CONSTRUCTION AND PROTECTION OF NEW SOILS IN DIVERSE BIOGEOGRAPHIC ZONES – THE CHALLENGE FOR SUCCESSFUL REHABILITATION IN THE AUSTRALIAN MINING INDUSTRY

L.C. Bell
Australian Centre for Mining Environmental Research, Brisbane Australia

Abstract

Although the Australian mining industry occupies a relatively small proportion of the nation's land surface compared to that devoted to other land uses such as agriculture, the local environmental impact can be severe. Government regulations in Australia require that the mining industry ensures (1) the post-mined landscape is stable to the erosive forces of wind and water, (2) the quality of the surrounding water resources is protected, and (3) the agreed post-mining land use is established to the satisfaction of the government and community.

The rehabilitation program of almost all surface mines operating in Australia involves the establishment of vegetation. In all cases, there is the need to either conserve all or part of the existing soil resources or develop a root zone from other materials to support self-sustaining vegetation.

This paper reviews the various approaches used by the mining industry in Australia to manage existing soil resources and construct new soils in diverse biogeographic zones. Because the topography of the post-mined landscape is often quite different from that existing prior to mining, the protection against erosion of replaced and new soils is a major issue, particularly where there is the requirement to protect underlying toxic wastes. This paper also briefly addresses this issue as an introduction to more specific papers on erosion control on mine sites at this conference.

Additional Keywords: materials characterisation, selective handling, sustainable landforms

Introduction

Australia is the world’s leading producer of bauxite, alumina, diamonds, ilmenite, rutile and tantalium, the second largest producer of zinc ore, the third largest producer of aluminium, iron ore, nickel and gold, and the fifth largest coal producer. It is not surprising then that mining and mineral processing makes a major contribution to the Australian economy with exports valued at A$43,900 million in 2002/2003, representing 38 per cent of the country’s total merchandise exports.

Whilst the area of the Australian landscape disturbed by mining is relatively small (<0.05%) compared to that devoted to cropping and grazing (≈ 60%), the potential for severe local environmental impacts on land resources can be substantial with removal of vegetation, complete or partial loss of soils and changes in topography and hydrology, which can lead to erosion and sedimentation, turbidity in water supplies and salinisation. The potential extent of the impacts may range from minimal to quite severe, depending upon the physical and chemical properties of the overburden and processing wastes (such as tailings), the climate, and location of the operation and its relationship with surrounding land uses.

Life-of-mine planning, which involves consideration of a progressive rehabilitation plan, is critical to the success of a mine site in minimising environmental impact. An important consideration in life-of-mine planning is the post-mining land use, which will be determined by the ecological potential of the post-mined landscape and the views of the surrounding community and of government. Climate is a major determinant of the ecological potential. Australia’s mines (>400) are widely scattered across the landscape and are found in 66 of the nation’s biogeographic zones (Lloyd *et al.* 2001); many, however, are found in arid or semi-arid areas. For a given climate, the post-mining ecological potential (and hence post-mining land use options) will be markedly influenced by the degree to which attention has been given to selective handling of materials to retain suitable plant growth substrates and to ensuring construction of a landscape that is stable to erosive forces.

Key components of a rehabilitation plan involve (1) comprehensive characterisation of soils, overburden and wastes in terms of their potential for plant growth and for water contamination, (2) selective handling of soil and overburden to create a satisfactory (non-hostile) root zone for plants and to protect water resources and (3) construction of a post-mining landscape, which is stable against the erosive forces of wind and water to ensure sustainability of the defined post-mining land use and the protection of surrounding water resources. This paper focuses on these issues for mines in diverse biogeographic zones. Whilst examples given are from Australia, the principles involved are relevant to mine sites in other parts of the world.

Characterisation of Materials

A prerequisite for an effective rehabilitation program is the characterisation of properties of soil and other materials (overburden, mineral processing waste, etc.) in terms of their limitations to plant growth and potential impacts on water quality. This characterisation should start as early as the exploration phase and continue through the prefeasibility and feasibility phases as a basis for mine planning. The requirement to continue characterisation continues during the operation of the mine, particularly where the ore grade and mine plan is changed in response to changing prices for mineral commodities.

