed overburden and coal fragments. Muir (1979) suggests that restoration involves great technical difficulties and expense due to this mixing.

In deep mining much of the waste material can be returned underground to backfill worked areas (Challen 1979). Both types of mining may give rise to waste dumps: of overburden or of treated materials. The latter may be heaped but where the material has been ground to a fine grade then dams (slimes dams) are used to store the waste. Waste dumps or dams may be large and of such a height as to alter the surrounding landscape (e.g. Johannesburg: Poynton 1977). Slag heaps at industrial localities may be waste rock or smelter residues.

Forestry is often concerned with maintenance of water quality. The threats posed by mining in water catchments are many and varied (Beggs 1972). Water supplies are essential to the establishment of mines, if only to support the infrastructure. Water has a role in many production processes and particularly in

solution mining and leaching treatments. Ground water contamination may be a problem with some heavy metal sources from tailings. Many deep mines and open cuts must be continually dewatered. The cessation of mining may leave artificial lakes. These may enhance the scenic and recreational values of a mined landscape but they will increase evaporative losses from stream systems.

Mining may affect water quality directly through sediment discharge and the release of soluble toxic materials into stream systems. The problems are likely to be more severe with deep mines for heavy metals. In Australia the Captain's Flat copper, gold, lead and zinc mine polluted the Molonglo River with acid water pumped from lower levels and waste water from the flotation plant (Beggs 1972). Slimes dumps collapsed resulting in tailings entering the water and destroying vegetation downstream. After closure in 1962 acid water continued to overflow from the abandoned workings. The restoration of this area is one of the largest and costliest attempts to improve a metalliferous mining area (Craze 1977a). This mine typifies the extremes of disturbance. The wastes have a low pH, high concentration of heavy metals and sulphur, very high salinity, and are of low permeability due to cementation. Rehabilitation efforts involved reshaping, surface covering and revegetation.

The Rum Jungle mine in Australia's Northern Territory has given rise to similar problems. Copper and acid run-off overflow into the Finniss River every wet season resulting in a large fish

kill. The cost of restoration of this site is put at many millions of dollars. In the U.S. acid and heavy metals from the Blackbird mine dump have eliminated all fish and benthos and most of the streamside vegetation in Blackbird Creek. Loss of the anadromous fishery for 40 km downstream is estimated as an annual loss of \$1.5 million (Richardson 1980). These examples illustrate that 'dead' mines may remain live sources of pollution to water bodies long after production of ore has finished.

Some areas of current concern in respect of water supply problems in relation to strip mining are the jarrah forest in Australia and the Wyodok beds in the U.S. Bauxite deposits underlie commercial forests of jarrah (*Eucalyptus marginata*) on water-catchment areas supplying water to the most densely populated areas of Western Australia. Mining removes 2-5 m of lateritic profile leaving an impervious kaolinitic clay, which is then covered with 10-30 cm of replaced topsoil (Coaldrake 1973). Prevention of salinization is paramount in areas where soil salt storage is high and this can only be achieved by rapid re-establishment of perennial plant species (Tacey 1980). The Wyodak beds of Wyoming's Powder River basin contain surface minable lignite and sub-bituminous coal averaging 20 m thickness. These or the zones immediately above them are the primary shallow groundwater aquifers (Orr 1975). Successful water management in this region is essential and rehabilitation trials are closely allied with hydrological studies.

In these and, no doubt, other cases, enlightened governments and mining companies are combining to avoid the excesses of the past.

#### Dumps and Slimes Dams

Overburden stripping gives rise to dumps of waste material. Each dump varies in composition. Surface properties can be planned by sequential placement to take account of chemical or physical characteristics of the strata to be removed. Problem dumps are often historically induced disasters derived from unplanned dumping resulting in one or more of acidic, saline or toxic surfaces, run-off or erosion products. General methods can be developed for treatment of types of material. Where there is extreme variability in chemical composition then vegetation treatments tend to be unique to particular dumps.

Waste material derived from ore-processing may be accumulated at sites distant from the mine. Ore grinding and crushing utilizing slurry transport result in development of slimes dams. Tailings spigoted on to a dam surface at a fixed point concentrate coarser fractions close to outlets and finer fractions distant from outlets (Chosa & Shetron 1976). Differential settling may give rise to persistent thixotropic conditions (Hore-Lacy 1979) with the dam unable to support machinery for some years after abandonment. Bauxite and nickel wastes are of concern due to their accumulation near industrial sites. These slimes are characterised by high soluble salt levels, high sodium concentration and alkalinity.

Smelter wastes and industrial products such as power station ash constitute a further source of land degradation. The former may be classed with problem dumps while the latter type of waste is more amenable to manipulation either for restoration in situ or for use in ameliorating other types of waste material.

a) Dumped Materials

Once mining has moved on the physical alteration of a dump is expensive. Treatment to return such areas to use will depend upon the physical and chemical nature of the material. Reject slate quarry waste is an example of extremely coarse dump material (Sheldon & Bradshaw 1976). Natural colonisation is restricted to moist pockets and losses following tree planting are likely to be high if drought occurs in the first year (Sheldon 1974). Asbestos tailings are also coarse with low water holding capacity but these form a seasonal crust in summer enabling underlying material to retain moisture. After 5 years a permanent 20 cm crust develops but rain splash erosion can cover and kill emerging seedlings with fibres (Moore & Zimmermann 1977).

An important physical factor is the angle of slope. The sides of spoils dumps built with machinery, tipping material directly, lie initially at 40° (90 per cent slope) and settle to 35-37° (Johnson & Bradshaw 1979). China clay tips have slopes > 35° (Sheldon & Bradshaw 1977). Typical coal tips in the U.K. are cone or ridge shaped, up to 60 m tall, with an angle of repose of 35° (Ayerst 1978). In S.E. Quebec asbestos residue dumps have



slopes of 35-40° (Moore & Zimmermann 1977). Where some harmony with the overall landscape exists then surface stabilization against erosion is desirable. In higher rainfall areas slopes devoid of vegetation may affect water courses far downstream (Armiger, Jones & Bennett 1976). A level of 30 per cent vegetation cover is the minimum required for the stabilisation of china clay sand tips (Marrs, Roberts & Bradshaw 1980). If the land area involved is to be used economically then some reduction in slope is required. While it has been suggested that 35° slopes may be suitable for afforestation (Johnson & Bradshaw 1979) most forest managers would prefer shallower slopes (Puchko 1977). Terracing for rice cultivation indicates that with careful contouring slopes should not inhibit intensive cultivation. For vegetation establishment Armiger et al (1976) describe a 'lateral groove technique' with terracing serving to hold water and improve the local microclimate.

Earlier mining often left wastes with higher grades of mineral than can be extracted with modern technology. In contemporary large mines it is often difficult to discriminate with big machines. Thus localised parts of waste dumps may contain a lot of ore material. Consequently two problems may exist. Firstly that of increased variability (e.g. local toxicity) in the dump and secondly the prospect of later reworking.

Liming is essential to counteract acidity in coal spoils if tree growth is desired (Keleberda 1972) and to ameliorate effects of

heavy minerals sufficient to allow grass growth on more difficult wastes (Keane 1977). In some cases adequate fertilising with nitrogen and phosphorus can obviate the need for nurse crops or organic matter addition (Heinsdorf 1976).

Asbestos tailings have been compared to serpentine tailings, with pH 9, high levels of magnesium, nickel and chromium and low levels of nitrogen, phosphorus, calcium and potassium. Acidification may improve the availability of phosphorus from fertilizer but may also increase heavy metal toxicity (Moore & Zimmermann 1977). Rangeland mined for bentonite gives rise to colloidal spoils with high sodium contents. Revegetation is particularly difficult as nutrient mobility and moisture availability are restricted (T. Yamamoto in Richardson & Pratt 1980).

While air and water access to acid generating wastes should be minimized, areas contaminated by hydrocarbons require aeration. Such contamination imposes an increased biological oxygen demand on the soil due to microbial activity giving competition for nitrogen between microbes and higher plants. Gudin & Syrratt (1975) recommend that such areas should be given improved aeration, added nitrogen (to restore carbon: nitrogen balance and increase the breakdown rate) and a legume cover crop. Black polythene sheeting can be used to increase winter soil temperatures, and a transparent cover would reduce evaporation in arid areas. *Pinus sylvestris* has been grown on levelled oil shale workings in Estonia. Lucerne sown with planted trees was

beneficial and tree growth responded to added nitrogen (Kaar 1972). On calcareous spoils peat incorporation improved the growth of *Larix* species (Kaar & Paves 1975).

b) Slimes Dams

Processed ores producing residues feature water percolation as a main problem. The usual solution is to physically stabilize tailings, ponds or dams. Sometimes disposal to the sea may be considered an environmentally sound option (Hore-Lacy 1979) for example at Bougainville (Hartley 1977). When dams are used to hold slimes then a stable engineered structure is needed with an impermeable lining to prevent ground water contamination.

Failures of earth structures are possible and failures can cause secondary degradation. Methods of stabilizing such wastes are required both to prevent pollution and to improve the visual appearance of mine workings (Smith & Bradshaw 1972). For a variety of reasons vegetation cover of a continuous nature is usually preferred. Mechanical stabilization is often useful, particularly in dry regions, with intractable materials, where dust is a problem (Marshall, Morrissey & Richmond 1978). However, rock and soil coverings are often expensive to apply. Where soil is used over slimes slip zones may develop as the latter absorb water more slowly (Poynton 1977). Artificial coverings are vulnerable to hail, cattle and wind erosion damage. Vegetation increases the land use alternatives available. Goldmine tailings in the Canadian Shield can be developed to give

a range of new land uses e.g. nurseries, cattle grazing, recreation (Keller & Leroy 1975).

Slimes containing heavy metals, with extremes of pH, often show great variation within the mass. Hill (1977a) used quartiles to measure surface and depth variation across dumps. In the case of copper, gold and nickel waste in Zimbabwe factors limiting plant growth are:

high concentrations of arsenic, nickel and copper

high surface soluble salt contents

acute deficiencies of one or two of nitrogen, phosphorus or potassium

Variation across slimes may be attributed to incomplete leaching or capillary action from deeper levels, both affected by differential deposition of size fractions (Hill 1977a). Temporal and seasonal variations further complicate slimes as potential growth media.

#### Adverse Soil Conditions

Rehabilitation is conditioned by chemical, physical and climatic properties. Mine wastes are usually sterile, nutrient elements may be deficient and toxic levels of some elements may be present. Acid wastes from coal, and other mines using sulphide ores, alter the availability of ions. Other wastes are strongly alkaline. Soluble salts may be present in excess.

The physical nature of waste is often inimical to plant growth. Materials may be unduly compacted or loose and exposed to

movement. Segregation of particle sizes will result in gradation of conditions with fine material prone to surface compaction and coarse material with little ability to hold moisture.

The unnatural assemblage of materials often renders spoils liable to wind or water erosion. Extremes of moisture and temperature may be more severe than at undisturbed locations within the same climatic region.

a) Compaction

Strip and surface operations often result in variable textured mixtures of subsoils and rock materials. These mixtures are more easily reclaimed than tailings accumulations. Tailings may have been processed through milling and when water deposited a texture gradient is established which leads to settling differences. Compaction tends to reduce moisture infiltration and result in poor plant growth (Geyer & Rogers 1972).

Grading of spoil derived from limestone or other parent material of high clay content may give undesirable compaction. However grading of coarse textured spoils is likely to improve growth conditions (Czapowskyj 1970). Traditional tipping of coal mine waste in Britain resulted in little compaction. Spaces between particles trapped air providing ideal conditions for combustion so that many tips burnt. When tip drainage was impeded the voids could absorb water and saturation would result in instability. The Aberfan disaster in 1966 resulted from saturation. Subsequently adopted regulations include provision for tips to be

constructed in layers to exclude air by compaction. Ayerst (1978) has argued that this causes hardpan-like conditions and that surface loosening prior to seeding is nullified if recompaction follows rainfall and subsequent drying. Root growth and penetration can be promoted by fertilizer but plants may still be drought prone (Fitter & Bradshaw 1974). The use of sewage sludge is superior and gives plants with a high root/shoot ratio, through provision of a more readily penetrable surface (Ayerst 1978).

The widespread use of heavy tracked machines for ore removal has resulted in compaction being a major rehabilitation problem. Machinery to deal with compaction include rippers to fracture and break up surfaces. Offset discs or chisel plough and the contour furrower are also used, especially where it is important to reduce runoff (Brown 1977). The benefits of ripping have been reviewed by Richardson (1980). These include improved aeration and water retention, better root-penetration and control of erosion. Soil amendments may be incorporated more readily. The breaking of aggregates in situ for seedbed preparation is more beneficial than removal or replacing with alluvial soil (Reynolds, Cwik & Kelley 1978).

Surface accumulation of fines in slimes dams may give a bulk density as high as  $7.5 \text{ g cm}^{-1} \text{ }^3$  with low infiltration (Ruschena et al 1974). Bulk density is a useful measure of compaction in relation to root penetration. Craze (1977b) compacted spoils with

17 per cent moisture content (the optimum for attaining 90 per cent maximum compacted dry density) at a range of densities to determine the limit of compaction possible coincident with adequate root penetration. For *Secale cereale* this was  $\approx 1.4 \text{ g cm}^{-3}$ . Roots are unable to penetrate some compacted coarse soils with adequate aeration. Zisa, Halverson & Stout (1980) suggest that measured soil resistance to penetration may predict seedling performance better than bulk density. Compaction of oil shale waste is reviewed by Bay (1976).

b) Heavy Metal Toxicity

In addition to adverse physical factors revegetation of wastes is influenced by nutritional conditions (Davison & Jefferies 1966). Soil acidity affects the availability of ions to plants, it may render nutrients unavailable or cause micronutrient elements or non nutrients to become available in toxic amounts. In alkaline soils  $\text{pH} > 8$  the micronutrients iron, manganese and boron become difficult for plants to absorb. Phosphate becomes unavailable as it becomes insoluble (Bradshaw & Chadwick 1980). Heavy metal toxicity has a very specific effect, seriously inhibiting root growth, making plants susceptible to drought and causing nutrient imbalances such as induced phosphate deficiencies (Smith & Bradshaw 1972). The heavy metals of most concern are copper, cadmium, lead and zinc. Others include boron, iron, manganese, aluminium, chromium, nickel, fluorides, arsenic, mercury and cyanide.

Colliery spoils and metal mine wastes are typically acid and

inhibit plant growth both because of the acidity and the increased mobility, and hence availability of toxic metal ions (Down & Stocks 1977). Aluminium, manganese and iron are often of greatest importance in coal wastes (Berg & Vogel 1973). In addition to direct toxic effects, at pH < 4-5 aluminium, with iron, combines with phosphate forming insoluble compounds making phosphate unavailable. Thus although phosphate fertilizers may render heavy metals insoluble through complexing (Smith & Bradshaw 1972) growing plants may become phosphorus deficient when seed reserves are exhausted (Craze 1977c). Acid soils also restrict microbial activity so that nitrogen release can be very low (Bradshaw & Chadwick 1980). The contents of potassium, iron, copper and zinc in plant tissues are much higher at pH 3.4 than 5.0 (Farmer, Richardson & Brown 1976).

Ruschena et al 1974 reviewed toxicity levels of heavy metals in relation to rehabilitation of the lead, zinc and copper tailings at Mt Isa in Queensland. Down & Stocks (1977) give some general levels: soluble aluminium, copper, nickel, zinc and lead are toxic to normal plants at concentrations of 1-10 ppm; manganese and iron toxicity levels vary with 20-50 ppm required before damage is caused; boron can be toxic at > 10 ppm, but some species can be quite tolerant e.g. *Lolium perenne* on power station ash (Cope 1965). To these can be added, at 5-20 ppm, cadmium (Williams & David 1977), and arsenic and antimony (Hill 1977a). Copper toxicity of mine water is reduced by the presence of other ions (Antonovics, Bradshaw & Turner 1971). Calcium may



affect the expression and type of metal tolerance as it reduces zinc and copper uptake (Hill 1977a) and ameliorates lead, zinc and nickel toxicity (Antonovics et al 1971). Craze (1977c) delayed sowing after liming until heavy metal precipitation occurred to avoid retardation of germination. Even after treatment low grade ore pockets give rise to 'hot spots' high in sulphide minerals and salts. Such spots will not support vegetation (Farmer et al 1976). The products of sulphide mineral oxidation render difficult, if not impossible, the establishment of vegetation without overburden modification (Richardson & Farmer 1981).

