Sherriff, M. M., Ladd, P. G., Bell, R. W., Samaraweera, M. K. S. A. and Mattiske, E. M. (2002). Developing Completion Criteria for Rehabilitation on Alluvial Mined Areas in Dry Tropical Savannas. In: *Proc 2002 Workshops on Environmental Management in Arid and Semi-arid Areas*. pp. 131 – 138 Goldfields Environmental Management Group, Boulder.

DEVELOPING COMPLETION CRITERIA FOR REHABILITATION ON ALLUVIAL MINED AREAS IN DRY TROPICAL SAVANNAS

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ABSTRACT

*Success on mine rehabilitation areas can be assessed on the basis of completion criteria. Argyle Diamond Mine (ADM) processes alluvial deposits along Limestone and Smoke Creeks in the Kimberley region and has mined over 1000 hectares of land that is in the process of being revegetated. ADM requires completion criteria to be formulated for mined terrace areas at their alluvial minesite. Few studies worldwide have addressed the issue of practical completion criteria for mined lands in dry tropical savannas, which are characterised by highly variable and strongly season rainfall, frequent fires and a mosaic of herbaceous and woody plant communities. This paper examines the plant ecological aspects of the alluvial mine rehabilitation process at ADM, and rehabilitation progress in relation to objectives. The characteristics of the tropical savanna system are compared with those of the southwest of Western Australia where rehabilitation of mine sites has a longer research record than in the far north. In both systems, understanding the biology of species and the impact of fire is critically important. However, there are also important differences related to the environment and the species and communities that occur in the respective locations. The vegetation on the terraces beside the creeks (*Plains *vegetation) was suitable as a reference community on which to base completion criteria for assessing the success of the alluvial mining rehabilitation areas. It appears unrealistic in the short-term, to expect rehabilitated communities to be closely similar to what existed before mining. However, reinstated plant communities should contain dominant local species that are functionally similar to those that were present before mining. During the development of completion criteria for the dry tropics it is necessary to take into account the patchy structure of the natural vegetation and the highly variable climatic conditions.*

INTRODUCTION

Dealing with the changes in landscapes and landforms resulting from mining and the large amount of waste produced in the mining and ore refining processes has undergone considerable change over the last 50 years (ANZMEC and MCA, 2000). In some parts of Australia rehabilitation practices are well advanced after many years of research and development. Strong commitment to research has produced a quite detailed knowledge of the way natural plant communities operate and how plants regenerate after disturbances (eg. Bell, 1999; Herpich *et al.*, 1994; Ward *et al.*, 1997). However, it is becoming apparent that there are no universal solutions to mine site rehabilitation. What is needed is knowledge of the function of ecological systems and the biology of the species in the area where the mine occurs (Lesica and Allendorf, 1999). Appropriate knowledge is needed to ensure a successful result with an optimal input of resources.

While considerable advances in rehabilitation techniques have been made, it is not always clear that the vegetation on rehabilitated mine sites will be self-sustaining. Community concern for the sustainability of rehabilitated landscapes and governmental requirements that companies, rather than the general community, are responsible for rehabilitation means that systems need to be in place to ensure success and accountability. Devising completion criteria is one approach that is intended to guarantee accountability for the proposals put forward by mining companies for their rehabilitation (ANZMEC and MCA, 2000).

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In southern Western Australia significant research into completion criteria has been undertaken on mineral sands mines in the Kwongan heathlands and bauxite mines in the jarrah forest. Minerals sands mining at Eneabba removes topsoil followed by extraction of minerals using either dry surface methods or wet dredging. Rehabilitation involves pumping of clay and sand tailings back to mined-out pits (Herpich et al., 1994). Bauxite mining differs as a complete soil horizon is removed in the mining process (Ward et al., 1988).

For Iluka's (formerly RGC's) Eneabba operation, completion criteria for vegetation take the form of targets for plant species/m^2, plant density/m^2 and percentage plant cover which is applied to all rehabilitated areas uniformly (Petersen and Brooks, 1996). Plant establishment is not predictable and establishment rates are linked to water availability and seed biology (Herpich *et al.*, 1994).

