Assessment criteria and successional pathways for rehabilitation after manganese mining on Groote Eylandt, Northern Territory

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Certification

I certify that the substance of this thesis has not already been submitted for any degree and is not currently being submitted for any other degree or qualification.

I certify that any help received in preparing this thesis, and all sources used, have been acknowledged in this thesis.

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Abstract

Groote Eylandt Mining Company (GEMCO) operates a manganese mine on Groote Eylandt in the Gulf of Carpentaria in northern Australia. The land is rehabilitated after mining, the pre-existing eucalypt-dominated woodland being the target ecosystem and land use. The success of the rehabilitation has been variable, with many areas failing to develop toward a mature natural woodland ecosystem due to a number of factors. Issues have included varying rehabilitation goals over time; acacias, grasses and weeds out-competing the target eucalypt keystone species, and high grass biomass resulting in frequent intense fire, so that keystone juvenile, fire-susceptible plants are killed or suppressed.

Vegetation monitoring was conducted over 2.5 years at 42 sites, including reference sites in natural woodland and rehabilitation ranging from 0.5 to 19 years of age. Univariate analysis of the vegetation data found that rehabilitation was somewhat similar to natural woodland in terms of species composition, but differed markedly in structure and the relative dominance of species. Multivariate classification and ordination analyses, based on a matrix of species composition and structural data, revealed that the 33 rehabilitated sites formed six distinct groups. These groups were ranked in decreasing similarity to woodland sites, based on location in the classification dendrogram as well as distance in ordination space. Three groups of rehabilitation sites were considered appropriate, transient states along the desired vegetation development or successional trajectory. The remaining groups were deemed ‘undesirable’ and unlikely to develop into the target eucalypt woodland, given the disturbance regime dominated by fire, without management intervention.

Ordination revealed the relationships between the vegetation composition and structure of the rehabilitation and natural woodland, on the one hand, and a range of environment and management variables. Six potential environmental or management determinants were significantly related to the variation in vegetation, including site age, litter depth, topsoil utilisation, seed mix, litter cover and fertiliser use. A field trial compared four substrates to achieve best early-rehabilitation germination and establishment. The substrates were fresh topsoil, subsoil, a topsoil–subsoil mix and a ‘sandtails’ waste product from mining. Subsoil achieved best germination and establishment percentages. Treatments containing topsoil showed less early establishment of keystone eucalypts and higher levels of grass cover compared to other treatments.

A combination of a vital-attributes approach to the response of key species to time and disturbance by fire, with a state-and-transition (S&T) model of the identified rehabilitation groups, was used to develop a comprehensive S&T model of the observed and predicted rehabilitation at Groote Eylandt. The model included catalogues and diagrams of the observed and hypothetical states and transitions between states, from which a set of interventions was developed for potential application by managers to redirect deviant states. A simplified version of the model was also developed, with quantitative assessment criteria, for immediate field trialling and application. GEMCO can use the assessment criteria in their monitoring program to identify early in the rehabilitation process whether sites are on a desirable or undesirable successional pathway. Sites on undesirable pathways will require appropriate management interventions to return them to the desired successional trajectory. Potential management interventions suggested as a result of this research include enrichment planting, weed management, fire, application of mulch, fresh topsoil islands and thinning of *Acacia* shrubs. As further monitoring and research is conducted, the model can be refined and updated to improve GEMCO's rehabilitation management.

The combination of vital attributes (VA) and state-and-transition (S&T) models in a VAST approach to defining successional development and assessment criteria in the rehabilitation of a natural ecosystem has considerable potential in ecological restoration elsewhere. It is applicable to a wide variety of ecosystems and land uses (e.g. mining, forestry and agriculture); it is practical, and valuable even in relatively simple, naïve form. It also has the virtue of being able to be refined and updated through repeated use and testing.

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1.1 Introduction

After mining an area of land, mining companies in many countries are required by law to set about returning the mined area to vegetation that is stable, self-sustaining, resilient to erosion and supports an appropriate post-mining land use (e.g. Mulligan 1996). Various post-mining land uses are possible, including areas for recreation, forestry or native vegetation (e.g. Alcoa 2002) depending on site limitations and government and community expectations (EPA 1995). Examples include returning sand dune vegetation after mining for zircon and rutile on North Stradbroke Island in Queensland (Rogers & Mokrzecki 1984), reinstating tall jarrah forests for timber production and biodiversity conservation after bauxite mining in south-western Western Australia (Alcoa 2002), and replacing prairie grasslands after coal mining in Midwest USA (Brothers 1990). This must be done despite the fact that mining can dramatically change the physical environment and consequently influence the type of vegetation able to be supported (Nichols 2004).

Vegetation of the target land use can be described in terms of completion or end-point criteria (EPC), to provide measurable indicators of success (ANZMEC/MCA 2000). While undisturbed sites of target vegetation, termed analogue or reference sites, are often used to develop or define EPC (e.g. Tongway *et al*. 1997), interim criteria are required to assess rehabilitation at intermediate (or seral) stages of development. Depending on the target land use, these intermediate rehabilitation stages may not necessarily resemble the undisturbed system. Thus, interim criteria need to be developed with ecological processes in mind so that only attributes or indicators relevant to the developmental stage are assessed. For example, at 6 months of age, tree height may not be as important as the presence of a minimum number of stems of a key target species whereas, in a more mature system tree, height may be very important, indicating progress towards the target vegetation structure.

The theory of vegetation dynamics and views about the most important mechanisms accounting for vegetation change (or plant ‘succession’), have varied though the twentieth century. A traditional view of succession is one involving the unidirectional progression of an ecosystem through a number of discrete, intermediate stages to a ‘climax’ stage (Clements 1916). More contemporary approaches acknowledge the variability in disturbance regimes and ecosystem dynamics, and view succession as the directional change from one plant community to another over time in response to disturbance and changes in the environment (McCook 1994).

Knowledge of the successional dynamics of a rehabilitated ecosystem would enable operators and regulators to (1) clearly identify the target land use, end-point criteria and interim developmental stages toward target rehabilitation; and (2) agree on a realistic, meaningful set of interim developmental criteria. It would also afford miners the opportunity to use management techniques to accelerate desirable successional changes and avoid or rectify undesirable vegetation development.

Rehabilitation management uses techniques to facilitate and accelerate the development of the maturing ecosystem towards desired end points, to meet measurable completion criteria (SER 2004). It is based on identifying desirable and undesirable successional trajectories, and this requires a comprehensive understanding of a wide range of ecosystem attributes and the behaviour of these over time under different environmental and management conditions.

The state-and-transition (S&T) model of succession can be applied to the successional development of rehabilitated areas of vegetation to assist long-term management (Westoby *et al.*1989) and identification of end-point criteria. The desired successional trajectory is the ecosystem developmental pathway that most directly leads to the establishment of a self-sustaining ecosystem that satisfies the rehabilitation objectives. During rehabilitation, including at its initiation, the ecosystem may depart from this desired trajectory, either as a result of disturbances including natural events (such as unplanned fire or cyclones) or inappropriate management. If rehabilitation sites have stabilised in states or are on trajectories unlikely to develop toward the target end point, these deviated stands of vegetation must be actively redirected back toward the desired trajectory, through management.

The vital attributes model of Noble and Slatyer (1981) is useful for elucidating the response of vegetation at different stages of development to a range of disturbances, especially fire. Characteristics of key life stages, such as time to reproductive maturity, are considered plant ‘vital attributes’ and are used to predict vegetation sequences and transitions between vegetation states in response to the passage of time interspersed by a variable disturbance regime.

Groote Eylandt Mining Company (GEMCO) has been rehabilitating open-cut manganese mines on Groote Eylandt in the Gulf of Carpentaria, Australia, since 1972. Lease conditions require that mined areas must be rehabilitated to the satisfaction of the indigenous Anindilyakwa people of the island. For over 20 years, rehabilitation efforts have focused on the establishment of vegetation communities as similar as possible to the open eucalypt woodland present in unmined areas. The young rehabilitation is variable in its structure and composition, largely due to uncontrolled fires, weed invasion and climatic variability. Many rehabilitated areas, including sites supporting mature vegetation, differ structurally and floristically from the surrounding unmined native ecosystems, and may not be developing towards the surrounding target vegetation. Identification of the management opportunities and actions required to redirect undesirable stands of rehabilitation towards the target end point, including improved methods of establishing rehabilitation, is required.

The overall objective of this study was to identify desirable successional trajectories that are likely to culminate in the target reference community for post-mining rehabilitated vegetation on Groote Eylandt, describe vegetation states that are unlikely to meet end-point criteria without further management interventions, and examine options to bring these sites back to the desired successional trajectory.

1.2 Literature Review

1.2.1 The Rehabilitation of Disturbed Ecosystems

Mining, while affecting relatively small areas compared to agriculture, for example, causes significant localised disturbance to the environment as it generally involves the complete removal of vegetation and total relocation of large volumes of soil and underlying substrates (Nichols 2004). This level of disturbance often precludes the restoration of ecosystems exactly like those present prior to mining, and so the term 'rehabilitation' is more appropriately applied to the act of re-establishing vegetation on mined-out sites (Bradshaw 1984). Rehabilitation can target land uses such as forestry, but in landscapes dominated by natural vegetation, is most often used to describe the return of a stable, self-sustaining native ecosystem as close as reasonably possible to that present prior to mining (Mulligan 1996).

1.2.1.1 Rehabilitation Objectives

It is critical that the rehabilitation objective is defined early in the project. The final land use must be identified and the strategy developed to achieve this aim. While some post-mining land uses include multiple activities such as forestry, agriculture and recreational values, around three-quarters of mines in Australia aim to return a native ecosystem (Mulligan 1996). Where this is the aim, such rehabilitation is intended to be sustainable in the long term, often providing for conservation and indigenous cultural values, and resilient in terms of withstanding the prevailing disturbance regime in the surrounding environment, such as fire.

The long-term objective of rehabilitation at Alcoa's bauxite mine in Western Australia (WA) is to establish a self-sustaining jarrah (*Eucalyptus marginata*) forest ecosystem, to enhance or maintain conservation, timber, water, recreation and other forest values (Elliot *et al*. 1996). At Worsley Alumina, also in WA, the broad objective of rehabilitation in forest areas is to 'regenerate a stable forest ecosystem with flora characteristics compatible with the eastern jarrah forest. Specific goals include the maintenance of recreation, conservation, timber production, landscape and hydrology values, and to minimise impact on undisturbed areas' (URS Australia 2004). At Groote Eylandt in the Northern Territory, GEMCO has made the commitment to the indigenous stakeholders 'that the land be brought back to what it was before GEMCO' (GEMCO 1999).

A major legacy of mining activity may often be a change in the substrate or landscape, precluding the return of the pre-existing vegetation type. Thus, selection of appropriate (i.e. achievable) target end land uses is critical. In some instances, such as on tailings dams or significantly lowered landforms, it is impossible to return the original vegetation. In this case, it is important that a transparent approach be taken, including ample consultation with regulators and external stakeholders, to arrive at an agreed, achievable target land use (EPA 1995).

1.2.1.2 Reference Ecosystems

Rehabilitation aiming to return a natural ecosystem must be based on a knowledge of the intrinsic characteristics and dynamic features of the natural system (Reddell & Meek 2004). This requires appropriate reference or analogue systems be studied for the purposes of comparison. They are used as a benchmark for mature rehabilitated areas and guide the assessment of rehabilitation progress through time. While many characteristics of immature rehabilitation are unlikely to resemble those of the reference ecosystem, empirical data and a knowledge of ecological principles should enable the distillation of meaningful progress measures for even young rehabilitation.

Caution must be taken to avoid unattainable goals that constrain rehabilitation efforts. Rehabilitated vegetation can be fundamentally different to reference ecosystems, follow different developmental trajectories and experience different disturbance regimes. Rehabilitation often occurs on modified landscapes that may differ from the original in many ways. In such cases, selection of a suitable reference ecosystem may require consideration of vegetation elsewhere in the region or alternative topographic positions in the surrounding landscape.

1.2.1.3 Rehabilitation Assessment Criteria

Once the target land use has been determined and appropriate reference ecosystems identified, ecosystem attributes must be selected to indicate the ultimate success of the rehabilitation. The mining industry recognises that criteria acceptable to landowners and the public are needed to determine when rehabilitation of mined areas has been effectively completed (e.g. ANZMEC/MCA 2000). Rehabilitation is successful when the site can be managed for its designated land use without any greater management inputs than similar, unmined land in the area used for the same purpose (EPA 1995). The final stage in relinquishing rehabilitated land is to demonstrate the quality, resilience and sustainability of the rehabilitation and ensure stakeholders are confident of this success.

Depending on the rehabilitation goal, restoration success can be thought of as achieving the desired native species composition as well as reinstating the ecological functions served by the original undisturbed vegetation community, such as primary productivity, water purification and soil erosion (Lockwood & Pimm 1999).

Lockwood and Pimm (1999) reviewed the success of 87 rehabilitation projects, with clearly defined goals of facilitated restoration of native ecosystems. The key criteria for success were the achievement of the stated biological goals of species composition and ecological function and the cessation of ongoing management effort (due to persistence of the restored ecosystem). The review found that 20% of projects failed to achieve either criteria, 61% failed one of the criteria (13% met all biological goals but management continued and 48% ceased management but did not achieve all the biological goals) and only 20% of projects achieved both criteria and ‘complete success’. The partial success of the largest group of projects, suggested by the cessation of management, was in fact even less so as some projects potentially ceased management efforts without necessarily ensuring that long-term persistence of the ecosystem had been fully attained.

The review suggests that, in the absence of clear pathways of secondary succession (e.g. a nearby source of propagules of original vegetation), it is unlikely that any restoration attempt will be successful. Full restoration will require the exact replication of original physical conditions, a most unlikely condition in a mining scenario. Additionally, “even given identical physical conditions, restoration of a particular species composition may be impossible, at best improbable, and even then, only transitory” (Lockwood and Pimm 1999).

Long-term persistence, and confident removal of management efforts, requires evidence from long-term monitoring of disturbance and community turn-over, the likes of which has rarely been seen. Lockwood and Pimm (1999) suggest that realistic goal setting should acknowledge that successful restoration should be able to build functional replicates of target ecosystems, but that they will not be structural (compositional) replicates. “Any attempt at hitting that one ‘target’ will almost surely fail.”

Evidence (or measures) of rehabilitation success are commonly termed end-point criteria (Grant 1997). This term implies that these measures equate to the characteristics of the final or climax target ecosystems. In fact this is rarely the case, as the development of rehabilitation to this stage would potentially take hundreds of years. Thus end-point criteria are usually only applied to characteristics of the target ecosystem. While rehabilitation may be different in structure to the target ecosystem, there should be confidence that rehabilitated sites will change with time towards the structure and composition of the reference vegetation. The stage at which confidence in the continuing development and sustainability of the rehabilitation is sufficient to support relinquishment is measured in terms of 'completion criteria'. The use of this term underlines the achievement of relinquishment as being the completion of the active rehabilitation phase and the miner's responsibility for the rehabilitation (Duggin *et al*. 2004) but not necessarily the achievement of the end point in ecosystem development.

Considering the long timeframe required for much rehabilitation to achieve even the completion criteria and be eligible for relinquishment (often a matter of decades), it would be unwise to ignore the development of the rehabilitation during this time and its successional progression. It is preferable to monitor this development to ensure that rehabilitation is proceeding at the desired pace and in the required direction to meet the completion criteria.

Many characteristics of mature ecosystems are not comparable to developing vegetation communities (Hobbs and Norton 1996), and interim developmental criteria should be identified to provide meaningful interpretation of the success of young rehabilitation. For example, overstorey species' heights in rehabilitation will not reach those of mature woodlands for some time; however, appropriate height for age should provide a degree of confidence that the rehabilitation will achieve the target height. Thus, although completion criteria may be meaningful once rehabilitation is sufficiently mature, a series of interim developmental criteria is important to the effective assessment and management of rehabilitation and its progress toward the completion criteria.

Interim developmental criteria require an understanding of the ecological processes at each stage of succession. For example, diversity measures and densities of target species (i.e. composition and structure) may be more important in the early stages of succession, while more mature rehabilitation should achieve functional targets such as reproductive maturity, habitat hollows, and maximum levels of soil nutrient cycling. A development trajectory for restoration of a natural ecosystem may utilise a variety of indicators of rehabilitation success, or key interim criteria, for various stages along the trajectory: failure to achieve these interim criteria would result in the rehabilitation being considered unsuccessful and likely to require management inputs to correct the problem or prompt an investigation of the criteria and whether they are too stringent.

Mining operations have the opportunity to improve rehabilitation techniques during the lifetime of a mine. They can develop and refine completion criteria, including interim developmental criteria that have been shown to lead to mature rehabilitation, progressing toward the desired end point. This evidence can be used to assure senior management, government and the community and reduce the financial liability (in terms of the size of the 'bond' held by the authorities for the duration of post-operational site maintenance) (DITR 2006).