Air pollution in Europe leads to a replacement of conifers by hardwoods (Kopp 1978). Heavy metal pollution of soil and plants is often particularly evident in the vicinity of smelters (Cartwright, Merry & Tiller 1977). *Sassafras albidum* and *Nyssa sylvatica* contained high levels of zinc and cadmium in the vicinity of a Pennsylvania zinc smelter (Jordan 1975). These species were the most common in polluted and burnt areas, but even these were scrubby and depauperate. Both species reproduce vegetatively and may be expected to replace the original dominant *Quercus* and *Acer* species. An examination of heavy metal content in species of high constancy on metal mine sites in North Carolina revealed not particularly high concentrations of lead copper or zinc in aerial parts of *Sassafras albidum*. The most mobile element, zinc, was accumulated most readily at up to 300 ppm in twigs. Several herb species had up to 50 ppm copper in aerial parts and up to 280 ppm in root tissues. These levels are

2-5 times higher than concentrations in normal soils (Wickland 1981).

### c) Acidity

Mine spoils containing iron pyrites generate acidity on weathering. A considerable range of acidity is encountered in coal spoils, from freshly exposed to well weathered. All are deficient in nitrogen and phosphorus (Davison & Jefferies 1966). Pyritic roof coals and black shales with high sulphur contents cause extremely low pH (2.4-3.0) in some areas of Appalachia (Armiger, Jones & Bennett 1976). In addition to toxic levels of metal ions, acidic coal wastes may be deficient in magnesium (Kimber, Pulford & Duncan 1978).

The amount of pyrite present is not always proportional to the acidity produced. Acidity tends to be more related to the particle size of the pyrite (Caruccio 1975). Iron sulphides are also important in association with sulphide ores of zinc, lead, silver, copper, nickel, gold and cadmium deposits (Hore-Lacy 1979). Surface acidity of dumps at the Captain's Flat mine have been recorded at  $\leq 3.0$  pH with values as low as 1.5-2.0 in run off (Craze 1977a).

The availability of metal ions to plants varies with acidity of the soil medium. Increased plant establishment will often follow liming and fertilizing. This has been attributed to precipitation of heavy metals in contact with lime and phosphorus. Depression

of yield at high lime levels ( $62.5 \text{ t ha}^{-1}$ ) has been attributed to increased zinc solubility (Craze 1977c). At higher soil pH some metal ions are taken up preferentially despite much higher levels in spoils of low pH. Lead uptake by plants, in particular, appears to be related to soil acidity rather than to absolute quantities present (Johnston & Proctor 1977).

Some South African gold mine dumps have pH as low as 1.5 though the Witwatersrand slimes are generally alkaline with restricted areas of pyrites. South African coal dumps may have pH  $> 8$  (James & Mrost 1965). In western U.S.A. surface mined coal spoils in arid country (150-400 mm) have comparatively high pH levels (5.2-8.0)(Howard, Rauzi & Schuman 1979) with little difference on some sites between topsoil and overburden (Howard, Schuman & Rauzi 1977).

### III. Planning Considerations

#### Land Use Objectives

Increased environmental awareness has led to restoration considerations being examined prior to the start of new mining enterprises. While the world is stuck with problem areas from the past the view that adequate pre-planning can avoid or mitigate further extremes is rapidly becoming accepted (Box 1979). Integration of rehabilitation strategies with mining plans will usually speed up restoration and reduce the total cost (Jeffrey, Maybury & Levinge 1974). Extraction of ores, separation of overburden, disposal of spoils and road alignments can all be planned so that post-mining topography, drainage and surface materials will accord with the future land use of the worked area. There are many examples of successful preplanning (Hunt & Farrant 1955). Tree establishment is a common land use on many mine wastes. Successful achievement of the post-mining land-use must be seen as the ultimate aim of the rehabilitation strategy. Arbitrary rules and procedures, perhaps useful in initially establishing a framework for planning, are being replaced by appropriate objectives for individual areas. For example Bradley (1981) notes that in reclaiming mined-over areas no effort is made to adhere rigidly to the arbitrary rule of restoration to the original contours, a principle long discarded as impractical. A managed forest is often the most practical use of mine waste areas, particularly in forest regions or where the climate is suitable. In the U.S.A. many state and federal laws require trees or other woody plants to be planted on steep slopes or other highly erodible sites (Plass 1978). Even in dry regions

woody plant establishment is an important aspect of revegetation of waste areas (Jurgensen 1979).

Land reclamation has three distinct elements (Johnson & Bradshaw 1979). These are firstly the identification of critical limiting factors, secondly the appropriate treatments and thirdly aftercare. Critical limiting factors embrace aspects of the environment and selection of appropriate rehabilitation objectives. Without some firm policy in respect of tenure the sequence may not be effectively applied. Although it may be biologically and technically possible to establish and maintain vegetation cover to stabilise surfaces it is not possible to completely restore destroyed plant communities. Stabilisation and rehabilitation are more accurately descriptive words than restoration in respect of natural communities (Coaldrake 1973). Vegetation methods of rehabilitation have advantages over physical or chemical methods due to the long term nature of the solution combined with low maintenance costs and improved aesthetics (Douheret 1973). Where wood can be produced then economic advantages also accrue. On an inert material the objective must be to speed up the formation of a soil where no soil existed before (Sheldon 1974).

When mining is proceeding it is the 'highest' economic form of land use but since minerals are finite, this land use is transient. Mining taking place on valuable agricultural land necessitates serious consideration being given to restoration to

the former level of productivity. There are clear advantages in knowing in advance of mining what land-use objectives are applicable to given areas. In this way any conflicts can be resolved at the planning stage. The majority of forest land is managed for several purposes. Conflicts between uses are often unavoidable (Köpp 1978) but especially where water supplies are scarce then assured rehabilitation to forest cover is required (Tacey 1980). Regions of higher rainfall generally provide direct economic justification for rehabilitation although in near-urban areas costs are likely to be biased in favour of industrial or commercial usage. Rural areas may provide a range of alternative or conjunctive possibilities. Land ownership is important as when the land is privately owned the future land-use (within some general constraints) may be defined by the owner.

Stable biological systems are desired (Tacey 1980) and we should pursue objectives which can be attained. We often tend to look to the highest form of land use. When agricultural restoration requires excessive inputs afforestation may be a second preference as on old tin workings of the Jos Plateau, Nigeria (Wimbush 1963). Here tree planting is considered a sound land use for five reasons: land hunger, to reduce erosion up slope, to provide poles and firewood, to provide grazing, and to give open pits supplying water resources for dry season irrigation (Orode, Adeka & Allan 1977). In other cases afforestation may be uneconomic or difficult to achieve in which case shrub cover could be a more appropriate objective.

Some examples of pre-planning are given by Ammer & Pohlmann (1977) and Comalco (1981). In the former case detailed plans were provided to convert a 25 m mound into a recreational area for both summer and winter activities. Natural *Picea abies* stands supplemented with deciduous trees were recommended for summer recreation areas, with a range of other conifers for winter sites. At Weipa, in North Queensland, Comalco has the following objectives in rehabilitating areas mined for bauxite.

- \* to produce a self-sustaining open forest with a wide variety of native species
- \* to maintain an experimental programme for planting of selected trees, crops and pastures with potential commercial value.

In addition the Company plans to stabilise tailings dams, to beautify the environs and to develop mined out areas for sound and responsible land use. Where mining removes material below watertables, as at the western end of Weipa Peninsula, then large scale artificial lake creation is possible.

#### Legal Provisions

During the past 30 years a number of countries have enacted legislation in attempts to control the effects of mining. Criteria generally considered useful (Muir 1979) include the following provisions:

- removal and storage of topsoil for reuse;
- refilling of mined areas to harmonize with the landscape and natural hydrology;
- planting of suitable ground cover on restored land;

- submission of a plan for mining and restoration prior to start of operations.

By 1970 21 states of the U.S.A. had adopted legislation requiring submission of a mining plan with a description of the area to be disturbed and measures to be taken to restore it (Muir 1979). Some 28 states had passed laws requiring restoration of strip-mined land by 1975 (Edgerton, Sopper and Kardos 1975). There were problems in adapting existing enterprises to fit these commendable laws (Bradley 1981) and much Federal legislation was enacted between 1969 and 1977 to overcome problems. The most important was The Surface Mining and Reclamation Act of 1977. This established nationwide standards governing reclamation but even so this itself became difficult to enforce due to industry pressure and a poorly organised regulatory bureaucracy with the States unprepared (Bradley 1981). In Pennsylvania coal operators were required by law from 1963 to grade stripping soils when mining was completed (Czapowskyj 1970). Latterly operators are required to bury acid-producing overburden and to spread topsoil on affected areas (Davidson 1979). Nevertheless large areas of ungraded spoils remain from earlier working. In Wyoming and Montana the law requires the land to be restored to its previous condition or better (Schuhart 1978).

In Australia agreements with State Governments and individual mining enterprises set out requirements for regenerating mined land (Comalco 1981). These agreements cover a wide range of



climatic types and land use options, generally referable to attempts at restoration to pre-mining land uses be they forest, range, or agricultural in nature. Werner (1973) discussed questions of law and policy relating to reclamation of spoil mounds in G.D.R. Federal Germany has a policy of 'raw material security zones' where mining interests take precedence over other types of land use, except in local special cases, thereby preventing developments that would complicate mineral extraction. Schleswig-Holstein enacted the Landscape Protection Act of 1973 which requires rectification of environmental damage by the body responsible (Clauss 1980).

#### The Problem of Retrospectivity

Unregulated mining may create new landscape patterns (Dimitrovsky 1973) which may not readily develop vegetation (Foggin 1977). Some resultant land surfaces present intractable problems, for example it is not possible to revegetate vertical rockfaces. There are extensive deep surface-washed tailings from tin workings in the hill country of Malaysia. Much of this is unplantable without carefully planned earth moving, drainage and river control (Mitchell 1957). Metalliferous mining areas may present major pollution problems. The Captain's Flat area cost nearly \$3,000,000 to clean up (Hore-Lacy 1977). Some types of mining result in tailings which may be a direct health hazard (e.g. asbestos fibres: Moore & Zimmermann 1977).

In each of the preceding examples it is probable that prior planning could have avoided post-mining problems or at least

mitigated the effects of mining. Existing wastelands differ from modern enterprises in that for the latter payment for reclamation work is usually associated with the operation involved (Box 1979) and is then a legitimate charge to the overall costs of mining. Reclamation costs are often high in relation to pre-mining land-use but low in relation to the value of the material removed in mining.

The introduction of regulation poses the problem of how to deal with unrestored prior workings. Should those who created wastelands restore them or should restoration be a common charge on the collective industry or to governments? The first option is generally the most difficult as operating companies may have disappeared and all ownership and taxation incentives be non-available. For past areas of dereliction the notion of a common fund, levied on all current operators, has merit (Mitchell 1957). Where land areas are large (e.g. 120,000 ha stripped in Pennsylvania prior to the 1971 Surface Mining Conservation and Reclamation Act of 1971) then government funded work is the only reasonable expectation. Initially this will tend to be experimental (Edgerton, Sopper & Kardos 1975) or selective in application. Davidson (1979) noted that U.S. federal legislation provided funds to reclaim orphan banks, but that some coal mining companies and private landowners were attempting reclamation of such areas without assistance.

The traditional taxation burden on mining enterprises has been

that of royalty where a levy on production is seen as the State's special tax on use of a finite resource. This provision is prevalent in federations where company taxation on profits accrues to the national purse. Both forms of tax have not generally been associated with direct government expenditure in relation to mining. The U.S. Surface Mining and Reclamation Act of 1977 provided for taxing of all newly mined coal and lignite to finance reclamation of land previously disturbed and neglected. The money raised was to be paid into a rotating fund, the 'Abandoned Mine Reclamation Fund' (Bradley 1981). Similarly Thailand has recently introduced a surface rental fee equal to 10 percent of royalty - used to reclaim mined areas and develop local areas near the mine (Suwanasing 1981).

The principal effect of these measures is to raise the price of the material mined. Greenbaum & Harvey (1978) discuss effects on the supply of land of pricing mechanisms taking restoration goals into consideration. It is suggested that if surface mined land was required to be restored to its original state then clearly no mining would be permissible in certain regions. In steep country, for example, flattened mountain tops, exposed high walls, land-slides, sedimentation, acid water, compromised wildlife habitat, are all irreversible outcomes that usually defy complete restoration. All states have the authority to regulate surface mining with permits and bonds. If the performance bond is set at rates below the cost of reclamation the desired reclamation standards are unlikely to be met, particularly where costs exceed the bond. Many states use funds collected for

reclaiming abandoned or orphan lands.

Greenbaum & Harvey (1978) argue that performance bonds per unit land area should be higher than reclamation costs. This device would induce firms to seek to minimise the length of time the bond is withheld - and to, if necessary, alter their production processes.

#### Costs of Rehabilitation

The greatest portion of costs go to earthworks. Two examples given by Kuzmenkov, Zastenskii & Steshkin (1978) give the cost of planting per se as 1.4 and 3.5 percent of total rehabilitation costs. Of the total per ha cost of \$10,000 for rehabilitating bauxite mines in W. Australia 90 percent goes to earthworks (Tacey 1980). Dune mining restoration costing up to \$3,000 ha<sup>-1</sup> involves 75 percent for machinery (Coaldrake 1973). Asbestos working described by Moore and Zimmermann (1977) is estimated to cost \$3,000 ha<sup>-1</sup> also.

Reduction in earthworks to a minimum will tend to have a large effect on land use options in the short-term. For example Treshchevskii (1974) applied cost-benefit analysis to alternative reclamation methods of a 40 ha tailings dump of the Kursk magnetic anomaly. Agricultural use was of little benefit due to the large cost of earth moving. Forests or trees with grass (as an anti-erosion use) were the most beneficial forms of land use. Mining is more able to support earthworks, than for example

inappropriate agricultural useage which may also give rise to land degradation. As a proportion of the value realised per unit of land the costs of restoration following mining are low. Gross returns from bauxite mining in Western Australian State Forests have been estimated as up to \$1,000,000 ha<sup>-1</sup> processed to alumina. By contrast forest production yields up to \$890 ha<sup>-1</sup> yr<sup>-1</sup> and water supply \$54-104 ha<sup>-1</sup> yr<sup>-1</sup> (Coaldrake 1973). Likewise coal from the Bowen Basin in Queensland yields up to \$0.5 m per ha. This may be contrasted with cereal or beef farming which yield returns of \$17-67 ha<sup>-1</sup> yr<sup>-1</sup>. An open cast coal mine employs 200 people and uses 90 ha of surface yr<sup>-1</sup>. This form of mining would require 9000 ha to support 200 employees over 100 years whereas the same area under agriculture would support only 7-8 people (Coaldrake 1973).

When the future land use is clearly defined then essential and costly spoil movements can be closely integrated with the mining operation. Reintroduction of machinery after mining will add costs as well as involve undesirable practices such as double handling. Amir (1975) notes that surface excavation can create opportunities rather than liabilities for a region. Excavation is a temporary land use and it is now well-accepted that pre-planning of future land use is desirable (Zundel 1977) even though not often used. One problem relates to changes in community standards - in Australia waste sand-mine material used for house base fill is now being removed due to a perceived radiation threat.

Public and private land ownership may generate different values apart from the simple economic costs involved in moving materials. Mineral ownership does not always reside with the landowner. Where the two resources are in private ownership this may of itself give rise to varied problems of land use. When mineral rights are vested in the State laissez-faire governments may do little more than tax enterprise, but increasingly mineral rights tend to be granted with provisions for restoration and for avoiding damage to other resources. In Thailand it has been estimated that 90 percent of the mine area belongs to the miners (Suwanasing 1981). Mining companies are reluctant to surrender land already worked where low residual ores may still remain (Wimbush 1963). In contrast mining companies with long leases on land that cannot be reworked have greater economic incentives to be involved in promoting long term viable land use (Nicholson 1974).

