# RECLAMATION IN AUSTRALIA'S HEAVY MINERAL SANDS INDUSTRY[1]

by

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Abstract. Australia is the world's major producer of heavy mineral sands products. Responsibility for control of mining in Australia is vested in the States although the Federal Government has over-riding legislation for the environmental assessment of major projects. Each of the three states involved, New South Wales, Queensland and Western Australia, have developed different regulatory mechanisms. However, in comparison with regulatory mechanisms in America, Australian procedures are less legalistic and more flexible. Since mining commenced in 1934, the industry has mined and reclaimed landforms ranging from coastal foredunes to old inland dunes up to more than 100m in height. With the exception of some agricultural land in south-west Western Australia, most reclamation programmes have involved native vegetation and emphasis has been given to restoring functional ecosystems. Natural ecosystems rehabilitated include littoral grasslands and shrublands, heathlands, hardwood forests, and wetlands. Climatic conditions encountered include sub-tropical, moist temperate, wet and dry mediterranean. Principles for reclaiming dryland ecosystems include landform reconstruction, topsoil management, surface stabilisation, plant establishment and nutrition and monitoring of seral development. Reclamation of wetlands has additional requirements including control of ground levels, control of water levels, specific topsoil management requirements and timing. A number of reclaimed mineral sands minesites are now incorporated in National Parks.

Key Words: regulatory mechanisms, natural ecosystems, wetlands, national parks, reclamation principles, beach stabilization.

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## Introduction

Australia is the world's major producer of the heavy mineral sands rutile, ilmenite, zircon and monazite. Mining for these minerals in Australia commenced in 1934 on the beaches at Byron Bay, on the north coast of New South Wales (Morley,

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1981). For more than four decades, the industry was concentrated on the east coast from just north of Sydney in New South Wales to near Gladstone in Queensland (Fig. 1). This development occurred because the world's richest deposits of rutile and zircon occurred in the sand masses along that part of the coastline (Shepherd, 1986). The technology for the efficient mining and separation of the minerals was developed in Australia during this period (Morley, 1981).

Meanwhile, mining commenced in Western Australia in 1956 (Baxter, 1977). For the first two decades, operations in that state were based on the mineral ilmenite at Capel, about 200km south of Perth. In the mid-1970s, a number of operations commenced on the northern sandplain near Eneabba, about 300km north of Perth, on ore bodies containing the full suite of minerals (Shepherd, 1986).

Up until the late 1970s, Australia produced more than 95% of the world's rutile and in excess of 80% of the world's zircon. A long series of land use conflicts caused a severe downturn of activity in the eastern states (Brooks, 1986), creating a window in the marketplace to be filled by overseas operations. Whilst some operations continue in Queensland and New South Wales, the industry has consolidated in Western Australia with major investment in new mines and downstream processing. Today, Australia's share of world markets is about 54% for rutile, 62% for synthetic rutile, 50% for ilmenite, 60% for zircon and 26% for monazite. As the world's major producer, AMC Mineral Sands Ltd, a division of Renison Goldfields Consolidated Ltd, supplies between about 20% and 40% of the world's market for these products.

