RESTORATION RESEARCH IN THE ALLIGATOR RIVERS REGION, AUSTRALIA[1]

by

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Abstract. *The Alligator Rivers Region includes the entire area of Kakadu National Park. Kakadu National Park is a world heritage area which consists of a variety of terrestrial and aquatic ecosystems, world famous Aboriginal rock art and significant reserves of uranium, gold and platinum group metals. The Australian Government has authorised mining in this area but has imposed a strict environmental regulatory regime. For example, the goal and objectives for rehabilitation of the Ranger mine site are such that the operator is required to establish on its decommissioned site a stable ecosystem whose plant species composition and density are similar to those existing in the adjacent undisturbed areas of mine sites. Such a requirement is unlikely to be achieved without further research since the information currently available on local ecosystems and on properties of mine soils is very limited. The Alligator Rivers Region Research Institute has established a research program to develop restoration procedures for disturbed mine sites of this Region. The program includes baseline studies (e.g. vegetation survey, phenology, seed technology, herbarium collection), silviculture (e.g. soil analysis, determining fertilizer requirement, isolating rhizobia and mycorrhizal fungi from native plants and testing their suitability to mine soils and developing necessary agronomic practices), establishment of large scale field trials, ecological studies (e.g. assessing the use of ants as bioindicators of restoration success and understanding ecophysiological strategies of local plants to survive and grow in this harsh environment) and long term management aspects (e.g. protection from bush fire, return of fauna and uptake of radionuclides by bush food plants). The overall aim is to develop practical restoration standards that are consistent with the agreed goal and objectives and to recommend methods by which these standards can be achieved with some degree of confidence.*

Additional key words: rehabilitation, revegetation, ecosystem reconstruction, native plants, open cut mine, waste rock dump.

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Introduction

The Alligator Rivers Region (ARR) is located approximately 120 km east of Darwin and is defined by the East, South and West Alligator Rivers. It comprises an area of 28, 000 km^2, of which the Kakadu National Park (KNP) occupies 71% (Fig 1). The ARR is an area of considerable environmental interest and concern because of the inclusion of KNP and the presence of large reserves of uranium.

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The KNP is of outstanding heritage value for its unusual combination of largely uninhabited wilderness areas with attractive wild scenery, abundant flora and fauna with many unique features, and a very large concentration of Aboriginal rock art. The KNP is rich in natural resources, having a variety of terrestrial and aquatic ecosystems including sandstone heathlands, open woodland, flood plains, large rivers, seasonal water courses, as well as significant reserves of uranium, gold and platinum group metals. The national and international importance of Kakadu is recognised by its inclusion on the Register of the National Estate and on the World Heritage List. Some of the flood plain areas are also listed in the Convention on Wetlands of International Importance.

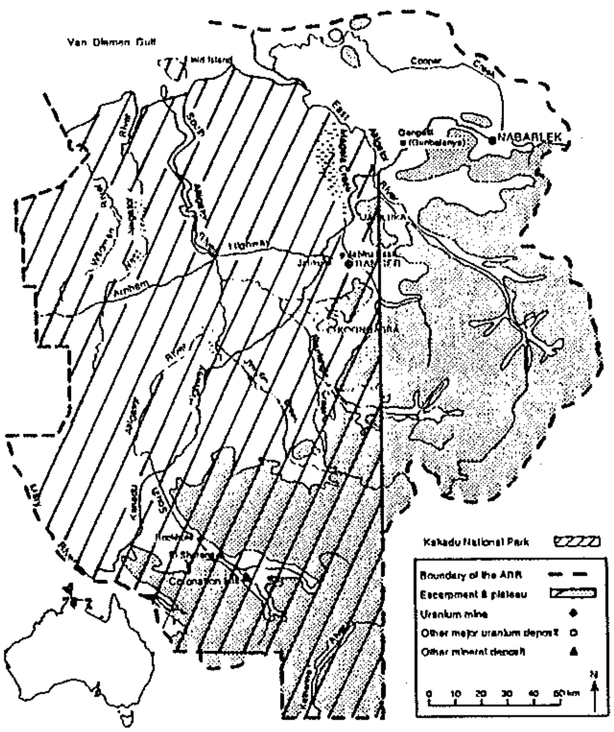

Figure 1. Map showing Alligator Rivers Region, Kakadu National Park and uranium deposits.