#### Pre-mining Procedures

The integration of mining and restoration requires prior knowledge of appropriate techniques which should be adopted. The first requirement is to calculate relative quantities of overburden, ore and tailings, and the sizes of resultant dumps.

In the example of the Jabiluka uranium project in Australia's Northern Territory pre-mining analysis identified tailings management as the main problem (Morley 1979). Techniques used at Bear Creek, Wyoming, were used as a guide to planning. The tailings pond was to be lined with compacted impervious clay.

During mining a blanket of water would minimize radon emanation; on completion the water would be allowed to evaporate and the surface covered with at least 1m of clay and then 2m of overburden and soil. The whole would be landscaped to give a gentle slope and then surface revegetated with local dwarf species of grasses and shrubs to avoid penetration of the clay cap.

In terms of plant growth possibilities pot trials can be undertaken prior to mining and are generally useful to indicate spoils management (Howard et al 1977). Different overburden materials can be tested e.g. Tunik, Levit & Filatova (1974) categorised 20 strata from strip mining the Sarbai iron ore deposit in Kazakhstan. Four suitability types were determined with Quaternary and Neogene deposits the most promising materials. Thum & Fiedler (1977) grew poplar cuttings in 10 different overburden strata without fertilizers to determine the most suitable material for vegetative growth. These authors also discuss differences between such bio-assay and the use of soil analytical results. Pot trials can quite quickly eliminate unsuitable vegetation solutions from further consideration (Craze 1977a). They are also useful in screening a range of species and in determining first approximations at fertilizer useage. Hartley (1977) uncovered a boron deficiency with pot trials to determine the best use of fertilizer on barren tailings. He confirmed this with foliar tissue analysis. Heinsdorf (1976) utilised both foliar and soil analysis for nitrogen and

phosphorus amendments with *Pinus sylvestris*, noting that N and P were unnecessary when foliar concentrations exceeded 1.3 percent for N and 0.10 percent for P.

Further refinements to pot culture include combination treatments. Plass (1974) used bands of fine and coarse material from 12 Kentucky spoils in wooden boxes, and contrasted growth of 7 species of *Pinus*. He was able to show that coarse textured material at pH 4.1 to 5.0 with adequate available phosphorus gave the best chance of success. Davison & Jefferies (1966) utilized a growth chamber and nutrient solutions to contrast effects on growth in pitheap spoil. Minor differences in growth can be analysed using frequent small harvests and calculating relative growth rates (Jensen 1981). Examination of tolerance to heavy metals is more involved. Wiltshire (1974) diluted soils with two parts of sand, gave adequate fertiliser additions and used short term yields to contrast a range of Zimbabwe soils. A drip-culture apparatus is described by Gadgil (1969) in testing resistance to toxicity.

A range of boxes (Sopper et al 1970, Di Lissio & Sopper 1975, Edgerton, Sopper & Kardos 1975), plastic tubes (Craze 1977b), plastic trays (Keane 1977), leaching chambers (McBride, Chavengsaksongkram & Urie 1977) and other lysimeters (Marrs & Bradshaw 1980) have been utilised to simulate layer and leaching treatments. These may be seen as intermediate steps between pot trials *per se* and the next, essential stage, that of a field trial (Keane & Craze 1978). In a well-planned integrated



operation the first year of an open cut or strip mine operation would involve a great deal of research activity. Confirmation and refinement of pot trial indications require translation into suitable workable techniques which can be adopted on a broad scale.

In all cases the vegetation objectives should preferably be stated in advance and a suitable plan derived to seek their accomplishment. An example is provided by Hill (1977a) who suggests that objectives for a biological stabilization programme on slimes dams should be

1. determine toxic components of the wastes
2. select plants likely to exhibit tolerance
3. establish such plants in the wastes
4. assess ability to produce vegetative cover
5. determine the advantage of applied nutrients in establishing cover
6. investigate the mechanism whereby successful plants would be able to establish themselves in toxic wastes.

#### Handling of Materials

The tendency has been for mining equipment to become larger and larger. The Rheinische Braunkohlenwerke use giant bucket wheel excavators capable of shifting up to 240,000 m<sup>3</sup> of overburden and lignite per day (Bradley 1981). Not all mining operations are amenable to mechanisation on such a massive scale. A range of machinery is used throughout the industry. Brown (1977)

described 28 pieces of equipment used in coal surface mining and reclamation.

Draglines have traditionally resulted in inverted profiles but have been satisfactorily utilised in restoration of ironstone strip workings to agriculture (Deakins 1953). Early identification (see above) of the most promising surfacing materials will allow selection of the most 'fertile' available. For forest growth Puchko (1977) recommends a surface layer of 1.7-2.5 m thickness. It is important to avoid double handling as much as possible and the most elegant operations can be highly methodical in the manner in which landscapes are moved about.

When ores have to be blended to meet contract grades several mining faces may be worked simultaneously. This leads to a scattering of areas for rehabilitation (Langkamp et al 1979) and complicates transfer of the different strata available. In cases where mixing of material has occurred then regrading of surfaces prior to rehabilitation treatments will result in the exposure of unweathered material (Kimber, Pulford & Duncan 1978). Variable surfaces require adequate sampling and assessment before planting or sowing of seed.

Management of topsoil is of especial importance. The use of forest topsoil enhances the potential for rapid cover production (Farmer, Cunningham & Barnhill 1982). It has been used as an amendment (Aldon, Springfield & Sowards 1976) and may provide a source of mycorrhizal spores (Allen & Allen 1980). The prior

removal, temporary storage and later return of stripped topsoil tends to be universally accepted as a sound technique in rehabilitation. Topsoil may be valued for its seed store, physical characteristics or both. The seed store is of greatest value where some attempt is made to return the prior native vegetation. Langkamp et al (1979) emphasise the importance of collecting site data of the pre-mining vegetation if restoration of native vegetation is an option (see also Reynolds et al 1978).

Bauxite mining is generally extensive and topsoiling treatments tend to be favoured. Typically the vegetation is cleared prior to mining and the surface soils over the bauxite layer are removed. These are often shallow, a function of the laterisation process. The bauxite is removed down to the next layer: to kaolin clay in Western Australia, to silica contaminated ironstone in northern Queensland, to limestone bed-rock in Jamaica, or to aluminium deficient weathered volcanic material in Hawaii. The exposed surfaces of these layers can then be graded, ripped or scarified, with reshaping of pit walls and slope contouring. The stockpiled "topsoil" can be spread and trees planted into it with fertilizer added. Shrub seed may be sown (Bartle, McCormick & Shea 1978) or pastures established. Tailings pits are soiled and grassed. Some 36 species of native trees are direct seeded in mixture at Weipa, Queensland. Machinery used is described in Comalco (1981). Cultivation is reduced to a minimum and done immediately before sowing (Leggate 1978).

Where the seed store can be drawn on then the use of topsoil is a short cut to species selection. Storage of topsoil leads to decline in the number of germinants over time. It is thus important to minimise storage (Clark 1975). In a paper describing an elegant series of experiments on bauxite areas, it was demonstrated that the seed store may be more realisable if "double stripping" is used (Tacey & Glossop 1980). The top 5 cm of soil containing the bulk of propagules (in its surface layer) gave better regrowth than did the bulked material from the top 40 cm of soil removed prior to mining. It is likely also that best results will occur if the top material is directly replaced onto a prepared mine-site rather than stockpiled. However, it may still be necessary to store the 5-40 cm layer for logistic reasons. Direct return can give a 12 fold increase in the number of seedlings established after 18 months (Tacey 1980).

In the Rhine Valley the coal deposits are overlain by 1-2 m of loess. With careful handling and replacement on finished dumps this may result in improved quality topsoil (Beggs 1972). The Rheinische Braunkohlenwerke undertake stringent measures to avoid long term storage. A slurry of 0.6- 1 by volume ratio of water to loess is used (Bradley 1981). Compaction is a problem in handling topsoil and Craze (1977b) has shown that bulk density of  $> 1.5 \text{ g cm}^{-3}$  for replaced topsoil inhibits root growth.

Timing of topsoil stripping may be crucial to obtaining a high diversity of species. In the Australian tropics poor results are obtained with topsoil removed after the rainy season (Langkamp &

Dalling 1979). If the timing is right then a wide range of species can be obtained. Tacey & Glossop (1980) report a Shannon-Weiner diversity index ( $H'$ ) of 1.4 for *Eucalyptus marginata* forest in Western Australia. Farmer et al (1982) obtained an index of 3.1 for surface-mined coal deposits in eastern Tennessee. The latter authors note that some aggressive pioneer species may be present in top soil seed banks and that first year biomass using topsoil may exceed that obtained with seeded grass legume mixtures.

The value of topsoil removal is recognized in recently adopted United States legislation (Farmer et al 1982) which now requires that it be done.

#### Amelioration of Unfavourable Media

The working of large scale open cuts can be a complex operation with continuous replacement of topsoil. It is important to avoid the placement of more toxic materials near the surface, particularly in stripping for coal production (Brown 1977).

Pre-planning of dumping sequences can mitigate the effects of acidity by burial of the most intractable materials. If this potential has been missed or is unavailable then amelioration of acidity can be attempted by liming (Carpenter & Hensley 1979). The amount of lime required to neutralise acidic spoils permanently is difficult to estimate. Even after sufficient lime is added to neutralise the acidity present, the pH may remain low

(James & Mrost 1965). A temporary rise in pH may be reversed by further oxidation of iron pyrites, though pH may continue to drift upwards in pot trials (Costigan, Bradshaw & Gemmell 1981; Fox & Mathie 1982). On low pH sites highest values may be attained after about 30 days when pH may decline again (Carpenter & Hensley 1979). Extremely pyritic materials may develop gypsum pans with high lime levels e.g. 2500 t ha<sup>-1</sup> at Bingham U.S.A. where after 6 months the pH returned to 3.5 (Hore-Lacy 1979).

It is impractical to relime acidic soils on a regular basis (Sorensen et al 1980) and an overestimate of the lime requirement is likely to be less costly than an underestimate, in the long term (Costigan et al 1981). Raising the spoil pH will not stop oxidation. The rate of oxidation of pyrite materials is related to the shape and size of particles, with the finer material undergoing more rapid oxidation. The normal agricultural requirement is the amount of lime necessary to neutralize the acidity present due to the soil's buffer capacity. The total lime requirement over time should also incorporate acidity generated from oxidation of sulphide sulphur in fine fractions and that derived from weathering of larger particles (Sorensen et al 1980). In order to determine a spoil's capacity to produce acidity it is recommended that spoils be analysed for pyrite content and acid neutralising capacity (ANC) immediately after regrading (Costigan et al 1981). Assuming complete oxidation 1 percent pyrite in spoil can give rise to a potential lime requirement of 40 t ha<sup>-1</sup> for pH control to 15 cm depth. 1 percent of ANC is equivalent to 23 t ha<sup>-1</sup> of limestone applied

for 15 cm of spoil. Costigan et al (1981) recommend that limestone should be incorporated to 45-50 cm depth and the application rate increased accordingly. High pyritic spoils may have lime requirements in the range 100-400 t ha<sup>-1</sup> for pH control to 45 cm depth.

In some cases 50 or more t ha<sup>-1</sup> is considered impractical (Craze 1977a) and the covering of minewaste by soil is preferred. In the case of Captain's Flat Craze (1977c) reported the use of a 22 cm layer of clay for sealing, with 45 cm of shale fill to provide lateral drainage and 30 cm of soil on top to support vegetation. The latter was a red earth of  $\rho = 1.45 \text{ g cm}^{-3}$  density.

The problems of germination testing at specified levels of acidity has been discussed by Redman & Abouguendia (1979). They suggest that often contradictory results from the literature may be explained by the use of differing culture solutions. Seedling growth is consistently reduced by acid and alkaline treatments. Low pH results in shorter, thicker roots and changes in fine structure. Normal or enhanced germination under acidic or alkaline conditions is not necessarily followed by normal growth. Prediction of species success on sites of extreme pH requires information on seedling growth.

The revegetation of unfavourable media can be approached in two ways. Techniques of altering spoil conditions will be examined in the next part and the use of tolerant plant populations will be considered in part V.

#### IV Rehabilitation Techniques

Rehabilitation of mined land is site specific. The unique properties of each waste determine the degree of vegetation establishment, within constraints of the local climate. The achievement of a suitable vegetation cover may require alteration of both physical and chemical properties. Climatic modification is limited to irrigation, and this must be restricted to preparation or establishment phases. The techniques developed owe much to previous efforts at maintaining productive land use systems within ecological zones. Thus in the Western United States rangeland management research provides a basis for dealing with mined areas (Bay 1976).

Within a given site non-uniformity of conditions may result in some areas reaching a cropping phase earlier than others (Blood, Jackson & Ormrod 1961). This may be both less important and more easily managed with tree crops than with agricultural crops or grazing systems. The variable nature of mine wastes predicates a lot of experimental work, as discussed above. Poynton (1977) refers to 1500 vegetation experiments on South African gold wastes. It is likely that fertilizer trials to test the most suitable nutrient amendment to improve the growth of established stands will have very localised value (Thum & Heinsdorf 1976).

Additionally, experimental work is fraught with difficulties. Perhaps the most problematical is the issue of re-mining. Experimental plantings on apparently abandoned sites may be sacrificed with renewed mining to recover lower grades with price



escalations (Mitchell 1957). Conversely miners resist reclamation if re-mining is at all a possibility (Suwanasing 1981). Unanticipated adjacent mining may destroy experiments (Czapowskyj 1970, 1978) and for some deep mines the bulk of the area may not be fully available until the mine is abandoned (Jones 1979). Other hazards include untimely grazing, destructive recreation (Marx 1975); below average weather conditions (Shetron & Carroll 1977) and 'reasons mostly unknown' (Farmer & Richardson 1981). Despite the obvious requirement for experimental work much information has been derived from experience and casual observation (Dryness 1975).

In the previous section the scope for advanced planning of rehabilitation was emphasised. In this section consideration is given to physical and chemical amelioration, irrigation and the use of fertilisers, mulches and liming to alter acidity.

#### Physical Amelioration

Many industrial and mining operations give rise to concentrations of waste with unique textural properties. Gemmell (1981) reports the use of industrial wastes as neutralising agents for acidic colliery spoil, including that from the Leblanc salt cake process for sodium carbonate. Calcareous pulverised fuel ash has been used in many countries.

Elutriation is used in tin mining and the finer materials are often the most difficult to restore. Loss of the clay fraction in effluent can be overcome by surface sliming of coarse sand

tailings. This may be done by dumping the clay fraction over sand by settling out or by the use of contour bunding (Mitchell 1957). Recombination of tin wastes examined by Maene, Mok & Lim (1973) gave a satisfactory plant growth medium when 40-50 per cent slimes was added to sand tailings. Meecham and Bell (1977) report successful combination of 20 per cent fly ash with 80 per cent 'red sand' wastes from an alumina refinery in Queensland. Alkaline red mud derived from the Bayer process in Western Australia can be ameliorated with gypsum and country sand. In addition to tin wastes, judicious mixing of sands and slimes is used in heavy mineral sand mining operations.

Physical amelioration may also be used to improve spoils by augmenting the supply of nutrients or by reducing toxic effects. Mixtures of slimes with soil were tested for the Captain's Flat mine (Craze 1977b,c). *Lolium rigidum* was grown with 0, 20, 40, 60 and 80 per cent slimes, at different levels of lime and with nutrients added. Large depressions in yield were reported from mixtures. Slimes as low as 20 per cent prevented plant establishment without lime. At 6 and 18 t ha<sup>-1</sup> lime the yield was depressed by 50 and 70 per cent respectively. Lime and clay were equally effective in reducing the capillary rise of toxic ions, but the effect of clay was more permanent (Craze 1977b).