Characterisation of materials normally involves mineralogical, physical and chemical analyses; microbiological analyses may also be conducted at the early stage of planning, but more commonly find a role in assessment of the performance of the reconstructed ecosystems on the rehabilitated land.

Mineralogical analysis is a useful aid in characterising mine wastes as it can identify the nature of the potentially acid-producing sulfides, which can seriously affect plant growth directly through pH values as low as 2 to 3, or indirectly through creation of excessive soluble metal concentrations. A comprehensive discussion of techniques for mineralogical analysis is given in the text by Dixon and Schulze (2002).

Tests which can be used to assess physical limitations to plant growth in mine materials are described by Williams and Schuman (1987), Hossner (1988), Sobek *et al.* (2000) and Dane and Topp (2002).

The range of tests which can be used to assess the chemical limitations in soils and mine wastes are covered in publications by Williams and Schuman (1987), Hossner (1988) and Sparks *et al.* (1996). Details of tests to predict the magnitude and rate of acid generation from sulfides, and of the measures which can be used to control this problem, are given by Williams and Schuman (1987), Hutchinson and Ellison (1992), Evangelou (1995) and Skousen *et al.* (2000). Comprehensive coverage of microbiological tests is given by Weaver (1994).

The value of laboratory analyses in the characterisation of mine-site materials is highly dependent upon the use of a rigorous sampling protocol. Dollhopf (2000), De Gruijter (2002) and Yates and Warrick (2002) provide useful guidelines in this regard.

Whilst laboratory analyses can provide a useful guide as to the potential of soils and mine wastes to support plant growth, plant growth trials in the glasshouse (Asher *et al.* 2002), and finally on the mine site, will provide a clearer assessment of rehabilitation options (Bell 2002).

Selective Handling of Materials for Root Zone Construction

Choice of Materials

The reconstructed root zone can consist of soil, overburden spoil, tailings or various combinations of these materials. The particular combination will depend on the nature of the requirements of the vegetation to be established; for example, where a return to cropping land is required, the entire soil profile may need to be conserved and replaced in order to achieve original productivity (Dunker and Barnhisel 2000).

Irrespective of the nature of the vegetation which it is desired to have established on a rehabilitated landscape, a major consideration is the depth of favourable root zone necessary to provide sufficient anchorage (particularly for trees in wind-prone areas) and sufficient available water to enable the plant community to survive through seasonal water stress. To achieve these requirements, a depth of 1 to 2 m of root zone material is generally required, but obviously this will be influenced by climate and the nature of the vegetation.

Selective Handling of Soils

Issues which need to be addressed in the rehabilitation program are (1) the necessity for soil retention, (2) the selection of soil horizons to be conserved, (3) the process of soil removal and placement, (4) the effect of stockpiling on soil properties, and (5) the optimum depth of replaced soil. Each of these issues will now be considered briefly in turn.

Necessity for soil retention – A decision as to whether soil should be conserved in a mining operation can only be made after a thorough evaluation of the nature and distribution of the soil and overburden types prior to mining. In general, soil should be conserved and used in the rehabilitation program when overburden material or tailings cannot support the desired post-mining land use, even if ameliorative treatments amounting to the cost involved in conserving and replacing the soil were applied (Hannan and Bell 1993).

Most surface soils have far fewer limitations to plant growth than overburden material, and the additional cost of soil handling is generally outweighed by greater success in the establishment of the vegetative cover. Occasionally, the mine-site soils may be no better than overburden spoil for the establishment of vegetation, however, and thus a decision on the use of soil must be based on a comprehensive characterisation of both soil and the underlying material. Some overburden materials weather rapidly, particularly in subtropical and tropical environments, and may provide a satisfactory medium for establishment and maintenance of vegetation provided that the input of nitrogen to the system is adequately catered for through introduction of nitrogen-fixing plants.