In the mid-1990s, Alcoa Aluminium worked with government regulators to develop interim and completion criteria for rehabilitation after bauxite mining in the south-western jarrah forests of WA (Elliott *et al*. 1996). Criteria were assessed under five categories relating to developmental stage:

- planning: to ensure that environmental parameters (e.g. land use) are taken into account during the evaluation process;
- very early (end of mining but prior to seeding): covers the rehabilitation operations such as landscaping and topsoil return;
- early (vegetation establishment to 5 years): parameters such as eucalypt survival, plant density and species diversity are assessed;
- mid (5–10 years after establishment): only the ability to withstand wildfire is assessed at this stage; and
- late (10–15 years after establishment): can the rehabilitation be integrated into broad-scale fire management and a final check of tree growth, survival and vegetation development.

Utilising over 30 years of rehabilitation experience and monitoring evidence, in 2005 Alcoa was able to obtain a certificate of completion from the WA government to successful rehabilitation of a 975 hectare area of the Jarrahdale mine (Gardner & Bell 2007). This formally returned management responsibility, and liability, to the state government.

Another example of completion criteria can be seen at the Worsley bauxite mine in Western Australia: the establishment of 500–700 stems per hectare for the total areas rehabilitated with tree species and the establishment of at least two native plants (one legume and one non-legume) per square metre (URS 2004).

1.2.2 Ecology of Natural Vegetation Ecosystems

Prediction of the medium and long-term behaviour of restored vegetation communities, and the development of effective and meaningful assessment criteria, requires sound application of ecological theory and knowledge of the ecosystems in question. Several features of natural ecosystems should be considered when proposing assessment criteria, including:

- vegetation composition and diversity;
- vegetation structure and function, including habitat development;
- species interactions, including competition; and
- resilience to external disturbances (drought, fire, disease, cyclones).

Vegetation composition refers to the identity of plant species present. In a tropical savanna woodland, long-lived overstorey trees dominate. These are termed the 'framework' and strongly influence site characteristics, including (Reddell & Meek 2004):

- resource availability such as light, nutrients and water;
- core habitat values for other plants and animals;
- overall functioning (e.g. primary and secondary production; nutrient cycling; hydrological balance; fuel characteristics etc.); and
- long-term stability of the plant community.

This influence results from the ecological characteristics of long-lived trees, including (Reddell & Meek 2004; Williams *et al.* 2003):

- high resistance to (or tolerance of) fire;
- primary reliance on vegetative regeneration strategies (through root suckers, lignotubers and rhizomes) to recover from disturbance;
- seeds which are short-lived and do not accumulate in the canopy (serotiny) or soil seed bank;
- a population structure dominated by even-aged cohorts from one or a small number of discrete recruitment events (usually from vegetative sprouts), resulting in highly discontinuous size class distributions; and
- high predictability of growth performance and development.

Framework species are the prime focus of efforts to rehabilitate tropical savanna ecosystems (Corbett 1999). On Groote Eylandt, they include the canopy eucalypts (*Eucalyptus tetrodonta* and *E. miniata*) and ironwood (*Erythrophleum chlorostachys*), and woody subcanopy species such as quinine tree (*Petalostigma banksii*), snotty-gobble (*Persoonia falcata*), and cocky apple (*Planchonia careya*). Failure to restore these key elements severely limits the prospects of success.

While the establishment of framework species is essential for successful rehabilitation, species diversity is usually related to a broader suite of plants that occur in all strata, predominantly the understorey (Fenshaw 1990). Due to the susceptibility of elements in this stratum to disturbance, in particular fire, diversity can be highly dynamic. For example, fire enhances emergence of seedlings in some perennial grasses, including black speargrass (*Heteropogon contortus*) (Tothill 1969). This dynamism, which is not necessarily related to the long-term stability of site functioning, means that diversity-related measures, such as species richness, may not be effective indicators of rehabilitation success.

Savanna eucalypt forests and woodlands have three distinct strata: a eucalypt-dominated canopy, a sparse midstorey and grass-dominated understorey (Russell-Smith 1995). Completion criteria may relate to the vegetation structure of complex natural ecosystems, including vertical and horizontal arrangement of structural elements and the occurrence, abundance, dispersion and diversity of key habitat elements (e.g. standing tree hollows). For example, Worsley Alumina identify material suitable for fauna habitat in areas about to be mined, and stockpile this material “along the edge of the clearing for later use in rehabilitation. This material includes logs (hollow, character type and solid logs and stumps) and debris (branches, small logs and rocks)” (URS 2004).

Vegetation function relates to the energy and material cycles involving the plants in an ecosystem, including primary productivity, nutrient cycling, soil erosion, and fire regime (Aronson *et al*. 1995). While these functions are, of course, influenced by species composition, they are not necessarily dependent on any one species. It is possible that similar functions could be provided by different species or combinations of species. Such assemblages do not need to have same number of species (Lockwood & Pimm 1999) nor do they have to be native or introduced (Aronson *et al*. 1995) to perform a given function.

1.2.2.1 Ecosystem Disturbance and Resilience

Vegetation communities are dynamic, with species vying for space, light, and nutrients. In systems where disturbances may be frequent or severe (such as recurrent bushfires in Australia), changes in vegetation composition, structure and function can be dramatic. The extent of these changes, and the similarity of vegetation to the pre-disturbance community, will vary depending on the vegetation community involved, and the type, intensity and duration of disturbance experienced (McCook 1994).

Disturbance is any event that causes a change in resources, substrate availability or the physical environment and thus disrupts ecosystem, community or population structure (White 1979). In the savanna woodlands and forests of northern Australia, fire is important in shaping and changing vegetation communities (Section 3.1.1).

Resilience can be described as the capacity of a system to absorb environmental changes without dramatically altering (Holling 1973). It can be measured by the pace, manner and degree of recovery of ecosystem properties following natural or human disturbance. An aim in studying the resilience of ecosystems is to predict the response to natural and human-induced disturbances (Westman & O'Leary 1986).

A number of theories have been developed in an attempt to describe the impact of disturbance on vegetation communities. The intermediate disturbance hypothesis (Connell 1978) proposes that species richness can be expected to be at its greatest some time after a disturbance, when the vegetation has recovered to some degree from the disturbance, and includes both early and later successional species. On the other hand, the initial floristic composition (IFC) model of succession (Egler 1954) suggests that the majority of species that will make up the developed vegetation community are those present immediately after the disturbance. In the rehabilitation context, this implies that only those species present in the topsoil or provided as seed at the establishment stage will be key components of the final vegetation community. Of course, subsequent disturbance can affect this composition and result in an entirely different final community type. Norman *et al.* (2006a) found that the IFC model explained vegetation succession rehabilitation after bauxite mining in Western Australia. They monitored rehabilitation of different ages through time and found little increase in species diversity after initial establishment. A key recommendation from this research was that restoration practitioners in that environment needed to immediately restore all target plant species, and could not rely on any assumptions of relay floristics, or colonisation, from external sources (Norman *et al*. 2006a).

Another approach to identifying ecological patterns, including dynamics that elicit ecological adaptations and alterations, is the use of rules of ecological assembly. Drake *et al*. (1999) identified ecological assembly rules as operators which exist "as a function or consequence of some force, dynamical necessity, or context, which provides directionality to a trajectory. The nature of this direction includes movement toward a specific state, some subset of all possible states, or a dynamical realm of definable character".

1.2.3 Rehabilitation and Succession

Succession is fundamentally important to rehabilitation. Knowledge of the long-term patterns and processes by which ecosystems develop is essential to attempts to restore desirable, self-sustaining ecosystems: 'The process of rehabilitation should aim to accelerate the natural succession processes so that the plant community develops in the desired way' (EPA 1995).

A number of successional theories have been proposed since the early concepts of Clements (1916; Egler 1954; Noble & Slatyer 1981 Westoby *et al.* 1989). Some of these have been applied to ecological rehabilitation after mining (e.g. Koch & Ward 1994; Grant 1997; Smith 2001). For example, in a study of the floristics of previously mined areas in the jarrah forest, Koch and Ward (1994) concluded that although the forest is believed to respond to fire according to the IFC model (Egler 1954), the response to a more severe disturbance (i.e. bauxite mining) that removes the predominant resprouting species is very different and leads to a predominance of obligate seeding species in the rehabilitated sites.

Succession can be thought of as the directional change from one community to another over time in response to disturbance and changes in the environment (McCook 1994). Primary succession occurs when a site not previously occupied by a living organism is colonised. Secondary succession is more common where a previous vegetation community has been disturbed so that new plant colonists and prior occupants compete for resources during vegetation re-establishment. Grime (1979) described succession as the 'process of change in the structure and composition of vegetation (over time)', which can be 'interpreted as a function of the strategies of the component plant populations'.

Since Clements proposed his ‘climax’ or ‘relay floristics’ theory of succession in 1916, many ecologists have recognised the difficulty of practically applying it. Clements (1916) viewed succession as being the unidirectional progression of an ecosystem through a number of discrete, intermediate stages, or seres, to a climax stage, whose vegetation was self-sustaining, unique to each climatic region, and able to regenerate in the presence of adults of the same species. The concept of a single climax per region is no longer widely accepted with the recognition of multiple stable states in vegetation (Walker & del Moral 2003). Relay floristics involves the successive appearance and disappearance of groups of species (seres), with each seral suite of species eventually making the site uninhabitable for themselves, thereby facilitating their replacement by the next group (autogenic succession). Early successional species tend to have adaptations for rapid growth and the production of copious numbers of offspring and are favoured in newly disturbed sites. The late succession environment, on the other hand, favours longevity, hefty provisioning of fewer offspring, and more efficient utilisation of resources (Horn 1974). Clementian seral pathways are seen as discrete and unidirectional and it has been suggested that this mechanism really only holds for cases involving abandoned pastoral and cropping land (Walker & del Moral 2003). Many alternative views and models have been proposed, each attempting to expand the framework of succession to accommodate all ecological circumstances. McCook (1994) pointed out that much of the debate over succession is unconstructive, often confounded by semantics, and that succession is basically a ubiquitous pattern of unique processes.

Egler (1954) proposed the Initial Floristic Composition model of succession for situations in which the plants appearing in later successional stages were present, as seed, roots, or rhizomes, at the initiation of the succession and when groups of grasses and shrubs that preceded the later stages did so temporally rather than causally. This mechanism is thought to apply generally to Australian forests (Noble & Slatyer 1981), however it still relies essentially on the ‘facilitation’ of species introduction. Connell and Slatyer (1977) acknowledged this facilitation pathway of succession, but added the ‘tolerance’ and ‘inhibition’ pathways where earlier seres either do not affect or inhibit, respectively, the establishment of later stages.

Three types of life-history characteristics of potentially dominant species have been identified as attributes vital to the ‘role of the species in a vegetation replacement sequence’ (succession) (Noble & Slatyer 1981). In the scheme of Noble and Slatyer (1981), the three vital-attribute groups involve a plant’s ability to arrive (seed dispersal, invasion etc.), to establish, and to achieve successful growth at the site. Vital attributes are especially influential after a disturbance, when the ability to be first to germinate in a vacant site may direct subsequent vegetation development. Westman and O'Leary (1986), in their examination of post-fire succession and resilience in coastal sage scrub, found that 'the relative vigour of resprouting by species populations, in particular, is a key predictor of competitive success, and hence a predictor of the pace, manner and degree of recovery following disturbance'. The vital attributes model is useful as it deals with species individualistically in terms of their response to disturbance and acknowledges the potential for frequent disturbances (as seen in areas of Australia exposed to regular fires). Morrison *et al*. (2005) developed a vegetation replacement series based on vital attributes for key species used in rehabilitation of the Osborne copper mine in northwest Queensland. This modelling provided specific predictions of species dominance after different frequencies of fire disturbances and enabled the operation to appreciate the suitability of completion criteria and the likely timeframe for which rehabilitation may require monitoring assessment and monitoring before such criteria can be met. Keith *et al*. (2007) also found that using a vital attributes approach to define groups of species as 'plant functional types' (PFTs) provided a powerful tool for prediction and generalisation of rehabilitation dynamics. They concluded that this approach may be useful for ecosystem managers to reliably predict average changes in abundance for groups of species in response to particular disturbance scenarios. Caution is advised, however, with regard to the generality of the approach, and Keith *et al*. (2007) suggested that additional management and monitoring of key species may be warranted.

Westoby *et al*. (1989) proposed the state-and-transition (S&T) framework of vegetation succession which describes ecosystems 'by means of catalogues of alternative states and catalogues of possible transitions between states'. Transitions can be favourable or unfavourable depending on the suitability of the resulting state to the management aim. Hazards leading to unfavourable transitions can be avoided, and opportunities resulting in favourable transitions seized. An important point of this model is that thresholds exist between stable states, and once a transition pushes a community over a threshold, significant 'work' (or management) must be invested to return it to a more desirable state; the simple removal of the causative agent is insufficient. This work can be in the form of catastrophic natural environmental change or, more likely, management activities such as burning, grazing, ploughing or herbicide application. For example, in semi-arid grassland and woodland in eastern Australia, Westoby *et al*. (1989) listed transition catalogues including heavy rainfall (germinating seedlings), plants maturing ('inevitable over time'), fire, and mass mortality of adult plants due to over-grazing, dieback and drought. Bestelmeyer *et al*. (2003) provided a comprehensive review of the development of S&T models for use in managing rangelands. S&T models have also been developed for many natural restoration scenarios (e.g. Stringham *et al.* 2003; Yates & Hobbs 1997) and some minesite rehabilitation cases (e.g. Grant 2006).

The S&T framework provides a holistic, practical, conceptual framework for vegetation rehabilitation, while the vital attributes approach enables the qualities of individual species to be taken into account to predict and manage succession. These two models, and ideas and components of others depending on the particular situation, provide the means for conceptualising the role of disturbance and management in initiating and directing rehabilitation towards desirable end points.

1.2.3.1 Practical Application of Succession models to Rehabilitation

Luken (1990) attempted to bridge the gap between the theory of succession and its practical application by rehabilitation and resource ecologists, by introducing the concept of modern succession management. Adopting notions central to S&T and vital attributes thinking, he emphasised that it is the rate and direction of succession that can be manipulated in plant communities, rather than the actual vegetation state. Hatton and West (1987), in studies on a revegetated strip mine in the USA, found that differences in the initial flora due to different management treatments affected the rate at which a given treatment reached some successional stage, but apparently did not alter its 'successional trajectory'.

Drawing on the vital attributes model and others, Luken (1990) explained that as there are three main factors influencing the success of a species and therefore the composition of an ecosystem, these factors are the key to managing succession. Of primary importance is site availability. Disturbances must be designed to create sites suited to defined species while eliminating sites more suited to others. Types of designed disturbances can include bulldozing, burning, flooding and draining, and soil compaction (Luken 1990).

As differential species availability strongly influences succession, there must be control of which species are able to colonise the site (through access or establishment). As noted by Noble and Slatyer (1981), immediately after a disturbance, there is a pulse of recruitment or regrowth under conditions of little competition for space and other resources. Species slower to take hold in this initial pulse are at a disadvantage. Depending on the particular situation, control of colonisation can be exerted through such things as broadcast seeding, seedling planting, watering, grazing, and fertiliser or herbicide application (Luken 1990). The return of topsoil after mining has been shown to have a significant effect on species recruitment, as it typically contains a substantial seed store representative of the pre-mining vegetation (e.g. Corbett 1999; Koch & Ward 1994; Tacey & Glossop 1980). This is one aspect of species access and establishment that is difficult to control, as topsoil is a valuable resource for a number of reasons, including nutrients and microorganisms. However, it can also contain large numbers of vigorous, early-successional species that can quickly out-compete deliberately sown middle and late seral species.

The third attribute vital to succession is the ability of a species to grow and mature at the site, meaning that species performance may need to be controlled by methods that enhance the growth and reproduction of desired species, while discouraging undesirables. Such methods include protection from fire, burning, grazing, fertilisation, herbicide application and so on (Luken 1990).

A knowledge of the vital attributes of key species enables prediction, and therefore management, of the transitions between states (Westoby *et al.* 1989). Together with an appreciation of the concept of thresholds between states, a combined vital attributes – state-and-transition (VAST) approach should enable much of the guesswork to be removed from rehabilitation management.

Rehabilitation management directs the development of the maturing ecosystem towards the desired end point and to meet required end-point criteria, based on successional trajectories. The desired successional trajectory is the path of development of the ecosystem that most directly (or, at least, successfully in the longer term) leads to the establishment of a self-sustaining ecosystem which, in this case, is as similar to the original ecosystem as possible. If the rehabilitation departs from this trajectory, a number of management techniques (or alterations to the initial establishment methods) may be used to redirect ecosystem development back to the preferred trajectory and thus towards the desired end point.

Timely identification of successful successional development and deviations in early rehabilitation can enable operations to continuously improve their rehabilitation techniques, and save time and money in retreating suboptimal rehabilitation.

S&T models have been developed for a range of ecosystems, particularly rangelands (e.g. Westoby *et al.* 1989; Ash *et al.* 1994; McIvor & Scanlan 1994). A rangeland example is the S&T model of McIvor and Scanlan (1994) for the herbaceous component of the northern speargrass (*Heteropogon contortus*) eucalypt woodlands (Figure 1-1). It assumes that the woodland tree layer remains intact. The model included an estimation of the probability of each transition occurring (Table 1-1). The timeframe of transitions can also be included (e.g. Stockwell *et al.* 1994).