For many intractable residues isolation is unavoidable. Covering with topsoil, subsoil, innocuous wastes or organic materials are all useful. Suitable dressings can render the surface rooting-zone favourable to plant growth. Burial of acidic or toxic

materials may be effective in preventing the re-occurrence of surface toxicity. A surface layer of 75 cm of coarse grained mineral waste will prevent movement of metals into the surface vegetation. High porosity and low cation exchange capacity (C.E.C.) are desirable features (Johnson & Bradshaw 1979). In the Kursk region 15-20 cm of sand is recommended for surface dressing of chalk-marl spoil derived from phosphorite ore mining, with cultivation to 40 cm (Andryushchenko & Treshchevskii 1976).

Surface loss of fine materials may be reduced in arid climates by spreading mullock over the mined area (Marshall et al 1978). Pulverised fuel ash from power stations contains essential nutrients except nitrogen but may have manganese and aluminium in potentially toxic quantities. At  $\text{pH} > 8.5$  phosphorus deficiency symptoms may be induced by excess aluminium even with nutrients added. Plant response to soil/ash mixtures varies: *Hordeum vulgare* showed reduced yield at 7 per cent ash while *Beta vulgaris* and *Sinapis alba* gave enhanced yields on up to 12 and 50 per cent ash respectively (Rees & Sidrak 1956). While grasses fail *Trifolium repens* will grow well (Rees & Warwick 1957). Fuel ash has a use in filling in of gravel pits (Gillham & Gelling 1969). It has also proved useful as a cover (22.5 cm) for copper smelter wastes, with annual nutrient dressings (Goodman & Gemmell 1978).

At Mt Isa in Queensland concentrator tailings from lead, zinc or copper ores are separated to give coarse material which is used

for underground fill, and slimes which go to tailings dams (Hunter & Whiteman 1974). The fine sandy silt is mixed with decomposition products from the reagents used in flotation. At the dams dry salts rise to the surface and oxidise to form a white crust. Two physical amendments were tried. Smelter slag was found to be toxic whereas flyash from the Company's coal fired power station was outstanding (Ruschena et al 1974). The flyash reduces bulk density and surface crust strength and increases the rate of leaching of soluble salts. Plant growth improves with an increasing proportion of flyash mixed with the tailings. Fines (mixed with some flyash) from a siltstone quarry, spread over the surface, provide a suitable seed bed for germination and growth of native species (Challen 1979).

The most successful treatment of zinc-smelter waste in U.K. is surface covering. With 15 and 22.5 cm layers of pulverised fuel ash and annual fertilizer application zinc tolerant swards root to 26 cm depth. Yields are greatest when organic wastes are added to the surface at the start (Gemmell & Goodman 1980). When organic matter is available then there is no advantage in using pulverised fuel ash as a substitute (Gemmell 1976).

A vegetation cover can be maintained on blast furnace slag, top dressed with organic wastes and given annual NPK fertiliser (Gemmell 1976). Deeper top dressings on copper smelter waste give rapid declines of yield attributed to reappearance of copper toxicity (Goodman & Gemmell 1978). Similar treatments on zinc smelter wastes show more rapid decline associated with the early

onset of metal toxicity in zinc waste (Gemell & Goodman 1980).

In the case of toxic sources clearly there is some combination of covering which is most suitable for each source. The long term maintenance of vegetation may be more appropriately determined by nutritional amendment, once the best physical condition has been attained. The latter is not easily determined and many of these wastes will fall into the category 'intractable'.

#### Organic Materials

Unless topsoil is available for respreading, mined surfaces tend to possess little physical structure. Organic matter is generally absent and surfaces tend to crust after rain and dry out rapidly. Surface temperatures are often high. Mulching materials are needed to alter the surface microclimate and to help conserve soil moisture during the critical phase of seedling establishment (Armiger et al 1976). Organic amendments assist plant establishment by improving moisture regime, moderating surface temperature, decreasing erosion, improving fertility, increasing C.E.C. and by detoxifying toxic metals (Jurgensen 1979).

A wide variety of organic materials are effective as mulches. Armiger et al (1976) review the use of pulp fibre, straw, sawdust, woodchips, cured hay, chemical agents and the use of in situ mulch. These authors note that selection of material will depend on cost and proximity of supply to the area to be treated.

Vimmerstedt & Finney (1973) demonstrate the feasibility of introducing earthworms into vegetated acid coal spoils to increase the rate of incorporation of organic matter.

a) Hydroseeding

A useful technique for difficult surfaces (steep slopes, unstable materials or those where machinery passage may be disadvantageous) is that of hydraulic seeding. Czapowskyj & Wriener (1970) report trials on coal spoils. These trials were largely unsuccessful, a reflection of surface variability in relation to an imposed uniform treatment. Nevertheless the hydroseeding technique has been adopted for a number of spoil types. General principles are given by Brown (1977). Refinements are reported for sand slopes (Sheldon & Bradshaw 1977) and at the Blackbird mine (Richardson & Farmer 1981). The system requires large volumes of water. Seed, fertilizer, and mulch amendments are applied in a fine spray. Seedling establishment is determined by microclimate effects and physiological requirements. Dyes can be used to confirm to the operator the area he has covered. On stoney ground (e.g. slate tips) a hydraulic seeding device can be used to provide a plug of growing material for transplanted trees (Sheldon & Bradshaw 1976) - the "pocket planting technique" (Sheldon 1975).

Any organic material that is capable of being shredded up can be used in hydroseeding. Emanuel (1976) used shredded bark wastes mixed with fines to avoid clogging. Newly sown areas in Montana are sprayed with wood mulch at 2.5 t ha<sup>-1</sup> to prevent soil

crusting (Schuhart 1978). For china clay wastes Sheldon & Bradshaw (1977) utilize 2.5 t ha<sup>-1</sup> of previously moistened, milled sphagnum peat. Richardson and Farmer (1981) report the use of *Medicago sativa* (lucerne) hay.

Hydroseeding is most useful for grass establishment. Few tree species can germinate and survive well under the conditions used (Lesko, Etter & Dillon 1975). However the technique of mulching can be utilised in conjunction with direct sowing or transplanting of tree seed or seedlings. In some cases mulching may provide a suitable substrate for volunteer woody regrowth (Little & Mohr 1979).

#### b) Use of Sewage

Municipal sewage sludge is another attractive waste which has been utilised in rehabilitation. Sewage sludge acts partly as a physical ameliorant but it may also render many toxic ions innocuous by chelation (Johnson & Bradshaw 1979). It tends to be high in nutrient content and buffering capacity (Jurgensen 1979). A covering of sewage sludge or soil/sludge will allow grass establishment (Rees & Sidrak 1956) and with adequate topsoil and good management pastures, fodder crops and cereal yields can compare favourably with undisturbed farmland.

Municipal sludge and sewage effluent has been used to establish cover on acidic bituminous spoil banks in Pennsylvania. These spoils contain toxic levels of iron, aluminium and manganese (Sopper et al 1970, Sopper & Kardos 1972). The sewage effluent

tends to be slightly alkaline (pH 6.8-7.2) and is enriched in nitrogen, phosphorus and potassium (Sopper & Kardos 1972). A successful application using 12 tree species is reported from Illinois by Roth, Jayko and Weaver (1979). Hardwood tree species respond better than conifers (Di Lissio & Sopper 1975).

Acid spoils planted with grasses and *Pinus sylvestris* in Denmark were treated with lime at 0 and 1-8 t ha<sup>-1</sup> and sewage at 0, 40 and 120 t ha<sup>-1</sup>. In this case sewage sludge was detrimental to pine survival. Losses were attributed to nutrient imbalance, toxic substances and enhanced weed competition (Olesen & OEvig 1978). McBride, Chavengsaksongkram and Urie (1977) draw attention to the hazards of heavy metal accumulation from sewage sludge into grass crops that may be grazed. These authors suggest that the following limits for metal additions should not be exceeded:

At C.E.C. > 15 meq 100 g	-1
Zinc	870 kg ha <sup>-1</sup>
Copper	435 kg ha <sup>-1</sup>
Cadmium	17 kg ha <sup>-1</sup>

In the trials reported these levels were exceeded. It was suggested that *Phalaris arundinacea* could be grown for erosion control, but if grazing were to be used then *Secale cereale* took up the lowest amount of foliar cadmium and should be preferred.

An important consideration in areas prone to wind erosion is that working will usually proceed downwind. This may reduce the



availability of wind borne seed into reclaimed areas from unmined land. Surface fines may also cover adjacent unmined land.

#### Chemical Amelioration

Even if mine wastes are not deficient in nutrient elements it may be anticipated that some improvement in growth will be possible with fertilizer useage. In all cases it must be stressed that chemical amendments can rarely be used alone and most of the examples given incorporate aspects of the physical or organic treatments dealt with above. On some problem soils grasses and legumes can be grown successfully with appropriate fertilizers (Baker & Chard 1961).

##### a) Chemical Stabilizers

Chemical products have been used as mulch substitutes in a variety of circumstances. Perhaps the most useful are bitumin or tar materials as sprays to hold down sand as an alternative to the spreading of costly brush material (Barr & McKenzie 1976). Suitable soil conditioners tested by Maene et al (1973) included hydrophobic bituminous emulsion and hydrophylic polyacrylamide solution. Sheldon and Bradshaw (1977) found chemical stabilizers less effective than peat mulch when hydromulching compacted steep surfaces. Hunter and Whiteman (1974) reviewed the use of a number of stabilisers including polymers, lignins and resins.

None of these sorts of products appear to be as useful as organic mulches. Most would be more costly on the broad scale often required in rehabilitation exercises.

b) Fertilizer Amendments

Two general cases may be distinguished:

- 1) the return of topsoil and attempts at restoration of the local vegetation;
- 2) reclamation of the mined area to vegetation.

The latter may make use of topsoil but its value lies more in its physico-chemical properties than its seed bank. Natural restoration of soil fertility can be a very lengthy process without intervention, whereas establishment of vegetation with fertilizer treatments can restore fertility and natural cycles broken by mining. Slow release fertilizers are to be preferred and fast release compounds should not be used to excess (Sheldon & Bradshaw 1977).

1. Return of natural systems

When topsoil return is augmented with moderate fertilizer treatment these generally have no significant effect on germination over a wide range of natural ecosystems from alpine tundra (Brown & Johnson 1980) to mediterranean heath (Fox & Black 1982).

Forest topsoils returned to surface coal mine areas in Eastern Tennessee were fertilized with  $168 \text{ kg ha}^{-1}$  of ammonium nitrate and  $280 \text{ kg ha}^{-1}$  of triple superphosphate (Farmer et al 1982). These levels are somewhat greater than those used in nutrient poor Australian heaths (Fox & Black 1982) reflecting a greater biomass in the pre-existing forest stands. It is standard practice to examine the effects of fertilizers on germination

prior to undertaking rehabilitation with topsoil treatments.

Fertilizer effects on species proportions are of importance. It is likely that initial applications will have long term influences on establishment, persistence and growth. The phosphorus component in particular requires careful handling (Coaldrake 1973). Some native species can respond to fertilizer and subsequent withholding of nutrients will allow the gradual re-entry of species for which seed is available in the soil. The long term objective with natural systems should include the restoration of competitive advantage to the component species. Mining must entail a net loss of species, particularly in species-rich areas (Lamont, Downes & Fox 1977). The quantity of fertilizer to apply for successful long term establishment should be commensurate with natural fertility levels (Specht 1975). Rapid growth following fertilization probably leads to earlier and more severe competition. Many species of inherently infertile sites show a decline with time and there is a tendency for dominance by those species able to respond to fertilizer (Clark 1975). For fragile or delicately balanced natural ecosystems Specht (1975) suggests the following precautions:

- \* avoid cover crops and widespread use of fertilizer
- \* establish perennials in a nursery
- \* use long brushwood and returned topsoil
- \* plant seedlings into brush and place balanced slow release fertilizers near the seedlings.

## 2. Establishment of Vegetation

Heavy initial applications of fertilizer are commonly used where establishment of cover or plantations are desired. Enhanced nutrition rarely affects germination-establishment (Hunter & Whiteman 1974) but may influence subsequent growth (Davison & Jefferies 1966). Germination tolerance to extremes of pH has been examined in four coniferous species by Abouguendia & Redmann (1979). At high pH all species tested had depressed germination, but at low pH *Pinus contorta* showed better germination than at pH 6.5 (distilled water). A number of fertilizer treatments are given in Armiger et al (1976) for coal spoils in Appalachia. Treatment of such spoils requires a pH amendment combined with NPK addition. Species responses differ and for continuing crops it may be necessary to repeat applications of the more soluble nitrogen and potassium fertilizers, and to take account of the differing solubility of phosphorus at altered acidity levels. An example is two stage establishment at White Oak Mountain on spoils with an initial pH of 3.8-4.0. Here 670 kg ha<sup>-1</sup> of 10:10:10\* fertilizer was used to produce an in situ mulch crop. This was followed by 7.3 t ha<sup>-1</sup> of dolomite and 56-134 kg ha<sup>-1</sup> of NPK for legume/grass establishment. Additional nitrogen was given at 56 kg ha<sup>-1</sup> at seeding, followed by 224 kg ha<sup>-1</sup> each spring (Armiger et al 1976). Under these types of regime germination can be affected

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\* The conventional expression of NPK combined fertilizers to show the proportion of the three nutrients present.

and grass seed may be sown to excess. High levels of soluble fertilizer depressed germination of *Lolium perenne* in trials on asbestos waste of pH 9 (Moore & Zimmermann 1977).

Lime will obviously raise pH, at least temporarily. Linear relations between plant yield and pH have been noted (Craze 1977c). At Bolt Mountain Armiger et al (1976) applied dolomite to spoils with an initial pH of 2.8

t ha <sup>-1</sup>	4.8	9.7	19.4	38.9
New pH	3.4	5.0	5.3	5.9

Best growth of *Eragrostis curvula* was obtained at the two higher levels, all treatments had uniform amendments of nitrogen and potassium at 140 and 112 kg ha<sup>-1</sup> respectively.

In considering growth of *Betula pendula* and *Pinus resinosa* on acidic coal spoils Welsh and Hutnik (1972) found the seedling response to liming was greater on the more acid spoils. They conclude that on less extreme spoil fertilizer application alone would give increased growth of acid-tolerant species. When toxicity is critical it is necessary to alter the pH before a response to fertilizer treatment can be obtained.

The following levels of fertilizer are reported by Craze (1977b) for *Lolium rigidum* in an artificial topsoil: superphosphate 600 kg ha<sup>-1</sup>, ammonium nitrate 290 kg ha<sup>-1</sup>, potassium sulphate 200 kg ha<sup>-1</sup>, and lime at 1.25 t ha<sup>-1</sup>. Similar levels of nutrients were used in slimes mixtures (Craze 1977c).

Where topsoil is available then development may be more rapid. Deakins (1953) describes agricultural restoration after ironstone working. At pH of 7 or more with low phosphorus and potassium the response to fertilizers is very strong, especially phosphorus. Areas dressed with topsoil required grazing within 8 weeks of sowing contrasted with 16 weeks for areas with no topsoil.

The only fertilizer required for establishment of a legume-based tropical pasture at Weipa in North Queensland is superphosphate with molybdenum at 200 kg ha<sup>-1</sup>. This supplies the elements phosphorus, calcium, sulphur and molybdenum. A light initial dressing of nitrogen may be necessary in the first year. For trees 0.5 kg per plant is placed at establishment (Coaldrake 1973). 500 kg ha<sup>-1</sup> of 16:9:8 is harrowed in to a depth of 5 cm after seeding of coastal dunes in Queensland (Barr & McKenzie 1976).