Experience has shown that, where cropping is to be reinstated after mining, soil retention and replacement is essential. In Australia, few mines occur in areas of prime agricultural land, and most companies are establishing native ecosystems following mining. In such cases, replacement of fresh surface soil is the most economical and reliable way of ensuring the re-establishment of the wide diversity of species which exists in native ecosystems (Bell 2001). Where the establishment of native ecosystems is desired, the grass seed load in surface soil, however, may be sufficiently high to out-compete direct-seeded native shrub and tree species, and, in some of these situations, initial establishment of the latter may be more easily achieved on overburden spoil alone. The specific advantages and disadvantages of soil retention and use in rehabilitation have been discussed by Hannan and Bell (1993).

Selection of soil horizons – Soils vary both laterally and vertically in their properties. For a given soil type, the subsoil material may differ markedly in its plant growth characteristics from the organically enriched surface horizon. The depth of suitable soil which may be stripped for use in the rehabilitation program should be based on detailed chemical and physical analysis and recorded on a soil stripping map. A number of options may be available for stripping, depending on the quality of the soil available and the proposed post-mining land use.

The use of the entire soil profile is usually only advisable if all horizons are satisfactory for plant growth (or able to be made satisfactory through chemical amelioration). The horizons may be removed, and subsequently replaced in order, or they may be mixed. Stripping of the surface horizon separately from the subsoil material provides the opportunity to recreate, as nearly as possible, the original soil profile with the nutrient- and microbial-rich surface horizon at the surface where it will receive maximum exploitation by the rooting systems of plants.

Where all the soil horizons are suitable for plant growth, mixing of the profiles during removal and deposition may provide a satisfactory medium for plant growth. In this case, the stripping and replacement operations are less complicated, but there is a dilution of the beneficial effects of soil organic matter, micro-organisms and propagules for native plants which are concentrated in the surface horizon.

The subsurface horizons of some soils possess undesirable characteristics such as high salinity and sodicity, or extreme acidity and associated aluminium toxicity and/or calcium deficiencies for many plants. The use of the sodic material, on its own, should be avoided in rehabilitation; acidic subsoils, while having chemical limitations, can be ameliorated. Many mines in Australia occur in areas where subsoils are saline and sodic, and commonly only the surface horizon is conserved in rehabilitation programs.

In cases where the re-establishment of native species is desired, as thin a layer as possible of the soil surface should be removed prior to stripping of further soil. Most native seeds are concentrated in the top 50 mm of soil (soil seed bank). Additionally, the maximum depth of emergence of these species ranges from 30 to 100 mm. Stripping and respreading of a surface layer greater than 100 mm can thus result in a considerable loss of potential seedlings. Ideally, the soil should be double stripped and the layers placed in order. An excellent example of the value of soil handling operations designed to retain the viability of native seeds in the soil and enhance biodiversity is that used in Alcoa World Alumina’s bauxite mining operations in Western Australia (Koch *et al.* 1996).

Soil removal and placement – Two important aspects of soil removal and placement to be considered are the nature of the equipment to be used and the moisture content of the soil. Both of these factors will influence the degree of soil compaction and structural breakdown that inevitably occurs during these procedures. Severe compaction can be difficult to ameliorate and can lead to a reduction in root growth. Extensive evidence from the USA indicates that, when replacing a considerable depth of soil, compaction is one of the major factors limiting the achievement of pre-mining yields on land being returned to cropping (Dunker and Barnhisel 2000).

Scrapers are perhaps the most versatile machines for selective removal of soil horizons, but they can cause significant compaction of underlying material during soil placement and have a limited haul distance of 500 m to 1000 m. Bulldozer spreading of soil from soil piles strategically placed by dumping from trucks or scrapers is one measure that can be used to reduce compaction. The use of the combination of front end loader, truck and bulldozer for the removal, transport and spreading of soil is the best combination to reduce compaction.