Completion criteria for vegetation at Alcoa's bauxite operations are applied uniformly at all locations but criteria change over time, reflecting the aspect of ecosystem function which is important at that stage of development. Rehabilitated areas are assessed at 9 and 15 months after rehabilitation, if criteria are not met at these times rehabilitation works may need to be repeated (Elliott *et al.*, 1994; Ward *et al.*, 1996). For bauxite mining in the jarrah forest, these approaches have been refined over thirty years of research and have shown that rehabilitation prescriptions produce predictable and relatively uniform outcomes on a year to year basis.

In this study we contrast the tropical savanna of northern Australia with those of the better known southwest in order to develop ideas about criteria for revegetation which could be used to judge the progress of rehabilitation work on alluvial mine areas at the Argyle Diamond Mine (ADM) in the east Kimberley region. We ask:

1. What are the main differences and similarities between the tropical savanna and southwest ecosystems that are relevant to land rehabilitation?
2. What is the intended state for the post mining landscape?
3. What are the appropriate analogues that could be used as a guide for planning rehabilitation activities?
4. What are appropriate preliminary completion criteria for assessing the revegetation success in the alluvial mine areas?

BACKGROUND

At ADM extensive areas of terrace deposits along Smoke and Limestone Creeks have been mined for alluvial diamonds. These areas have been the subject of rehabilitation treatments over a number of years and are the focus of this study. ADM is located in the East Kimberley region of Western Australia, 110 km south of Kununurra at the headwaters of Smoke and Limestone Creeks. The region has a dry tropical climate that is characterised by a hot dry-season and highly variable wet season rainfall (Argyle Diamond Mine, 2000).

Diamondiferous alluvial gravels occupy recent and historic drainage lines within the Argyle lease area. The alluvial diamond deposits are classified into 4 classes, which reflect the age of the alluvial terraces and their geomorphic setting. They indicate the level of the land surface when alluvial sediments were deposited along the river valleys.

The D terrace represents current stream beds while A terrace gravels (that occur at higher elevations in the land scape) were deposited around 20 million years ago and are expressed as isolated low lying duricrust capped hills. B and C terraces represent intermediate age deposits (Argyle Diamond Mine, 1999b). The C terrace is the most extensively mined alluvial terrace at ADM (Botje, 2001).

Alluvial gravels are mined in shallow trenches using an excavator. A mobile screening unit separates the diamondiferous gravels (particles > 2 mm) from the reject material that is returned to the mined trench (Argyle Diamond Mine, 1999b).

Topsoil and/or overburden along with stockpiled vegetation is respread on the surface of levelled trenches. Construction of drainage lines, absorption banks and shallow ripping along contours complete the landforming operations. A seed-mix containing local plant species is broadcast by hand and seedlings are transplanted in some areas. Patches of vegetation that are usually of about 0.03-0.05 ha are left undisturbed within the mining area. These tree retention clumps usually centre around large boab trees (*Adansonia gregorii*) and are intended to aid the rehabilitation process once mining is completed (Argyle Diamond Mine, 2000).

The rehabilitated alluvial terraces at ADM are to be integrated with the management of surrounding unmined vegetation to support cattle production and traditional aboriginal use (Samaraweera *et al.*, 2000). To comply with this use, the vegetation is required to be safe, stable, self-sustaining; and maintenance free. (Argyle Diamond Mine, 2000; Mattiske Consulting Pty Ltd, 1998, 2000; Samaraweera *et al.*, 2000). In the case of future traditional uses of rehabilitated land, the establishment of plants of cultural significance is an additional major goal (Argyle Diamond Mine, 2000 ;Samaraweera *et al.*, 2000).

In the absence of specifically derived completion criteria, ADM has applied the approach developed by Muir (1996, cited in Argyle Diamond Mine, 2001). This system is derived from field data and based on the estimation of two parameters; total cover index (TCI) and rainfall variability index (RVI), and relates fauna re-colonisation to floral richness (Samaraweera and Muir, 2001). However, the system has not yet been validated in the dry tropical environment.