Far less effort has been paid, however, to developing S&T models for natural woodland and forest communities, or anthropogenic efforts to restore or rehabilitate native vegetation after mining. The exceptions include Grant (1997) who developed an S&T model for rehabilitation of jarrah forests after bauxite mining in Western Australia. However none have been developed relating to rehabilitated native tropical woodland ecosystems like those on Groote Eylandt.

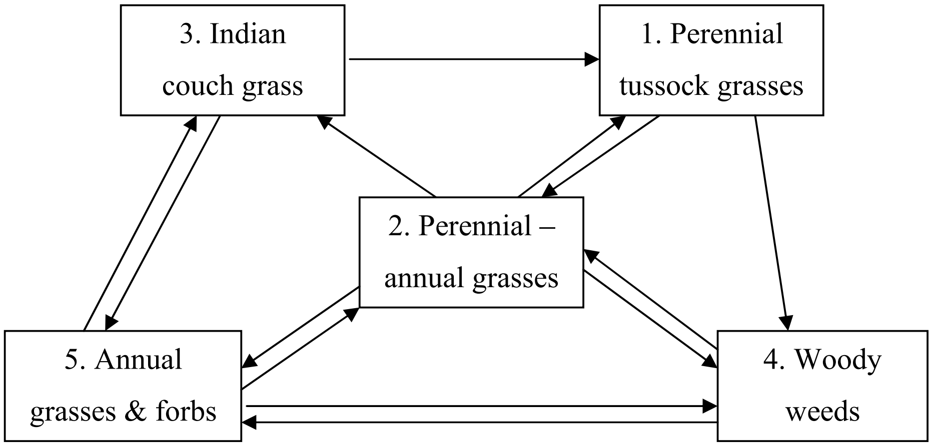

Figure 1-1 State-and-transition model for northern speargrass (*Heteropogon contortus*) woodlands of north Queensland (after McIvor and Scanlan 1994). Descriptions of all states and transitions are provided in Table 1-1

1.2.3.2 Studying Succession

Two general methods are widely used to study succession: chronosequence and repeated measures (Walker & del Moral 2003). The chronosequence method involves sampling vegetation of various ages at one point in time, the assumption being that the different stands are different seres of the same successional pathway. This approach assumes sites are similar in soils, climate, topography, and prior disturbance history, and that stochastic events in some sites or from time to time do not unduly influence successional outcomes. As rehabilitation has been conducted on Groote Eylandt for a number of years, a range of rehabilitated sites of different ages now exists, many of which have received different establishment and ongoing management treatments depending on the desired end point at the time. The implied variety in rehabilitation establishment techniques does not meet the requirements of a chronosequence study in the strict sense and Pickett (1989) instead proposed that space-for-time substitution enables a one-off measurement program to obtain data representative of the behaviour of the ecosystem (taking into account site, vegetation, management differences etc.) over time. Whether succession is inferred from chronosequences, space-for-time substitution or from repeated measures, succession can be conceptualised as a ‘simple’ graph of vegetation characteristics over time (e.g. Figure 1-2). Where significant differences exist in methods of establishment and management of rehabilitation, comparison may be of limited value (e.g. pasture vs native vegetation). However, the objective to re-establish native vegetation has been part of the GEMCO rehabilitation strategy for over 18 years, and so sites range from that age to current-day plantings.

Table 1-1 Definitions of northern speargrass savanna vegetation states and transitions (after McIvor & Scanlan 1994)

State	Description
State 1	Perennial tussock grasses Vegetation dominated by palatable, native, perennial tussock grasses. Typical species: *Heteropogon contortus*, *Themeda triandra*, *Bothriochloa bladhii*, *B. ewartiana*, *Dicanthium* spp.
State 2	Perennial annual grasses Vegetation dominated by a mixture of perennial (as in State 1) and annual grasses and forbs (as in State 5). Typical species: *Chrysopogon fallax*, *Bothriochloa decipiens*, *Eragrostis* spp. (plus those named for States 1 and 5)
State 3	Indian couch grass Vegetation dominated by Indian couch grass (*Bothriochloa pertusa*)
State 4	Woody weeds Vegetation dominated by native or introduced woody weeds. Typical species: *Cryptostegia grandiflora*, *Ziziphus mauritiana*, *Acacia nilotica*, *Eucalyptus* regrowth, other *Acacia* spp., *Carissa ovata*, *Parkinsonia aculeate*
State 5	Annual grasses and forbs Vegetation dominated by annual grasses, forbs and unpalatable perennial grasses. Typical species: *Aristida* spp., *Tragus australiana*, *Sporobolus australasicus*, *Boerhavia* sp., *Portulaca* spp.

Transition	Cause and Probability
T 1→2	Cause: high utilisation during the growing season, especially in below-average rainfall years. Probability: medium–high
T 2→5	Cause: very high utilisation for extended period. Probability: low
T 1→4, 2→4, 3→4, & 5→4	Cause: Seed source, sufficient rainfall for germination and establishment of woody plants, lack of fire; favoured by medium–high utilisation. Probability: low–medium
T 2→3	Cause: seed source, high utilisation. Probability: medium
T 3→5	Cause: very high utilisation for extended period. Probability: low
T 2→1	Cause: low utilisation, above-average rainfall, fire. Probability: medium
T 5→2	Cause: seed source, low utilisation, may require above-average rainfall. Probability: low
T 3→1	Cause: seed source, low utilisation, fire? Probability: low
T 4→5, 4→2	Cause: chemical or mechanical intervention, fire (which transition occurs depends on seed availability). Probability: low
T 5→3	Cause: seed source, medium─high utilisation. Probability: low─medium

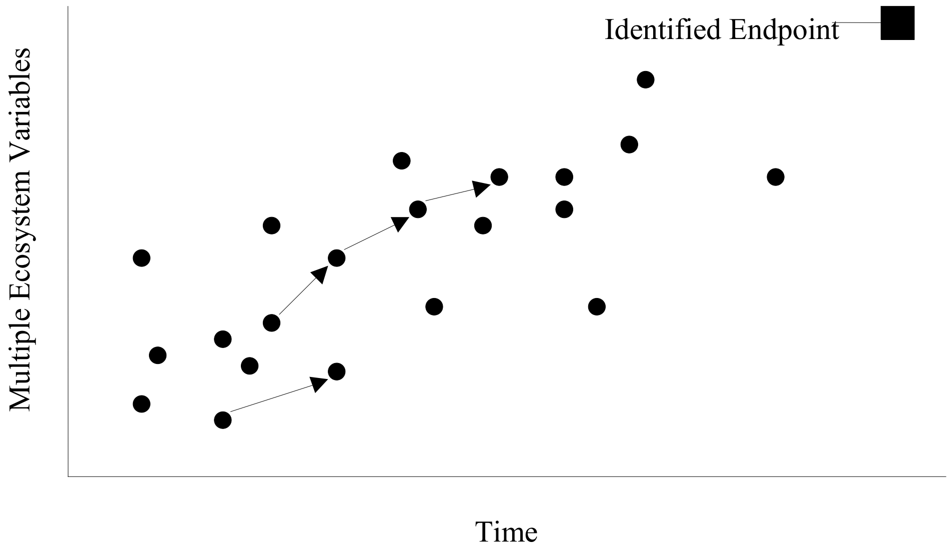

Figure 1-2 Example of successional trajectories of rehabilitated areas towards a desired end point, incorporating both chronosequence and repeated-measures (arrows) data (after Grant & Duggin 2000)

However simple the concept, the development of actual successional trajectories can be confounded by a number of dynamic or variable ecological properties (Gauch 1982), including:

- the complexity of driving forces (such as fire frequency and severity);
- complex spatial patterns between sites of various successional stages;
- the tendency for successional pathways to branch and loop, rather than follow a simple sequence; and
- the influence of stochastic factors.

1.3 Thesis aims, objectives and structure

The overall aims of this research are to identify desirable successional trajectories in rehabilitation on Groote Eylandt that are approaching the identified end point, describe vegetation states where development is undesirable and unlikely to develop into target ecosystems anytime soon, and examine management options to bring deviated sites back towards the desired successional trajectory.

Specific objectives were to:

- describe and compare the characteristics of natural woodland and rehabilitation in various successional states (Chapter 3);
- identify the relationships between management and environmental factors and the floristic composition and structure of rehabilitation at Groote Eylandt (Chapter 4);
- identify and investigate management options to address substandard rehabilitation (Chapter 5); and
- develop a state-and-transition model for rehabilitation at Groote Eylandt including a catalogue of passive and management-driven transitions (Chapter 6).

The thesis provides background information in the form of a literature review (Chapter 1) and a description of the environment of the study region and operations of the Groote Eylandt Mining Company (Chapter 2).

Chapter 3, the first data chapter, documents the vegetation composition and structure in the native woodland and of the rehabilitation. End-point criteria are defined based on the reference, undisturbed *E. tetrodonta* woodland. Differences between the vegetation communities in the native woodland and rehabilitated vegetation based on composition and structure, and the species and structural attributes that characterise these groups, are documented.

Chapter 4 describes the impact of different environmental variables and management history on the composition and structure of the rehabilitation and natural woodland communities. Chapter 5 reports findings of a field trial investigating management treatments to initiate establishment of a satisfactory mix of plants, in particular the optimal substrate mix for rehabilitation at GEMCO. Chapter 6 presents the proposed state-and-transition model for Groote Eylandt, using data from the preceding data chapters as well as application of the vital attributes model.

Chapter 7 is a synthesis and discussion of the implications of the major findings of the thesis, based on information presented in preceding chapters. This chapter also presents recommendations for GEMCO management and further research.

Chapter 2 Study Area and GEMCO Case Study

2.1 Study Area

2.1.1 Location and History

Groote Eylandt is an island in the western bight of the Gulf of Carpentaria, approximately 50 km from the east coast of Arnhem Land, Northern Territory. The island is approximately 2260 km^2, making it Australia's third largest island (ABS 2007).

Aborigines are the original inhabitants of Groote Eylandt. However, it was not until 1644 that it was named by the Dutch explorer Abel Tasman. The name reflects this heritage, meaning 'big island' in Dutch. Aboriginal residents of Groote Eylandt live in two main communities, Umbakumba and Angurugu.

Mining for manganese began in the 1960s after an extensive 4-year exploration by BHP to define the ore body. The Groote Eylandt Mining Company (GEMCO) was formed in 1964 on special mining leases negotiated with the Commonwealth Government, traditional owners and the Church Missionary Society (CMS). A number of milestones has seen production volumes increase, including the commissioning of a 1 million tonne per annum (tpa) concentrator in 1972, an upgrade to 2.3 million tpa capacity in 1986, and a shipping record in 2004 making GEMCO the world's largest manganese ore mine, producing more than 3 million tpa. GEMCO is currently jointly owned by BHP Billiton (60%) and the Anglo American Corporation (40%).

The island is home to more than 1200 indigenous people and around 1200 people of European ancestry (ABS 2007), the latter based primarily in the mining township of Alyangula. The island is under the control of the Anindilyakwa Land Council, from whom visitors are required to obtain a permit. The Anindilyakwa Land Council manages the receipt and distribution of royalties received from GEMCO in return for mining undertaken on Aboriginal land.

Groote Eylandt and a large surrounding area were declared an Indigenous Protected Area (IPA) by its traditional owners in 2006. This designation indicates an intention to manage the area according to international conservation guidelines, and the area is now included in Australia's National Reserve System. This also recognises the high value of the Groote Eylandt region in terms of biodiversity and conservation. The Land Council will receive government funding to support an Indigenous Rangers Program to provide natural resource management for the area as well as training and employment opportunities for community members.

In addition to the traditional indigenous utilisation of island plants, the first botanical collections from Groote Eylandt were made by the botanists Robert Brown and Ferdinand Bauer in 1803 (Specht 1958). In 1948, on the 'American-Australian Expedition', Ray Specht and Charles Mountford visited Groote Eylandt (specifically Little Lagoon and Hemple Bay) for the purpose of collecting plant specimens (Specht 1958b).

2.1.2 Climate

Groote Eylandt experiences distinct wet and dry seasons typical of tropical Monsoon regions (Figure 2-1). The majority of the total annual average rainfall of 1200 mm falls during the summer months of December to April. Very little rainfall is experienced during between May and November. However, as the wet season approaches in October and November, the 'build up' begins where humidity and storm activity increase significantly. In the absence of rainfall, the lightening from these storms can result in hot fires in country where a fully cured (dried) fuel load is still present.

Despite the distinct seasonality of the wet–dry tropics, the timing, extent and duration of the wet and dry seasons can vary considerably (Taylor & Tulloch 1985). The onset of the wet season rains, as opposed to irregular storms, is often unpredictable, and can vary from early November to late January. The decline of regular rainfall toward the end of the wet season can also vary, sometimes ceasing as early as February and other times continuing to fall as late as May–June. While average annual rainfall is 1200 mm, variability between years can range from 630 mm to almost 1950 mm (1970–2005 Bureau of Meteorology [BOM] data for the Alyangula Police Weather Station #14507).

Temperatures range from a minimum monthly average of 17°C in July to an average monthly maximum of 34°C in December (BOM data for the Alyangula Police Weather Station #14507). Variability within days (i.e. between the minimum and maximum) averages no more than 8°C.

Relative humidity remains high year round, with a slight increase during the build-up months of September to November (Figure 2-2).

Unusually high rainfall and high wind speeds, for example in excess of 100 km/hr, are often associated with cyclones and can result in widespread flooding as well as broad-scale destruction of above-ground vegetation. On average, Northern Australia is directly affected by around 1–2 tropical cyclones each year, generally occurring during the summer months (Figure 2-3).

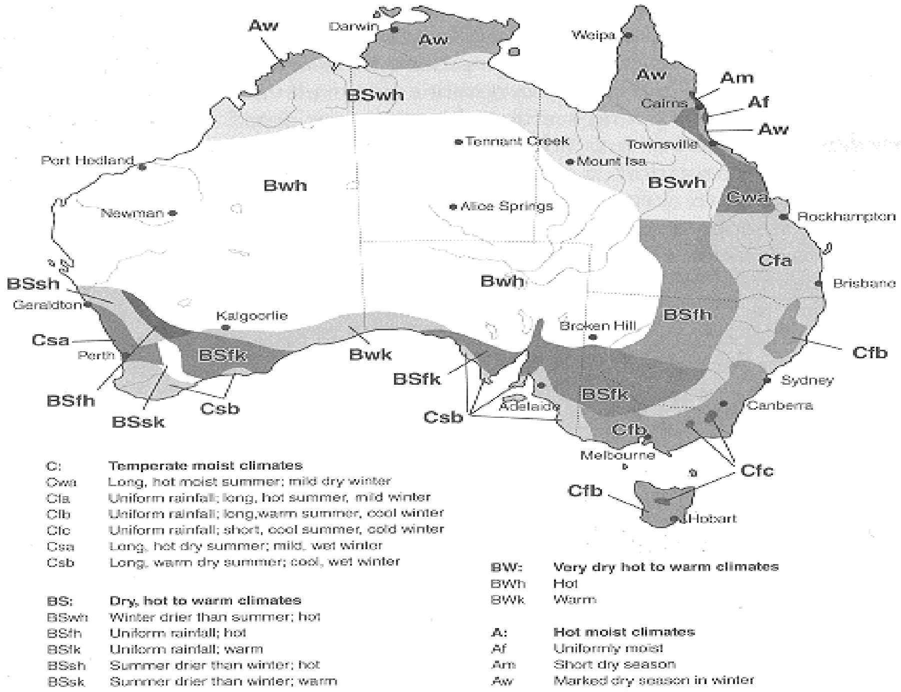

Figure 2-1 Map of climatic zones in Australia (adapted from Russell & Coupe 1984; in Bell 1996)

2.1.3 Geology and Soils

Groote Eylandt is part of an ancient landscape, the quartzite basement rocks dating back to the Proterozoic period (Figure 2-4). The eastern and southern areas of the island are characterised by sand dunes, clayey sand and alluvium of Quaternary age (Langkamp *et al.* 1979). The centre of the island is dominated by a dissected sandstone plateau, rising to 220 m at Central Hill.

The manganese ore body, and therefore location of the GEMCO lease area, is located along the western edge of the island. The ore body is an undulating sedimentary layer, consisting of pisolitic (sedimentary rocks containing spherical or subspherical concretions between 2 and

5 mm in diameter; The Macquarie Dictionary 1997) manganese oxides, between clay and sand beds lying between 20 and 40 m below the soil surface and varying in thickness between 5 and 20 m. It was created by the combination of chemical precipitation and wave action over many millions of years.