For all soils, there is a moisture content above which it cannot be handled by equipment without being compacted to a point where plant growth will seriously be affected. The bulk density of a soil steadily increases to a maximum as its water content is increased when a constant load is applied. For many soils when moist, a fully loaded scraper can increase bulk densities above the critical values for root growth. Bulk density is an indirect measure of aeration and mechanical impedance which directly affect plant growth, and values above which plant growth is affected, for soils at field capacity, range from about 1.3 g cm^{-3} for clay soils to 1.8 g cm^{-3} for sandy soils.

Optimum depth of soil replaced – The depth of soil replaced on spoil, tailings or other waste will be governed by such factors as the desired vegetation, the quantity and quality of the surface and subsoil available and the nature of the underlying material. A general principle is that the constructed root zone should have sufficient plant-available water (PAW) to support the desired vegetation throughout the driest season. The optimum PAW capacity can be determined with the use of water balance models and confirmed with field trials. The required PAW can be achieved either by increasing the depth of replaced plant growth medium or by using materials with a high available water capacity where these are available. Models which will simulate water balance, plant growth and erosion and their interactions can aid in root zone design (e.g. Thomas et al. 1995).

If chemical and physical tests show that the underlying material does not have major limitations to root growth such as salinity, sodicity or acidity, a layer of soil as thin as 50 mm will aid vegetation establishment by providing a suitable environment for seed germination, by allowing infiltration of water, and by supplying nutrients and micro-organisms; additionally, in cases where a return to native ecosystems is desired, this soil may be an important source of the seed of the species required. Once the vegetation is established, the roots will exploit the underlying material for both water and nutrients.

Where the underlying material has adverse characteristics for root growth, the depth of soil, which must be applied to achieve long-term productivity, will be a function of the nature and severity of the material’s properties. Although 100 mm to 200 mm of soil applied to a saline and/or sodic spoil will usually result in satisfactory establishment of native species or improved pasture, the longevity of the vegetation may be reduced by water stress in dry periods resulting from poor root penetration into the spoil. Additionally, if the hydraulic conductivity of the underlying material is low, salt movement upwards into the replaced soil may be sufficiently pronounced as to markedly reduce the beneficial effects of soil replacement. Upward migration of salt will be less when the underlying material has a moderate hydraulic conductivity.

The application of thin layers of soil to try to ameliorate acid-toxic spoil resulting from sulfide oxidation may be successful initially, but the vigour of the vegetation cover will decrease with time as acid continues to be generated from sulfidic oxidation and moves upward into the overlying soil. Heavy applications of lime to the spoil prior to soil addition will assist in delaying the onset of toxic subsurface conditions, but a major objective of any rehabilitation program, where sulfidic waste rock occurs, should be to selectively place this material well away from the root zone.

In situations where waste rock or tailings contains acid-generating sulfides, there may be a need to develop a plant-supporting root zone which is underlain by a compacted clay layer to reduce water and oxygen ingress to the sulfidic material (Hutchinson and Ellison 1992). Wilson *et al.* (2003) provide an update on the integrity of cover systems for sulfidic wastes, while Bell and Menzies (2000) and Taylor *et al.* (2003) draw attention to the need to consider the impact of biotic factors in cover design.

Stockpiling of soil – Ideally, soil should not be stockpiled but should be lifted, transported and spread on a recontoured area in the one operation. Weather conditions and the difficulties in timing rehabilitation to suit mining activity, however, dictate that, in some situations, soil must be stockpiled for later use.

Stockpiling for periods longer than about 6-12 months may cause structural degradation and death of seeds and micro-organisms (Ward *et al.* 1996a). The deterioration in quality can be reduced by constructing dumps of minimum height (e.g. <2-3 m) and maximum surface area, consistent with the space available. Surface and subsoil material should be stockpiled separately. Seeding of the stockpile with a grass/legume mixture or native species will assist in erosion control and reduce the loss of beneficial soil micro-organisms.

Selective Handling of Overburden

Selective extraction and placement of overburden layers is practised for two reasons, viz. (1) to bury material which is adverse to plant growth or which may contaminate surface or groundwater supplies, or (2) to salvage materials which will assist in the rehabilitation program. Particular overburden strata may be undesirable because of their salinity, sodicity or potential to produce acidity through sulfide oxidation.