## Regulatory Mechanisms

Mining development in Australia is

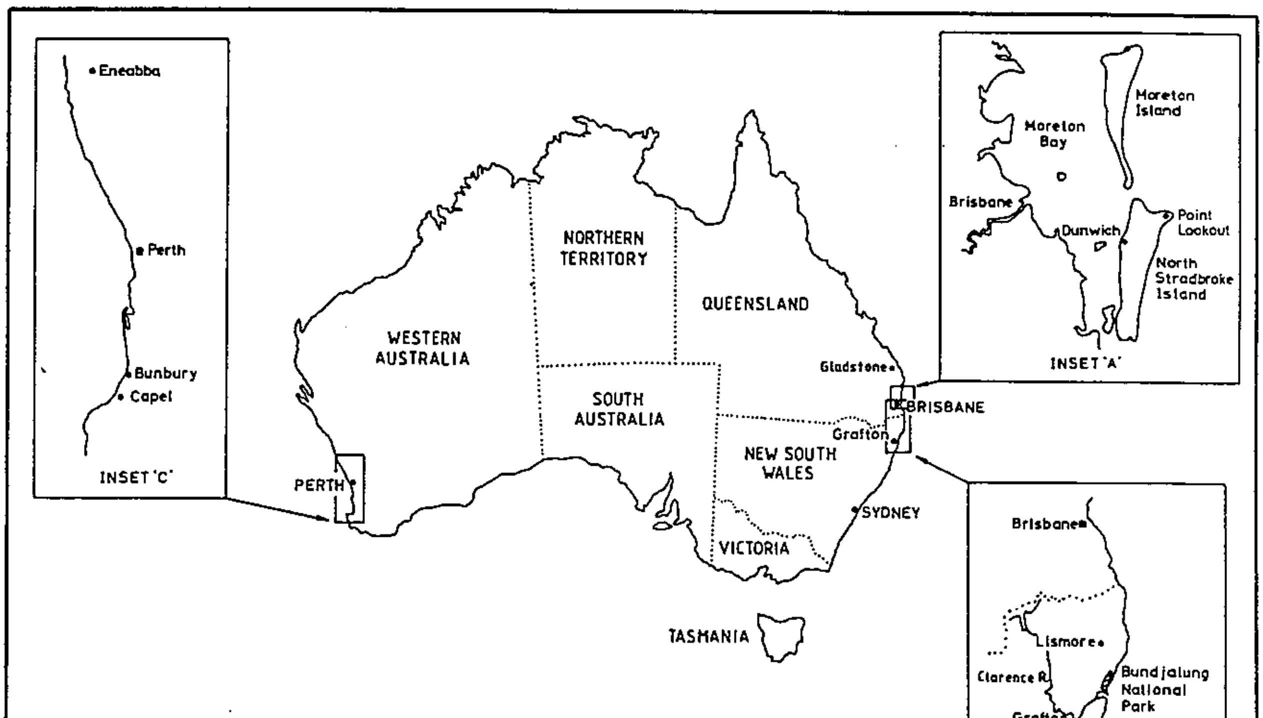


Figure 1--Location of mineral sands reclamation case studies along the eastern and western coasts of Australia.

based on the principle of Crown ownership of minerals, with a few minor exceptions. Under the Australian constitution, which is a federation of seven states, control of resources and land use is vested in the States. However, the Commonwealth becomes involved in the environmental assessment of major projects through such indirect powers as export and foreign investment controls. Whilst administrative arrangements between the Commonwealth and States have been agreed upon to deal with each Government's interest in assessment (Australian Environment Council, 1986), the potential for conflict at a political level remains. Some mineral sands projects have been thwarted by the Commonwealth refusing to grant export licences, against the State's wishes.

Procedures for the control of environmental aspects of heavy mineral sands mining, especially reclamation, vary between the states. In Queensland, controls are vested in the Department of Mines. Requirements for assessment and ongoing management of operations are set out in special conditions attached to the mining lease. The lease conditions in Queensland are the most detailed and strictest of any state. Whilst some critics argue that this system leads to less control and low standards as no specialist environmental agency is involved, its purpose is that the environmental aspects are fully integrated into the operation. The Department employs specialist officers to ensure this occurs. The operator reports to only one agency which has a full understanding of the nature and effects of operations. In practice, it is a flexible, workable system, and some of the industry's best reclamation in the world has been achieved within it.

The situation in New South Wales is complex involving a number of agencies and a rigid regulation based system. Environmental assessment of new operations is conducted by the Department of Environment and Planning, whilst responsibility for pollution control rests with the State Pollution Control Commission. The centralisation of powers within these specialist agencies often means that the officers dealing with mining proposals are unfamiliar with the practical aspects of the operations they are considering. This has led to difficulties in negotiations and to vague and impractical conditions being imposed in some circumstances. However, the Department of Mineral Resources retains responsibility for controls over reclamation, and this is generally achieved through special conditions attached to the mining lease. In this case, specialist officers within the Department deal directly with the operating companies.

Western Australia has three different legislative provisions under which mining is carried out: pre-1899 "minerals-to-owner" rights, Mining Act tenements and State Agreement Acts (Clarke and Bradley, 1987). All major mining proposals are referred to the Environmental Protection Authority (EPA) for assessment. The EPA then submits recommendations to the Government through the decision making authority, in this case either the Department of Mines or the Department of Resources Development.

Minerals-to-owner land occurs mostly within the south-west of the State and covers a number of mineral sand deposits. Environmental conditions applying to such operations can be specified in the Agreement with the landowner, through Local Government development approvals or by way of recommendations from the EPA.

Operations under Mining Act tenements are controlled by the Department of Mines through special conditions attached to the mining lease. Reclamation conditions may be changed through the tenure of the lease. Whilst this may mean that onerous conditions may be applied during the life of the mine, the system has the flexibility to deal with changes in operating conditions or reclamation technology. Again, these procedures are administered by specialist officers within the Department.