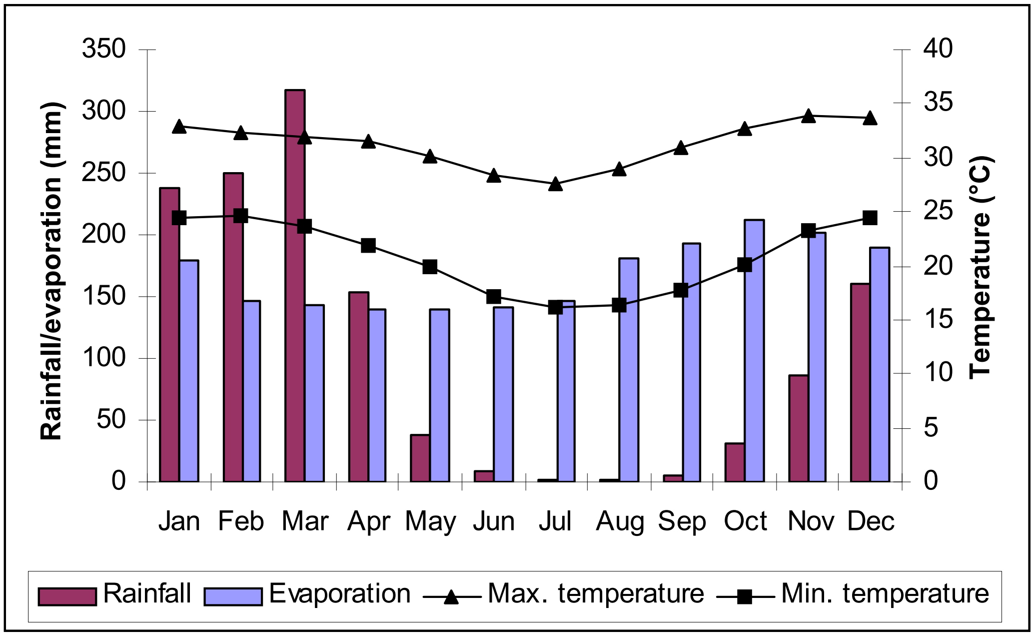

Figure 2-2 Average monthly climatic data for Groote Eylandt, NT (BOM data for the Alyangula Police Weather Station #14507)

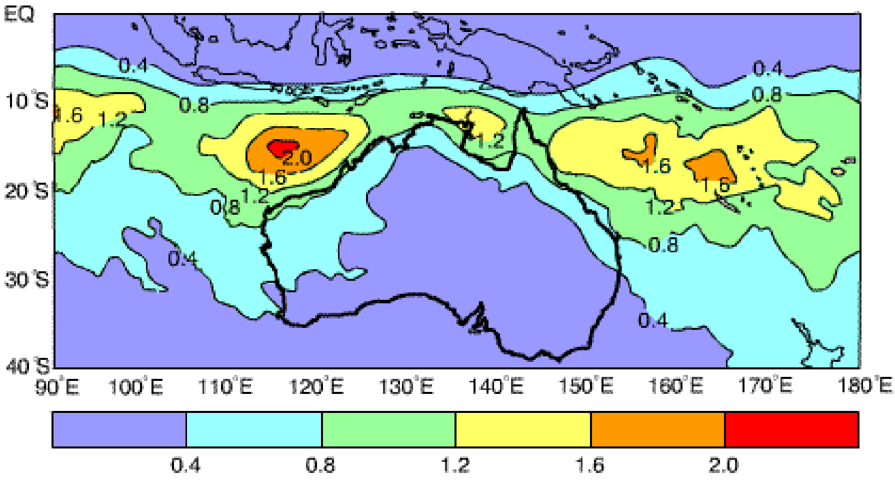

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Figure 2-3 Map showing average annual frequency of tropical cyclones in the Australian region (BOM 2001)

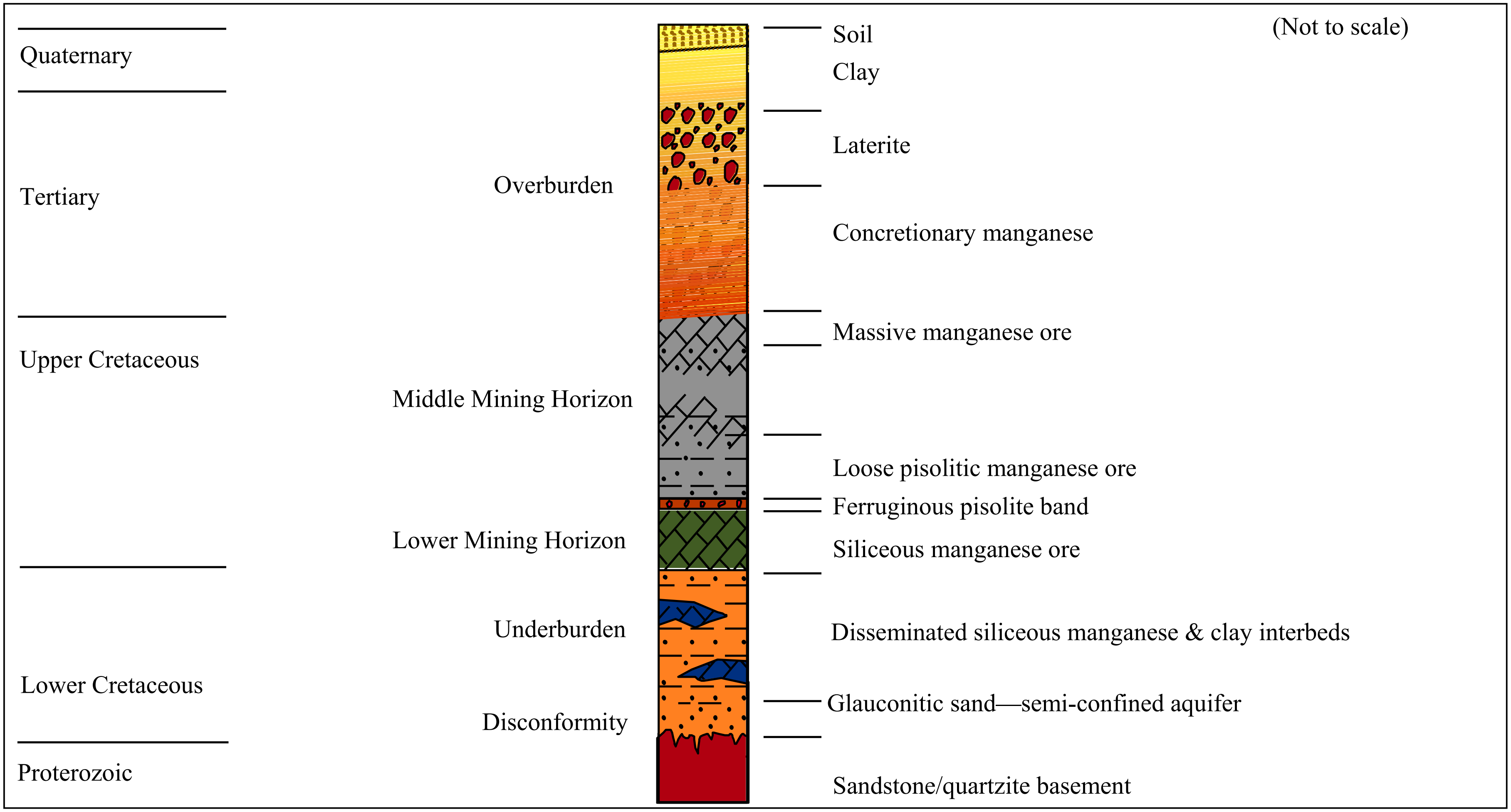


Figure 2-4 Geological profile schematic for Groote Eylandt mining areas (GEMCO 2000)

Northcote (1968) provided a general description of the soils of Groote Eylandt. Mining activities occur in the western gently sloping terrain characterised by yellow earthy sands (Uc 5.22) and sandy yellow earths (Gn 2.21). Also to be found are red sandy earths (Uc 5.21), ironstone gravels (Js-Uc 4.11) and neutral and acid red massive earths (Gn 2.11, Gn 2.12). These soils, as with soils typical of the tropical north of Australia, are very old and highly leached. This means they have inherently low fertility, including a particularly low phosphorus and nitrogen content (Langkamp & Dalling 1979).

Langkamp and Dalling (1979) characterised the profile of a soil typically disturbed as part of the mining and rehabilitation processes, for the purposes of assessing the requirements for establishment of agronomic crops and found profound deficiencies in nitrogen and phosphorus, as well as possible deficiencies of trace elements, potassium, calcium, magnesium and sulphur. However, compared to nutritionally demanding agronomic plants, native plant species might be expected to cope with the nutritional status of the soil, and gain only limited benefit from any fertiliser applications (compared with that experienced by agronomic species) (Langkamp & Dalling 1979). In fact many Australian natives are sensitive to agronomically desirable levels of P. For example, 18% of over 800 native species trialled with five levels of phosphorus showed some symptoms of phosphorus toxicity at even low rates of phosphorus addition (Handreck & Black 2002).

2.1.4 Vegetation

The vegetation of Groote Elyandt is comprised of three structurally homogenous communities: *Eucalyptus tetrodonta* open forest (on laterite substrates), *E. tetrodonta* low open woodland (co-occurring with manganese deposits) and *Callitris intratropica*/*E. tetrodonta* open forest (sandstone) (Langkamp *et al.* 1979). As the GEMCO mining leases occur mostly over manganese deposits with significant laterite overburden, open woodland communities dominated by *E. tetrodonta*, often co-dominant with *Eucalyptus miniata,* are the dominant vegetation types disturbed during the mining process (Crooks 1995; Figure 2-5). *Eucalyptus ferruginea*, *E. polycarpa and E. confertiflora* are occasionally also found in the woodland canopy. A variety of woody species can be found in the generally sparse midstorey, including *Buchanania obovata*, *Erythrophleum chlorostachys, Petalostigma banksii*, *Cycas arnhemica* and acacia species. The understorey is dominated by perennial grasses, predominantly *Heteropogon triticeus*, but also *Sorghum stipioedeum* and a number of species of *Aristida* and *Eriachne*. Legumes dominate the understorey herb layer, including *Desmodium trichostachium*, *Crotalaria montana* and *Vigna* spp.

Figure 2-5 Undisturbed *Eucalyptus tetrodonta* open woodland community

Traditional Aboriginal interaction with the Groote Eylandt environment included regular burning of large areas of country to facilitate hunting and food gathering (Cole 1975). With the centralisation of modern Aboriginal communities, and the development of vehicle track networks providing access to recreational and foraging destinations, this traditional requirement no longer exists. Despite this, frequent, often annual, burning is still observed, especially in those areas adjacent to the communities and access routes. Areas that experience reduced burning frequencies have increased ground litter cover, and also increased density and complexity in the midstorey vegetation layer. Of note are the shrubs, *Acacia latescens* and *Hakea arborescens*, in less frequently burnt areas (Langkamp *et al.* 1979).

2.2 GEMCO and The Mining Process

2.2.1 Groote Eylandt Mining Company (GEMCO)

The 60% BHP Billiton-owned Groote Eylandt Mining Company (GEMCO) mines high-grade manganese from leases extending over an area of approximately 50 km^2 on the western side of the island. The GEMCO leases used for mining and associated activities cover approximately 94 km^2 in area. Mining operates in any of nine different quarries around the lease (Figure 2-6), and occur in an area spanning approximately 16 km (north–south) by 6 km (east–west) at its widest points.

GEMCO is now the largest manganese-producing mine in the world. The company employs around 250 people and has increased mining so that recent annual exports have exceeded 3 million t (GEMCO 2005). The manganese deposits of Groote Eylandt are in the vicinity of 186 million t of *in-situ* ore.

2.2.2 Legal Responsibilities and Completion Criteria

The situation on Groote Eylandt relating to completion criteria is unique because the lease conditions require that mined areas must be rehabilitated to the satisfaction of the Anindilyakwa Land Council (ALC). The current expectation of the ALC is that ‘the land be brought back to what it was before GEMCO’ (B. Todd, GEMCO, pers. comm. 2000). This seemingly simple expectation has never been clearly defined from either GEMCO’s or the land owners’ perspective. The fact that this land is Aboriginal land and the perception of Aboriginal people is yet to be quantified determines that definitions are required prior to determination of scientifically substantiated assessment criteria for rehabilitation.

It is beyond the scope of this study to endeavour to undertake the significant consultative effort required to adequately identify the anticipated final land use after mining at Groote Eylandt. In the absence of this agreed target, it is assumed that native woodland areas adjacent to rehabilitated mines are representative of the native vegetation present prior to mining and are, therefore, suitable as reference for end point criteria determination.

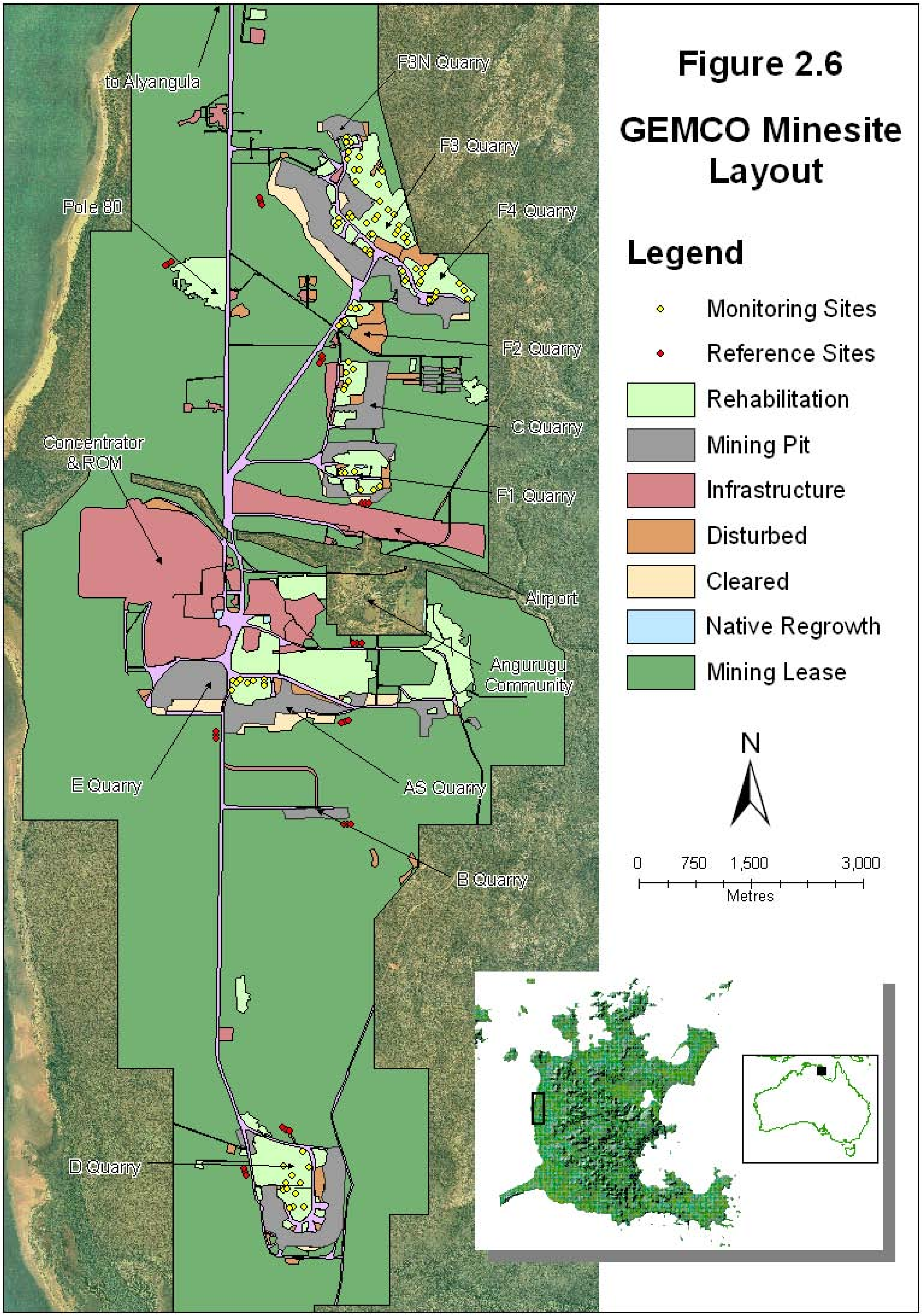


Figure 2-6 Location and layout of GEMCO western mining lease and quarries

2.2.3 Rehabilitation Objectives

GEMCO mine site rehabilitation began in 1972 focusing on revegetation with pasture species and later inclusion of some forestry trials. Rehabilitation techniques developed through time, with the involvement of traditional owners, toward sustainable ecosystems. Revegetation for the past 18 years has been focused on the establishment of the open savanna woodland present in unmined areas. Rehabilitation has been variable in its success, largely due to uncontrolled fires and weed invasion. Refinement of management techniques, monitoring and research into the GEMCO rehabilitation program has been lacking.

With the transition through time of rehabilitation targets from pastoral and forestry to native vegetation, the seed mixes used in rehabilitation have also changed. Earlier rehabilitation targets and seed mixes included:

- Focussing on a pastoral final land use target, the seed mix contained all exotic pasture grasses and leguminous herbs such as *Chloris gayana*, *Stylosanthes humilis* and *S. scabra*;
- After the failure of pastoral attempts, native vegetation was introduced, with exotic grasses maintained for soil stability and organic matter accumulation;
- Attempts to increase the success and development of overstorey canopy species, as well as investigate the potential for south-eastern Australian eucalypt species for forestry production, led to a change in the seed mix to include ‘exotic’ species such as *Eucalyptus alba*, *E. papuana*, *E. bigalerita*, *E. ferruginea*, *E. camaldulensis*, *E. tereticornis* and *E. tintinnans*;
- As these trials failed to thrive, the focus again shifted back to mostly local species, being the main overstorey eucalypts (*Eucalyptus tetrodonta*, *E. miniata* and *Corymbia polycarpa)* and various acacias, some non-local, for their nitrogen-fixing properties and ability to rapidly colonise a site (e.g. Table 2-1); and
- In more recent times, this local native seed mix has been further diversified by the inclusion of a number of subcanopy and midstorey trees and shrubs including *Planchonia careya*, *Terminalia ferdinandiana* and *Petalostigma banksii*.