No more than about a 2 m thickness of non-toxic overburden or waste material should need to be placed over the adverse material. This is the maximum depth of root zone needed for most types of vegetation. Where the major part of overburden is saline or otherwise unsuitable for plant growth, selective handling should be directed towards salvaging the best available strata for placement at or near the final reshaped surface. Where only a small proportion of the material is adverse, selective handling should be aimed at ensuring that this material does not finish up near the surface.

There are two important aspects to the handling of potentially acidic or saline overburden layers and contaminated wastes. They should not be placed near the final surface for the reasons mentioned above and should not be placed at a depth where they could contaminate ground water supplies.

Where the pre-mining overburden contains sulfidic material which may produce acid drainage, the surface weathered (oxidised) zone is a valuable resource, and care needs to be taken to ensure that all of this material does not end up being buried by sulfidic rock at the end of the mining operation. The range of engineering options to minimise the occurrence, or control the effects, of acid drainage resulting from oxidation of sulfidic material in mine waste dumps and tailings has been considered by Hutchinson and Ellison (1992).

Selective Handling of Mineral Processing Wastes

The capacity of fine-grained mineral processing wastes (tailings) to support plant growth depends on the nature of the original mineral or coal resource and the extraction process. If the resource contains high concentrations of sulfide, then there is the potential for the tailings to become extremely acid and toxic to plant growth.

In some situations, it is feasible to produce a final surface layer which is more favourable for plant growth by modification of the particle size of material deposited in the last few metres (e.g. Ward *et al.* 1996b). Additionally, the chemical nature of the surface layer can be modified by leaving a portion of non-toxic ore to be processed at the end of mine life. This approach can be particularly effective in some gold mining operations where the bulk of the ore may be high in sulfides, but the surface oxidised ore is low in these minerals.

Construction of Sustainable Landforms

The effort expended in selective handling of soils, overburden and processing waste to ensure a medium for plant growth and protection of water resources will be wasted if the post-mining landscape is not stable to the erosive forces of wind and water. The objectives of landform design are to (1) meet post-mining land use requirements, (2) ensure a stable drainage network across the site, and (3) minimise surface erosion to prevent impacts on surrounding water resources.

The general principles of landform design for rehabilitation, which need to be applied to waste rock dumps, tailings storage facilities and open cut pits, have been addressed by Toy and Hadley (1987) and Toy and Black (2000), while Nicolau (2003) gives a recent review of the trends worldwide in post-mining landform design. In Australia, Lindbeck and Hannan (1998) have authored a booklet on basic principles of landform design plus best practice case studies from Australian mine sites. This booklet is one of 25 best practice environmental management in mining booklets produced as a joint effort of the Australian Commonwealth Government and the mining industry, and which can be accessed on the Internet at: www.deh.gov.au/industry/industry-performance/minerals/booklets.

Post-Mining Land Use Requirements

Pre-mine surveys of land use and land sustainability will provide a guide as to what post-mining land use is sensible. The use after mining, however, may be different from pre-mining because of the alterations in topography and hydrology. It is important, however, that the recontoured landscape is compatible with the defined land use, i.e. for cropping, land slopes should generally be less than about 5-8 per cent, whereas, for sustainable pastures or forestry/native ecosystems, much steeper slopes can be accommodated.

Stable Drainage Network

Following reshaping of a mined site, the surface drainage density (total length of all water courses per unit catchment area) should be compatible with the post-mining land use and not markedly different from that in the pre-mine landscape to avoid concentrations of runoff that could cause watercourse erosion. Additionally, reshaping needs to ensure that all runoff from the site reaches surrounding watercourses in volumes and at velocities which will not cause erosion or sedimentation (Lindbeck and Hannan 1998).

Erosion Control

For each of the rehabilitated units within a mine site (waste rock dumps, tailings storage facilities, etc.), it is important to control surface erosion to enable a sustainable post-mining land use and to protect surrounding surface water resources from sedimentation. In designing the post-mine landscape, it is desirable to have an appreciation of (1) the soil loss that can be tolerated from various units on the site and (2) the capacity of the surrounding streams (receiving environment) to receive sediment without significant environmental impact.