Major mineral development projects that have complex infrastructure requirements are usually developed under special State Agreement Acts. These acts facilitate the development and operation of the project, as well as providing for integrated control procedures for the Government. Mineral sands operations north of Perth operate under Agreement Acts, which are administered by the Department of Resources Development.

Under these State Agreements, environmental management, including reclamation, is controlled by the approved proposals mechanism. The Company is required to submit proposals for Ministerial approval on such matters as environmental protection, monitoring, reclamation, investigations and research. Annual and more detailed Triennial Reports are also required. Significant changes to the approved proposals brought about by changing operating conditions or technology can be made by variation procedures or through the Triennial Reports.

This system provides the necessary control mechanisms for Government and appropriate flexibility for the operating company. It is not based on detailed and complex regulations, but provides for high standards of reclamation to be achieved and maintained.

Through its operations in Florida, AMC is in a unique position to compare the regulatory mechanisms of America and Australia. The heavy mineral sands industry in America is small, though strategically important. Many of the regulatory procedures developed for mining in America, and specifically Florida, have been designed to apply to other forms of mining, and are not easily applicable to some of the unique features of mineral sands mining. By comparison with Australia, the Company has found the American system to be regulation driven, detailed and complex, rigid and inflexible. The regulations tend to restrict innovation in the development of reclamation technology, which is considered to be counter-productive. However, there are indications that the agencies are attempting to be more flexible in their approach to the mineral sands industry than previously. This trend should be encouraged as the environment will benefit in the long term.

In contrast to the American system, the Australian system is proponent driven, whereby the proponent company is required to identify the environmental effects of its operations and propose an environmental management system for approval by the Government. The system is flexible, has wide scope and encourages innovation. The proponent is judged by its corporate philosophy and commitment, thereby providing the motivation to achieve a high standard of reclamation.

## Reclamation Principles

As a consequence of its development, Australia's heavy mineral sands industry has mined in a range of landforms, vegetation and climates, and developed its reclamation technology accordingly. On the east coast, major landforms mined include frontal dunes, extensive heath plains of low relief containing strand lines of late Pleistocene age, and aeolian high dunes ranging in age from Holocene to Pleistocene. Vegetation types encountered include sand spinifex grasslands of the frontal dunes, closed scrubs, sclerophyll forests, heaths and wetlands of various types. The climate varies from temperate in the south to sub-tropical in the north, although annual average rainfall is in the range of 1,100-1,600 mm.

On the west coast, the landform consists of extensive sand plains with subdued topography, possibly of late Tertiary or early Pleistocene age. Much mining has occurred on agricultural land, particularly in the south-west, although some forests have also been encountered. In the Eneabba area, north of Perth, low heathlands cover much of the mining areas. The climate is mediterranean, with rainfall ranging from 530 mm in the north to 830 mm in the south.

Thus, with the exception of agricultural land in south-west Western Australia, most reclamation programmes have involved native vegetation, and emphasis has been given to restoring functional ecosystems.

Heavy mineral sand mining has some unique characteristics that have an important bearing on reclamation. First, there is minimal volume loss, thereby allowing the landform to be substantially reconstructed. Volume loss due to product removal, of the order of 1-5%, is compensated by swellage in the tailing sand. Second, there are no toxic wastes to interfere with plant growth. The minerals are concentrated by gravity separation in a water slurry, and tailings comprise the soil components silica sand and clay or humate slime. Third, most ore bodies are shallow, so the mining is mobile and a short term land use.

These factors have enabled high standards of reclamation to be achieved around Australia. Mined out areas now have a variety of land uses including agriculture, urban development, recreation and conservation. The industry has demonstrated its compatibility with multiple land use, even with conservation.

Although each minesite has its own characteristics, the variety of ecosystems reclaimed has enabled the development of basic principles that could be adapted to each site. These principles involve the following:

1. Landform reconstruction to re-establish topographic patterns, with particular attention being given to drainage patterns. On wetland sites, re-creation of water table/ground surface relationships are critical.

2. Careful management of topsoil because of its organic enrichment and seed load. The majority of native species regeneration comes from seed contained in topsoil.

3. Surface stabilization to enable establishment of native species, seedlings of many of which are small and establish slowly. Numerous techniques are available.

4. Direct seeding of native species as the most efficient means of enhancing regeneration from topsoil, both biologically and economically. Seed should be collected from the site to ensure it is genetically adapted to the site conditions.