Landscape

The landscape of the ARR is shown in Figures 1 and 2. In the eastern part, Kombolgie Sandstone forms the Arnhem Land Plateau which rises 200-300 m above the adjacent plains. To the south lie the dissected foothills, stony hillocks and occasional granite tors. Extending north from the dissected foothills and the sandstone plateau is the Koolpinyah surface which covers nearly 40% of the area (Williams 1991). The Koolpinyah surface is deeply laterised and well drained but contains numerous closed depressions which contain fresh water during most part of the year. These depressions are known in the Northern Territory (N.T.) as 'billabongs'. The presence of billabongs in the Koolpinyah landscape plays a considerable role in animal life during the Dry season.

The Koolpinyah surface consists of level to gently sloping wooded or forested lowlands (Fig 2). Incised into the Koolpinyah surface is a series of rivers which rise in the uplands to the south and flow north to the Arafura Sea. Among the four rivers, South Alligator river is the largest, which lies almost entirely within the KNP.

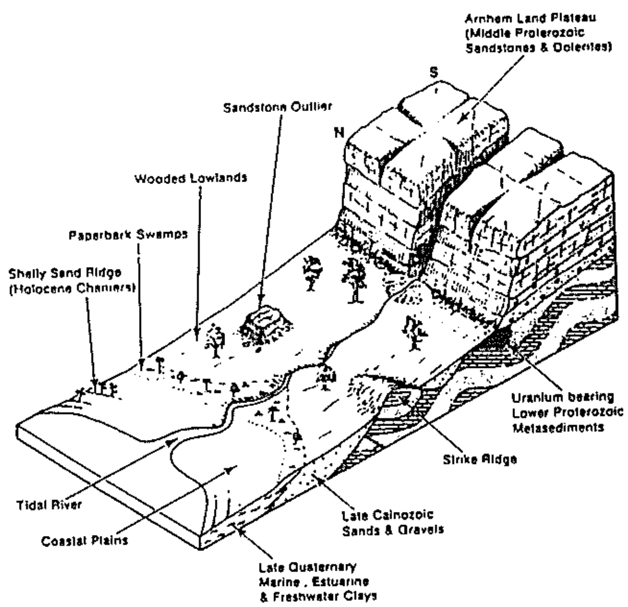

Figure 2. Block diagram showing major features of the landscape of Alligator Rivers Region (Williams 1991).

The Environment

The ARR, in common with much of far northern Australia, has a monsoon-like climate. Rainfall is generally confined to the November-March period with virtually no rain between May and September (Fig 3). The dry season lasts from about May to September; and October and April are transitional months. Annual rainfall averages 1475 mm at Jabiru, the regional centre for Kakadu National Park. Effective evaporation (approximately 1900 mm per annum) exceeds rainfall during most months of the year (Fig 3). The maximum and minimum monthly mean temperatures range from 31 to 37 °C and 18 to 25 °C respectively (RUM 1989).

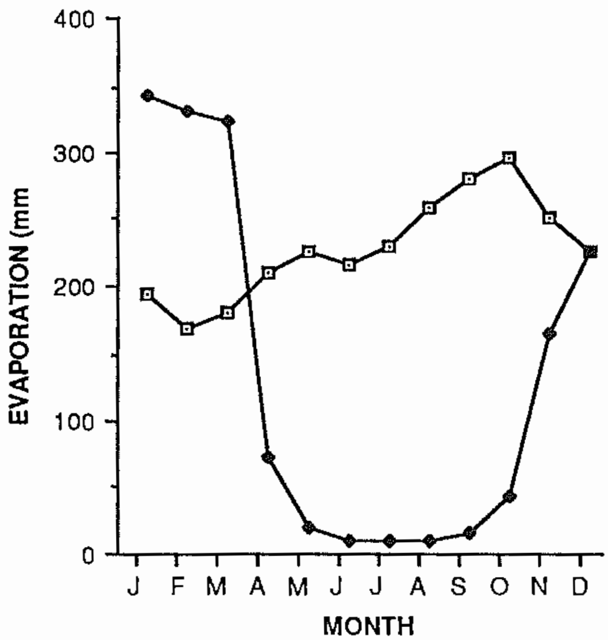

Figure 3. Rainfall (closed symbols) and open pan evaporation (open symbols) data for RUM. The data are average of 19 years.