This project examines vegetation monitoring data collected annually by ADM to explore the development of completion criteria. The study areas were mined C terraces from the 1996, 1997 and 1998 years of rehabilitation. The plots from these areas are prefixed R, S and T respectively. These areas were chosen as they occupy similar positions in the landscape and received the same rehabilitation treatment but were subject to differing rainfall distributions in their first year following seeding. Detailed methods and results are reported elsewhere (Mattiske Consulting Pty Ltd, 2000; Sherriff, 2001).

Community composition was sampled using 50 m^2 quadrats located in undisturbed vegetation and rehabilitated areas along Limestone and Smoke Creeks. Quadrats were ordinated using multivariate analysis based upon the Bray-Curtis similarity in the PRIMER package. The scaling was done on percentage cover for perennial species because the inclusion of annual species may have distorted the output due to seasonal fluctuations.

Total annual rainfall and its distribution were highly variable in the period from July 1996 to June 2001 in which the three rehabilitation areas were established (Figure 1).

The wet season rainfall for the establishment year for the R and T rehabilitation areas was above the long-term average of 568 mm (Argyle Diamond Mine, 1999a) totalling 999 mm and 894 mm, respectively.

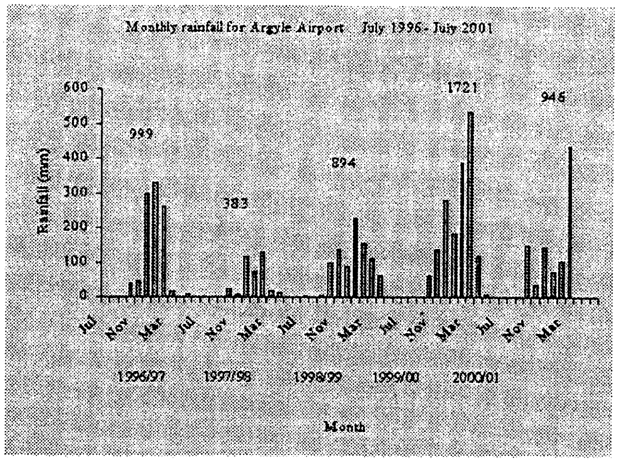

Figure 1: Monthly rainfall (mm) received at Argyle Airport since 1996. Total wet-season rainfall (months) is included as numerals above each year.

The R area received the bulk of this rain in a three-month period and the T area received substantial rainfall throughout the wet season. The S rehabilitation area received below average rainfall in its first year (383 mm). Since establishment of these areas above average rainfall has occurred: 1721 mm in 1999/2000 and 946 mm in 2000/01.

DEVELOPING COMPLETION CRITERIA

Differences and similarities in ecosystems that are relevant to environmental restoration

The dry tropical savanna has extremely seasonal, unreliable summer rainfall (Walker and Gillison, 1982; Williams et al., 1996). The strong seasonal rainfall results in a limitation of plant-available soil water and suspension of plant growth during the dry season (Walker and Gillison, 1982). Perennial plants cannot persist in these landscapes unless they are able to find ways to access groundwater or stored water during the dry season (Harrington, 1991; Scholes and Archer, 1997). Establishment of a species during a wet season following rehabilitation is no guarantee that the species will remain alive in the longer term. If a wet season has very low rainfall, survival over the subsequent dry season may be very poor. In the south rain is also highly seasonal but occurs in winter and is relatively reliable while the summer is generally dry. At Eneabba early germination of plants is desirable so that root development can reach a stage where plants can persist through the dry summer on the sandy soils (Petersen and Brooks, 1996).

In the jarrah forest rainfall is higher than at Eneabba, plant growth is slow during the cool winters (Gentilli, 1989) but is also slow or absent in the summer. However, seedling survival is more reliable than at Eneabba.