5. Enhancement planting of nursery raised stock, with emphasis on species that are difficult to propagate with field techniques. This operation ensures the return of species that may be important ecologically.

6. Monitoring of the seral development of the vegetation to ensure its proper development. This can range from visual inspection through to botanical sampling for a computerised data bank. Information gathered is useful for ongoing management of the reclamation.

Successful reclamation of wetland sites imposes specific requirements. From AMC's experience, a number of important inter-related principles have been developed and these are now being utilised by the Company in Florida.

First, it is essential to re-establish ground levels accurately. In this type of country, variations in contour are subtle, and changes in ground level of as little as 15 cm can have a profound effect on drainage and vegetation patterns. Therefore, control of tailings placement by operations personnel is critical and needs to be carefully planned.

Second, drainage of the area before and after mining is essential. Prior to mining, surface water needs to be removed to enable the topsoil to be stripped in moist though not sloppy conditions. Otherwise, saturated topsoil would cause a loss of viability of propagules following disturbance. Drainage of the site following mining is also important so as to keep the water levels at or below the ground surface whilst the vegetation re-establishes. During summer months, wetland vegetation can suffer scalding from inundation in the establishment phase as shallow surface water heats up. Drains can be removed once the vegetation has gained sufficient height and maturity to cope with inundation. Experience has shown that wetland vegetation establishes and grows best during dry weather, when water levels fall below the ground surface and soil moisture is still adequate.

Third, topsoil handling procedures are critical because a high proportion of wetland vegetation can recover from vegetative propagules in the soil. Not only is moisture content important, but the topsoil needs to be handled carefully by the bulldozer operators. At one of the Company's sites, a double stripping method was developed in order to minimise disturbance to the soil and damage to the plant propagules. The top 20-25cm was removed in slices by the bulldozer so as to retain the soil and plants in large lumps, and stored to one side of the mine path. A further 10-15cm was then stripped and stored separately. Immediately after the mining plant had returned the tailings to the mine path, the topsoil layers were returned to their respective positions. The topsoil storage time was governed by the rate of forward progress of the mining plant, but was of the order of 1-3 months.

Fourth, timing of reclamation operations is critical, especially contouring of tailings and return of topsoil. In wetland sites, the mining operation itself provides the best opportunity to control the large volumes of water involved. Any delay to reclamation procedures will increase the probability of local flooding from heavy rainfall which will result in reduced regeneration success. Therefore, mining operations of wetland sites need to be carefully planned and conducted to take account of the particular site conditions and reclamation requirements.

Lastly, the application of a moderate dose of mixed fertiliser shortly after topsoil return will boost vegetation recovery. The Company's experience has shown that species richness and growth rate will increase, resulting in a balanced plant community. Also, the regenerating vegetation will be vulnerable to adverse conditions for a reduced period of time.

## Case Studies

To illustrate the development and application of these principles, a number of sites mined and reclaimed by AMC are discussed below.

### Frontal Dunes

Although a number of frontal dune sites have been mined and reclaimed by AMC and other companies along the coast of New South Wales and Queensland, the largest programme occurred on North Stradbroke Island in southern Queensland (Fig. 1). A total of 32 kms of frontal dunes was mined and reclaimed. The scale of the project provided the basis for considerable development in frontal dune reclamation technology (Brooks, 1976, 1980; Brooks and Bell, 1984), with attention being paid to reconstruction of natural ecosystems.

Before mining, the dune system was largely unvegetated and unstable. Wind erosion carried large volumes of sand landwards away from the beach system, progressively burying a freshwater swamp behind the dunes. During storms the beach and dunes were further eroded by wave attack.

The first prerequisite of reclamation was to construct a stable dune landscape. This involved creating a moderate frontal slope (10 to 15°), a well defined dune crest and a varied topography to allow the development of a range of microhabitats. The planned placement of tailing sand using the hydraulic stackers at the rear of the mining plant enabled the desired landscape to be constructed at minimal cost. It was also possible to move large volumes of sand towards high water mark, thereby returning the sand to the beach system.

The second prerequisite was to commence stabilization at high water mark to prevent windblown sand from the beach burying establishing vegetation. Where sand spinifex grass (spinifex sericeus) remained on remnant dunes, fertilisation of the grass dramatically improved dune stability. In the absence of remnant dunes, sand trap fences had to be constructed. Whilst a range of materials can be used for these fences, artificial mesh fences were used mainly for greater efficiency (Brooks and Bell, 1984). Sand trapped by these fences ultimately formed new dunes when colonised by adjacent vegetation (Brooks, 1980).