Bush fires are regular events in the Region and are caused by natural events such as lightning and regular burning by the staff of KNP. The bush is currently burned in a 1-3 year rotation during April to October.

Biological Diversity

The distinctive subregions and the large seasonal changes give rise to a wide diversity of plant and animal habitats. As a consequence, the Region is rich in numbers of species of flora and fauna. It is representative of a large part of the far north of tropical Australia and is regarded as one of the most biologically rich areas in Australia. For example, approximately 1700 species of plants have been recorded, more than one-third of the total bird species found in Australia have been sighted, and about a quarter (46 species) of all recorded species of Australian freshwater fish occur in KNP. Large populations of waterfowl on the wetlands are one of its outstanding features. The large area of KNP helps to maintain the integrity of its wide range of ecosystems, which provide a suitable habitat for several endangered species, such as the red goshawk and the Gouldian finch. The KNP also provides habitats for both Australian and migratory birds and international agreements exist for the protection of migratory birds.

Mining in the Region

Among the two mines which operate within the ARR, Queensland Mines Ltd. (QML) at Nabarlek is due to complete its decommissioning (Fig 1) and the Ranger Uranium Mine (RUM) near Jabiru is currently in operation. The ARR also contains two large uranium deposits in the East (e.g. Jabiluka and Koongarra), and one gold, platinum and palladium metals deposit in the south (e.g. Coronation Hill). None of these has Commonwealth Government authorisation to mine.

The RUM is the only mine currently operating in the Region. It commenced its open cut mine operation in 1979 and mining is expected to continue well into the next century. It has two major orebodies; Orebody No.1 and Orebody No.3. Mining of Orebody No.1 is nearly complete and the mining of Orebody No.3 is expected to begin in the near future.

Environmental Protection

In response to the proposal for mining at Ranger, the Commonwealth Government set up the Ranger Uranium Environmental Inquiry (RUEI) in April 1975. On the basis of the recommendations of the RUEI (Fox 1977), the Government announced its decision to authorise the mining and export of uranium (in August 1977), under very strict requirements for environmental control. Simultaneously, the Government established the Supervising Scientist for the Alligator Rivers Region to carry out research on environmental protection and to supervise and coordinate environmental activities in the Region.

The Alligator Rivers Region Research Institute (ARRRI) of the Office of the Supervising Scientist undertakes research in four major areas, viz Baseline Research, Operational Phase Research, Rehabilitation Research and Techniques Research. This paper describes the restoration aspects of the Rehabilitation Research Program; that is, the establishment of local native flora on disturbed sites and development of procedures to monitor and assess success of restoration on decommissioned mine sites.

Restoration Research Program of the ARRRI

Background

The Commonwealth and the N.T. Governments have established the Goal and Objectives for rehabilitation of disturbed sites at RUM.

The Goal is *"to establish an environment in the Area that reflects to the maximum extent that can reasonably be achieved the environment existing in the adjacent areas of Kakadu National Park, such that the rehabilitated Area could be incorporated into Kakadu National Park without detracting from Park values of adjacent areas"*.

The major objective relevant to revegetation is *"to revegetate the disturbed sites of the Ranger project area with local native plant species similar in density and abundance to that existing in adjacent areas of Kakadu National Park, in order to form an ecosystem the long-term viability of which would not require a maintenance regime significantly different from that appropriate to adjacent areas of the Park"*.

Thus, the mine operator is required to establish on its disturbed sites an environment which is similar to that existing in adjacent areas of KNP, use local native plant species and grow these plants in similar density and abundance as in adjacent areas. In addition, RUM is required to ensure that the established vegetation is viable on a long term basis and does not require long term care such as irrigation, the use of fertilizers and protection from fire.