Fire is a conspicuous part of both southern (Bell *et al.*, 1989) and northern systems (Walker and Noy-Meir, 1982; Williams *et al.*, 1999). In the jarrah forest (Bell, 1999) and Kwongan heathlands (Dixon *et al.*, 1995) fire promotes seed germination of many plant species (Bell, 1999) and has been used to enhance plant establishment on mined lands (Ward *et al.*, 1997). Relatively slow build up of fuel in the heathlands and jarrah forest ensures a fire return frequency of several years, which is in contrast to the possibility of 1 - 2 year fire cycles in the tropical savanna. In the dry savanna, fire limits woody plant recruitment by killing seedlings in the period before individuals have developed sufficiently to withstand grass fires (Scholes and Archer, 1997; Williams et al., 1999). Established sprouter tree and shrub species may be maintained as suppressed individuals due to repeated removal of sprouts by short return fire intervals (Bond and van Wilgen 1996). The balance between the rapidly growing annual component of the plant community and the more slowly growing perennials is strongly influenced by fire frequency. Including criteria specifying the number of fire tolerant woody plants per hectare may assist in judging resilience to fire. Developing a classification of plants as fire tolerant or not, based upon size or age would be helpful in assessing the prospects for plant survival. This subject would benefit from further research.

Table 1: Comparison of nutrient status of tropical savanna and jarrah forest soil.

Location	Nitrogen (mg/kg)	Phosphorus (mg/kg)	Source
Tropical savanna (Melville Island)	84-283	<5	(Wilson and Bowman, 1994)
Jarrah forest (Boddington)	10-20	10	(Raphael, 1994)

Soils are low in nutrients in both the Australian dry tropical savanna (Cole, 1982) and the Kwongan heathland (Wisheu et al., 2000). Jarrah forest soils are also low in N but slightly higher in P when compared to savanna soils (Table 1).

Bauxite and mineral sand mining operate in areas of very high species diversity (Wisheu et al., 2000). However, structurally the communities are relatively uniform. In these areas rehabilitation prescriptions are applied with minor site-to-site variation in an attempt to recreate the pre-mining systems. By contrast, the dry tropical savanna around ADM has relatively low species diversity but is characterised by herbaceous and woody dominated vegetation on the plains with densely wooded forest along the creeks. This presents a range of challenges to rehabilitation as plant communities with different species compositions and structural pattern may need to be established in different but adjacent areas. A summary of factors relevant to environmental rehabilitation in the dry tropics and the Mediterranean southwest is listed below (Table 2).

Appropriate analogues for rehabilitation at ADM

The unmined vegetation sampled in this study was classified into two main vegetation groupings, the heavily wooded *Riverine* vegetation and the *Plains* vegetation complex (after Weston 1980). The contrast between the groups was most distinct at Smoke creek where very high woody plant density (<3500 plants/ha, mostly *Terminalia canescens*) was observed along creek channels adjacent to areas with low density of woody plants (<700 plants/ha). The Limestone Creek channel was not as heavily wooded but the forest did spread further from the channel than at Smoke Creek. This may be correlated with substrate differences related to greater water holding capacity of the soil near the Limestone Creek channel.

Vegetation in the R (1996), S (1997) and T (1998) C terrace rehabilitation was more similar to the *Plains* complex than to the *Riverine* vegetation. The *Plains* vegetation occupied the C terrace away from creek channels. And most of the mining is also situated in this part of the landscape.

Table 2: Comparison of climatic and biotic factors and vegetation characteristics relevant to rehabilitation between dry tropical savannas of north west Australia and the Mediterranean south west.