The vegetation sown on these frontal dunes was endemic to these situations to withstand the rigours of wind, sand and saltspray. Sand spinifex grass was the mainstay of the programme, although other species were also used to increase plant diversity, especially in certain microhabitats. Techniques were developed to harvest, process and sow large quantities of sand spinifex grass seed, as well as to establish a stable vegetative cover on a large scale. Following the establishment of the grass cover, a range of tree and shrub species were introduced from the Company's nursery.

Stabilization of the surface was critical to enable the vegetation to establish. Given a ready source of supply, brush matting proved to be the most effective material for this purpose, although alternatives included stubble mulch and chemical stabilizers (Barr and McKenzie, 1976).

During the landscape reconstruction, a number of depressions were formed in the dune system, many of which intersected the ground water table. Techniques were developed to stabilize and reclaim these sites as wetlands using the rhizomatous sedge Carex pumila (Brooks, 1988a). The natural recolonization that followed (Fig. 2) provided opportunities for the study of successional development of new wetland ecosystems. It appears that birds and other animals were the main dispersal mechanism for the colonising plants.

The use of the techniques described created a diverse habitat on the newly stabilized dune system. The natural sand accretion/erosion processes also re-established within the beach zone. International experts have described this project as the best of its type in the world (Bradshaw and Chadwick, 1980; D.N. Ranwell, pers comm).

## High Dunes

The high dunes of eastern Australia are described by Thompson (1983), and are characterised by massive soil profile development over time (Thompson, 1981). Whilst high dunes have been mined at Myall Lakes and Fraser Island, North Stradbroke Island is the main centre of these operations. Mining commenced in the high dunes of North Stradbroke in 1966

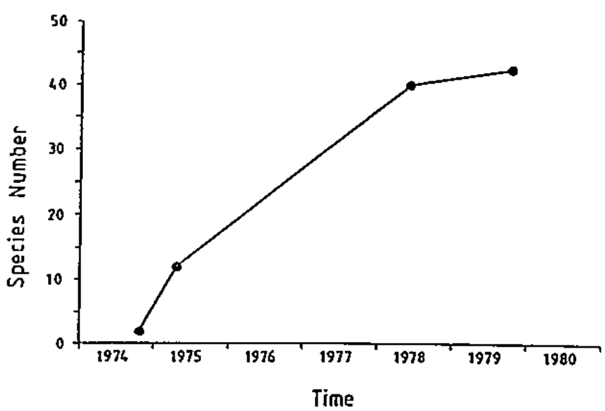


Figure 2 - Natural colonization over time by aquatic macrophytes in an interdunal wetland on North Stradbroke Island, Queensland.

(Morley, 1981, p.154) and continues today. Much of the relevant reclamation technology was developed there (Brooks, 1976; Brooks and Bell, 1984).

Most of the reclamation effort on high dunes goes into landscape reconstruction. Dunes up to 100m in height have been re-built using hydraulic stackers and land lines fitted with booster pumps. As the organically enriched topsoil is responsible for over 90 per cent of the seed source of regenerating vegetation, its recovery from areas to be mined and subsequent replacement is critical. The options for topsoil management on these massive dunes are limited, and basically come down to engineering considerations. Storage of topsoil for periods of three years has been necessary and does not appear to have adversely affected the success of reclamation of this vegetation.

Seed of the tree and large shrub species fail to survive topsoil handling or are absent from the topsoil (Brooks and Bell, 1984). However, observations in 1973 revealed that these species readily regenerated from seed carried in with brush matting used to stabilize the soil surface (Brooks, 1976). It was concluded that direct seeding of these species could be a useful technique, and a major seed collection programme was initiated. Techniques were developed to direct seed these native species both at the initial establishment phase and at later phases when it was desired to upgrade previously established vegetation (Brooks, 1987).

The direct seeding techniques have been highly successful. Carey and Brooks (1985) found that densities of the upper canopy species up to ten fold greater than pre-mining densities have been attained, providing ample allowance for attrition caused by competition and suppression of slower growing individuals. Consequently, the dependence on nursery stock has been greatly diminished.