Ecosystem development requires the accumulation of sufficient levels of nutrients to allow efficient recycling. Accumulation of nutrients has been demonstrated in plant, root and soil pools (Roberts, Marrs & Bradshaw 1980). It has been postulated that the minimum soil capital of nitrogen for a self-sustaining ecosystem is of the order of 750 kg ha<sup>-1</sup> (Roberts et al 1981). Achievement of this level requires continuing fertilization (Bloomfield, Handley & Bradshaw 1982). Loss of nitrogen is likely to be high through leaching during the establishment phase (Marrs & Bradshaw 1980). Losses persist in older swards but may

equal the input from precipitation and can be reduced by legume nitrogen fixation (Dancer, Handley & Bradshaw 1977b). Nitrogen fertilizer should not be added in dry periods as scorch may occur (Marrs & Bradshaw 1980). A comparison of nitrogen given as ammonium or nitrate in metal tolerance work showed that most species tested yielded more with nitrogen as ammonium. Those species that gave low yields with nitrate on control soils accumulated high concentrations of aluminium and iron (Wiltshire 1974).

Once established, maintenance dressings of fertilizer may be required to maintain productivity in many kinds of artificially generated vegetation types. The response to 50 kg ha<sup>-1</sup> of nitrogen as ammonium nitrate by *Lolium perenne* reported by Bloomfield et al (1982) was a significant increase in dry weight production on a range of reclaimed colliery spoils and urban wastelands. Tree plantations with a longer rotation than grass cover may require continued attention over a long period.

Plantations on lignite spoils in East Germany have received much attention. Nitrogen added to 18 year old poplar and *Pinus sylvestris* in 3 applications over a six year period gave maximum increased yields of 1.6 m<sup>3</sup> and 2.5 m<sup>3</sup> respectively. Pine required less nitrogen than poplar (Thum & Heinsdorf 1976). Potassium deficiency is likely to be a limiting factor in growth of poplar (Thum 1978a). Addition of nitrogen alone to pine on sandy sites deficient in phosphorus reduced growth. Growth was

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also inhibited when more than 100 kg ha<sup>-1</sup> nitrogen was placed on soils of relatively high nitrogen status. Both effects were associated with marked increase in foliar nitrogen and decrease in phosphorus (Heinsdorf 1976). Pines planted on moist spoils suffer from severe nitrogen deficiency. On fresh spoil where phosphorus reserves are less than 1800 kg ha<sup>-1</sup> in the top 80 cm phosphorus deficiency also occurs. Addition of nitrogen or nitrogen and phosphorus increases growth to that of natural forest soils. Similar relationships occur for birch and *Quercus rubra* (Heinsdorf 1979).

Finally a brief consideration of two extremes, sites with high pH and toxic tailings. The fertilizer requirement to produce a grass sward on alkaline asbestos tailings is comparatively high. Moore & Zimmermann (1977) record 10,000 kg ha<sup>-1</sup> of 9-11-9 plus 40 t ha<sup>-1</sup> of farmyard manure. High pH in slimes may give rise to boron deficiency in *Eucalyptus* (Hill 1977a). *Eucalyptus tereticornis* can be grown on sandy riveraine deposits below the open-cut porphyry copper mine at Bougainville if nitrogen, phosphorus and boron are regularly supplied (Hartley 1977).

Fertilizer treatments to deal with wastes where heavy metal contaminants are present have been successful in establishing vegetation cover. In South Africa the standard method for treating the dry tops of gold slimes dams is a five stage process:

- \* regrade slopes
- \* instal mist spray



- \* add lime at  $7.5 \text{ t ha}^{-1}$
- \* rotovate surface 7.5 cm
- \* seeding, rolling and fertilizing.

Fertilizing consists of two applications of  $6 \text{ t ha}^{-1}$  of 2:3:2 followed by two of urea at  $50 \text{ kg ha}^{-1}$  (Poynton 1977). Similarly at Mt Isa in Queensland plant growth is attained by leaching out of soluble salts and making large fertilizer additions (Challen 1979). Grassland maintenance on smelter wastes in U.K. utilizes an initial fertilization of  $1000 \text{ kg ha}^{-1}$  of 10:10:18 or 500 kg of 20:10:10 with continued heavy dressings thereafter (Gemmell 1976). Hill (1978) reports the use of 50 g per tree at planting of 8:15:10 fertilizer for tolerant species on slimes dumps. A further 50 g per tree of nitrogen fertiliser is given the next year. For grass swards  $400 \text{ kg ha}^{-1}$  of NPK in the first year is followed by  $200 \text{ kg ha}^{-1}$  in the second.

The overburden waste pile from the Blackbird copper-cobalt mine in Idaho was bare for 18 years and a source of acid mine drainage (Farmer et al 1976). Attempts at controlling the emanation of acidity from this source re-enforce the desirability of pre-mining planning. Establishment of plant cover can protect the sources of pollution from erosion by wind and water (Richardson 1980) and dust is an important component of the acid cycle (Farmer & Richardson 1980). By 1981 it seemed that all attempts at correction had not led to abatement of acid drainage: "The suggestion that a thin layer of topsoil and a heavy stand of

grass can reduce or stop the oxidation of waste sulphates no longer appears justified" (Farmer & Richardson 1981). The investigators were left with the possibility that complete submergence of such wastes by water could be an effective, but limited solution.

#### The Use of Irrigation

Two main uses of irrigation are in leaching of toxic salts and in securing establishment of seedlings. Leaching prior to plant establishment is well developed in South Africa (Poynton 1977) but impracticable in Zimbabwe (Hill 1978). A gentle spray or drip system is used to slowly leach soluble salts and pyritic oxidation products from the rooting zone to a relatively low water table whence they are adsorbed to the clay fraction (Hore-Lacy 1977). Water is applied equivalent to the infiltration rate (James & Mrost 1965). A similar system has been reported in use in Don Basin coal tips (Logginov 1979) and at Mt Isa, Queensland (see above).

Water availability and problems of waste water treatment preclude leaching in many cases (Sorensen et al 1980). Irrigation of untreated waste is of doubtful value (Farmer et al 1976) and in arid areas sprinkling prior to sowing causes crusting and reduces germination (Jones 1979). Some other results of additional water in arid areas - whether to put down dust or for general living - include the establishment of water dependent species, build up of large populations of feral species, loss of tolerant (arid) native species and an increase in periodic visits of water

dependant migrants.

Rehabilitation of vegetation in arid areas is extremely difficult without irrigation for establishment. Toy (1979) suggests that rehabilitation potential is inversely related to water deficiency. As the rate of revegetation depends on productivity to give cover rather than efficiency of water use, it may be desirable to maintain soil moisture at or near field capacity, at least until a significant root system has developed. In some climates slope is important in potential water use and where moisture is a problem basin farmers or gougers can be used to provide additional micro-catchments (Brown 1977).

Successful use of irrigation for establishment is reported from New Mexico (Aldon et al 1976) and Arizona (Nowotny & Wood 1975). At the New Mexico site with annual rainfall of 150-180 mm some 6-20 mm of sprinkler irrigation was provided at 1-2 day intervals for the first 2 weeks after seeding. This was followed by less frequent applications to give a total of some 125 mm over 2 months (net of evaporation and system losses) in early summer. Survival over two growing seasons was best on areas receiving most water. At the Arizona site, a desert shrubland of 200 mm rainfall, plants of *Cercidium* and *Prosopis* spp. were transplanted into overburden capped with 2-2.5 m of soil material and provided with drip irrigation.

## Successful Rehabilitation

The most satisfactory account noted in preparing this review is that of Bradley (1981), in describing techniques used by Rheinische Braunkohlenwerke. In brief: the fill is furrowed prior to topsoil deposition to avoid a sharp interface. When the final layer of loess topsoil has dried the new surface is cultivated and planted to *Medicago sativa*. This prevents compaction and keeps out weeds. During the next 3-5 years structure is developed and soil enriched with fertilizers and in situ mulching to build up humus and nitrogen. Winter rye follows the lucerne and then rape which is ploughed in. Some 150-200 kg<sup>-1</sup> ha of phosphorus and potassium and up to 200 kg ha<sup>-1</sup> of nitrogen are required for acceptable fertility. Some 40 per cent of restored land is used for agriculture. Areas originally forest are reforested as are some areas of former agricultural land. Large spoil dumps are afforested as are the surrounds of artificial lakes (about 4 per cent of the total area). The latter are developed when there is a shortage of overburden for fill.

There is a clear need for aims to be enunciated regarding the type of vegetation that should be attained by completion of rehabilitation. The problem is to define the stage at which a particular site can be considered sufficiently restored. Ecosystem development to a stage of natural sustention or to reasonable sustention with management inputs, to the level of that normally available, is generally accepted as the overall objective. More specific criteria for individual cases must

inevitably depend upon what is known to be possible for that class of case. An example of vegetation development analysis is given in Fox, Majer & Sanford (1982).

Particular difficulties occur with historical disaster areas. Farmer & Richardson (1981) suggest that abatement of acid mine drainage has probably never been accomplished on an operational scale. They suggest that where it has occurred, the change probably owes more to nature and time than to any conscious action by people.

The following summarises the main vegetation solutions, ranking from least to greatest difficulty in achievement:

- \* material stabilised, ground cover sufficient to minimize erosion
- \* soil suitable for carrying a tree plantation
- \* vegetation palatable to stock and renewable with good management, for grazing
- \* soil amenable to cropping with good management
- \* a 'natural' ecosystem with, say, 50 per cent of the original biota present and in reasonable balance.

The creation of a simple system is clearly more straightforward than obtaining a more complex one. The contrast between extremes is examined in some detail in the next part.

## V Succession and Species Selection

Restoration is an ecological problem incorporating planning of future land management. The harsh environments available after mining necessitate the use of pioneer species, whatever the eventual, planned, outcome (Darmer 1963). Engineering treatments may be conceptually simple but vegetation establishment is usually less expensive than restructuring of spoils (Sheldon 1975). Restoration to agriculture may require some restructuring. Natural succession is often slow, reflecting the extreme edaphic conditions which mining creates (Mitchell 1957). Attempts at rehabilitation should build on our understanding of natural processes and be tailored to them. This may mean mirroring natural succession and accentuating it where possible, or seeking to initiate succession where unaided it may not eventuate. In creation of, or conversion to, agricultural crops then simplified ecosystems are the rule.

Direct agricultural cropping after mining is uncommon even with considerable pre-planning of spoil deposition. As noted above in respect of Rheinische Braunkohlenwerke the new soil surfaces require development through sequential treatments. Considerable expertise has been developed in the U.K. in respect of open cast coal and ironstone working. Reseeded reclaimed land requires a high standard of management (Dougall 1950). When land for agriculture is in short supply and adequate burial of toxic materials is possible then a range of crops can be grown (Hunt & Farrant 1955, Edmondson 1961, Blood et al 1961).

Often monocultures are the basis of successful cropping. Under this condition the requirement is to both create and maintain the system at an early successional stage. Many fast-growing trees which have captured the attention of tropical foresters are successional pioneers (Ewel 1980). The same is true of many of the temperate species which feature in the bulk of rehabilitation literature.

As in agriculture the most productive forest tree plantations are monocultures. These tempt fate in the same manner as all simple systems. Rehabilitation is often commenced by choosing one of two avenues. The first consists of planting a wide range of species, hoping for the best, to eliminate poor performance and select candidates. The second is to concentrate on a few known useful species and test out nutrient balances to give best growth. Either approach may have merit when set against the background of existing knowledge of similar, historical, efforts. Both necessitate risk taking in that the full value of species selection will not be apparent until the trees approach maturity.

In this part natural succession and succession sequence are discussed in terms of stages. Natural colonising species are described with reference to particular genera of some general utility. Soil micro-organisms relevant to plant establishment on mine wastes are dealt with. Consideration is then given to site improving species not already mentioned. Finally species selection for rehabilitation programmes is outlined. Criteria for selection and suitable species reported in the literature are

summarised.

### Natural Succession

The colonisation of bare ground in nature follows a sequence dependant on the interacting environmental factors peculiar to the site. Readers will be familiar with the ecological theories of natural succession. Here an attempt is made to demonstrate some aspects relevant to rehabilitation.

Achievement of a self sustaining vegetation cover can be approached through plant succession utilizing pioneer species able to exist under harsh soil conditions. These may ameliorate the site through their rooting and incorporation of organic matter gradually changing the soil in order that later successional species can be grown. Lower plants with minute air-borne propagules are often first on the scene. Some attempts have been made to use algae, lichens and mosses in tailings stabilization (Jurgensen 1979). On pit-heaps the rate of pioneer establishment is accelerated by the presence of a moss-lichen surface layer (Richardson 1958). The sedge *Typha* is the only plant naturally colonising the drainage edge of tailings dams at Mt Isa (Hunter & Whiteman 1974).

Grasses have value as a first stage (Hunter & Whiteman 1974) not least through reduction of surface temperature extremes (Richardson 1958). Early colonizers include legumes (Gudin & Syrratt 1975) and other nitrogen-fixing species or ectomycorrhizal



tree species (Marx 1975). Plant succession is strongly influenced by seed availability (Dancer, Handley & Bradshaw 1977a, Luk'yanets 1977). Direct seeding is useful in speeding up successional change (Bartle et al 1978, Tacey 1980) and it is obviously better to use if possible (Plass 1974). Under some conditions transplants may be preferred (Brown & Johnston 1976, see also Brown et al 1976).

Where mining replaces a topographically varied surface with a more uniform one the vegetation returning will exhibit less variety (Clark 1975). Finely ground tailings containing toxic elements may restrict succession severely. In the case of tin mining particle size separation results in variable succession, with the coarse fraction showing little change in time. Mitchell (1957) reports that after 20 years the levels of organic matter and nitrogen attained may be less than one fifth that of plantations. Change is much more rapid on slimes. A low community will establish within 3 years, followed by shrubs to about 15 years, and then trees of species similar to disturbed secondary forests (Palaniappan 1974).

In northern Canada the progress of succession on mine tailings varies with surface stability, availability of nutrients in run off and the ability of colonizing species' roots to reach the buried humus layer. Factors inhibiting succession include acidity and associated heavy metal toxicity, incidence of drought and lack of nutrients (Taylor & Gill 1973). The variability inherent in acidic spoils leads to differential colonisation and

survival generally (Tasker & Chadwick 1978).

### Succession Sequences

Ecological studies include the sequence landward from the sea across dune systems as an interesting example demonstrating temporal stages of succession. Mining is only one form of disturbance to virgin coastal sands. Unplanned development of dune systems often leads to serious sand drift and in most countries efforts have been made to restore or stabilize such areas. Perhaps only in the case of sand-mining is planned rehabilitation possible (Coaldrake 1973). Beach and dune stabilization practice thus has direct relevance to the rehabilitation of heavy mineral sand mining areas. In the north-west of N. America three vegetation phases are used. Initially a foredune is established using picket fences. Then sand-stilling grasses are planted. *Ammophila arenaria* is most used, with *A. breviligulata* or *Elymus mollis* also suitable. The second phase is 2 years later when the sand is partially stabilized and the original grasses thin out. A mixture of legume and grass seed is then sown to give more permanence. Species include *Lupinus littoralis* and *Lathyrus japonica* and the grasses *Poa macrantha* and *Festuca rubra*. On some sites woody shrubs are planted e.g. *Cytisus scoparius*, *Lupinus arboreus* and *Braccharis pilularis*. These may act as nurses for the third phase: the establishment of tree species. The semi-permanent *Pinus contorta*, *Alnus rubra* and *Salix hookeriana* and the longer lived *Picea sitchensis*, *Tsuga heterophylla*, *Thuja plicata*, *Malus fusca* and *Pseudotsuga*

*menziesii* have been found to be most useful (Schwendiman 1977). A number of trees and shrubs can be planted bare-root into dunes. In Delaware, on the N. American east coast, *Pinus thunbergii* grew 1.2 m in 6 years and several species (of some 23 planted) survived and grew well without fertiliser or organic amendment (Sharp & Hawk 1977). In New South Wales rehabilitation after mining of zircon and rutile from beach sands involves the use of the grasses *Ammophila arenaria*, *Spinifex hirsutus* and *Cynodon dactylon* for primary stabilization. In the secondary phase the creepers *Carpobrotus aequilaterus*, *Senecio crassiflorus*, *Canavalia maritima* are utilised with the shrubs *Acacia sophorae*, *A. saligna* and *Vitex trifolia*. In the tertiary phase the trees *Banksia integrifolia*, *Casuarina equisetifolia* and *Erythrina corallodendron* have been found useful (Sless 1956).