Considerable research in agriculture has provided the soil loss tolerance values for various soil types, but such data for replaced soils, spoils and other mining waste is more limited. Geological erosion in a natural landscape varies depending on the climate and parent material, but rates may be of the order of 0.01-0.1 mm yr^{-1} ($\approx$ 0.15-1.5 t ha^{-1} yr^{-1}). Tolerance values set for agricultural land may range from 0.5-1.0 mm yr^{-1} ($\approx$ 7.5-15 t ha^{-1} yr^{-1}). For unrehabilitated mine sites, values may exceed 10-20 mm yr^{-1} ($\approx$ 150-300 t ha^{-1} yr^{-1}).

To assist in the design of the reconstructed landforms, a range of erosion models, which predict sediment loss at a given location for different materials under various combinations of degree and length of slope, vegetative cover and surface micro-topography, are available (Evans 2000; Nicolau 2003). These range from the empirical Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.* 1994), which is useful in giving an indication of soil loss at the initial stages of design to the complex topographic evolution model, SIBERIA (Willgoose and Riley 1998). The latter model, which has been used in the design of landforms at the Ranger uranium mine in northern Australia, is a sophisticated 3-dimensional topographic evolution model which simulates runoff, erosion and deposition, and predicts the long-term development of channels and hill slopes in a catchment (up to 1000 years).

In Australia, the optimum design of waste rock dumps to achieve long-term stability is still being trialled in some mining regions with highly dispersible spoils and/or with high intensity rainfall. Whilst the State governments provide guidelines for construction, the opportunity exists for mine sites to trial innovative approaches. Many mines use a traditional approach to controlling erosion through reducing both the degree and length of outer slopes, with the latter being achieved with berms which direct runoff to rock-lined drop down structures (Lindbeck and Hannan 1998). The use of berms with spoils prone to tunnel erosion, however, can lead to major surface instability.

Some mines are dispensing with berms and using sigmoidal-shaped slopes to mimic natural landforms. Whereas it is generally sensible to shed water off the top of dumps that contain substantial acid-generating material, increasing infiltration into the top of the dump has the advantage of (1) reducing runoff onto outer slopes and (2) increasing vegetative growth which, in turn, assists in erosion control. Two good examples of this approach are the ponded landform system employed at the Oaky Creek coal mine in the Bowen Basin, Queensland (McNamara *et al.* 1999) and the “store and release” cover system used at the Kidston gold mine, north Queensland (Williams *et al.* 2003).

Some innovations in landform design involving tailings storage facilities in Australia include (1) the use of a concave outer slope for the retaining wall with or without rock armouring, (2) thickened tailings to enable creation of required surface topography (e.g. in bauxite refining), and (3) co-disposal of coarse waste and tailings (e.g. in coal mining).

Conclusion

While the principles of soil conservation, which have been developed over a long period for agricultural land, can be applied to mining sites, the necessity to construct new soils over often hostile materials with often grossly modified terrain, has resulted in the development of new methodologies of soil management and erosion control to meet the objectives of mine rehabilitation.

References

Asher, C., Grundon, N., and Menzies, N. (2002). How to Unravel and Solve Soil Fertility Problems. ACIAR Monograph No. 83. Australian Centre for International Agricultural Research, Canberra.

Bell, L.C. (2001). Establishment of native ecosystems after mining – Australian experience across diverse biogeographic zones. *Ecological Engineering* 17, 179-186.

Bell, L.C. (2002). Remediation of chemical limitations. In “Restoration and Management of Derelict Land – Modern Approaches”. M.H. Wong and A.D. Bradshaw (Eds.). pp. 112-127. World Scientific Publishing Co., Singapore.

Bell, L.C. and Menzies, N.W. (2000). Biotic factors in the design of covers for the long-term containment of sulfidic wastes. In “Proceedings of Fourth Australian Workshop on Acid Mine Drainage”. N.J. Grundon and L.C. Bell (Eds.). pp. 171-177. Australian Centre for Mining Environmental Research, Brisbane.