With the current knowledge of the ecosystem and mine site, the extent to which the above Goal and Objectives could be achieved is limited. The data on species composition and density are sparse, the symbiotic association of native plants is not adequately understood and information on seed germination, fertilizer requirements and silvicultural methods for local plant species is limited. Further, the mine site has not been satisfactorily characterised for factors that may affect plant growth, so the response of native plants to disturbed mine soils and their long term viability on these soils will be difficult to assess.

The ARRRI has recently established a restoration research program following consideration of current environmental requirements, past mining practices, and a review of available literature on restoration and the natural ecosystem. The studies proposed and the order in which they will be undertaken, are shown in Figure 4. Prior to describing the program, characteristics of the plants that inhabit this Region are described and the properties of mine soils are compared with those of natural soils.

Characteristics of Local Native Plants

The hot weather in association with distinct Dry and Wet seasons, assured rainfall during the Wet season, sharp ending of the Wet season irrespective of its early or late start and regular bush fires, all resulted in the development of special mechanisms by local plants to enable them to survive the long Dry season and then respond quickly and compete effectively during the relatively short but intense Wet season. Survival through the Dry season is achieved by two strategies: obtaining moisture from the lower layers of the soil (i.e. remaining active) or becoming dormant (Dunlop and Webb 1991).

Many tree species remain evergreen during the Dry season as they develop deep root systems to facilitate water uptake from clay layers (e.g. *Acacia mimula*, some eucalypts). Some are semideciduous and have reduced water requirements (e.g. some eucalypts and acacias), and others are fully deciduous and remain dormant during the Dry season (e.g. *Cochleospermum fraseri*, *Brachychiton* *diversifolius*). Perennial shrubs and vines survive by producing annual aerial parts and perennial and often tuberous roots (e.g. *Ipomoea graminea*). Local species also appear to have developed special physiological adaptations to regulate tissue water relations and to continue to fix CO_2 under stress, but these mechanisms are not clearly understood.

Annual species survive the Dry season in the form of seeds either by developing dormancy or by adapting some special mechanisms. For example, seeds of wild sorghum (*Sorghum intrans*) are protected from fire and predation by the tough persistent glumes. The glumes contain a corkscrew-like awn which is sensitively hygroscopic. On absorbing moisture, the awn twists vigorously, driving the sharp pedicle into the upper layers of the soil to facilitate self sowing. This species also has a period of dormancy and will germinate rapidly following a light rainfall (about 20 mm). Because of these special abilities, wild sorghum dominates the understorey of this ecosystem. Other species which propagate through seeds appear to have developed several other strategies (hard seed coat, recalcitrant nature) which have not yet been studied.

Most importantly, local native species appear to have developed specific symbiotic associations with rhizobia and mycorrhizal fungi in order to assist in the uptake of nutrients and water from the soil which is usually less fertile and deficit of water. These associations are, however, poorly understood.

Comparison of Mine Sites with Undisturbed Natural Sites

The natural soils of this Region are deeply laterised (Williams 1991). The surface is well drained and the subsurface contains a distinctive clay layer. The soils have moderate water holding capacity (20-30%) and contain low to moderate quantities of organic matter. The soils are acidic (4.5-5.5; in 1:5 water) and are characterised by low cation exchange capacity, low conductivity, low P and N compared to agricultural soils (Milnes 1989). Nevertheless, natural soils support a distinctive type of savanna woodland vegetation (500 to 2000 trees and shrubs per hectare; K. Brennan, unpublished data) which serve as a nutrient source for growing vegetation via litter decomposition and mineralisation.

The surface soils on decommissioned uranium mine sites will be dominated by waste rock produced in the mining process. Preliminary studies on waste rock dump (WRD) soils of RUM suggest, in general, that these soils are capable of supporting plant growth (Milnes 1989). However, the WRD soils are characterised by low infiltration rates (Riley and Gardiner 1991), very low overall water holding capacity (as the rocks will constitute a large proportion of the soil) and little access to the ground water table. They also lack a clay layer in the subsurface, which is most important for plant growth during the Dry season. Compared to natural soils, mine soils have higher pH (6-7 in 1:5 water), higher CEC, higher conductivity, higher P, higher K, lower N and an unbalanced Ca:Mg concentration ratio. Mine soils also contain higher concentrations of Cu, Pb, Zn and U (Milnes 1989). Vegetation and soil fauna are lacking on fresh dumps of waste rock and the lack of soil fauna may restrict the availability of nutrients to the the initially established vegetation.