Such a generalised three phase system entails sequential planting or sowing, each stage representing a distinctive cost. Clearly rehabilitation practitioners show interest in reducing the number of establishment events. When two or more phases can be integrated, or one stage eliminated, then success is more readily appreciated by funding authorities. The sowing of species mixtures representing shrub or understorey components, together with planting of tree seedlings, may also achieve diversity rapidly (Bartle et al 1978). Similar objectives underlie the use of brush matting containing propagules. Topsoil return should always speed succession in one way or another.

It may not be possible to bypass or truncate successional stages. In Queensland dunes Thatcher and Westman (1975) note that grass cover may not provide sufficient protection for tree establishment. There is evidence that a native herb and low shrub stage may be necessary for development of a tree stratum. Instead of grasses assisted by fertilizer addition the establishment of stress-resistant early seral stage species may produce better long term effects.

#### Natural Colonisers

Plants which appear on abandoned workings provide a source of potential species to be used in formal rehabilitation efforts.

##### a) Grasses and Herbs

At high altitude in Montana Brown and Johnston (1976) were able to use the grasses *Deschampsia caespitosa*, *Poa alpina* and *Phleum alpinum*. These natives performed better than introduced species and responded to fertilizer treatment. At the Captain's Flat mine Keane (1977) found a mere 4 species of which only the grass *Danthonia pallida* was at all frequent. Other colonisers noted were *Dodonaea attenuata*, *Lomandra longifolia* and *Rumex acetosella*. The last of these is found on very acid soils where aluminium and manganese toxicities are coupled with induced phosphorus deficiency (Rees & Sidrak 1956).

Colonisation of abandoned pit heaps in U.K. commences with scattered grass and herbs. These gradually spread and give way to shrubs and trees. A period of 30-100 years may see the

formation of closed woodland (Davison & Jefferies 1966). The rose bay willow herb *Chamaenerion angustifolium* is a common pioneer on derelict land, tolerant to a range of acidity (Kimber et al 1978). One of the early grasses is *Deschampsia flexuosa*, on acid soils. This responds to phosphorus and liming. At the Blackbird mine the native *Deschampsia flexuosa* invaded areas sown to a set of 11 introduced species especially where these declined due to re-acidification (Richardson & Farmer 1981).

#### b) *Atriplex* as a Special Case

The association of halophytic species with tolerance of toxic substrates is noted by Antonovics et al (1971). The salt bushes *Atriplex* and other *Chenopodiaceae* may be expected to do well on waste sites high in soluble salts. In U.K. *Atriplex hastata* var. *deltoidea* often forms a pure stand on power station fly ash (Rees & Sidrak 1956). This species shows tolerance to aluminium and can also accumulate relatively high levels of iron, manganese and magnesium. It is little affected by nitrogen shortage. *Atriplex nummularia* survived five years on nickel-rich wastes in Zimbabwe. Several other Australian *Atriplex* species also grew well but died after three years (Hill 1977b). *Atriplex* is seeded on South African slimes dumps (Poynton 1977). *A. canescens* is used at an open pit uranium mine (Reynolds et al 1978) and on coal spoil (Aldon et al 1976) in New Mexico. This species responds well to nitrogen fertilizer (Howard et al 1977). At the Belle Ayr mine best growth is shown by seeded *Atriplex canescens* and the volunteer *Salsola kali* (Orr 1975). I have observed natural

Forestry Abstracts

Review Article

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Rehabilitation of Mined Lands

J.E.D. Fox B.Sc.,M.F.S.,M.Sc.,Ph.D.  
School of Biology,  
Western Australian Institute of Technology,  
Kent Street, Bentley 6102  
Western Australia

Abstract

Problems involved in the treatment of land and surfaces disturbed by mining activities are reviewed. Land-use is closely related to pre-existing patterns, with highest values in more closely populated regions. Historical disaster areas provide the onus for avoiding future difficulties, with most problems stemming from slimes and toxic residues. In many cases pre-

colonisation of gold battery tailings at Sandstone (27°59'S, 119°18'E) by *Atriplex bunburyana*. This grows there together with *Eremophila longifolia*, *Exocarpus aphylla*, *Lycium australe* and *Maireana pyramidata*. This suite of species is associated with salt pans, an edaphic environment with some similarity to the tailings.

#### Trees as Pioneers

The most frequently encountered hardwood deciduous pioneers of the northern temperate zone are of the genera *Alnus*, *Betula* and *Salix*. While these species may sometimes be the first plants into a site, there is undoubtedly much looseness in the use of terms denoting pioneer status. Foresters will be mainly interested in potential wood producers and the distinction between natural pioneers and species able to tolerate initially poor site conditions may have little practical value. Many conifer species may be established directly into mineral soil and leguminous (or other nitrogen-fixing) species will always be attractive as soil improvers. The role of *Betula* is dealt with separately below.

#### a) Alnus and Salix

*Alnus* and *Salix* are found in moist sites in nature and tend to be favoured in heavier spoils. As a genus capable of fixing nitrogen *Alnus* is more favoured. In north-western Bohemia Dimitrovsky (1976) reports the use of the local pioneers *Alnus glutinosa* and *A. incana* on clayey lignite spoil. However Jonas (1972) reports *Acer pseudoplatanus* and *Fraxinus excelsior* as

pioneers on clay spoil from lignite in northern Bohemia.

On acidic sandy coal spoil in Denmark *Alnus glutinosa* is reported as a good early colonizer. This is overtaken at 5-7 years by *Betula alba* and *Populus tremula* x *tremuloides*. Species of *Salix* were the most robust after eleven years (Schlatzer 1970). In Pennsylvania Davidson (1979) found the alders were poor on acidic sites in contrast to *Betula* (see below). Kimber et al (1978) list 19 colonising species on coal waste including the woody *Betula*, *Salix* and *Rhamnus catharticus*. The three hardwoods *Alnus glutinosa*, *Populus maximowiczii* x *P. trichocarpa* and *Robinia pseudacacia* survived better and grew taller than a range of conifers on anthracite strip mine spoils in Pennsylvania (Czapowskyj 1970).

Natural colonization of colliery waste by *Alnus glutinosa* and *Betula pendula* is reported by Dennington and Chadwick (1978). Fifteen species of *Salix* are reported to naturally colonize mining wastes in the Urals (Lukyanets 1979). An examination of reclaimed coarse sand tips from China clay workings in U.K. showed that 31 species had colonized one or more of the 68 sites studied. *Salix atrocinerea* and *Quercus robur* were included (Marrs et al 1980). In Bulgaria *Fraxinus ornus*, *Platanus occidentalis*, *Quercus robur*, *Q. rubra* and *Robinia pseudacacia* are reported as pioneer colonisers of coal spoil and brick waste (Donov et al 1978). The most strongly rooting species on spoils from sulphur working in Poland form two groups. On sand *Populus*



tremula and Robinia pseudacacia develop while marl heaps favour Populus alba and P. nigra (Fabijanowski & Zarzycki 1969).

Salix spp. cuttings are useful in stabilizing iron mine slime tailings (Chosa & Shetron 1976) and they also give best growth and survival on copper tailings (Shetron & Carroll 1977).

b) The Pioneer Status of the Birches

The genus Betula is widely used in rehabilitation. Species of this genus are typical pioneers, with plentiful, light-weight seed, able to persist in soil seedbanks. Trees tolerate low nutrient levels and will grow rapidly on moist or dry sites once established. Of 5 promising species (taken from 33 grown) on open cast rock-phosphate mine sites in Estonia two were birches - B. pubescens and B. verrucosa\* (Margus 1973). These sites had 20-30 times the level of phosphorus as in normal soils. Other promising species were Pinus sylvestris, P. mugo and Populus x berolinensis. Plass (1975) noted that B. lenta and B. pendulata were more suited to low pH soils compared with B. lutea. Both Betula pubescens and B. pendula allow development of a dense undergrowth, including Salix caprea on clayey sites (Sheldon 1975). The deciduous habit provides enhanced organic matter for soil development (Sheldon & Bradshaw 1976). Betula pendula has shown good growth on mineral sands workings in the Ukraine (Dan'ko 1978). Davidson (1979) reported the growth of 16 species

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\* Synonymous with B. pendula.

of trees and shrubs grown on 10 coal spoil sites in Pennsylvania. After 11 years two birch species had best growth overall and highest survival. These were *Betula populifolia* (gray birch) and *Betula pendula* (European white birch). Both appear able to tolerate low pH to about 3.3. The paper birch *Betula papyrifera* from New Hampshire performs as well as *B. pendula* on very acidic spoils (Davidson 1977b). *B. papyrifera* is also reported to have colonised serpentine asbestos wastes (Moore & Zimmermann 1977).

*Betula nigra* is the primary invader along river bottoms affected by acid mine drainage in Ohio. This species appears limited to acid environments due to inability to compete in more moderate ones. It may thus be useful on coal spoils (Cribben 1973).

Establishment tends to be localised so that natural regeneration is restricted to favourable microsites (Sheldon 1975). On abandoned slate waste species with smaller seeds - *Betula* and *Salix* - are only able to establish on moister sites where drought is not a problem. In contrast species with larger seeds e.g. *Quercus petraea* and *Acer pseudoplatanus* can root into deeper zones where water is not limiting (Sheldon & Bradshaw 1976).

#### Soil Micro-organisms

The role of micro-organisms in rehabilitation has received less attention than correction of nutritional deficiencies and imbalances, toxicity, moisture deficits and wind erosion (Hutnik

& Davis 1973). In successional terms the soil microflora is important in nutrient cycling. Development of a suitable microflora on wastes could be an important element of a successful rehabilitation effort. Micro-fauna are also of importance. Majer (1981) has drawn attention to the role of ants and termites in aeration and efficient soil turnover. As many micro-organisms require organic carbon then their increase follows the success of plant growth.

The more extreme environments are perhaps of greater concern in terms of micro-organisms. Mycorrhizal development appears inhibited by copper in tailings (Harris & Jurgensen 1977). Micro-organisms generally are more sensitive to heavy metal concentrations than are plants (Jurgensen 1979). Caution is necessary in distinguishing between measuring rehabilitation progress and advocacy of earlier establishment of particular biota to ensure success. However it is clear that some plant species will not grow well if particular micro-organisms are lacking. The ectomycorrhizae of pines are the striking examples familiar to foresters.

Spoils differ in activity (Keleberda 1973) and inoculation of roots may assist with afforestation (Mejstrik 1971, Marx 1975). Presence of fungal hyphae in association with roots of colonizing plant species suggests fungi have a role in aggregation and phosphorus uptake (Jehne & Thompson 1981). Bacteria are important in the legume nitrogen phenomenon and in the acidification of pyritic spoils.

a) Mycorrhizae

A review of the role of mycorrhizal association types in tropical succession is given by Janos (1980). He notes that early pioneer species are often non-mycorrhizal. Early ectomycorrhizal development is essential for seedling establishment in species of *Betula*, *Pinus*, *Populus* and *Quercus* on coal wastes (Marx 1975). Table 1 illustrates the type of mycorrhizae recorded for some commonly used tree species. Maximum mycorrhizal development was found in the top 15 cm in autumn (Mejstrik 1974).

Table 1: Type of Mycorrhiza

	Ecto-	Endo-	Ectendo-
<i>Alnus glutinosa</i>	+	+	+
<i>Betula verrucosa</i>	+	-	+
<i>Fraxinus excelsior</i>	-	+	-
<i>Populus x euramericana</i>	+	+	+
<i>Quercus rubra</i>	+	+	+
<i>Sambucus racemosa</i>	-	+	-
<i>Tilia tomentosa</i>	+	+	-

(After Mejstrik 1974)

Rothwell and Vogel (1982) give mycorrhizal status of 306 plant species found naturally or planted on mine spoils in Kentucky and Tennessee. General agreement is shown for vicarious species to those of Table 1.

Endomycorrhizae are sometimes reported as important associates of pioneers (Jehne & Thompson 1981). The endomycorrhizae may be

particularly useful in detoxifying heavy minerals by chelation (Lamont 1978). Endomycorrhizal fungi produce larger spores than ectomycorrhizal species which are largely wind dispersed and hence universal (Jurgensen 1979). Spores of endomycorrhiza may be spread in animal droppings (Ponder 1980) and may persist from top soil or be introduced via planted nursery grown tree seedlings (Marx 1975). Endomycorrhizae are more common in association with grasses and legumes. Marx poses the questions:

- are plants pioneers because they do not require endomycorrhizae for normal growth?
- if sufficient endomycorrhizal inoculum were available would the same succession of herbaceous species prevail?

These problems remain unanswered in definitive terms.

The relation of mycorrhizae to growth is not clear cut. Shufstall and Medve (1979) examined mycorrhizae on 6-10 year old plants of 14 species of which 10 were colonizers and 4 commonly planted exotics. They were unable to relate the percentage or type to successful growth. In a series of experiments Nicholas & Hutnik (1971) successfully inoculated both *Betula verrucosa* and *Pinus resinosa* with *Pisolithus tinctorius* and *Cenococcum graniforme*. However growth response on 3 coal spoils was greater with lime or fertiliser than with inoculation.

The presence of fungal hyphae in association with roots of colonizing plant species in bare dune areas has been reported. Hyphae meshed with sand grains form aggregates which may be

important in stabilization. Depletion of phosphorus from meshed grains suggested that the fungi may obtain phosphorus from sand grain surface coatings. Thus it is noted that deliberate re-establishment of effective mycorrhizal fungi could assist plant establishment and reduce the need for fertilizers (Jehne & Thompson 1981). The use of soils low in mycorrhizal inoculum and of non-mycorrhizal annual plants may inhibit early growth of mycotrophic perennials and slow down succession (Allen & Allen 1980). Topsoil and native species will result in early mycorrhizal colonisation (Farmer et al 1982).

The species *Pisolithus tinctorius* is the usual ectomycorrhizal fungus on roots of species of *Betula*, *Pinus*, *Populus* and *Salix* in N. America and Europe. This species forms an association with, at least, some 35 species or varieties of *Pinus*, 3 of *Betula*, 2 *Eucalyptus*, 2 *Populus* and 6 *Quercus* (Marx 1975).

This fungus has received much attention in recent years in matching mycorrhiza with a host. It is particularly catholic and therefore of wide potential utility (Jurgensen 1979). It can be added to pines in the nursery and these are reputed to perform better on low pH coal spoils. Where the appropriate species of ectomycorrhizal fungi are not known then it is possible to use soil extracts to inoculate cuttings (Harris & Jurgensen 1977).

b) Bacteria

Rhizobia

Nitrogen is required in greater amounts by plants than any other soil nutrient. Before a stable community can be attained soil nitrogen levels must be sufficient to ensure adequate cycling of nitrogen. Some strongly seasonal climates may have low net nitrogen accumulation rates (Langkamp, Farnell & Dalling 1981).

Nitrogen fixation in the legumes is dependant on successful infection of the legume root by *Rhizobium* bacteria. Nodules are formed in a symbiotic manner on the root hairs of the legume. Agronomists have developed techniques of pelletising cultivar seed with the appropriate *Rhizobium* strain. Little effort has been put into selection of *Rhizobia* strains and leguminous plants adapted for growth on mine wastes (Jurgensen 1979). Under acid conditions leguminous plants exhibit poorer growth than grasses (Edgerton et al 1975). Certain legumes e.g. the herbs *Lespedeza japonica*, *Lotus corniculatus* and, as noted above, the tree *Robinia pseudacacia* show greater tolerance to acidity than most (Jurgensen 1979).

The relationship between acidity and growth is indirect. When soil pH is raised, root growth can increase with the increased availability of nutrient elements and decreased availability of toxic elements such as aluminium and manganese. Nodulation and hence nitrogen fixing also increase. Some legume species require relatively high pH levels combined with availability of calcium for best growth. For example Czapowskyj and Sowa (1976) could

not establish *Coronilla varia* on coal spoil at pH 3.7-4.0 without lime. However 6.3 t ha<sup>-1</sup> was as effective as 12.6 t ha<sup>-1</sup> in obtaining good survival and cover. Different cultivars show varied sensitivity to manganese toxicity in relation to acidity and calcium levels. This may contribute to poorer growth of some legumes on acid or water logged soils (Robson & Loneragan 1970).