Dane, J.H. and Topp, G.C. (Eds.) (2002). Methods of Soil Analysis. Part 4. Physical Methods. Soil Science Society of America, Inc., Madison, Wisconsin.

De Gruijter, J.J. (2002). Sampling. In “Methods of Soil Analysis”. Part 4. Physical Methods. J.H. Dane and G.C. Topp (Eds.). pp. 45-80. Soil Science Society of America, Inc., Madison, Wisconsin.

Dixon, J.B. and Schulze, D.G. (Eds.) (2002). Soil Mineralogy with Environmental Applications. Soil Science Society of America, Inc., Madison, Wisconsin.

Dollhopf, D.J. (2000). Sampling strategies for drastically disturbed lands. In “Reclamation of Drastically Disturbed Lands”. R.I. Barnhisel, R.G. Darmody, and W.L. Daniels (Eds.). pp. 21-40. American Society of Agronomy, Madison, Wisconsin.

Dunker, R.E. and Barnhisel, R.I. (2000). Cropland reclamation. In “Reclamation of Drastically Disturbed Lands”. R.I. Barnhisel, R.G. Darmody, and W.L. Daniels (Eds.). pp. 323-369. American Society of Agronomy, Madison, Wisconsin.

Evangelou, V.P. (1995). Pyrite Oxidation and its Control. CRC Press Inc., Boca Raton, Florida.

Evans, K.G. (2000). Methods for assessing mine site rehabilitation design for erosion impact. *Australian Journal of Soil Research* 38, 231-247.

Hannan, J.C. and Bell, L.C. (1993). Surface rehabilitation. In “Australasian Coal Mining Practices”. A.J. Hargraves and C.H. Martin (Eds.). pp. 260-280. Australasian Institute of Mining and Metallurgy, Parkville.

Hossner, L.R. (Ed.) (1988). Reclamation of Surface-Mined Lands. Vol. 1 and 2. CRC Press Inc., Boca Raton, Florida.

Hutchinson, I.P.G. and Ellison, R.D. (Eds.) (1992). Mine Waste Management. Lewis Publishers, Boca Raton, Florida.

Koch, J.M., Ward, S.C., Grant, C.D., and Ainsworth, G.L. (1996). The effect of bauxite mining and rehabilitation operations on the topsoil seed reserve in the Jarrah forest of Western Australia. *Restoration Ecology* 4, 368-376.

Lindbeck, K. and Hannan, J. (1998). Landform Design for Rehabilitation. Best Practice Environmental Management in Mining Booklet. Environment Australia, Canberra.

Lloyd, M.V., Barnett, G., Doherty, M.D., Jeffree, R.A., John, J., Majer, J.D., Osborne, J.M., and Nichols, O.G. (2001). Managing the Impacts of the Australian Minerals Industry on Biodiversity. Report to AMEEF for Australian Mining, Minerals and Sustainable Development (MMSD) Project. Australian Centre for Mining Environmental Research, Brisbane.

McNamara, R., Lefebvre, N., Joyce, J. (1999). Assessment of mine-site rehabilitation performance at the Oaky Creek coal mine, Bowen Basin, central Queensland. In “Proceedings of the Workshop on Indicators of Ecosystem Rehabilitation Success”. C.J. Asher and L.C. Bell (Eds.). Melbourne. 23-24 October 1998. pp. 125-137. Australian Centre for Mining Environmental Research, Brisbane.

Nicolau, J.M. (2003). Trends in relief design and construction in opencast mining reclamation. *Land Degradation and Development* 14, 215-226.

Renard, K.G., Laflen, J.M., Foster, G.R., and McCool, D.K. (1994). The revised universal soil loss equation. In “Soil Erosion Research Methods”. 2nd Edn. R. Lalo (Ed.). p105-124. Soil and Water Conservation Society, Ankeny, Iowa.