In summary, mine soils differ from natural soils in water availability, soil fauna, symbiotic microorganisms and mineral concentrations. The benefits of their optimal pH and high P and K concentrations cannot be utilized by plants unless these are matched by an increase in N input, preferably through the establishment of nitrogen fixing plants.

Goal and Objectives of the Program

The broad goal of the ARRRI Restoration Research program is:

- *To evaluate the physical, chemical and biological factors that limit plant growth on disturbed mine sites and hence develop revegetation techniques and standards for mine site restoration.*

The major objectives of the program are to:

- *Determine the density and abundance of vegetation types in the vicinity of mine sites in the Region, understand their* *phenology and seed germination characteristics and establish the principal symbiotic associations;*

- *Identify the factors that limit plant growth on disturbed mine sites, develop suitable methods to overcome these limitations and select suitable species based on field observations and controlled experiments;*

- *Determine ecophysiological basis of growth and survival of selected local native plants in their natural habitats to assess their suitability for establishment on disturbed mine sites and to enable prediction of their long-term viability on these sites; and*

- *Establish standards for assessing restoration success.*

The broad structure of the program and the tentative order in which the research will be carried out are shown in Figure 4 and brief descriptions of research projects are given in the following sections.

Research Projects

Biology of Native Plants. Three sub-projects are currently underway on the native plants; baseline vegetation survey, phenology of local native plants and seed technology.

The baseline vegetation survey is being carried out to determine the composition and density of plants that occur in areas adjacent to RUM. The height, diameter and basal cover of trees and shrubs (with height > 1.5 m) have been determined. The studies on determining composition and biomass of grasses, herbs and sedges are underway.

This sub-project will also determine density and composition of plants at various landforms that resemble the RUM waste rock dump in topography, and possibly in water availability, with a view to finding suitable species for establishment on the waste rock dumps. These sites will also be used as control natural sites to monitor progress of mine site restoration and to develop restoration standards for mine sites.

The sub-project on phenology of native species will document flowering and fruiting times of native species over a range of sites covering a 300 km^2 area within the ARR. This information will be made available to mining companies to plan their seed collection programs in addition to its use in the ARRRI research program.

The seed technology sub-project will include germination experiments and investigate appropriate pre-germination treatments for local species, as many local species appear to have developed special mechanisms to survive under prolonged heat and drought. Some species are known to be recalcitrant and the others only able to be propagated by vegetative means. This sub-project will investigate storage procedures for recalcitrant species and develop propagation techniques for vegetatively propagated species. These studies are currently being initiated.

Characterisation of mine soils. The principal objective of this project is to determine the chemical and physical properties of mine soils (in the ARR) that will influence growth and long-term viability of local plants on these soils.

Chemical properties of disturbed mine soils differ from those of undisturbed soils either in their elemental concentrations or in their relative proportion. This may induce deficiency or toxicty symptoms in some plants, or may encourage rapid growth of some undesirable species which, in turn, may suppress the growth and survival of desirable species. Diagnosing the cause(s) of deficiency or toxicity symptoms of local species is currently difficult as little is known about symptom development or leaf mineral composition of local native plants.