Most recently, but not in areas included in this study, the acacia component of the seed mix has been significantly reduced in recognition of the significant impact these plants have on early rehabilitation through competition for limited resources, especially water. The contribution of acacias to soil nitrogen concentrations or the organic carbon cycle is not sufficient to mitigate the negative effects of this competition.

2.2.4 Mining and Rehabilitation Operations

Mining operations at GEMCO involve the removal of manganese ore by open-cut strip mining. This results in a major change to the natural substrate, in terms of chemistry, compaction, stratification and so on, all of which can have implications for subsequent rehabilitation establishment and success.

The mining process is a continuous cycle where mined-out areas being prepared for rehabilitation use material being removed from adjacent areas about to be mined. This ensures that the total area disturbed at any one time is minimised, and also that fresh material is used to best effect to improve the quality of rehabilitation outcomes. Thus rehabilitation is conducted as an ongoing component of the mining process with recently mined areas being rehabilitated as soon as possible after completion of mining, as the mining pit progresses following the manganese ore seam.

In line with mine planning, areas to be mined are cleared of vegetation by large bulldozers, with logs, branches and most of the other vegetative material being stockpiled and burnt. Although returning this material to the rehabilitated landscape would be desirable in terms of additional organic matter and provision of habitat structures, it is not currently feasible. Earthmoving equipment is not designed to move potentially large logs along with the earth, and this increases the safety risks associated with the earthmoving process. Individual replacement of logs after the substrate has been returned has been considered, and is practised on some mine sites elsewhere (e.g. Alcoa; Koch 2007a). However there are issues associated with compaction of the returned soil profile and the added costs of this activity which have yet to be addressed adequately so that salvaging of the cleared logs can be included in the rehabilitation procedure.

After clearing, topsoil is removed by front-end loaders and trucked to nearby areas being prepared for rehabilitation, or else stockpiled if such areas are not available. The overburden is pushed aside by D11 bulldozers to reveal the manganese ore. The upper layer of ore is blasted with explosives to break it into pieces able to be loaded into haul trucks by the 120-t O&K excavator (Figure 2-7). The haul trucks deliver the ore to the beneficiation plant, or ‘concentrator’ where it is crushed, sorted and washed to create the final manganese product. Wastes from this process are pumped to the nearby tailings dams as thickened slurry, which are called ‘sandtails’ once dewatered and dry enough to be handled. Physically, sandtails are similar to a coarse sand although they are black-grey in colour.

Figure 2-7 Mine pit with the O&K excavator loading manganese ore into a Komatsu 785 haul truck

The finished manganese product is transported by road trains along the 16-km ‘highway’ to the Milner Bay port facility, where it is loaded onto large ocean-going vessels to be exported to customers around the world. Following the removal of ore, overburden is backfilled into the mined-out pits by bulldozers. Fresh topsoil from adjacent areas being cleared is placed on top of the backfilled material. Sometimes stockpiled soil or sandtails is used, but this is then amended with additions such as fertiliser to increase its value as a growing medium.

After all of this handling, the substrate can be very compacted, which may impede water infiltration, root penetration and thus affect plant establishment and development (Bassett *et al.* 2005). Ripping is the act of using a long pick towed behind a bulldozer, and pushed at least 1 m into the ground, to ‘rip’ apart this compacted material and provide access for water and roots into the material. On Groote Eylandt, the ripping dozer tows behind it a large ‘flattening’ bar which levels off the final surface.

Failing to satisfactorily relieve this compaction may negatively impact vegetation establishment and development in a number of ways, including:

- Create waterlogging due to lack of water infiltration and decreased oxygen availability causing unhealthy plants (Bassett *et al.* 2005) and ultimately inability of drier forest and woodland species to persist, favouring wetter species such as melaleucas;
- Result in a reduced maximum canopy height in mature rehabilitation due to the shallow roots providing insufficient stability of tall trees against strong winds (Kodrik & Kodrik 2002). This has been observed at the, now decommissioned, Narbarlek uranium mine in western Arnhem Land (pers. obs. 2003); and
- Stunted woody plant habit due to lack of rooting depth or nutrient availability.

Soon after ripping, the soil surface is scarified to even out the topsoil and break up large clumps of soil. Fertiliser, in the form of superphosphate and di-ammonium phosphate, is applied by a spreader pulled behind a tractor at a rate of 200–300 kg/ha for both (GEMCO 1999). Lime at 500 kg/ha is also applied, to improve soil structure and ameliorate any increased acidity due to soil handling or stockpiling. Following this, and just prior to seeding, the area is scarified a second time to incorporate the fertilisers into the topsoil and also to provide a suitable seedbed for early plant establishment to a depth of 30 cm.

GEMCO uses a range of plant establishment techniques including broadcast seeding in the very early wet season, wet-season hand planting of seedlings and dry-season planting followed by irrigation. The technique chosen depends on the season, site location and other site characteristics such as pre-existing vegetation structure and composition, hydrology and soil type. Direct seeding is the most broadly used technique, with seed applied by tractor-towed fertiliser spreader at rates calculated to achieve the target densities of desired species (Table 2-1). Smaller seeds, including eucalypts, are bulked with a dilutant, like sieved potting mix, to ensure an even spread. Large seeds, that would not fit through the aperture of the fertiliser spreader, are manually sown by employees walking across the rehabilitation area (GEMCO 1999).

Most hand planting of seedlings is conducted during the wet season, when water is ample. During the dry season, what little rehabilitation is established is by direct planting only and requires irrigation (daily hand watering) for at least 2 months. Seedlings of mostly eucalypts are grown onsite in the rehabilitation nursery, which can produce over 15 000 plants each year (GEMCO 1999). The target seedling planting density is approximately 1000 plants/ha in total.

Table 2-1 1998 Native species mix

Botanical Name	Common Name	Anindilyakwa Name	Seed Rate (g/ha)
Acacia aulacocarpa	Broad leaf wattle	Merrika	50
Acacia auriculiformis	Pale barked wattle	Marra	25
Acacia latescens	Ball wattle	Mebina	50
Acacia torulosa	Deep gold wattle	Mebina	25
Alphitonia excelsa	Red ash	Jangawila	50
Callitris intratropica	Cypress pine	Yimundungwa	50
Eucalyptus miniata	Darwin woolybutt	Mawurdarra	50
Eucalyptus polycarpa	Bloodwood	Alumilya	100
Eucalyptus tetrodonta	Darwin stringybark	Alabura	100
Grevillea heliosperma	Red flowering grevillea	Yilingbirradangwa	50
Grevillea pteridifolia	Fern leaf grevillea	Yinungkwurra	50
Hakea arborescens	Yellow hakea	Arrarruwurra	10
Melaleuca leucodendra	Weeping paperbark	Yirarrnganga	100
Pandanus spiralis	Screw palm	Mangkurrkwa	500

Both establishment techniques and management after establishment can have significant influences on the successional progress of a community. Management manipulations can involve any aspect of the management process that has the potential to influence the successional progress and ultimate 'success' of the rehabilitation. This can range from amended establishment techniques (e.g. species composition, seedling planting or direct seeding, timing, soil materials and preparation and fertilisation) to post-establishment management techniques (e.g. weed removal, fire protection or exposure, and fertilisation).

Areas that are shown by monitoring to have too few of the key species are remediated by hand planting. If affected by weeds, they may be included in the weed management program to receive chemical or physical weed treatment. Chemical weed treatment normally involves the use of herbicides, such as glyphosate-based Round Up^{TM}, applied to weeds from back pack or vehicle-mounted spray units. Physical control techniques can include removal of smaller plants with hoes or mattocks, cultivation with tractor-towed ploughs or chainsaw or axe removal of larger woody weeds.

2.3 Current Status of Groote Eylandt Rehabilitation

A substantial proportion of the rehabilitation on Groote Eylandt was considered substandard due to heavy weed infestations or inappropriate species composition due to unbalanced seed mixes, variable germination success or burning by wildfires, particularly late in the dry season (Grant & Duggin 2000). On Groote Eylandt, it is critical that rehabilitated areas are resilient to the management regimes of the traditional owners, particularly fire, and do not act as havens for the invasion of weed species. Another major factor in the long-term success of rehabilitation is the development through time of the site and its vegetation along a desired trajectory such that it is likely to attain the ultimate desired set of characteristics or criteria. Depending on the success of techniques adopted in the preceding stages of the rehabilitation process, as well as other ongoing pressures (e.g. climate, surrounding weeds, fire and feral animals), the rehabilitated area may require ongoing management efforts such as protection from fire or competition from 'weeds' or thinning if plant densities are too high.

In the late 1990s, GEMCO identified a need to rectify this situation as well as improve techniques to avoid substandard rehabilitation in future. To do this, meaningful measures of successful rehabilitation were desired, so that management could:

- Clearly assess their existing rehabilitation in terms of assets and liabilities;
- Respond to early failures or identify opportunities for improvement in newly established rehabilitation; and
- Identify appropriate management techniques to improve substandard rehabilitation.

In 1999, GEMCO invited Dr Carl Grant and Dr John Duggin to Groote Eylandt to provide preliminary advice on how to initiate this improvement in knowledge of rehabilitation development and management. The resulting trip summary highlighted a number of the key observations and proposed a research program that would assist GEMCO in reaching its objective of best practice in ecosystem rehabilitation (Grant & Duggin 2000). Specifically, the research program proposed to provide the mine with:

- Identification of the various rehabilitation 'states' present
- Quantifiable criteria to describe these states; and
- Identification of potential management options, and proposed management manipulation experiments, aimed at getting substandard areas back on the right trajectory.

The first phase of this program, which is addressed by this thesis, would focus on vegetation composition and structure. Later phases of the program should be extended to look at rehabilitation in terms of nutrient cycling, invertebrate and vertebrate recolonisation, seed set and presence of pollinators.

Grant and Duggin (2000) proposed that a set of rehabilitation 'states' exist at Groote Eylandt that could be considered in terms of a state-and-transition model with a desired developmental trajectory (Figure 2-8). Some of the states, however, represented undesirable deviations from this trajectory that would be unlikely to reach the target end point without further management effort.

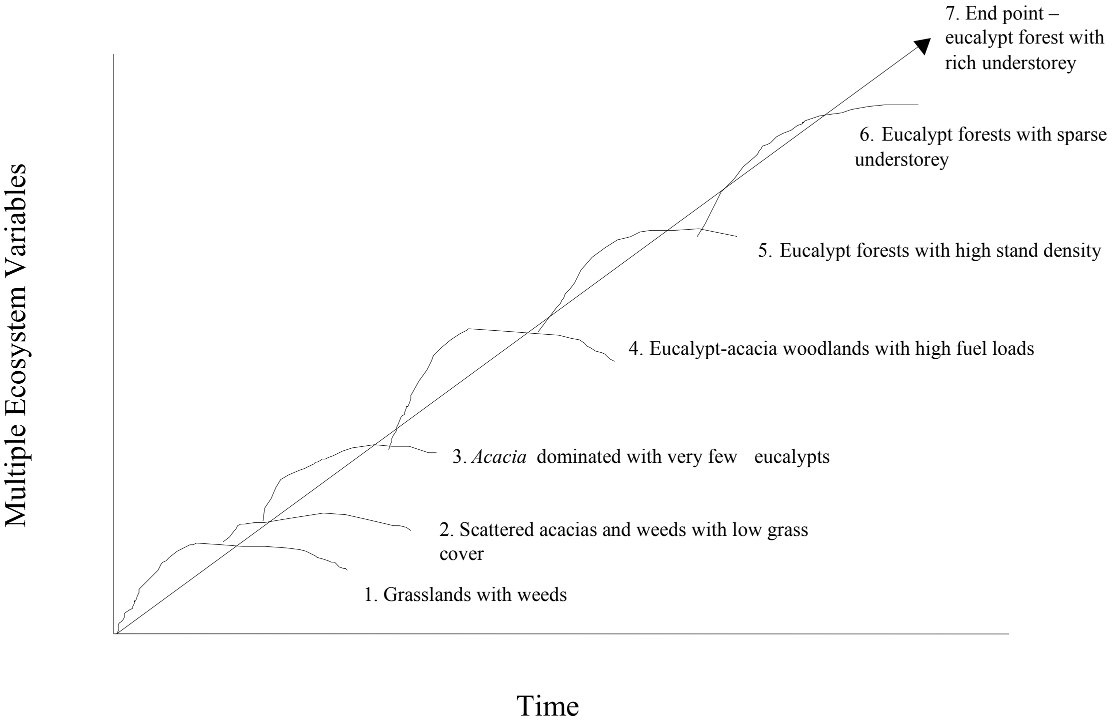


Figure 2-8 Identified states in GEMCO rehabilitation (after Grant & Duggin 2000)

Chapter 3 The Characteristics of Natural Woodland and Rehabilitation at GEMCO

3.1 Introduction

Critical to assessing the success of mining rehabilitation in a wooded environment is a knowledge of the ecology of the natural forest or woodland, including the natural ecosystem's composition, structure and function, as well as the disturbance regime, such as fire or seasonal drought. Rehabilitation is, by definition (Aronson *et al.* 1995), different to mature reference ecosystems. Comparisons between natural woodland and rehabilitation that attempts to mimic it must be made with regard to the ecological principles that govern the behaviour of natural and reconstructed ecosystems, including disturbance dynamics. While the two systems may share many characteristics in common, there may also be fundamental differences, which may all but preclude the comparison of some traditional ecological measures without careful consideration. On the other hand, rehabilitation and target woodland can share similar characteristics in terms of vegetation composition, structure and function (i.e. occupy the same ecosystem 'state'), but are likely to have had very different origins, or been subject to different disturbance regimes.

3.1.1 Ecology of the Eucalypt Savanna Woodland Ecosystem

Eucalypt-dominated savanna woodlands and forests cover the great majority of northern Australia (Boland *et al.* 1992). Such a broad distribution throughout the wet–dry tropics is controlled predominantly by four factors (Williams *et al.* 1996):

1. Underlying geomorphology, which influences site hydrological features and soil fertility;
2. Mean annual rainfall;
3. Seasonality and predictability (inter-annual variability) of climate; and
4. Frequency and severity of disturbance events, especially fires.

These factors govern the structural complexity (e.g. height, biomass, number of strata, size class distributions, root depth and distribution patterns), species composition and the functioning of the vegetation (e.g. water use, nutrient uptake, regeneration strategies, phenology; Reddell & Meek 2004). Where water is not the limiting factor, vegetation patterns generally follow soil nutrient or texture gradients (Florence 1996).

Plant adaptations reflect the environmental conditions in which they evolved and thus plants have adapted to one or more extremes of soil nutrient deficiencies, drought, frost, waterlogging, salinity, heat, soil acidity and fire (Kriedemann 1996). Key natural selection influences in the evolution of northern Australian vegetation include the disturbance regime, for example fire, cyclones, and wet–dry seasonality. The plants of these communities fall into two groups based on their survival strategy: *K*-strategists (long-lived plants with low reproductive rates) and *r*-strategists (short-lived plants with high reproductive rates).

Plants exhibiting a *K*-strategy, or sprouters (Whelan 1995), include all the long-lived, keystone species in the *Eucalyptus* savanna woodlands or forests, and rely on an ability to resprout from lignotubers and root suckers (Ward *et al.* 1997; Lacey & Whelan 1976; Fensham & Bowman 1992). Although they produce and shed seed, seedling regeneration is considered rare in *Eucalyptus tetrodonta* and *E. miniata* (Fensham 1992) and the chance of an individual seedling surviving by the end of the first dry season is extremely low, considering their slow growth and the combined pressures of lack of water and the likelihood of fire. One study found that, of 5000 young seedlings of framework species observed in census plots, not one survived after 2 years (Reddell & Zimmermann 2002). Other research in north Australian eucalypt savannas has found that seedlings of *Eucalyptus miniata* and *Acacia oncinocarpa* grown from seed were all killed by fires in the first dry season after germination (Setterfield 2002). Emergent seedlings of the two species that were not burnt were reduced by 75% and 65%, respectively, by the end of the first dry season, and this had further dropped to only 11% and 33%, respectively, survival by the middle of the following dry season. In contrast, woody resprouts of keystone species are common components of the ground and understorey layer of these communities. These sprouts spring from subterranean lignotubers, and thus avoid being eliminated by the frequent low-intensity fires that are a major disturbance in the northern savannas.