Sowing of low density cover crop has become standard practice to assist surface stabilization and provide some protective cover during the first 12 months whilst the native species are establishing. Moderate quantities of a mixed fertiliser have been applied routinely with the cover crop to aid its establishment and partially compensate for losses of macro-nutrients in the mining process. A great deal of consideration has been given to the use and fate of applied fertiliser because of fears of phosphorus toxicity in certain species (Brooks and Bell, 1984). However, studies revealed that increased species richness and plant density resulted from moderate levels of fertiliser under reclamation conditions.

In addition to cover crops, other methods of surface stabilization have been necessary to promote the regeneration of native species. Brush matting has been used extensively for this purpose, as it has the advantage of introducing significant quantities of seed in certain circumstances (Brooks and Bell, 1984). However, Barr and McKenzie (1976) found that chemical stabilizers were an effective and less expensive alternative. Terolas ®, a bituminous compound applied in a water emulsion, has been widely used.

The seral development of the vegetation has been described in detail by Brooks and Bell (1984). Investigations are in progress on the role of endomycorrhizal fungi and Rhizobium bacteria in undisturbed and regenerated vegetation and their reintroduction where necessary.

Studies on fauna in rehabilitation have been limited to ants because of their usefulness as bio-indicators of vegetation status. In a survey on North Stradbroke Island, Majer (1984) found that ant recolonisation proceeded rapidly in the early years of regeneration. In a related study, ant activity, as indicated in ant-seed relationships, recovered quickly on rehabilitated ground (Majer 1985).

The full recovery of the ecosystems on the high dunes will, of necessity, take a long time. Whilst the preliminary studies are very encouraging, further investigations are warranted. Indeed, many opportunities for additional research exist. However, Rogers (1982) was able to conclude that the complete ecosystem is being re-established.

## Coastal Lowlands

Many mineral sands ore bodies on the east coast occur as ancient strand lines underlying extensive heath plains referred to as coastal lowlands. The topography of these lowlands is subdued with complex drainage patterns giving rise to a mosaic of dryland and wetland vegetation associations. Typical vegetation types include low dry open forests and shrublands, dry heaths, wet heaths, sedgelands and swamp woodlands.

One such area occurs on the north coast of New South Wales at a location known as Jerusalem Creek, now in the Bundjalung National Park. Since it was discovered in 1890, mining has had a checkered history here (Morley, 1981). Large scale operations were conducted by AMC from 1969 to 1982 over an area of about 13 square kilometres. From 1974, the Company mined on low lying country supporting a variety of wetland vegetation associations. On this landform, the water table is typically at or above the ground surface for 4-6 months of the year, falling below ground level during the dry late winter-early spring months. The vegetation type is governed by moisture relationships, with wet heaths being slightly higher and inundated for shorter periods than sedgelands. Swamp woodlands carry surface water at all times except droughts.

Techniques for rehabilitating these wetlands were developed from hard experience. Early attempts were thwarted by a series of flood events. Vegetation attempted to regenerate from rootstock and seed in the replaced topsoil a number of times. On each occasion, the young vegetation was killed by scalding because of warming of the shallow surface water following heavy rains during summer months. Finally, about two years after the initial topsoil return, a short-term drought allowed the water table to fall below the surface and enabled freshly regenerated vegetation to develop above the height of normal water levels. The vegetation has since continued to develop satisfactorily.

From this experience, the principles for reclaiming wetland vegetation were developed. Subsequent experience has shown they are applicable to all wetland vegetation types encountered so far.

Application of fertiliser had a significant effect on the regenerating vegetation (Brooks, 1988a). As early as age 16 months, fertilised wet heath vegetation had a higher species number, percent cover and abundance than unfertilised heath (Table 1). The increase of species number over the pre-mining level was caused by the topsoil disturbance stimulating seed of species lying dormant in the soil. These species were often short-lived pioneers.

Table 1.--Response of reclaimed wet heath at Jerusalem Creek to fertiliser at age 16 months (from Brooks, 1988a).

| | FERTILISER | |
|---|---|---|
| | – | + |
| Species Number | 25 | 39 |
| Percent Cover | 1.2 | 34.9 |
| Abundance | 1.15 | 5.27 |
| Species Number Pre-Mining | 34 | |

The effect of the development of topsoil handling techniques was demonstrated in the regeneration of a key species in this vegetation, *Xanthorrhoea resinosa* subsp. *fulva*. This species is a multi-crowned shrub with an acauline habit and considered difficult to regenerate following disturbance. Double stripping of the topsoil gave rise to a large response compared with single stripping (Table 2). As the disturbance stimulated the plants to flower within three years, there was the potential to further increase the population of the species.