In the case of some legumes soil acidity also directly affects growth and survival of Rhizobia. Armiger et al (1976) suggest that utilizing a Rhizobium inoculant is worthwhile at pH of 4.5 or over, but that nodulation is poor at pH less than 4.0. Low acidity will inevitably give lower growth than when plants are grown in soils of their optimum pH range. Two options are available - firstly to alter the conditions, by addition of lime and fertilizer; secondly to select strains which grow well and fix nitrogen under acid conditions (Jurgensen 1979). Nitrogen fertilization may depress Rhizobia activity. If legumes are an integral part of a rehabilitation scenario then some care needs to be adopted in respect of nitrogen quantities added.

The comparative values of a range of legume species in building up nitrogen levels and increasing growth in a companion grass have been investigated by Jefferies et al (1981). Nitrogen may become available to associated species within two years of sowing. *Lupinus perennis* was the most effective of the species examined. It is estimated that 80 per cent of legume nitrogen becomes available through decay of root nodules (Lanning &

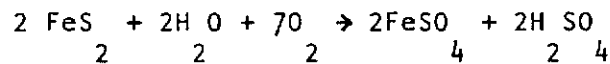


Williams 1980). Inoculation of the rhizosphere of perennial grass species with free living N-fixing bacteria has been advocated (Cundell 1977).

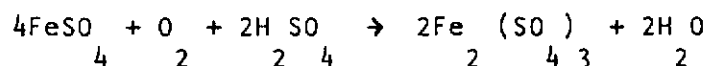
### Thiobacillus

The oxidation of pyrite in acidic wastes is assisted by bacteria of the genus *Thiobacillus*. Three species *T. thio-oxidans*, *T. ferro-oxidans* and *T. denitrificans* have been implicated in accelerating the oxidative decomposition of pyrite (Craze 1977a). The bacteria are independent of organic matter and utilize carbon dioxide as a carbon source (Jurgensen 1979) deriving their energy from oxidation of the sulphides or ferrous sulphate. The reactions have been described as an example of a natural solvent regeneration process (Hore-Lacey 1979). The bacteria are particularly active in surface layers with acidity optima at pH 2 to 3. They are not usually active at pH more than 6. Activity is inhibited as pH is raised but the organisms are not killed below pH 9.

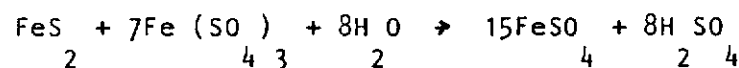
Chemical oxidation of pyrite will increase acidity and can occur as long as pyrite and oxygen are present:



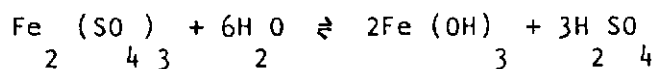
Conversion of ferrous sulphate to ferric sulphate is accelerated by the metabolic activity of *Thiobacillus*:



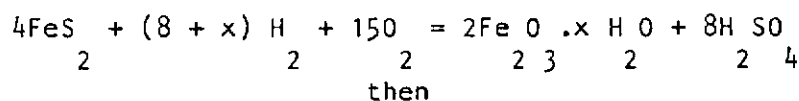
Under acidic conditions oxidation of pyrite by ferric sulphate is rapid:



Ferric sulphate may also undergo hydrolysis:



The sulphuric acid produced solubilizes toxic quantities of heavy metals making vegetation establishment difficult (Sorensen et al 1980). The only satisfactory solution to permanently halt acidification is to bury acid forming materials (Jurgensen 1979). Limestone materials have been used to neutralise acidity. For example at a pH of 7.5 with 6 percent iron pyrite, neutralisation of potential acidity by dolomite is the result of:



$$\text{CaCO}_3 + \text{MgCO}_3 + 2\text{H}_2\text{SO}_4 + 7\text{H}_2\text{O} = \text{CaSO}_4 \cdot 2\text{H}_2\text{O} + \text{MgSO}_4 \cdot 7\text{H}_2\text{O} + 2\text{CO}_2$$

Pyrite in spoil oxidises to sulphuric acid which is neutralised by the dolomite yielding calcium and magnesium sulphates. The soluble magnesium sulphate crystallises out on the surface (Ruschena et al 1974). Raising the pH will not stop oxidation, the rate of oxygenation may increase. As revegetated surfaces age a natural barrier to rapid sulphate oxidation should form with reduced availability of oxygen to subsurface layers. Cundell (1977) suggests that sulphur oxidising bacteria could be harnessed to lower soil pH in reclamation of alkaline coal spoils in the western US.

#### Site Improving Species

The legume/Rhizobium symbiosis enriches soils with nitrogen. Leguminous species are important colonisers on abandoned mine spoils (Jefferies, Bradshaw & Putwain 1981). Johnson & Bradshaw (1979) list 19 perennial legumes most useful for reclamation.

With time some 17 woody legumes appear in rehabilitated bauxite mines in Western Australia (Fox et al 1982). The predominance of legumes on revegetated mine sites suggests that these have an advantage in colonising spoils especially low in available nitrogen (Dancer et al 1977a).

Other genera capable of fixing nitrogen apart from the legumes include *Alnus*, already described and also *Casuarina*, *Ceanothus*, *Cercocarpus*, *Elaeagnus*, *Hippophae*, *Purshia* and *Trema*. These non-legumes are believed to utilize a symbiotic relationship with Actinomycete fungi particularly on infertile soils (Monsen 1975).

Four species capable of nitrogen-fixing: *Alnus glutinosa*, *Elaeagnus umbellata*, *Robinia fertilis* and *R. pseudacacia* all showed promise on very acid (pH 2.8) spoils with the addition of lime (Carpenter & Hensley 1979). *Alnus glutinosa* has also been shown to be effective in USSR (Verbin & Keleberda 1974).

The first use of legumes on nitrogen deficient wastes in U.K. is claimed by Rees & Warwick (1957). *Trifolium repens*, on material of pH 8.5, outyielded five grasses. Strong differences in cultivars were also exhibited. Skeffington and Bradshaw (1980) suggest that up to 50 kg ha<sup>-1</sup> of nitrogen can be given to *T. repens* before nitrogen fixation is reduced by reduction in nodule formation. Excessive liming may cause lime-induced iron deficiency in *T. repens* (Gemmell 1981). Depression of growth by high liming may be countered by phosphorus or magnesium addition

(Costigan, Bradshaw & Gemmell 1982). The value of herbage legumes in combination with grass in restoration to agriculture has been long recognised (Brook & Bates 1960).

Other legume species of interest to rehabilitation include *Cytisus scoparius*, *Lupinus arboreus* and *Ulex europaeus* which can all grow in calcium and phosphate deficient soils (Johnson & Bradshaw 1979). *Leucaena leucocephala* shows promise on alkaline coal spoil in Queensland (Coaldrake & Russell 1978). *Medicago sativa* was the best of five legumes on high pH waste grown by Moore and Zimmermann (1977).

a) Nurse Crops

Species used as intermediates may function as nurse crops. Such species may assist in soil amelioration or provide other assistance to crop plants. Dan'ko (1978) describes afforestation of open-cast sites worked for mineral sands in Zhitomir, Ukraine. Here *Pinus sylvestris* is mixed 3:1 with *Alnus glutinosa*, and perennial lupins sown between the pine. Dimitrovsky (1976) used *Acer platanoides*, *A. pseudoplatanus*, *Fraxinus excelsior*, and *Ulmus montana* in mixture with alders.

*Lupinus polyphyllus* has been grown successfully where *Betula pubescens*, *Salix caprea* and *Populus tremula* failed. On spoil mounds worked for talc in Styria Fuchs (1973) reports that the lupin promoted humus formation so well that *Picea abies* could be successfully interplanted after 3 years, as large transplants. Thum (1978b) sowed *Lupinus polyphyllus* and *Melilotus albus* into

poplar planted 6 months earlier, as a cover crop. *Lupinus arboreus* has value as a pioneer or nurse crop. It enriches the soil with nitrogen fairly rapidly (Palaniappan, Marrs & Bradshaw 1979). *L. arboreus* has been termed a primary colonist on sand waste where it will form pure stands (Dancer et al 1977a). Stands of *Robinia pseudacacia* and *Pinus echinata* planted in 1938-39 in Illinois on land strip mined for coal were underplanted with up to 9 species of hardwoods in 1947. Assessment of growth at 30 years showed that survivors of most species were larger in the *R. pseudacacia* stand. N, P and K levels were lower in the *P. echinata* stand (Ashby & Kolar 1977).

b) The Black Locust

*Robinia pseudacacia* has received much attention in the literature. Brown (1973b) recommends light covering (0.6 cm) of soil for spot-sown scarified seed to give good establishment. He has also produced a table to predict height growth according to physical characteristics of West Virginia coal spoils (Brown 1973a). Although it is the most frequent nitrogen fixing species of communities on disturbed sites it suffers from insect infestation (Carpenter & Hensley 1979).

*Robinia pseudacacia* showed better survival and height growth than 6 other species grown by Sopper et al (1970) in coal spoil treated with sewage. This species was the only hardwood to survive in gravel pit workings described by Bourdo and Willis (1975). The same species showed highest survival on Kansas coal

spoils where *Pinus taeda* gave highest volumes (Geyer & Rogers 1972). On very acid spoil it responds well to added phosphorus and nitrogen at the time of planting (Plass 1972). Of 13 species sown in sand waste from zinc/lead ores at pH 7.8, high in magnesium, iron, zinc and lead with little nitrogen, *R. pseudacacia* showed most tolerance to type of treatment (Kluczynski 1973).

On a variety of spoil-banks left after fire clay extraction Grechushkin (1978) showed survival high only with *R. pseudacacia* and *Alnus* spp. It is generally considered to be the most acid-resistant of legumes commonly planted on mine wastes, with growth and nodulation at  $\text{pH} < 4$  reported in coal spoils (Jurgensen 1979). However both survival and growth fall off on more acid soils (Helgerson & Gordon 1978) and it is difficult to establish on steep ungraded spoil (Czapowskyj 1970). It is not recommended for spoils less than pH 3.5 by Davidson (1979). Davidson reports poorer survival with *Robinia fertilis* but this species can sprout by runners to 5m from parent plants. This latter species has a marginally lower pH tolerance to 3.3.

c) Sea Buckthorn

*Hippophae rhamnoides* tolerates saline conditions. Barannik (1979) reports in excess of 400 ha of plantation in Kuzbass region of western Siberia. This species shows best growth of a range tested on white clay and carbonaceous clay loam left after open cast coal mining. It will attain 2.2 m in six years.

*Hippophae rhamnoides* is also grown on alkaline coal spoils in Ukraine, Crimea and Moldavia. Its nitrogen fixing capability causes rapid soil improvement and influences the growth of companion species e.g. *Betula*, *Pinus* and *Coryllus*. It produces abundant suckers and is thus useful for erosion control on slopes. Keleberda, Dan'ko and Zharomskii (1978) recommend planting it every third row with two rows of trees. Seedlings and root suckers are better than stem and root cuttings (Treshchevskii & Selivanov 1979).

In other cases pines may be used as nurses e.g. *Pinus banksiana* (Bourdo & Willis 1975). Judicious species mixtures may involve a 'nurse' effect. An example would be the use of *Alnus glutinosa*, *Larix leptolepus* and *Pinus contorta* on open cast workings in Ireland (Condon & O'Carroll 1975).

Non-native species used for rapid cover establishment and to build up soil organic matter may be replaced by native species when fertiliser is discontinued. Richardson (1980) demonstrates this at the Blackbird mine in relation to grasses.

#### Species Selection

The first stage of selection depends on the amount of pre-existing information. It may be necessary to test a wide range of species. Where a short list of possibly useful species can be decided on empirical grounds then these can be tested under conditions of altered nutrition. Foresters have generally sought out the most suitable species for given sites through species

trials. Matching of environments concentrates on climatic similarities or particular edaphic tolerance. For most tree crops climatic controls override cultural or nutrient manipulation. With crops of higher value than trees the desirable nutrient balance can be determined and suitable varieties screened for the local environment.

Within suites of suitable tree species fast growth coupled with wood utility become of overriding concern. Evaluation is primarily concerned with survival, followed by growth but initial selection should include effective soil stabilisation, soil improvement and ease of propagation. On extreme sites the range of plants suitable for cultivation is limited by the toxicity present. Survival of the more acid-tolerant species is unpredictable at pH less than 3.5 (Davidson 1979). Laboratory studies of germination may assist in screening species (Abouguendia & Redman 1979).

For unusual or intractable sites an examination of natural colonization is recommended. Keane (1977) examined areas adjacent to the mine and downstream for potentially useful species. Some 200 species were collected adjacent to old dumps or mineralized areas near Mt Isa (Ruschena et al 1974). For tin sand tailings Mitchell (1957) considered tree species capable of growth in similar extreme edaphic environments. These included *Fagraea* species found on natural sandy heaths and *Casuarina equisetifolia* of the beach sands. *Lonicera ciliosa* is a rocky



outcrop species of the western USA. It is resistant to toxic smelter fumes and is also useful for borrow pits and road slopes (Monsen 1975).

Where no old mine workings with tolerant populations exist then species which can be associated with high natural surface mineral concentrations may be considered as candidates for tailings. For example *Bulbostylis barbata*, *Eriachne mucronata* and *Polycarpha glabra* indicate high zinc concentrations. The latter is also an indicator of high copper concentration (in Hunter & Whiteman 1974).

a) Selection of Grass Cultivars

Obvious advantages exist in selection procedures for grasses compared with the woody perennials. Mixtures of seed can be sown, the time scale for assessment is short and development of varieties is rapid. For rapid cover well-known species tend to be used. In the long term local species may require less maintenance and give enhanced compatibility with surrounding landscapes (Hore-Lacy 1977). Grass establishment is often best achieved by seeding with legumes or into established legume stands (Einspahr 1956). Examples of grass species providing rapid cover and with tolerance to low fertility are *Festuca rubra* in temperate climates, *Eragrostis curvula* in dry regions and *Chloris gayana* in the tropics (Johnson & Bradshaw 1979).

*Chloris gayana* cv 'Pioneer' is used as a cover crop for endemic seeded species at Groote Eylandt (Langkamp & Dalling 1979). Sub-

optimal fertilization allows rapid establishment for erosion control but not persistence. Its rapid decline assists the goal of return to an endemic ecosystem. *Chloris gayana*, together with *Cenchrus ciliaris* and *Cynodon dactylon*, is useful as a summer grass cover on treated tailings dams (Ruschena et al 1974). The first two of these three plus *Panicum maximum* grow well on Queensland coal spoil, clayey with high pH and low in nitrogen and phosphorus (Coaldrake & Russell 1978).

*Eragrostis curvula* (weeping lovegrass) is a short lived perennial useful as a nurse cover. It has rapid germination, fast growth, a good root system and is tolerant of acid conditions (Armiger et al 1976). This species outperforms other grasses on acid spoils and is recommended where pH is 4-4.5. At pH greater than this *Festuca arundinacea* is recommended (Vogel & Berg 1968). *Eragrostis curvula* was the best grass in work reported by Edgerton et al (1975).

*Festuca rubra* grows well on smelter waste (Gemmell 1976) but a mixture with *Dactylis glomerata*, *Phleum pratense*, *Lolium perenne* performed best over time. *Lolium perenne* is an aggressive species which yields well at high fertility levels (Elias 1982). It is widely used in rehabilitation (Keane 1977, Moore & Zimmermann 1977, Sheldon & Bradshaw 1977).

Species surviving in mixed grass sowings include *Bromus inermis*, *Dactylis glomeratus* and *Phleum pratense* as the best species after 6 years growth at the Blackbird mine (Richardson & Farmer 1981).

Lists of suitable grass species for a range of spoils are given in, for example, Aldon et al 1976, Allen & Allen 1980, Armiger et al 1976 and Deakins 1953.