Some *K*-strategy species, such as eucalypts, can resprout from relatively small pieces of root, rhizomes or lignotubers (Fensham 1992). While most eucalypts with the ability to resprout from roots do so from shallow rhizomes, *Eucalyptus tetrodonta* is unique in that it is able to resprout from lateral roots (Brooker & Kleinig 1994). An extensive root system is also important in most plants with limited nutrient and water resources, and is further enhanced by the existence of a lignotuber. Lignotubers are swellings around the base of the stem, often underground, that accumulate and store nutrients and house dormant buds which enable rapid regeneration after disturbance, especially fire (Bond & Midgley 2001; Westman & Rogers 1977; Langkamp & Dalling 1979; Florence 1981). Lignotuberous plants exposed to annual fires may be able persist as a suppressed layer of resprouts, but will be unlikely to develop in stature until fire is excluded for 3 to 5 years (Williams *et al*. 2003a). The lignotubers of many species diminish as plants mature, but those growing in areas where nutrient supply is particularly deficient, can persist and form a significant component of the mature tree (Florence 1996). A study of the biomass allocation of three dominant canopy tree species in Kakadu National Park (Werner & Murphy 2001) found that, as a tree grows, there is a decreasing proportion of total biomass below ground. For example, *Eucalyptus tetrodonta* was found to have a root–shoot ratio of 0.50 for trees less than 10 cm in diameter-at-breast height (DBH), 0.40 for trees of 20 cm DBH, and 0.25 for trees 40–55 cm in DBH (Werner & Murphy 2001).

The benefits of below-ground biomass, including lignotubers, are more important to young plants. The temperature gradient generated by a fire decreases with increasing height above ground (Whelan 1995). Thus, once plants reach a minimum height, say around 2 m (Andersen *et al.* 2005), they escape destruction of their above-ground stems caused by a typical Top-End fire and will be able to emerge from the fire-suppressed understorey.

Plants with an *r*-strategy are typically short-lived plants with high reproductive rates, and include the majority of ground-storey grasses and herbs as well as some short-lived shrubs and trees, such as many acacias and grevilleas. These species generally rely on seed for reproduction and develop a soil seed bank (Ward *et al.* 1997). This strategy is based on the ability to rapidly colonise a disturbed area and capture the resources made available by the disturbance. The frequency and intensity of fire has a major effect on the composition of *r*-strategists that capture a disturbed site (Andersen *et al*. 1998; Fensham & Bowman 1992; Grant & Loneragan 2001; Lonsdale & Braithwaite 1991; Williams *et al*. 1999, 2003b). Such species may not contribute significantly to ecosystem stability, but provide important habitat and food resources for fauna.

Groote Eylandt *r*-strategists include acacias, which can be reasonably grouped together due to their shared traits but include a range of life forms, including species with a low groundcover habit (*Acacia yirrakallensis*), medium shrubs such as *A. latescens*, and trees like *A. aulacocarpa*. A common feature of acacias is that they grow rapidly, making them popular for agroforestry (e.g. Doran & Turnbull 1997). They are also relatively short-lived, compared to other overstorey species such as eucalypts. However, this trait is more variable and correlated with life form. For example, the medium-height, shrubby *Acacia holosericea* is short-lived (maximum of 10–12 years; Doran & Turnbull 1997), while the large trees of *A. aulacocarpa* are longer-lived (> 30–40 years).

Recalcitrant species are a special case and will not successfully establish in rehabilitation even with topsoil handling that suits most species, seed collection and application efforts, or self-colonisation over time via a range of dispersal mechanisms (animals and wind). Worsley (URS 2004) defined a species as recalcitrant if its frequency of occurrence in rehabilitation-monitoring plots is less than 30% of that in the forest-monitoring plots. These species are often resprouters which is the plant type most depleted by mining activities. At Alcoa, many recalcitrant species are grasses and sedges that have little viable seed. These are propagated in a state-of-the-art nursery–laboratory, enabling Alcoa to achieve world's best-practice success in restoring biodiversity (Koch 2007b).

Most natural disturbances, such as fire, predominantly affect above-ground biomass, favouring long-lived, keystone *K*-strategists that have persistent below-ground structures. Unnatural disturbances, including mining, that destroy these below-ground structures, remove the competitive advantage and ability to persist of these species. Rehabilitation of mined-out ecosystems will not be able to utilise the resilient features of keystone species, but must reinstate these features through facilitating recolonisation and development from seed. The most important aspects of the establishment of keystone species from seed are (1) protection from fire, while below-ground structures develop, and (2) minimal competition from faster-growing, *r*-adapted plants. Until the resilience of keystone species is reinstated, the successful long-term development of rehabilitation is less likely.

3.1.2 Fire Ecology

Fire is a major exogenous feature of Australian eucalypt-dominated ecosystems, especially subtropical savanna woodlands (e.g. Gill 1981; Bradstock *et al*. 2002). Removal of vegetation and litter by fire strongly influences nutrient cycling in savanna ecosystems of northern Australia (Cook 1994). The frequent occurrence of fire has driven the evolution and development of savanna woodland and has resulted in the fire-tolerance and reproductive adaptations that enable the range of plant and animal species found in these systems to persist.

In northern Australia, savanna forests and woodlands are often burnt due to traditional burning of country by indigenous peoples, prescribed burning for infrastructure protection and biodiversity conservation, and wildfires. Tropical savannas worldwide are intentionally burnt every 1 to 3 years (Andersen *et al*. 1998).

Intensity, frequency and timing are all important factors that impact on the influence fires have on the environment (Gill 1981; Bradstock *et al*. 2002; Woinarski *et al*. 1999). Intensity is often related to timing, for instance late dry season burns are usually more intense as fuel is very dry, but can also be influenced by the type of fuel (e.g. fire-promoting grasses such as gamba grass (*Andropogon gayanus*)). Deliberately lit fires usually occur earlier in the dry season than wildfires, and therefore are generally less intense and less destructive to vegetation.

Two major research projects in the Northern Territory, Munmarlary and Kapalga, have examined savanna dynamics in relation to different fire regimes at landscape scales (e.g. Bowman and Panton 1995; Andersen *et al*. 1998, 2003, 2005). Sites at Kapalga that had been unburnt for a number of years were found to have less grass cover (7% in November and 13% in March) than sites that had been burned annually (for 5 years) in the early or late dry season (Setterfield 2002). These previously-burned sites had 11% and 15% grass cover, respectively, in November and over 25% for both by the end of the wet season in March.

With the pattern of frequent dry-season fires on Groote Eylandt often affecting rehabilitation of all ages, any litter accumulated is removed by burning. Nutrient cycling in tropical, fire-dependent ecosystems, such as the Groote Eylandt eucalypt woodlands, is driven by this disturbance regime (Cook 1994). Annual litter accumulation can be significant (depending on vegetation composition and structure), especially due to grass, and fallen leaves and branches. In the humid wet season, this organic material is rapidly decomposed by soil micro-organisms, providing significant nutrient input, much of which is available to plants at the precise time they are growing most rapidly and require it. As the dry season progresses and soil moisture is depleted, and with the removal of the litter layer by fire, microbial activity declines (Cook 1994).

Figure 3-1 Fire resilient strategies of the eucalypts include (a) root sprouts, (b) basal resprouts from lignotubers, and (c) epicormic sprouts

Figure 3-2 Woodland fires are typically of low intensity and only affect the ground layer

3.1.3 Aims and Objectives of this Chapter

In 1999, a review of the GEMCO rehabilitation monitoring program (Grant & Duggin 1999) recommended that permanent plots of rehabilitation of different ages be established and repeatedly measured to enable the successional trends in rehabilitated sites to be determined (Section 2.3). As a result, GEMCO and UNE collaborated to support the current study.

Rehabilitated sites of various ages (0.5 to 19 years old) and quality (e.g. good quality, weed-infested), often the subject of different rehabilitation goals (e.g. pasture establishment, forestry and native vegetation) and rehabilitation techniques (e.g. substrate handling, seed mix, fertiliser application, and remediation) were chosen along with adjacent sites in unmined areas (reference woodland sites). Measurements of soil and vegetation parameters were undertaken twice per year over 3 years so that both site-specific and chronosequence information was obtained.

This chapter aims to describe and compare the characteristics of forest sites and rehabilitation areas in various successional states. The specific objectives of this chapter are to:

- document the differences in vegetation composition and structure between the natural woodland and rehabilitation as a whole;
- define end-point criteria based on the composition and structure of the *E. tetrodonta*-dominated savanna woodland;
- identify potential changes in rehabilitation over time through the use of chronosequence data; and
- identify and describe groups of rehabilitated sites sharing similar vegetation composition and structure.

3.2 Methodology

3.2.1 Site Selection, Layout and Sampling

3.2.1.1 Experimental Design and Sampling Strategy

The collection of chronosequence-type data involved the stratified, random selection of a suite of rehabilitated sites of different ages spread across the GEMCO mining leases. Using the ArcView™ GIS program, the leases were stratified into quarries, overlaid with a grid, and computer-generated random numbers used to select sites of different rehabilitation age within each quarry. Areas included in the selection process were only those that were more than 1 ha in area, considered to reflect the rehabilitation objective of native woodland return, and did not contain any anomalous features, such as significant heterogeneity in vegetation type, cover, patchiness, low-lying wet or boggy areas, steep, erosion-prone contours and the like. Undisturbed woodland sites were selected randomly from zones inside the lease area and within 1 km of each quarry, in areas where the strip-mining process was not planned to proceed in the medium term. Types of vegetation community within the lease area that are not regularly disturbed by mining activities (e.g. *Callitris* forest) were not included in the selection process. Once chosen, the grid method was again used to randomly determine the position of three replicate monitoring plots within each site.

A total of 42 sites were initially selected for inclusion in the monitoring program which included nine areas of undisturbed woodland and 34 areas ranging in age from 0.5 years to 19 years (Table 3-1).

Table 3-1 Number of sites by age and quarry

Year of Rehabilitation*	Age**	Quarry (numbers in parentheses indicate number of sites per quarry if > 1)	No. of sites
2000	0.5	F4	1
1998	2	AS, F1, F3	3
1997	3	D, F1, F3, F3N	4
1996	4	D, AS, F3, F4 (3)	6
1994	6	F3N	1
1993	7	AS (2), F3, F3N	4
1992	8	C	1
1989	11	D, F2, F3, F1	4
1988	12	F3	1
1987	13	F3N, F4	2
1986	14	F3	1
1985	15	D, F2, F3	3
1983	17	F1, F3	2
1981	19	Pole80	1
Woodland	Woodland	Ang, ASth, B, C, D (2), ESth, F1, F3	9
Total			43

* Year of rehabilitation is based on the most recent rehabilitation activities applied to the area; some areas have received repeated rehabilitation and/or remedial treatments

** Age is calculated as at Year 2000

Each monitoring site consisted of three plots randomly located within the selected rehabilitation or undisturbed woodland area (Figure 3-3). To remove edge effects, where possible plots were established no less than 50 m into the woodland or rehabilitation area. Plots of 10 x 10 m were used, based on the assessment that the savanna woodland had an average tree density of around 1000 stems/ha (J. Duggin, pers. comm. 2003.), and that this would provide an adequate sample size of approximately 10 stems in an area of 100 m^2. Plots were square quadrats to facilitate ease of establishment and because of the relatively homogenous nature of the vegetation in rehabilitated plots.

A preliminary study of understorey species diversity produced a 'species area curve' (Kent & Coker 1992) that indicated that the minimum area required to measure this vegetation stratum was 4 m^2. Thus, each 100-m^2 plot was laid out with a 2 x 2 m quadrat located in each of its four corners for understorey monitoring.

Sampling of the 42 sites was conducted in approximately February and July of each year, commencing in July 2000 and concluding in February 2003. Unfortunately, due to time constraints, the final sampling round was incomplete and not all sites were assessed. Thus complete data were only available for three dry season and two wet season sampling rounds.

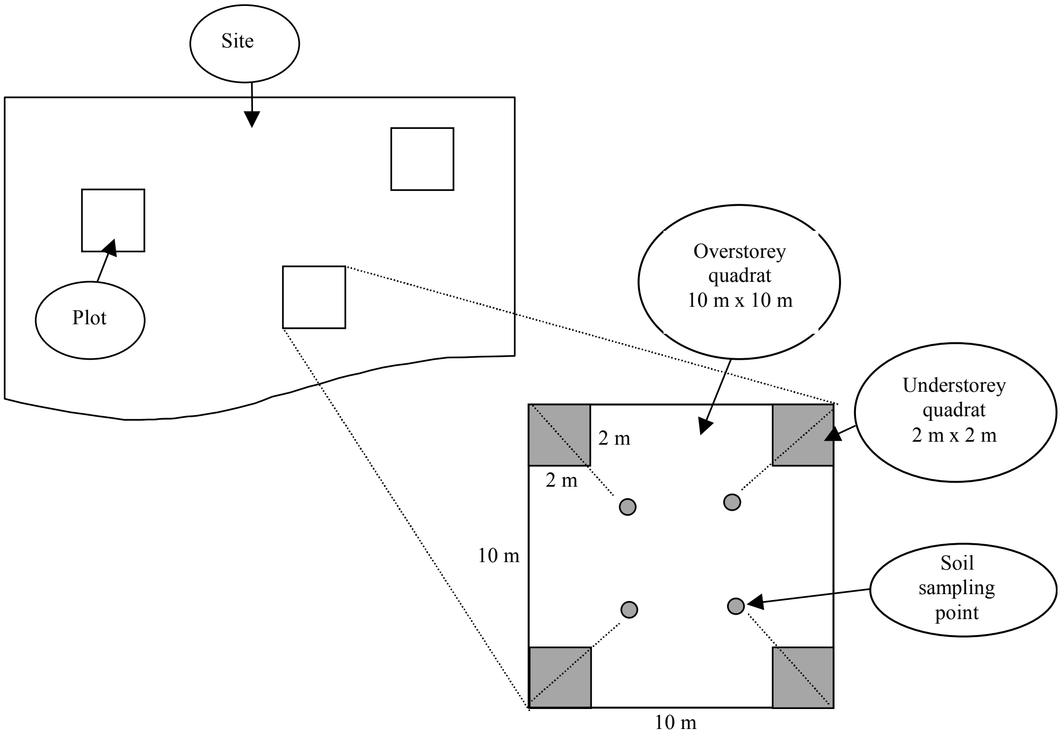


Figure 3-3 Layout of monitoring sites and plots

3.2.1.2 Data Collection and Collation

A broad suite of biotic and abiotic features were recorded for all monitoring plots (Table 3-2). Some aspects, such as understorey composition and density, were measured in both the wet and dry season sampling rounds. Other features, namely overstorey or midstorey characteristics, were measured in only one season (dry season and wet season, respectively).

Table 3-2 Monitoring information collected from each of the 42 sites (126 plots)

Site characteristics	GPS locations General site description, including basic topography, and any anomalous feature Evidence of fire
Vegetation data	Overstorey composition, canopy cover, diameter (dbhob) and health rating Understorey composition and abundance (cover and density) Structure (density and height of dead/live matter) Ground cover (e.g. live vegetation, bare rock, litter)
Soil sampling	Leaf litter depth Topsoil (0-10 cm) samples sieved in field to 2 mm, and analysed for a suite of chemical properties in the soil laboratory at UNE (Section 3.2.2.1) Survey of past substrate replacement and preparation practices using 1-m deep, 15-cm diameter soil auger cores to visually describe depths and composition of substrates layers.

Information on topography and aspect was recorded once. Rehabilitation age and other establishment information were determined from the GEMCO GIS database. Woodland sites, being of indeterminable age, were arbitrarily assigned an age of 100 years where required for the purposes of statistical analysis. Other data were collected during every visit and included high-impact site variables (e.g. weed infestations, notable disturbances such as fire) that can have a significant influence on the rehabilitation status of a site over time. There was no system for keeping records of fire events at GEMCO, making assessment of the impact of this major disturbance on vegetation difficult. For this study, evidence of fire was recorded according to a rating system (Table 3-3) that considered the extent of the removal of groundcover (patchiness) and signs of scorching (flame height) on tree trunks (e.g. Figure 3-4).

Table 3-3 Fire severity rating system for estimating the impact of fire on sites

Code	Severity	Description
0	Nil	Not burnt
1	Low	Patchy, trickle burn, little or no scorch marks on trees
2	Medium	Most litter removed, some burn/scorch marks on tree trunks
3	High	All litter removed, most low plants/shrubs denuded, burn/scorch marks on tree trunks

Figure 3-4 Dry season fires in monitoring plots were a regular occurrence

The GPS location of the centre of all plots was measured using a Magellan ProMark V GPS. These coordinates were entered into the rehabilitation GIS database. A photo point was designated as the NW corner of each plot and a photograph was taken each sampling event.

Topsoil samples were collected for chemical and physical analysis in July 2000. Sampling involved the collection of four stratified random samples (Figure 3-3) in each plot from an area of 100 cm^2 to a depth of 10 cm using a small spade. The four samples were sieved to 2 mm into a bucket and manually mixed in the field. One composite sample of ~150 g was removed, bagged, labelled and returned to the Ecosystem Management laboratory at the University of New England for chemical analysis.

In January 2001, a survey of past rehabilitation substrates was conducted using 1-m soil cores taken from each monitoring plot. This provided information on the nature of the returned substrate underlying the rehabilitation, in particular with regard to the sand, clay or gravel content of the material. Two replicate 1-m deep cores were sampled with a 15-cm auger in each of the 126 monitoring plots. Soil type (e.g. sandy brown earth, clayey loam), texture and substrate boundaries down the profile were described.