The adoption of the reclamation techniques described enabled the various vegetation associations, including swamp woodlands, to recover rapidly and successfully. The mined area was incorporated in the Bundjalung National Park following the cessation of mining in 1982. The area is also listed on the Register of the National Estate. In considering that registration, the Australian Heritage Commission formally congratulated the Company on its success in re-establishing native ecosystems.

## Wetlands in the South-West

A unique opportunity is being taken in the south-west of Western Australia to implement a project

Table 2.--Recovery of crowns of Xanthorrhoea resinosa subsp. fulva from different topsoil handling regimes at Jerusalem Creek (from Brooks, 1988a).

| | SITE 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Density (crowns per hectare) | 430 | 670 | 110 | 1,970 | 6,540 |
| Age (year) | 3 | 3 | 2 | 2 | 1 |
| Topsoil Storage Time (months) | 1-2 | 3 | 1-2 | 1 | 1-2 |
| Stripping Method | Single | Single | Single | Double | Double |

after mining specifically for the purpose of waterbird conservation. The Company has been mining at Capel (Fig. 1) since 1956. Part of the ore body was very high grade in ilmenite, and the removal of this mineral caused a significant volume loss. This volume loss was accounted for by creating a system of lakes in worked out pits that intersected the water table. The main lake system, consisting of eight lakes with a total water surface of about 44 hectares, was formed during mining between 1975 and 1979.

The majority of the lakes occur within a State Forest which previously supported a pine forest of low productivity. After mining, the foresters have taken the opportunity to adopt a multiple land use plan involving forestry, recreation and conservation.

In 1984, the Company commissioned the Royal Australasian Ornithologist's Union (RAOU) to advise on the potential of the lakes for development of self-sustaining wetland ecosystems for the purpose of waterbird conservation. Following a favourable report, the Company initiated a wetlands project by establishing the AMC Wetlands Centre in 1986.

A Management Committee has been established for the Centre to advise the Company on objectives and priorities, management and research proposals and budgets, and to review progress. Through its membership the committee taps the main expertise and responsibilities for wetlands and waterbird conservation in the state, thereby forging links with appropriate Government authorities, and research and conservation institutions. There is representation from the Company, RAOU, Department of Conservation and Land Management, University of Western Australia, Murdoch University and Curtin University of Technology. The RAOU has been engaged as Project Manager.

The objectives of the Centre are:

1. To develop self-sustaining wetland habitats for the conservation of waterbirds;

2. To conduct research into wetland ecosystems, their development and management;

3. To develop opportunties for public education and recreation; and

4. To develop and demonstrate wetland reclamation technology.

One of the first steps in the project was to initiate a series of multi-disciplinary baseline studies to determine the current ecological status of the lakes and to indicate priorities for future research and development. Nearby natural wetlands were used as control sites. These studies confirmed the potential of the lakes for their development as self-sustaining ecosystems, whilst indicating the limitations of the undeveloped habitat in supplying food and shelter for the waterbirds (Brooks, 1988a). The need to increase the productivity of the lakes through habitat development was highlighted.

With the benefit of these studies, a long-term conceptual plan has been developed for the Centre. It is planned to create a variety of habitat types to provide refuge for a large range of waterbird species on these permanent freshwater bodies. The plan also involves the development of education and passive recreation facilities in keeping with the multiple-use concept for this zone of the State Forest integrating conservation, recreation and education with nearby forestry. A visitor's centre is planned with parking and picnic facilities. A number of walking trails will be developed incorporating a series of hides and viewing towers at strategic locations.

Site development works commenced during the 1987/88 summer to enhance the limited habitat range by providing feeding, breeding and loafing sites for the birds. The work programme includes earthworks to create channels, moats and islands, land-scaping of banks, mass plantings of wetland trees, shrubs and emergent vegetation, construction of wave barriers and artificial floating islands, and installation of nest-boxes. These works will continue over a five year programme.

An ongoing research programme is an integral component of the project. The programme integrates studies of wetland development and waterbird ecology, with particular emphasis on the food chain. There are studies on sediment/water/nutrient inter-actions, vegetation, algae and diatoms, invertebrates, frog and reptile recolonisation, bird diets, breeding patterns, and the pattern of usage of the developing ecosystem by birds. The project will have obvious benefits in wetland conservation, particularly in view of the loss of natural wetlands in south-west Western Australia. The multi-disciplinary nature of the research programme, integrated by the Management Committee, is a key attraction to scientists working at the Centre. The project will increase understanding of wetlands, and will also help to develop and demonstrate the technology for the reclamation of wetlands. It is believed that the project is unique in Australia.