	Dry tropical savanna	Mediterranean south west
Environmental factors		
Soil nutrient status	Low	Low
Rainfall	Strongly seasonal, highly unreliable.	Strongly seasonal, relatively reliable winter rainfall and occasional summer storms
Annual temperature variation	Low	High
Fire	Destroys new seedlings and suppresses established resprouts	Required for germination of many seeds and revitalises some resprouters Destroys new seedlings and suppresses established resprouts
Rehabilitation substrate	Entire soil profile rearranged, similar to original but depleted in fine soil fraction	Bauxite -upper soil horizons removed. Mineral sands - entire soil profile rearranged, replaced material physically similar to original
Reconstructed landform	Similar to original	Bauxite- landscape relief and drainage increased. Mineral sands - similar to original
Biotic factors		
Plant species richness	Low	High
Plant growth period	Limited period following summer rain and stops in the winter dry period	Plant growth from late winter into early summer
Plant establishment	Germination requirements for many species are poorly understood. Growth to fire resistant stage is critical to recruitment	Fire may be required for germination. Growth to fire resistant stage is critical to recruitment
Life forms	Dominant annual and perennial components	Dominant perennial component
Vegetation structure	Patchy, characterised by competing herb and woody plant dominated vegetation	Patchy if attention given to providing variation for fauna and plant communities

Hence the Plains vegetation group is an appropriate model for rehabilitation of mined C terraces and may also be applicable to B terraces.

The *Riverine* vegetation would provide a suitable natural reference state with which to construct completion criteria for mined D terrace areas, which occupy recent creek channels and banks. Preliminary visual observations of the vegetation on rehabilitated D terraces indicate that some *Terminalia* and *Eucalyptus* species and boabs are occurring at a relatively high frequency.

Completion criteria derived for C terraces may not be appropriate to A terrace. The deeply weathered A terrace material readily breaks down into weathered constituents leaving a mined profile that is higher in fine material than are the B, C and D terraces, in which the rocks remain intact during the mining process (Botje, 2001). The findings of this study should not be applied to A terrace lands without further examination and are more applicable to the younger terraces.

Like C terrace rehabilitation, rehabilitated B and D terraces are unlikely to mirror unmined analogue areas in the short-term. In setting rehabilitation objectives and completion criteria for these areas it is not appropriate to expect all the species in the unmined areas to return. However, it is reasonable to expect plant communities be reinstated whose dominant species are functionally similar to those on unmined areas.

Preliminary completion criteria for the biological systems in the mine area

Hobbs and Norton (1996) proposed that criteria for success of rehabilitation can be developed which show the natural range in variability for parameters which have been determined as important to ecosystem function. In their method mean values from rehabilitated areas are compared to the natural range in variation of a suitable reference system.

The following completion criteria were developed using this approach, the parameters used recognise that identical species composition to unmined areas is not presently a realistic goal and uses lifeform groupings as a basis for developing a suitable vegetation structure. The *Plains* vegetation group is used as the natural reference state from which the ranges in these parameters were determined.

For herbaceous taxa total percentage cover is used as the measure of abundance as herbaceous plants establish themselves quickly in rehabilitation and cover allows useful comparisons to be made. Density (plants/ha) is used for woody plants as density estimates allow more meaningful comparisons to be made between younger rehabilitation and more mature ecosystems.

As the reference system contains a wide range of cover for the herbaceous lifeform species, the total range may not provide a useful target for rehabilitation. First and third quartiles are proposed in preference to the total range in natural variation. Preliminary criteria for herbaceous plant lifeform cover are summarised in Table 3.

The very large range in natural variation of woody plant density reflects the patchiness in distribution of these species in the *Plains* vegetation group. First and third quartile ranges are very narrow for woody plant density and would not be appropriate in constructing completion criteria. For woody species, the range of density that represents a 90% confidence interval of the mean, calculated from the *Plains* vegetation group for each plant lifeform is proposed.

For the deciduous tree lifeform (primarily *Adansonia gregorii*) the lower confidence interval is 0 plants/ha. Clearly this is not a suitable target for a completion criterion. Given that this study showed that *Adansonia gregorii* established at values in excess of the *Plains* vegetation mean value, a lower limit to deciduous tree density of 20 plants per hectare is tentatively suggested. Given that *Adansonia gregorii* seedlings are fire sensitive this criterion should be further refined to 20 fire tolerant plants per hectare (Table 3). The size at which *Adansonia gregorii* becomes fire tolerant needs to be further investigated so that a time frame can be assigned.

For herbaceous and woody plant abundance measures, lower limits are more important than the upper limits prescribed in Table 3.