Plants were identified to species level where possible, using names sourced from current NT Herbarium listings (Cowie & Albrecht 2005). Primarily local resources were utilised including the locally held plant collections of GEMCO and a reference collection of the Angurugu Community (prepared by Waddy and Levitt and housed in the Angurugu Library and Resource Centre; Waddy 1988). Unrecognised plant specimens were removed from the island for identification using other resources including the N.C. Beadle Herbarium at UNE in Armidale (NE), the Herbarium of the Conservation Commission of the Northern Territory in Palmerston (DNE), the Queensland Herbarium in Brisbane (Bris), or various references including Wheeler *et al.* (1992), Dunlop *et al.* (1995) and Brock (1988). Weeds were defined according to the List of Introduced Flora of the Northern Territory (Cowie 2004) and endemics identified according to current NT Herbarium listings (PCWNT 2005).

Vegetation structure was recorded using a modified Levy pole technique (Sneeuwjagt & Peet 1985). The 3.9-m long, 1-cm diameter pole was divided into 30-cm intervals and placed at 2-m intervals along both diagonals per plot, resulting in 14 placements per plot. The numbers of live and dead vegetation contacts in each 30-cm height interval were recorded separately.

Overstorey was defined as all vegetation reaching more than 4 m in height. The diameter (at breast height over bark), height (using an altimeter) and identity of every overstorey plant was recorded, generating a density for every overstorey species per 100-m^2 plot. For multi-stemmed trees and shrubs, the diameter of all stems per plant was recorded, basal area calculated and summed. Crown cover was measured using a convex spherical densiometer with readings taken from the centre of the quadrat facing outwards to each corner. The health of each overstorey tree was also rated using a visual system modified from Grant *et al.* (1997; Table 3-4). As burning is a common feature in this ecosystem, the health rating system included special ratings for trees which had recently been burnt but were showing signs of recovery in the form of basal (lignotuberous) or aerial (epicormic) resprouting.

Table 3-4 A visual rating system for estimating the health of overstorey trees (modified from Grant *et al.* 1997, to allow for effects of recent exposure to fire)

Code	Description
0	Dead
1–4	Recently burnt and at least partially defoliated by burning
5	Unburnt but with weak patchy crown
6–7	Healthy crown

Plants occurring in the 2–4-m stratum were defined as midstorey. Measurements of midstorey plants included number, height, health and species identity in each 100-m^2 plot. Understorey composition and abundance were measured in each of the four 2 x 2-m quadrats per plot (16 m^2; Figure 3-3). This involved identifying and counting each individual plant less than 2 m in height and which was rooted in the quadrat. Estimations of the percent projected foliage cover were also made for all species in the quadrat, regardless of where they were rooted. These measurements were repeated in both wet and dry seasons as composition and abundance varied significantly with season.

Understorey percent cover was a better indicator of understorey dominance than plant density, as cover reflected both the number of plants and their size or degree of site capture. Cover provided by plants originating from outside the quadrats was included in counts and all cover, including overlapping vegetation, was included (hence some totals are greater than 100%).

Midstorey and understorey data were collected after the wet season so as to capture the maximum number of species as possible but before the impact of dry season burns on the lower vegetation and litter strata. Species were grouped according to a range of taxonomic, functional and life form differences resulting in the following groups: eucalypts, acacias, other trees, shrubs, grasses, herbs, sedges/lilies, climbers and weeds. These groupings will be generally termed ‘life forms’ henceforth in this thesis.

Other ground cover categories recorded were bare ground (e.g. exposed rock surface, topsoil present versus absent), leaf litter, mosses and lichens. Leaf litter depth was recorded for at least

12 points in each quadrat using a specialised gauge developed by R. J. Sneeuwjagt (1973) of the Western Australian Forestry Department.

The repeated measurements collected during the six fieldtrips were progressively amalgamated to produce a series of matrices of site and vegetation indices over time. Historical information about establishment treatments at each site was brought together in a 'management' matrix.

Several response variables were generated from the vegetation monitoring information including (1) Shannon-Wiener Diversity index; (2) species richness; (3) overstorey and midstorey basal area; (4) density and cover in the understorey, midstorey and overstorey of species for the following life forms: (a) eucalypts, (b) acacias, (c) 'other' trees, (d) sedges and lilies, (e) orchids, (f) shrubs, (d) grasses, (e) herbs, (f) vines, and (g) weeds or alien species.

3.2.2 Analysis

3.2.2.1 Soil Analyses

Topsoil samples were analysed for pH, electrical conductivity (EC), organic matter (loss on ignition), exchangeable bases (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}), ammonium and nitrate, micronutrients (Mn, Fe, Zn, Cu) and phosphorus (total and available). Prior to analysis, all soil samples were dried at room temperature for 72 hours and then passed through a 2-mm sieve.

Soil pH was measured in 1:5 water suspensions using a Metrohm 744 pH meter based on methods outlines by Rayment and Higginson (1992). The same solutions were measured for EC using a calibrated YSI conductivity meter (Model 30/10 FT, 30 Salinity Conductivity Temperature). Soil ammonium was extracted using 2M KCl solutions and measured by the sodium salicylate – sodium nitroprusside solution method (Rayment & Higginson 1992) on a Technicon AutoAnalyzer II. Soil nitrate was determined on the same extract by the cadmium reduction method (Rayment & Higginson 1992). Soil total phosphorus was extracted using the combined phosphorus and sulphur digest method (Till *et al.* 1984) and measured by inductively coupled plasma – atomic emission spectroscopy (ICP; Model 3560B ARL). Available phosphorus was determined using the fluoride extractable Bray I method (Rayment & Higginson 1992) and read using a UV visible spectrophotometer (Varian DMS 80 model).

The micronutrients (Mn, Fe, Zn, and Cu) were determined using the DTPA extraction method of Lindsay and Norvell (1978) as presented in Page *et al.* (1982). Exchangeable cations (Calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and potassium (K^{+})) were extracted from a solution with ammonium chloride (Rayment & Higginson 1992) and analysed by ICP (Model 3560B ARL). Effective cation exchange capacity (CEC_e) was calculated from the equation:

$$CEC_e = Ca + Mg + K + Na \text{ (all units in cmol/kg of soil)}$$

As pH was > 5.5, the exchangeable acidity of the soil was assumed to be quite low, so its omission would not have created a significant error in estimating CEC. Soil organic carbon was determined by loss on ignition (Allen *et al.* 1986) using the UNE muffle furnace for 2 hours at 550°C.

3.2.2.2 Univariate Analyses

The PRIMER v5 statistical software package was used to calculate indices for floristic richness and diversity for each site (Clarke & Gorley 2001). Species richness was the total number of species per sample (site). Shannon-Wiener diversity (H') was calculated for each site using the equation:

$$H' = -\Sigma (p_i) \ln(p_i)$$

where p_i was the proportion of the *i*th species. A higher H' value indicates greater diversity.

The different vegetation strata were considered together or separately, depending on the variables being assessed. The midstorey stratum (2–4 m) was considered separately for investigations of the presence and resilience of this layer, especially regarding woody species recruitment to the overstorey over time and response to fire and other factors. However, the midstorey and overstorey (> 4 m) data (collected 6 months apart) were pooled to represent all vegetation over 2 m for a given period. In this case, the 2000 dry season overstorey data were combined with the February 2001 wet season midstorey data.

Plant species were aggregated under life forms for some analyses to enable consideration of the functional and structural attributes of floristic composition. The majority of the vegetation data attained in the monitoring program was used to calculate means and standard errors for measures such as species richness, diversity, overstorey and midstorey life-form densities, overstorey trunk diameter, understorey plant density and cover, understorey life-form cover, and litter depth and cover. Single-factor analyses of variance (ANOVA) were carried out to determine the significance of differences between natural woodland and rehabilitated sites for these measures. Repeated–measures ANOVA was used to compare data from the 2000/01 and 2001/02 sampling rounds (Appendix D). Square-root transformations were applied to satisfy the normality assumptions of ANOVA for overstorey eucalypt density and understorey eucalypt cover. Some variables (i.e. overstorey acacia density, overstorey 'other' density, average overstorey height, average overstorey diameter at breast height over bark [dbhob], midstorey eucalypt density, midstorey acacia density, midstorey 'other tree' density, understorey acacia cover, understorey juvenile 'other tree' cover, understorey weed cover, litter cover and litter depth) could not be transformed to meet the assumptions of ANOVA and were analysed using the non-parametric Kruskal-Wallis test. A Bonferroni correction was performed to correct for alpha inflation due to multiple comparisons.

Single-factor analyses of variance (ANOVA) were carried out to determine the significance of 2000 and 2001 dry season fires on understorey characteristics including grass cover, weed cover, litter cover and understorey species richness. Grass cover was transformed (square-root) to satisfy the normality assumptions of ANOVA while understorey species richness could not be transformed and was analysed using the non-parametric Kruskal-Wallis test. A Bonferroni correction was performed to correct for alpha inflation due to multiple comparisons.

Soil chemistry was also analysed and compared between natural woodland and rehabilitated sites using single-factor ANOVA. Soil organic matter data were not normal and were subjected to square-root transformation prior to analysis. EC, soil nitrate, available phosphorus, calcium, magnesium, CEC, manganese, iron and zinc could not be transformed to meet the assumptions of ANOVA and were analysed using the non-parametric Kruskal-Wallis test. A Bonferroni correction was performed to correct for alpha inflation due to the multiple comparisons. Mean values are presented in the text ± one standard error in parentheses.

3.2.2.3 Multivariate Analyses

Species–site matrices for 2000/01 and 2001/02 data were created (Table 3-5), consisting of the understorey (US) cover (%) and midstorey–overstorey (MSOS) density (stems per hectare) for each species (both normalised) and MSOS dominant height and average overstorey (OS) diameter at breast height (dbh) for each site (both normalised).

Multivariate statistical ordination endeavours to summarise the maximum amount of information into the minimum number of axes, simplifying complex datasets. An unconstrained ordination, detrended correspondence analysis (DCA), was performed on the 2000/01 species–site matrix, with detrending by segments, down-weighting of rare species and Hill's scaling, as described by ter Braak and Šmilauer (2002). This was done using the CANOCO statistical software package (ter Braak 1988). The aim of this ordination was to extract the axes of maximum variation in species composition. A species–site bi-plot aided visual interpretation of the relationships of particularly influential species and sites.

Table 3-5 Structure of the species–site matrix including floristic and structural data

	Sample 1	Sample 2	Sample 3	Sample 4
Sp. A OSMS Dens	..	..	..	..
Sp. A US % Cover	..			
Sp. B OSMS Dens	..			
Sp. B US % Cover	..			
..	..			
Avg. OS dbh	..			
Dominant height (MSOS)	..			

Classification using group-average cluster analysis of the species–sample dissimilarity matrix was conducted using the Primer statistical package (Clarke & Gorley 2001). This produced a dendrogram showing the levels of dissimilarity between sites based on the structural and composition species data, presenting groups of sites less dissimilar to each other than other sites.

3.3 Results

3.3.1 Overall Differences between Woodland and Rehabilitation

3.3.1.1 Floristics

A total of 195 species was recorded from the 132 plots over the six sampling rounds (Appendix A). Eight of the 195 species could only be identified to family level and five species could not be identified at all (these have been referred to as 'unknown sp. 1' etc.). The most common family was Poaceae (represented by 28 species, including five non-natives), followed by Fabaceae (16 species, including three non-natives), Euphorbiaceae (15 species, including one non-native), Myrtaceae (11 species), Cyperaceae (10 species, including one non-native) and Mimosaceae (10 species).

Species richness was significantly different between natural woodland and rehabilitated sites (51 ± 2.7 and 41 ± 1.4 species, respectively; Table 3-6). Woodland species richness ranged between 38 and 63 species while rehabilitated sites had a maximum of 60 species (in a 4-year-old site) and as few as 26 species (a 13-year-old site).

Eight species were listed by the NT Herbarium as endemic to the Northern Territory (PWCNT 2005). Fourteen 'non-native' species were recorded in plots, a category which, in this thesis, includes weeds and other species not naturally found on the island. Of these, nine species were only recorded in rehabilitated sites and five were introduced as part of the rehabilitation seed mix in previous years (Table 3-7), including the legumes, siratro (*Macroptilium atropurpureum*) and stylo (*Stylosanthes scabra*), and the grasses, rhodes grass (*Chloris barbata*) and guinea grass (*Panicum maximum*).

The most common life form was herbs, which included 53 species (or 27% of all species), followed by 'other trees' (34 species), vines/lianes (24 species) and grasses (23 species) (Table 3-8). Just over 7% of all species were non-native.

Woodlands were dominated by the herbs *Hybanthus enneaspermus*, *Spermacoce gilliesiae*, and *Tacca leontopetaloides*, while rehabilitated sites contained mostly *Alysicarpus vaginalis*, *Polygala pycnophylla* and *Hibbertia lepidota*. Vines, including *Arnhemica cryptantha*, *Flemingia parviflora* and *Ampelocissus acetosa* (wild grape), were slightly more common in woodland sites than rehabilitated areas, which contained vines dominated by *Mukia maderaspatana*, *Passiflora foetida* (stinking passionfruit), *Cajanus scaraboides*, and *Merremia quinata*. Sedges and lilies in woodland areas were typified by *Lomandra tropica* and *Schoenus sparteus* and, in rehabilitated areas, by *Thysanotus chinensis* and *Centrolepsis exserta*, although some *L. tropica* and *S. sparteus* did occur.

Including species in all strata from the 2000/01 sampling data, the Shannon–Wiener diversity index (H') was not significantly different between the two groups of woodland and rehabilitated sites (average H' = 2.9 ± 0.09 and 2.5 ± 0.07, respectively; Table 3-6).

Some 39 species were recorded in the midstorey and overstorey strata (plants > 2 m in height) across all sites. These were predominantly species of Myrtaceae (eleven species or 28% of the total, including six eucalypts), followed by acacias (Mimosaceae) (18% or seven species) and Proteaceae (10% or four species). Of these, six species were only found in woodland sites: *Buchanania obovata*, *Canarium australianum*, *Cycas arnhemica*, *Exocarpos latifolius*, *Hakea arborescens* and *Wrightia saligna*. Cycads were observed in a number of rehabilitated areas (especially more recent sites), however none occurred within plots randomly selected for sampling. In contrast, 16 species were only found in rehabilitated sites (not in woodland plots). These included six acacias and two eucalypts, *Eucalyptus camaldulensis* (used in early forestry plantings) and *E. bigalerita*. Seven of the 11 mid and overstorey Myrtaceae were only found in rehabilitated areas, including a number of the melaleucas and *Asteromyrtus* species.

Some 154 species, or 79% of all species recorded in this study, were only recorded in the understorey or as groundcover (< 2 m in height). Of these, 27 (18%) were grasses (Poaceae), including four non-native species, 16 (10%) were Fabaceae (including three non-natives) and just over 8% (13 species, including one non-native) were Euphorbiaceae. Of these, seven grass species, including one non-native, were only found in rehabilitated sites. Four species (11%) each of the Asteraceae and Fabaceae (including two and three non-natives, respectively) and three species of Cyperaceae (including one non-native) were only found in rehabilitated sites. Some 14 understorey and groundcover species were only recorded in woodland sites (Table 3-9), including three Euphorbiaceae (*Bridelia tomentosa*, *Drypetes deplanchei* and *Petalostigma quadriloculare*).