Skousen, J.G., Sexstone, A., and Ziemkiewicz, P.F. (2000). Acid mine drainage control and treatment. In “Reclamation of Drastically Disturbed Lands”. R.I. Barnhisel, R.G. Darmody, and W.L. Daniels (Eds.). pp. 131-168. American Society of Agronomy, Madison, Wisconsin.

Sobek, A.A., Skousen, J.G., and Fisher, Jr., S.E. (2000). Chemical and physical properties of overburdens and minesoils. In “Reclamation of Drastically Disturbed Lands”. R.I. Barnhisel, R.G. Darmody, and W.L. Daniels (Eds.). Agronomy Monograph 41. pp. 77-104. American Society of Agronomy, Madison, Wisconsin.

Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T., and Sumner, M.E. (Eds.) (1996). Methods of Soil Analysis. Part 3. Chemical Methods. Soil Science Society of America, Inc., Madison, Wisconsin.

Taylor, G., Spain, A., Timms, G., Kuznetsov, V. and Bennett, J. (2003). The medium-term performance of waste rock covers – Rum Jungle as a case study. In “Proceedings of Sixth International Conference on Acid Rock Drainage”. T. Farrell and G. Taylor (Eds.) pp. 383-398. Australasian Institute of Mining and Metallurgy, Melbourne.

Thomas, E.C., Gardner, E.A., Littleboy, M.M., and Shields, P. (1995). The cropping systems model PERFECT as a quantitative tool in land evaluation: an example for wheat cropping in the Maranoa area of Queensland. *Australian Journal of Soil Research* 33, 535-554.

Toy, T.J. and Black, J.P. (2000). Topographic reconstruction: the theory and practice. In "Reclamation of Drastically Disturbed Lands". R.I. Barnhisel, R.G. Darmody, and W.L. Daniels (Eds.). Monograph 41. pp. 41-75. American Society of Agronomy, Madison, Wisconsin.

Toy, T.J. and Hadley, R.F. (1987). Geomorphology and Reclamation of Disturbed Lands. Academic Press, New York.

Ward, S.C., Koch, J.M., and Ainsworth, G.L. (1996a). The effect of timing of rehabilitation procedures on the establishment of a Jarrah forest after bauxite mining. *Restoration Ecology* 4, 19-24.

Ward, S.C., Slessar, G.C., Glenister, D.J., and Coffey, P.S. (1996b). Environmental resource management practices of Alcoa in southwest Western Australia. In "Environmental Management in the Australian Minerals and Energy Industries". D.R. Mulligan (Ed.). pp. 383-402. University of New South Wales Press, Sydney.

Weaver, R.W. (Ed.) (1994). Methods of Soil Analysis. Part 2. Microbiological and Biochemical Properties. Soil Science Society of America, Inc., Madison, Wisconsin.

Willgoose, G. and Riley, S. (1998). The long-term stability of engineered landforms of the Ranger Uranium Mine, Northern Territory, Australia: application of a catchment evolution model. *Earth Surface Processes and Landforms* 23, 237-259.

Williams, D.J., Currey, N.A., Ritchie, P. and Wilson, G.W. (2003). Kidston waste rock dump design and 'store and release' cover performance seven years on. In "Proceedings of Sixth International Conference on Acid Rock Drainage". T. Farrell and G. Taylor (Eds.) pp. 419-426. Australasian Institute of Mining and Metallurgy, Melbourne.

Williams, R.D. and Schuman, E.D. (Eds.) (1987). Reclaiming Mine Soils and Overburden in the Western United States. Analytic Parameters and Procedures. Soil Conservation Society of America, Ankeny, Iowa.

Wilson, G.W., Williams, D.J. and Rykaart, E.M. (2003). The integrity of cover systems – an update. In "Proceedings of Sixth International Conference on Acid Rock Drainage". T. Farrell and G. Taylor (Eds.). pp. 445-452. Australasian Institute of Mining and Metallurgy, Melbourne.

Yates, S.R. and Warrick, A.W. (2002). Geostatistics. In "Methods of Soil Analysis". Part 4. Physical Methods. J.H. Dane and G.C. Topp (Eds.). pp. 81-118. Soil Science Society of America, Inc., Madison, Wisconsin.