Table 3: Examples of the tentative completion criteria for alluvial diamond mining areas on C terrace landforms.

	Lower range	Upper range
	Herbaceous vegetation	
Herbs	9 % cover	77 % cover
Annual grass	20 % cover	72 % cover
Perennial Grass	4 % cover	50 % cover
	Woody vegetation	
N-fixing Shrub	682 plants/ha	1902 plants/ha
Shrub	381 plants/ha	1526 plants/ha
Tree	153 plants/ha	832 plants/ha
Deciduous tree	20 plants/ha	46 plants/ha

The results showed that most of the rehabilitation from 1996-1998 had achieved a total cover similar to control values, indicating that if one or two of the lifeforms are just achieving the minimum level, the other lifeforms should compensate by occurring at abundances in excess of their lower limits.

Completion criteria are particularly difficult to define for a landscape such as occurs in the northwest of Australia, which is highly heterogeneous, and is situated in a very unpredictable and variable climate. A broad leeway needs to be accepted to encompass the variation due to natural stochasticity in climate and other aspects of the environment. Further monitoring on rehabilitated land will help to clarify the dimensions of vegetation change and help refine notions of what is achievable and acceptable.

CONCLUSIONS

Completion criteria and rehabilitation goals need to be based on an understanding of plant establishment within the landscape in which the mine occurs, so that they are flexible enough to account for temporal and spatial variation that is characteristic of the area, and yet ensure that the long-term resilience and function of the system is maintained.

In setting completion criteria it is not appropriate to expect all the species in the unmined areas to return (Environmental Protection Agency, 1995b). Factors affecting the establishment of some species still need to be investigated. However it is reasonable that plant communities be reinstated whose dominant species are functionally similar to those in the unmined areas, allowing rehabilitated lands to be incorporated into the management of the surrounding lands. Completion criteria also need to account for nutrient dynamics and faunal recolonisation to ensure successful rehabilitation (Environmental Protection Agency, 1995b). These topics are subject to ongoing research and monitoring at ADM.

Some of the approaches used in the Mediterranean south west may be applicable but with modifications to allow for the variation in climate and natural vegetation patchiness. Germination of desirable structural and functional species is regarded as critical for long term vegetation establishment within rehabilitated bauxite mines in the jarrah forest and has led to the development of criteria which are applied to rehabilitated lands after 9 months (Environmental Protection Agency, 1995a).

Timing of the vegetation assessment of rehabilitated lands in dry tropical savannas has historically been undertaken on an annual basis at the end of the wet season to accomplish the assessment of both annual and perennial growth as well as success of regeneration of plant species. The regularity of additional monitoring times is constantly under review as it is recognised that species can continue to emerge three or more years following topsoil application and their survival is critically dependent upon available soil water. Given the variability of the annual rainfall (total amount, length of the wet season and the nature of the rainfall events), and the complex nature of particle size distribution of the newly created soil profile, yearly assessment during the initial phase (first three years) and subsequent regular (once in every three to five years) assessments are suggested.

In addition to high variation in annual plant establishment, there are the highly unpredictable grass fires. Knowledge of the age or size at which individual woody species become tolerant to 'typical' early dry season grass fires needs to be incorporated into completion criteria in order to provide a basis for estimating the resilience to fire of particular components of the vegetation on mined alluvial lands.

Unlike approaches for completion criteria in the southwest where criteria are often expressed as minimum targets, a range of acceptable values is proposed for dry tropical savannas. All rehabilitated lands studied achieved vegetative cover values similar to those of analogue sites. By assigning a range of acceptable woody plant densities and herbaceous plant cover, the spatial heterogeneity of the vegetation can be incorporated into the completion criteria. If for instance woody plant density is close to its minimum acceptable value, the deficit in plant cover should be compensated by herbaceous plants and *vice versa*.

This approach to completion criteria for dry tropical savannas may also be of some use in other arid environments. In these areas, seeds can remain viable in the soil for many seasons, plant establishment is critically dependent upon an unpredictable rainfall regime, and the vegetation is structurally heterogeneous.

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