This project will involve the collection of soils from disturbed sites and their adjacent natural sites for determining chemical and physical properties relevant to plant growth. Biological aspects of these soils will be studied as part of the work on 'Symbiotic Microorganisms'. A greater number of samples will be taken from RUM than from other mines, as this is the largest mine in the Region and

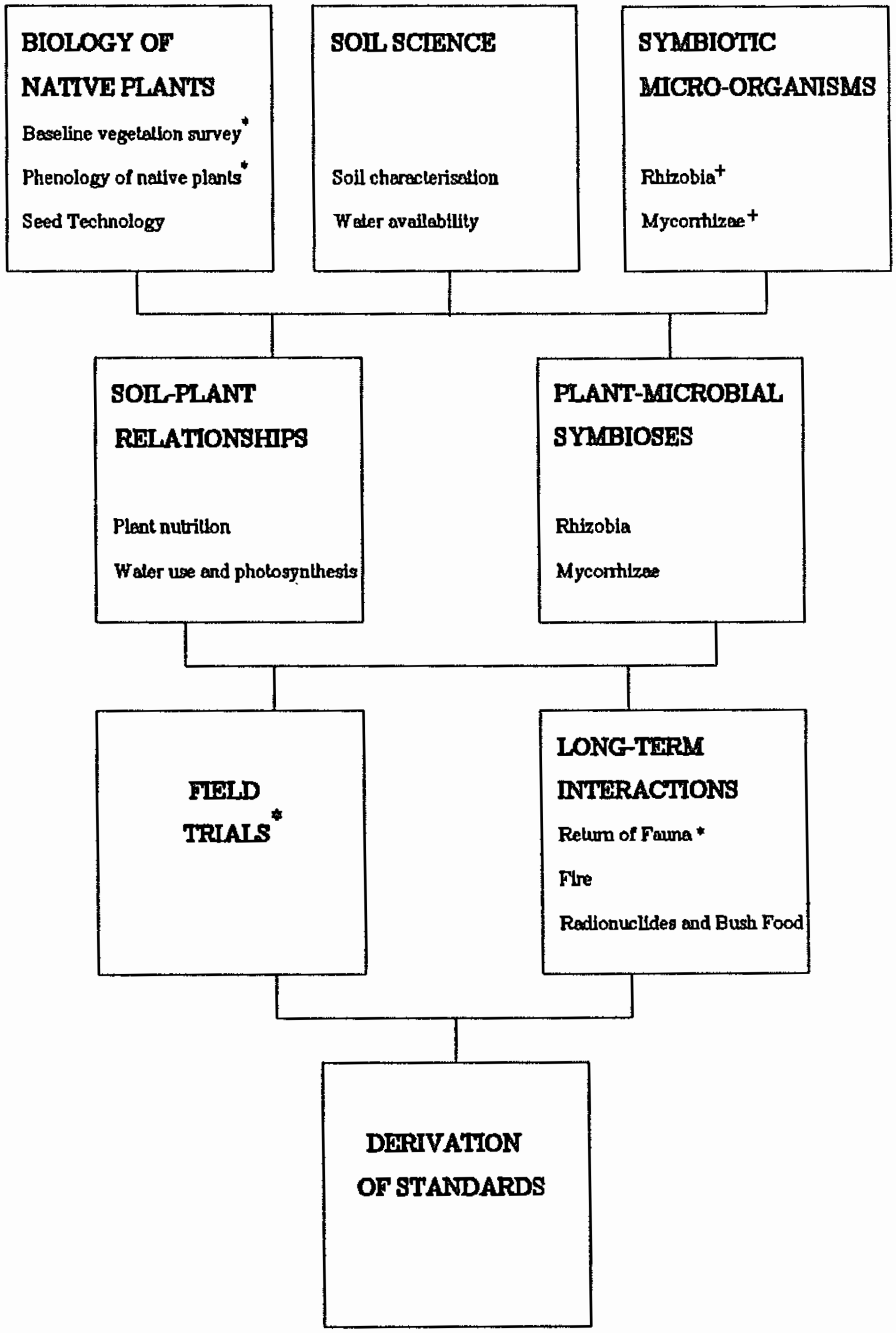

Figure 4. Structure of the restoration research program of the ARRRI. All projects will include field and laboratory experiments except those marked with '*' or '+' which will include either field or laboratory experiments respectively.

our future field experiments will be established on this mine site.

Chemical analysis will determine total, exchangeable, extractable and/or water soluble elements (plant nutrients, U, Pb, Al, Na), and physical characterisation will include particle analysis, water holding capacity and moisture retention characteristics. The other physical attributes (erosion, hydrology etc) will be studied in the erosion research program of the Institute.

This project has commenced and the soil analysis is underway.