Bradshaw (1952) demonstrated that tolerance of toxicity can occur in ecotypes of a species. Populations from old mine spoils tend to be more tolerant of the specific toxic metal ion(s) of that particular soil, than those found on more recent material (Gadgil 1969). The process of natural selection is particularly rapid in annual grass species and it is from such plants that most progress is reported. Tolerant populations show better root and shoot growth on untreated spoils than do non-tolerant populations (Smith & Bradshaw 1970).

Tolerance may be evaluated using an index:

$$\text{Index of Tolerance} = 1 + \log \frac{A}{B}$$

Here A is root growth in two days in calcium nitrate solution. The root is then observed in calcium nitrate plus heavy metal solution such that B is root growth over the third and fourth days in the latter. An index of 2.0 represents a diminution of growth rate to 10 per cent (Gadgil 1969, after Wilkins).

Species particularly characteristic of acid metalliferous soils are *Agrostis tenuis* and *Festuca ovina*. Those of calcareous metalliferous soils are *Festuca rubra*, *Agrostis slolonifera* and *Plantago lanceolata* (Smith & Bradshaw 1979). *Anthoxanthum odoratum* also shows tolerance to zinc-rich wastes (Gadgil 1969).

Development of cultivated varieties to match particular artificial spoil types is a logical progression from selection of tolerant populations. Cultivars have been developed for temperate climates. These are *Agrostis tenuis* cv Goginan tolerant of acid lead/zinc wastes; *Festuca rubra* cv Merlin tolerant to calcareous lead/zinc waste; and *Agrostis tenuis* cv Parys tolerant to acidic copper materials (Smith & Bradshaw 1979). Good progress has been made in Zimbabwe with populations of *Cynodon aethiopicus*, *C. dactylon*, *Panicum repens*, *Paspalum vaginatum* and *Sporobolus virginicus* (Hill 1977b).

Grazing is an important consideration in grassland maintenance. Short growth of grasses or clover is preferred by grazing animals (Armiger et al 1976). Grazing will assist nutrient cycling, mowing of steep slopes is hazardous and burning results in loss of phosphorus and nitrogen. Prospects for grazing will often influence the selection of a system leading to tree cover (Marrs, Granlund & Bradshaw 1980). If the forage crops absorb high levels of particular metal ions then grazing is hazardous. Erdman, Ebens and Case (1978) reported copper deficiency in sweet clover growing on coal spoil and suggest that low copper:molybdenum ratios will cause nutritional imbalance. In another study phosphorus deficiency was identified (Erdman & Ebens 1979). In the case of tolerant populations, failure to establish (bare patches) is associated with phosphorus deficiency. Fertilizing will allow establishment (Smith & Bradshaw 1979).

Tolerant populations may absorb more of the toxic ion but translocate less to the shoots (Wiltshire 1974). Legumes raised by Edgerton et al (1975) accumulated high levels of toxic metals in foliage in contrast with grasses where increased yield was associated with lower foliar concentrations. Species may exclude heavy metal ions from active metabolic sites and some species can preferentially absorb cadmium relative to zinc (Leavitt, Dueser & Goodell 1979). As a general rule grazing is not normally advisable where tolerant populations are established (Smith & Bradshaw 1979).

b) Selection of Woody Species

Jeffrey et al (1974) suggest the selection of *Rhizobium* ecotypes. It is possible that with trees much of the selection must involve the microflora associates of the crop plants. Monsen (1975) reviews selection and breeding of plant ecotypes in the western USA. He notes that selection of species is difficult because comparable natural communities do not exist. In a number of cases species selection has produced sets of useful trees for rehabilitation. Coal tips in the Don Basin for example are planted with the preferred species *Acer negundo*, *A. tataricum*, *Fraxinus pennsylvatica* and *Robinia pseudacacia* with some shrubs (Logginov 1979). *Acer rubrum*, *Crataegus* species, *Populus tremuloides*, *Robinia pseudacacia* and *Sassafras albidum* grow better on spoil than non-spoil sites in the Pennsylvania coalfield. In addition to these good growth is shown by *Aralia spinosa* and *Rhus glabra* (Shuffstall & Medve 1979). Significant changes in soil properties are reported with successful

plantations on spoils (Keleberda 1978).

There are numerous examples where high value/volume tree species have been imposed with little attention to soil amelioration with mixed results. Uncertainty over the possibility of developing useful stands in the Rhine lignite area led to the use of poplar because of its fast growth. However by 1955 it had been demonstrated that generous use of loess, sand and forest gravel in building up top soil coupled with soil enrichment allows healthy forests of commercial species to be grown (Bradley 1981). For the 40,000 ha reported as reclaimed in G.D.R. by Werner (1973) *Populus* spp. occupied most area, with *Pinus sylvestris* and *P. nigra*. On slopes *Robinia pseudacacia* and *Hippophae rhamnoides* were used.

The performance of poplar on coal spoil is extremely varied, largely depending on microclimate effects (Czapowskyj 1978). Individual plants grow well but survival is poor (e.g. Shetron & Carroll 1977). Canker infection of poplar clones has been associated with reduced vigour of material planted in spoils (Dochinger & Bender 1972).

*Eucalyptus camaldulensis* was first tried on tin mine workings in Nigeria in 1948 (Wimbush 1963). It has been successfully grown there (Orode et al 1977) and in Queensland. The small seed is pelletised in finely ground rock phosphate dust for direct sowing (Middleton 1979). As it is susceptible to termite attack its use at Groote Eylandt is limited (Langkamp et al 1979). At Weipa 5

valuable species, the mahogonies *Khaya senegalensis* and *Swietenia macrophylla*, and the conifers *Callitris intratropica*, *Pinus caribaea* (Coaldrake 1973) and *Araucaria cunninghamii* (Nicholson 1974) show promise. However the environment is harsh, with a strongly seasonal climate and mine floors lined with hard ironstone. Fire and termites take their toll and the local *Erythrophloeum chlorostachys*, being termite resistant, is more useful than *Eucalyptus* species in native vegetation return. The faster growing *Eucalyptus* species are of value in plantation establishment when adequate care is available.

A range of conifers are grown on rehabilitation sites. The northern temperate conifers are often readily established on fresh mineral spoils. Plass (1974) examined responses of 7 pine species to coal spoils of pH 2.5 to 8.4. *Pinus echinata*, *P. palustris*, *P. taeda* and *P. virginiana* emerged at low pH but *P. resinosa*, *P. rigida* and *P. strobus* did not. Coarse textured spoils with pH 4.1 to 5.0 with adequate phosphorus gave best overall results. *P. taeda* and *P. palustris* grew well on a range of spoils but showed a tendency to slower growth on material of pH 5 or higher. *Pinus sylvestris* and *P. mugo* are used on rock phosphate spoils in Estonia (Margus 1973). *P. sylvestris* tested by Davidson (1979) gave mixed performance on spoils of pH more than 3.5. On some sites it showed best survival and height growth at pH 3.4-3.8. On anthracite spoil in Pennsylvania *Pinus virginiana*, *P. banksia* and *Larix leptolepis* perform well (Czapowskyj 1970). *Picea glauca*, *Pinus resinosa* and *P. banksiana*

grow well in gravel borrow pits in Michigan (Bourdo & Willis 1975). Davidson (1977a) reports growth and survival over six years for progeny from 49 sources of *Pinus ponderosa* planted in Pennsylvania coal spoils. Eight sources produced seedlings average or better in both height growth and survival. At pH 3.4 these eight superior sources averaged 80 cm after 5 years. This contrasts with 64 cm for *Pinus resinosa*, a species usually preferred.

#### Selection for Particular Requirements

The time necessary to confirm success with particular species is related to both climate and substrate. At least two growing seasons are needed to determine whether a stand is established under semi-arid conditions (Aldon et al 1976). For trees the full rotation is needed to demonstrate the yield. Twenty year yields are reported by Nille (1974) for German lignite workings. Annual production of 9.4 t ha<sup>-1</sup> in 14 year birch and willow is reported from France (Kestemont 1974). Growth differs with topographical position on mounds (Luk'yanets 1977). In the Ukraine *Pinus sylvestris* on lignite spoil yields 108 m<sup>3</sup> ha<sup>-1</sup> to 15 years, not dissimilar to growth on unmined land (Pertsev 1978). In Nigeria *Eucalyptus camaldulensis* grows to 3 m in the first year and 9-14 m in 8 years. Even on compacted spoils it grows at 0.6 cm diameter per annum (Orode et al 1977).

Two extreme cases are considered here. Firstly woody species for slimes where toxicity is important and secondly bauxite pits where little overburden of friable material is available.



a) Woody Species for Slimes

On tailings high in soluble salts plants with particular rooting structures could be selected in relation to local variations. Phreatophytic, xerophytic or halophytic plants may be selected to tap water tables at depth, to withstand drought and tolerate salinity respectively (Hill 1977a). In a relatively infertile environment a low yielding species with a relatively well developed root system may have competitive advantages. *Coronilla varia* and *Lotus corniculatus* had the lowest growth rates of seven legumes tested by Elias and Chadwick (1979). *Coronilla varia* is an excellent soil conserving species which spreads rapidly and grows well on eroded soils (Armiger et al 1976).

*Acacia karoo* can tolerate soil arsenic levels of 10,000 ppm whereas *Euphorbia tirucalli* can tolerate 5,000 ppm (Wild 1974). *Tamarix aphylla* will grow better than *A. karoo* on arsenic-rich wastes, but the latter is better on copper wastes. Both *Acacia saligna* and *Casuarina glauca* grow well on arsenic, nickel and copper-rich wastes (Hill 1977b). Several *Acacia* species e.g. *A. baileyana* and *A. melanoxylon* are included in standard seed mixes used on S. African slimes dumps. These wattles provide wind breaks which reduce dust blow, trap seeds and provide cover for wildlife (Poynton 1977). More attention needs to be given to the use of *Acacia* in rehabilitation. The genus is large and variable and a number of species reach good sizes.

b) Bauxite Working

Restoration in areas of mediterranean climate is particularly difficult. French bauxite spoils of calcareous rock have been planted to Spanish broom *Spartium junceum* on slopes and conifers on terraces. The conifers include *Cedrus atlantica*, *Cupressus arizonica* and *Pinus* spp. (Deserts & Chevalier 1977). This operation utilized a top dressing of 40-80 cm of local soil.

A large number of *Eucalyptus* species have been planted in bauxite mined areas formerly carrying forest cover in Western Australia (Tacey 1980). In this case the top soil available is limited to about 40 cm. It is not known whether the particular conditions will support a high value production crop. At least 20 years has been suggested as necessary to determine whether a successful stand of trees can be grown in a comparatively high rainfall zone (Beggs 1972). As mining moves inland to drier, salinity-prone forests it is becoming critical to select particular species which will restore the hydrological balance after mining. Conventional species trials are complemented by the use of evaluation criteria indicating successful adaptation to the environment (Bartle & Shea 1978).

Similar work in the Ukraine to select species suitable for planting open-cast sites, left after mining manganese ore in the dry steppe, is reported by Zherebtsov & Petrenko (1972). In this region development of both horizontal and vertical root systems is important. The following six trees (and some shrubs) are considered suitable: *Acer tataricum*, *Caragana arborescens*,

*Elaeagnus angustifolia*, *Pinus sylvestris*, *Robinia pseudacacia* and *Ulmus pumila* var. *arborea*. A further fourteen species were unsuitable as they did not develop vertical root systems. In the Western Australian case deep rooting and high transpiration to maintain low water tables are seen as important properties (Bartle & Shea 1978).

## VI. Conclusion

Rehabilitation efforts cover the range of uses to which man has put the land. Even with non-productive (in an economic sense) land there exist needs to stabilize spoils, to reduce run-off, to minimize dust problems, and to improve the appearance of mined and waste areas. This review suggests that man is coming to terms with the notion that land surfaces should not be left in poor condition just because, at one time, their use generated considerable benefits. Plants can be cultured in a wide range of non-soil media. It is not surprising therefore that plant growth of some kind has been attained on the range of mine waste materials available. Prospects for the economic cultivation of tree crops are poor however and limited to sites where disturbance is relatively innocuous and/or readily reversible. Mining which gives rise to such conditions tends to be on a larger scale than that producing spoils of a more intractable nature. Thus in some regions forestry has become an important post-mining land use.

Much stress is laid on the notion of pre-planning for successful rehabilitation. There are limits to the extent to which this can be taken, particularly in the case of tree crops. No open and shut case studies exist from pre-mining through a subsequent rotation to harvest. In successful afforestation enterprises success has followed an iterative process involving trial and error. Pre-planning is likely to be most productive in avoiding the creation of major disaster scenarios and in best arranging overburden and spoil dumping while mining is in progress.

Screening trials for species should commence with pot trials in the range of available final surface materials. Pot trials with suitably amended spoil should precede field trials even when dealing with orphaned sites. Soil moisture relationships and the effect of climate must await site availability. Some sites with combinations of extreme conditions: high salinity, fluctuating water table, low rainfall, and poor fertility; are difficult to improve. Recovery may depend on a particular, unusual, set of climatic conditions in such cases. Often inordinate expenditure is required to achieve doubtful results. Prior decisions on land use with provision for physical amelioration ought to be able to avoid such disaster areas in future.

The eventual aim of many rehabilitation projects is the securing of a form of self-sustaining forest or woodland. Evidence suggests that time to achieve some stability in this sense will vary with the original treatments and the manner in which the species used modify sites. The selection of species for planting is crucial. On barren sites only those introduced are likely to play dominant roles and without deliberate introduction; succession will follow early classical stages only. That is wind-borne, light-weight, propagules of the weedy or pioneer species found in the region will enter. The entry of species characteristic of later seral stages is much more problematical. The use of topsoil, preferably directly placed with minimal storage, can increase the rate of return of species. In species-rich areas some species will be eliminated. Some will respond to fertilizer treatments and others to no fertilizer. Some useful

options are available to speed up the time needed for succession.

Long term stabilization necessitates a functioning plant community to supply organic matter. Organic amendments, often useful in speeding up succession, play a minor role in building up a large stable organic matter fraction (Jurgensen 1979). Plant species capable of high production initially will lead to more rapid accretion of surface organic matter. This should assist growth of species of longer life and of greater economic value. Deep rooting plants will resist drought and high surface temperatures. On acidic spoils fertilizer is more important than liming per se in encouraging good root growth (Fitter & Bradshaw 1974).

When waste materials of variable properties occupy a small proportion of the total landscape devoted to conventional cultivation then there is a danger of disproportionate effort (Blood et al 1961). In reported cases of detailed provenance or clonal testing (Davidson 1977, Czapowskyj 1978) the availability of material was probably fortuitous. This is not to denigrate future advances in selection for particular media however and society itself will largely direct research efforts in two general ways. Firstly small-scale disturbances near to settled areas, or which pose potential dangers to man's institutional arrangements, will clearly demand high levels of achievement. Secondly larger disturbances, by their very nature, require commensurately greater effort in selection as the need to manage

large land areas is generally greater than for small areas.

Rehabilitation must generally refer to a future potential of the land disturbed. Restoration to its previous condition is rarely possible. It is appropriate to suggest that rehabilitation be considered successful when planned future-land use is achieved. This will usually mean that stability is consonant with long-term use, productive or otherwise, and that management inputs necessary are no greater than for similar land uses on unmined land. Our custody of the land has not reached the level where society is prepared to forgo the benefits of mining because rehabilitation is considered impossible. Rather man is incurably optimistic in relying on research to produce hitherto unforeseen solutions. Rare is the scientist or land manager prepared to resist conventional progress in this sense. It is in relation to preservation of the status quo, usually in terms of the inherent special value of the existing land use that mining is opposed on occasion. Even then the "no mining" option is rarely followed.

The question remains - should rehabilitation be undertaken? Kopp (1978) poses such problems as: what are the total costs? are there limits to investments? what are society's returns? Legislation may provide legitimacy to an enterprise but only the achievement of worthwhile, attainable, goals will lead to net increases in human welfare and to acceptance by future generations of our reasonable stewardship of the earth's surface. We have a long way to go.

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