## Northern Sandplain

Mining on the northern sandplain of Western Australia has centred on heathlands on Vacant Crown Land and Flora and Fauna Reserves south of Eneabba (Fig. 1). The vegetation consists of low shrubland with a high level of species richness and endemism, and a low order of dominance. A vegetation survey on an area of 20km$^2$ covering the ore bodies recorded 429 species (Hopkins and Hnatiuk, 1981), 15% of which could not be identified to species level. A total of 50 families and 162 genera were represented in the survey. About 10% of the species recorded were classified as rare or poorly known. Thus, the vegetation is complex and of outstanding diversity and significance (Lamont, Hopkins and Hnatiuk, 1984). Little is known about many of its components, and a number of species are difficult to propagate.

The Eneabba climate is harsh, and is characterised by long, dry, hot summers, with temperatures often exceeding 40°C. Average annual rainfall is about 530mm, and rainfall exceeds evaporation only during the months of June, July and August (Hopkins and Hnatiuk, 1981). Hence, the growing season is short and discrete. Conditions during the summer months are aggravated by frequent strong easterly winds. Reclamation at Eneabba follows the same basic principles used on the east coast, i.e., return of topsoil, surface stabilization including the use of mulch, cover crops and fertiliser, and propagation of native species by direct seeding and planting of nursery stock. The main task is to adapt these principles to the local climate and vegetation. A comprehensive research programme is in progress involving soils, plant nutrition, flora, fauna and micro-organisms (Brooks, 1988b).

The main thrust of the reclamation programme focusses on various techniques to propagate this complex flora. Generally, the plant species can be classified into two broad groups, viz, soil stored (seed stored in topsoil) and bradysporous (seed stored in woody fruits within the canopy).

Again, management of the topsoil is a key issue because of its importance as a seed source. Stripping and spreading of topsoil in two layers has enhanced regeneration of the native species, with the seed laden top layer being spread to about 2.5 cm depth. Storage of the surface layer is restricted to less than 12 months to aid vegetation recovery. Monitoring studies reveal that regeneration of soil stored species continues over a number of years (Carey and Jefferies, pers comm).

Standing vegetation on the mine path is mulched and spread on land being reclaimed, partly as a stabilization technique and partly as a source of seed. Mulch contributes significantly to the species richness and density of regenerating seedlings, and establishment from this source usually occurs within two years (Carey and Jefferies, pers comm).

Considerable attention is given to seed collection and direct seeding of a wide range of species, a typical seed mix consisting of about 100 species. However, a number of difficulties arise. Many species produce limited quantities of seed or produce seed of poor viability (Carey and Jefferies, pers comm). Seed quality varies greatly from year to year in some species. Hence, germination testing of seed lodged in the seed store is becoming routine practice as data on the germination requirements of these species becomes available.

Field research has shown that time of sowing has a significant effect on establishment of the native species (Osborne, Lloyd and Brooks, 1986). May is the optimum sowing time and this coincides with the normal commencement of winter rains. Therefore, all field establishment procedures are planned to be completed by the end of May.

As a support of the field establishment procedures, the Company produces seedlings in its own nursery. Seedling production is restricted to those species which are difficult to propagate in the field or for which limited seed is available, and which are considered to be important elements of the vegetation. The nursery has a capacity of 70,000 seedlings. Planting out occurs as soon as soil moisture reserves are replenished, usually in June/July. The seedlings depend entirely on rainfall for their moisture supply, despite the limited growing season.

Because much of the mining to date has taken place in a Flora and Fauna Reserve, the Government has adopted quantitative standards to assess the success of reclamation. Parameters assessed include species richness, plant density and canopy cover. The Company has developed an electronic botanical data management system to collect and process data on the seral development of the vegetation from its monitoring programme (Brooks and O'Neill, 1987).

Data from this programme have shown the results of the development of reclamation techniques in recent years. Plant densities for first year reclamation blocks has risen from less than one to more than seven plants per square metre from 1981 to 1987 (Carey and Jefferies, pers comm). Although the Government's standards have yet to be achieved, a number of reclamation blocks are expected to reach them within a few seasons. Certainly, areas reclaimed in recent years are starting with a much stronger establishment base than those reclaimed in earlier years. It is considered that meeting these standards will be a significant achievement on what is arguably the most difficult site the mineral sands industry has had to reclaim anywhere in the world.

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