Symbiotic Microorganisms. Disturbed mine soils initially contain a limited number and diversity of beneficial microorganisms as they are derived from rocks buried deep (up to 200 m) below the surface. These microorganisms may be necessary for many local plant species as they have established long term symbiotic relationships to take up nutrients from soils that are usually infertile, and to absorb water from the soil which is dry for a prolonged period. Because waste rocks weather rapidly and form their own soil, the mining companies are not keen to use top soil, despite its potential to serve as an inoculum, seed source, fertilizer and a soil amendment. Further, the type of mining operation, location of the mines within KNP and the prevailing climatic conditions are not conducive for collection, storage and re-use top soil.

For these reasons, our research program has given great emphasis to this project. Two sub-projects are currently underway. One involves isolating rhizobia from leguminous trees, shrubs and herbs, and the other involves isolating endo- and ectomycorrhizal fungi, in order to characterise and culture various strains. These sub-projects will involve collection of samples from various landforms of the ARR. The rhizobium study is being carried out by Institute staff, and the mycorrhizal study is being undertaken as a collaborative project with the University of Western Australia.

The projects commenced in 1991 and about 500 putative rhizobium isolates have been made from native shrubs and herbs. These isolates are currently being tested for their authenticity. A similar number of strains will be isolated this year, mainly from tree legumes.

Samples of soils and sporocarps were collected from various natural sites within the ARR. Endomycorrhizal fungi were isolated from the soil by growing bait plants and collecting spores and organic matter by sieving. Ectomycorrhizal fungi will be isolated from the sporocarps collected from the field, or those induced in pot culture by growing host plants on soils collected from the field. The isolated strains will then be characterised and stored for future use on disturbed mine sites. Soil samples will also be collected from disturbed mine sites to determine the nature and extent of colonisation by mycorrhizal fungi and to compare colonisation of disturbed soils with that of natural soils. The strains thus isolated will be characterised, photographed and stored at the ARRRI. These strains will then be used in glasshouse (using WRD soils) and field experiments to select promiscuous, adaptable and effective strains.

Soil-Plant Interrelationships. This project will commence after the completion of the projects described above.

Preliminary studies by Milnes (1989) suggested that the plants grown on WRD soils may suffer from Ca:Mg imbalance. This speculation has not been tested using local native species. Further, the waste rock soils contain higher concentrations of heavy metals (e.g. U, Pb) compared to natural soils and the response of local plants to these ions has not been studied.

Both glasshouse and field experiments will be conducted to elucidate the effect of Ca:Mg imbalance and heavy metals on selected local plants, and to investigate means of overcoming these problems.

Preliminary studies have also suggested that there will be a water deficit of 150 mm per year on RUM waste rock soils if they are covered with vegetation to a similar density as in natural sites (Emerson and Hignett 1986). Studies are therefore necessary to test this speculation and find alternatives, if necessary, to restore these soils. It may be possible to identify drought tolerant species (or varieties) and increase the representation of these species (or varieties) on the WRD in order to balance water availability with its demand.

This project will investigate water use and photosynthetic behaviour of native species to identify suitable species for mine soils. Local species appear to have developed unique ways of coping with stresses and a comparison of the water use and photosynthetic behaviour of plants grown on WRDs with those occurring on adjacent areas will help to assess adaptability of a species to mine soils. These studies are necessary to predict, by computer modelling, the long term viability of established plants on WRDs.

Plant-Microbial Symbioses. It is known that symbiotic processes are more sensitive to stresses (water, mineral, temperature, pH) than the growth and survival of the host or the symbiont (Munns 1986). Mine soils are likely to be exposed to these stresses, resulting in reduced symbioses. Thus, the strains isolated in the sub-project 'Symbiotic Microorganisms' will be tested in glasshouse and/or in the field to select strains that will survive and induce effective symbioses on mine soils. The selected strains will then be recommended for further multiplication and use in mine site restoration. In addition, tests will be carried out on the competitive ability of introduced strains against residual strains that may be present in mine soils.

Long-term Interactions. Once vegetation is established on a disturbed mine site, several processes will take place. A range of fauna will return, new species will appear and fuel will build up, increasing the likelihood of fire. In addition, Aboriginal traditional owners may use this area to collect bush food. The impacts of these interactions on established vegetation and on its long term viability requires assessment.

Because the disturbed mine sites (only those located within KNP) will be incorporated, on their decommissioning, into KNP, the return of fauna to these sites is considered important to meet the requirements of "Park Values".

The tropical monsoonal ecosystem of this Region contains a large variety and number of ants. Studies have recommended the use of ants as bioindicators of ecosystem disturbance (Anderson 1990, Major 1989). However, this concept has not been tested and described adequately, and the interrelationship between ants, vegetation and other fauna (such as soil invertebrates) which play a significant role in the long term viability of plants has not been established.

A project has been developed to determine the number and diversity of ants, soil fauna (except nematodes) and foliage arthropods on various landforms around RUM. The project will examine the role of fauna in soil development and plant growth by studying litter decomposition, infiltration, soil turnover, seed dispersal and protection of plants from foliage pests.

Bush fire is a common and a regular event that takes place in these ecosystems. Mining companies will protect rehabilitated sites at least in the initial stages. Protection measures are, however, unlikely to be completely successful and some sites may be burnt prematurely. Thus it will be important to identify the growth stages that are critically sensitive to fire, determine the desirable period of protection and estimate the consequences of fire at other stages of plant growth.

Some Aboriginal people in the Region continue to lead a tradition lifestyle and their diet includes, to a limited extent, traditional items such as the fruits and tubers of native plants. Since the soils of decommissioned mine sites will contain radionuclides at higher concentrations than those present in natural soils, the uptake and accumulation of these elements by native plants require investigation to estimate radiation exposure of members of the public arising from the choice of any particular revegetation plan.

Establishment of Field Trials. The results of the above studies will be tested in a field trial on the WRD of RUM. Local native plants will be established by providing them with necessary silvicultural care, such as pre-germination treatment, inoculation with appropriate symbionts, addition of necessary fertilizers or soil amendments and protective irrigation.

It is proposed that the trials will be established on a large area (up to 5 ha) and several treatments will be imposed at the commencement and/or at various stages. The nature and the type of the treatments will be decided after baseline data on plants, soils and symbionts are collected. It is likely that the following aspects will be studied: suitability of species, fertilizer requirements, benefits of inoculation, effects of burning, nutrient cycling, return of fauna.

Results of field experiments are expected to answer the following questions:

What species are best suited to WRD?

What fertilizers to use and how much?

What silvicultural procedures are necessary?

How long will it take for the established plant community to reach its climax?

Can WRD conditions support long term viability of plants?

How do plants respond to fire at their early stages of growth? and how long will they require protection from fire?

What successional or structural changes take place in the established vegetation?

Do nutrient cycling and soil development processes proceed normally?

What monitoring methods should be used? and

How should success of restoration be assessed?

Derivation of Standards for Assessing Restoration Success. It is the responsibility of the Northern Territory Government to set standards for rehabilitation of mine-sites within the ARR and of the ARRRI to assist in the development of such standards. In the case of revegetation, standards not only need to be designed to meet the goals and objectives of rehabilitation but also must be practicable.

The research program of the ARRRI has been designed so that, after the ecological studies, laboratory experiments and field trials it should be possible to specify which ground cover species, shrubs and trees can be successfully established on disturbed mine sites and at what densities they can be maintained on these sites.

Not all the information required for assessing the final success of a restoration plan can be obtained from such a program. The time required before any revegetated plot reaches maturity will be of the order of 30 years and it is likely that the mine operators will wish to be discharged from any further responsibility long before that time. It will be necessary, therefore, to develop predictive tools to assist in assessing the likely condition of any revegetated plot at maturity. It is therefore anticipated that assessment of the final success of restoration will be carried out in an iterative way that will include the establishment of preliminary standards for the early stages of rehabilitation (based on the ecological studies, laboratory experiments and field trials), the establishment of a detailed monitoring program, development of computer models to predict long-term performance based on the results of monitoring and, finally, revision of numerical standards based on the results of the monitoring and modelling program.

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