Table 3-6 Vegetation characteristics of rehabilitated and woodland sites (2000 dry season overstorey data; 2000/01 wet season midstorey and understorey data)

Attribute	Unit	Rehabilitation (n = 34 sites)			Woodland (n = 9 sites)			Analysis of Variance	Significance
		Avg.	SE	Range	Avg.	SE	Range		
Total species richness[1]	number	41	1.4	26–60	51	2.7	38–63	(n) F = 11.1, P = 0.0019	*
Shannon–Wiener diversity index[1]	H’	2.5	0.07	1.7–3.2	2.9	0.09	2.5–3.2	(n) F = 9.07, P = 0.0045	
Canopy cover	%	43	4.2	0–85	59	3.6	45–78	(n) F = 3.47, P = 0.0696	
Overstorey eucalypt density	stems/ha	454	88	0–1933	489	76	167–900	(sqrt) F = 1.09, P = 0.3020	
Overstorey acacia density	stems/ha	308	58	0–1300	44	36	0–333	(np) KWstat = 6.8, P = 0.0090	
Overstorey 'other' density	stems/ha	106	28	0–600	48	27	0–200	(np) KWstat = 0.97, P = 0.3240	
Average overstorey height[2]	m	6.8	0.34	4.4–12	12	1.3	7.1–21	(np) KWstat = 15.2, P = 0.0001	**
Average dominant height	m	7.6	0.55	2.0–15	15	1.4	8.3–23	(n) F = 35.6, P = 0.0000	***
Average overstorey dbhob[3]	cm	13.2	1.1	6.5–33	18.8	2.2	10.5–30	(np) KWstat = 6.25, P = 0.0124	
Midstorey eucalypt density	stems/ha	408	63	0–1167	409	67	167–750	(np) KWstat = 0.176, P = 0.6748	
Midstorey acacia density	stems/ha	289	50	0–1017	44	24	0–200	(np) KWstat = 5.87, P = 0.0154	
Midstorey ‘other trees’ density	stems/ha	83	21	0–500	70	38	0–300	(np) KWstat = 0.156, P = 0.6983	
Understorey plant density	plants/m^{-2}	14	0.95	2.4–24	18	1.5	7.3–24	(n) F = 4.27, P = 0.0452	
Understorey cover[4]	%	77	5.0	17–138	90	7.0	55–126	(n) F = 1.66, P = 0.2045	
Understorey juvenile eucalypt cover	%	2.1	0.34	0–8.7	5.8	1.9	0.05–18	(sqrt) F = 7.6, P = 0.0085	
Understorey acacia cover	%	5.1	0.88	0.17–19	2.5	0.75	0.15–6.5	(np) KWstat = 2.32, P = 0.1279	
Understorey juvenile ‘other’ tree cover	%	3.6	0.81	0–26	22	2.0	8.5–29	(np) KWstat = 18.7, P = 0.0000	***
Understorey grass cover	%	35	3.2	1.6–73	37	3.3	21–55	(n) F = 0.06, P = 0.8055	
Understorey weed cover	%	12	2.5	0.04–64	0.66	0.34	0–3.1	(np) KWstat = 12.2, P = 0.0005	**
Litter cover	%	57	6.0	0.9–98	68	6.5	44–90	(np) KWstat = 0.15, P = 0.6979	
Litter depth	cm	1.2	0.24	0–8.0	0.7	0.13	0.2–1.3	(np) KWstat = 1.43, P = 0.2315	

[1] Based on amalgamated 2000 dry season overstorey data and 2000/01 wet season midstorey and understorey data. [2] OS height only includes those sites with plants > 4 m high. [3] dbhob = diameter at breast height (1.3 m) over bark. [4] Understorey cover may exceed 100% due to overlapping vegetation. Bonferroni correction for 21 tests: ***P ≤ 0.000048, **P ≤ 0.00048, *P ≤ 0.0024. np = non-parametric, P = parametric, sqrt = square-root transformed data

Table 3-7 Non-native species found in rehabilitation plots of the GEMCO leases (an asterisk denotes species previously included in rehabilitation seed mixes)

Family	Common Name	Species	Rehab. Seed Mixes	Sites Recorded (Rehab. Age)
Asteraceae	Red tassel flower	*Emilia sonchifolia*		12 rehab. sites (1985–2000)
	Tridax daisy	*Tridax procumbens*		1 rehab. site (2000)
Cyperaceae	Annual sedge	*Cyperus compressus*		1 rehab. site (2000)
Euphorbiaceae	Milkweed	*Euphorbia heterophylla*		1 rehab. site (1997)
Fabaceae	One-leaf clover	*Alysicarpus vaginalis*		3 rehab. sites (1997–1998)
	Siratro*	*Macroptilium atropurpureum*	1972 –1976	1 rehab. site (1997)
	Stylo*	*Stylosanthes scabra*	1972–1979	11 rehab. sites (1981–1998)
Lamiaceae	Hyptis	*Hyptis suaveolens*		F1 woodland; 12 rehab. sites (1981–2000)
Malvaceae	Sida	*Sida cordifolia*		Ang and C woodlands; 18 rehab sites (1981–1998)
Poaceae	Rhodes grass*	*Chloris barbata*	1972–1987	2 rehab. sites (1989 & 1996)
	Couch*	*Cynodon dactylon*	1984–1987	Ang, B & F woodlands; 3 rehab. sites (1985–1993)
	Red Natal grass	*Melinis repens*		23 rehab. sites (1985–2000)
	Guinea grass*	*Panicum maximum*	1972–1974	A-south and E-south woodlands; 5 rehab. sites (1985–2000)
Verbenaceae	Snakeweed	*Stachytarpheta jamaicens*		1 rehab. site (1998)

Table 3-8 Number and proportion of species in each life form

Life Form	Woodland	Rehabilitation	Total Species	Percent of Total
Eucalypt	4	5	5	2.6
Acacia	7	10	11	5.6
Tree, other	29	25	34	17.4
Shrub	6	7	11	5.6
Vine	18	23	24	12.3
Herb	44	52	53	27.2
Orchid	1	0	1	0.5
Fern	1	0	1	0.5
Grass	17	21	23	11.8
Sedge/Lily	16	17	18	9.2
Non-native	6	13	14	7.2
Total	149	173	195	

3.3.1.2 Overstorey and Midstorey Characteristics

Eucalyptus tetrodonta, E. miniata and *E. polycarpa* were the dominant species (in decreasing order) in the savanna woodland environment of Groote Eylandt. Other common overstorey species included a number of acacias (mostly *Acacia torulosa, A. latescens, A. auriculiformis* and *A. aulacocarpa*), red ash (*Alphitonia excelsa*), ironwood (*Erythrophleum chlorostachys*), green plum (*Buchanania obovata*), *Terminalia* spp., cypress pine (*Callitris intratropica*) and *Melaleuca* spp.

Table 3-9 Fourteen species only recorded in the understorey stratum (< 2 m in height) or as groundcover in woodland plots

Family	Species	Life form
Adiantaceae	*Cheilanthes contigua*	Fern
Amaryllidaceae	*Crinum uniflorum*	Sedge/Lily
Combretaceae	*Terminalia sp. 2*	Tree, other
Erythroxylaceae	*Erythroxylum ellipticum*	Tree, other
Euphorbiaceae	*Bridelia tomentosa*	Tree, other
	Drypetes deplanchei	Shrub
	Petalostigma quadriloculare	Shrub
Lecythidaceae	*Planchonia careya*	Tree, other
Melastomataceae	*Melastoma affine*	Shrub
Orchidaceae	*Habenaria ochroleuca*	Orchid
Rubiaceae	*Oldenlandia mitrasacmoides*	Herb
Sterculiaceae	*Brachychiton diversifolius*	Tree, other
Unknown	Unknown herb sp. 1	Herb
	Unknown sp. 1	Tree, other

Focussing on the 2000 dry season overstorey sampling data as a snapshot, the average canopy cover was not significantly different between rehabilitated and woodland sites, averaging 43% (± 4.2) and 59% (± 3.6) respectively (Table 3-6).

Overstorey densities of the dominant life forms (i.e. eucalypts, acacias and ‘other’ trees) were not statistically significantly different, although they are worth outlining. The dominant eucalypt species occurred in the natural woodland overstorey at an average density of 489 (± 76) stems per hectare, ranging from 167 to 900 at the nine sites (> 4 m in height) (Table 3-6). In contrast, areas of rehabilitation had an average overstorey eucalypt density of 454 (± 88) stems/ha (Table 3-6), ranging from 0 (at seven sites, including two 6-month-old sites) to 1933 stems/ha (at a 7-year-old site). Although woodland sites averaged 44 (± 36) acacia stems/ha, acacias were not found in the overstorey of six of nine sites. Acacias occurred in rehabilitation at an average density of 308 (± 58) stems/ha (Table 3-6), ranging from 0 (at nine sites, including two 6-month-old sites) to 1300 at a 7-year-old site. Densities of other overstorey trees ranged from 0 to 200 stems/ha (averaging 48 [± 27] stems/ha in woodland sites; Table 3-6), with 67% of sites not containing any at all. Rehabilitation areas averaged 106 (± 28) stem/ha, ranging from 0 (at 15 of 34 sites) to 600 stems/ha at a 7-year-old site.

Average overstorey height was significantly different in rehabilitated and woodland sites, both for the average of all heights over 4 m (average overstorey height) and the average of the tallest two plants in every site (avg dominant [top 2] height) (Table 3-6). The dominant height measure included younger rehabilitation sites that may not have had plants in the overstorey (> 4 m) stratum. The tallest trees in woodland and rehabilitated sites averaged 15 (±1.4) m and 7.6 (± 0.55) m in height, respectively.

There was no significant difference between woodland and rehabilitated sites in average overstorey stem diameter, although the two groups of sites averaged 18.8 (± 2.2) cm and 13.2 (± 1.1) cm respectively (Table 3-6).

The 2000/2001 wet season survey of the midstorey and understorey vegetation found that densities of the main midstorey plant life forms (i.e. eucalypts, acacias and 'other' trees) were not significantly different between woodland and rehabilitated sites (Table 3-6). However, while the density of midstorey eucalypts was similar in woodland and rehabilitation sites (409 ± 67 and 408 ± 63, respectively), woodlands ranged from 167 to 750 stems/ha, while some rehabilitated sites lacked eucalypts in the 2–4 m stratum entirely and others had as many as 1167 midstorey eucalypt stems/ha. Rehabilitation sites averaged 289 (± 50) acacia stems/ha in the midstorey, with over 1000 stems/ha at one site. Woodland sites averaged only 44 (± 24) acacia stems/ha, ranging between 0 and 200 stems/ha over the nine sites.

Understorey plant density averaged 14 (± 1.0) plants/m² in rehabilitated sites, compared to an average of 18 (± 1.5) plants/m² in woodland sites (Table 3-6). Some rehabilitated sites had as few as 2.4 plants/m² in the understorey while woodland sites had no fewer than 7.3 plants/m².

Average total understorey cover was not significantly different for woodland and rehabilitation sites (Table 3-6). Overall, rehabilitated sites averaged 77% (± 5) projected foliage cover, due mostly to grasses (35 ± 3.2%), ranging from an average of only 17% cover in the 12-year-old rehabilitation plot to 138% cover (due to overlapping species) in the 8-year-old rehabilitation plot. Woodlands averaged 90% (± 7.0) cover and had a higher average understorey cover than rehabilitated areas for all life forms except acacias and weeds. Woodland sites averaged higher understorey eucalypt cover than rehabilitated sites (5.8 ± 1.9% and 2.1 ± 0.34% cover, respectively), except for the single 14-year-old site with > 8% eucalypt understorey cover.

As in the midstorey and overstorey of undisturbed woodland sites, acacias were present in the woodland understorey at much lower densities than eucalypts. Across all rehabilitated sites, however, acacias, especially *Acacia multisiliqua* and *A. aulacocarpa*, were generally more common than eucalypts (averaging 0.23 m^{-2}).

A notable difference between natural woodland and rehabilitated sites was the lack of juveniles of non-eucalypt and non-acacia tree and shrub species in the understorey of the latter. Understorey cover of juvenile 'other' trees was significantly greater in woodland than rehabilitation sites (22 ± 2.0% vs 3.6 ± 0.8%, respectively). In woodland areas, the commonest juveniles of the 'other' trees were ironwood (*Erythrophleum chlorostachys*), *Buchanania obovata* and *Melaleuca viridiflora* while the juvenile 'other' shrubs were most often *Exocarpus latifolius* and *Distichemon hispidulus*. Rehabilitated areas, on the other hand, frequently had juvenile shrubs of *Lithomyrtus retusa*, *Hibbertia oblongata* and *Keraudrenia corollata* and juvenile trees of *Clerodendrum floribundum*, *Grevillea pungens* and *Asteromyrtus symphyocarpa*.

The understorey cover of native grasses varied widely across rehabilitation sites (range 2–73%), although the overall average approximated that of woodland sites (35 ± 3.2% vs 37 ± 3.3%, respectively; Table 3-6). The composition of the dominant grasses generally differed between woodland and rehabilitated sites, however. In woodland areas, the dominant grasses were *Ectrosia leporina*, *Eriachne avenaceae* and *Heteropogon triticeus*, while rehabilitated areas were dominated by *Yakirra muelleri*, *Eriachne avenaceae* and *Thaumastochloa pubescens*. Relatively low numbers of the exotic grasse,s *Melinis repens* and *Digitaria decumbens,* were found in some woodland sites, while rehabilitated sites sometimes contained the exotics, *Cynodon dactylon* and *M. repens*.

Average weed cover was significantly less in woodlands than rehabilitated areas (0.7 ± 0.34% and 12.2 ± 2.5%, respectively). Common weeds in rehabilitated areas included *Macroptilium atropurpureum* (siratro), *Stylosanthes* spp. (stylo), *Hyptis suaveolens* (hyptis) and *Stachytarpheta jamaicensis* (snakeweed). Woodland sites contained some exotic grasses and also low densities of other weeds including *Stylosanthes scabra*, *Sida cordifolia* and *M. atropurpureum*.

3.3.1.3 Fire Occurrence and Severity

In the 2000 dry season, only five monitoring sites were impacted by low to medium severity fire: three natural woodland and two rehabilitated sites (Table 3-10). The following year, 20 sites were affected by fire, including five high severity fires in rehabilitated areas. Only two woodland sites were burnt in 2001 and those fires appeared to be of low severity. Over the two sampling events, only one woodland site and one rehabilitation site were burnt in both years.

Table 3-10 Burn severity rating and description for all woodland and rehabilitation sites for the 2000 and 2001 sampling years

Year of Fire	Burn Rating	Description	Number of sites (n)	
			Woodland	Rehab.
2000	0	Not burnt	6	31
	1	Low severity	2	0
	2	Medium severity	1	2
	3	High severity	0	0
2001	0	Not burnt	7	15
	1	Low severity	2	8
	2	Medium severity	0	5
	3	High severity	0	5

A selection of understorey characteristics, namely understorey species richness, litter cover, grass cover and weed cover, were used to compare the effects of fire and fire severity on monitored sites (Table 3-11).

There were no statistically significant differences between sites burnt in the 2000 dry season and unburnt sites, in terms of the four understorey characteristics compared. Of interest, however, was the higher level of understorey species richness in burnt sites compared to unburnt sites, averaging 44 ± 3.3 and 36 ± 1.2 species, respectively (Table 3-11).

Sites burnt in the 2001 dry season (n = 20) had significantly higher levels of grass cover in the preceding wet season than unburnt sites (44 ± 3% vs 29 ± 3%, respectively; F = 10.1, P = 0.0028). Grass cover in the subsequent wet season remained higher on average in burnt sites than for unburnt sites (31 ± 3% vs 26 ± 3%, respectively). Litter levels in burnt sites were also higher in the preceding wet season than for unburnt sites (70 ± 8% vs 52 ± 7%, respectively). Litter cover in the subsequent wet season (circa February 2002) was significantly lower than unburnt sites (43 ± 7% vs 70 ± 6%, respectively; F = 9.83, P = 0.0032).

Weed cover was much lower in burnt sites both before and after the 2001 dry season fires than unburnt sites, possibly indicating that these herbaceous weeds displace otherwise fire-promoting species such as native grasses and reduce the incidence of fire in these areas.

There was no significant difference between sites affected by fires of differing intensities, although the highest average grass cover, both before and after the 2001 dry season fire, was found in the group of sites affected by the highest severity fires (Table 3-11). Sites that received relatively low intensity burns had similar levels of grass cover in the preceding wet season as those sites that carried a high severity fire (42.4% – 45.3%). By the wet season after the fires, however, grass cover was reduced by almost half in the low intensity burn sites while high severity sites had returned to almost the same high grass cover levels as before the fires.

3.3.1.4 Litter Cover and Litter Depth

There was no significant difference in average litter cover or depth between rehabilitated and woodland sites, although some rehabilitated sites had < 1% cover compared to a minimum of 44% litter cover in woodland sites. Litter depth was fairly shallow at most sites, reaching a maximum of 8 cm at one rehabilitated site that was thought to have avoided burning. Woodland sites exhibited litter depths of only 0.2–1.3 cm, most likely reflecting the influence of regular fires, but also the potentially rapid turnover rate of vegetative matter in these seasonally wet tropical environments.

3.3.1.5 Vegetation Structure

The Levy pole technique described vegetation structure in terms of live and dead touches at heights up to 390 cm. It afforded quantitative comparisons between sites and times.

In the 2000 dry season, natural woodland and rehabilitated sites had a similar number of average touches up to 3.9 m (4.4 vs 4.5 touches, respectively; Figure 3-5). In woodland sites, an average of 1.6 (37%) of these touches were with live material compared to 1.1 (24%) in rehabilitated sites. By far, the greatest number of touches with live and dead vegetation was in the lowest height intervals, especially the 0–30 cm range, in both woodland and rehabilitated sites (Figure 3-5). Average number of touches decreased with increasing height in both types of sites, but rehabilitated sites recorded more touches than woodlands > 180 cm. In fact, woodland sites had more than 90% of all touches at heights < 90 cm, while rehabilitated sites had only 78% of touches under this height. Woodland sites averaged 0.9 live touches to 2.1 dead touches (totalling 3.0 touches) in the 0–30 cm height interval (Figure 3-5b). Rehabilitation sites had significantly fewer live touches (0.3) than woodland sites ($F = 10.5$, $P = 0.0024$), but similar touches (2.4) for dead material in this same interval (Figure 3-5b).

Almost 22% of all touches in rehabilitation sites occurred in the 90–390 cm height range, almost half of which were with dead vegetation. For all height ranges, rehabilitated sites averaged more dead touches than woodland sites, except in the 150–180 cm interval where woodland and rehabilitated sites were similar. In particular, rehabilitation sites averaged significantly more touches with dead material in the 240–270 cm interval ($F = 5.29$, $P = 0.0268$). Woodland sites averaged more live touches than rehabilitated sites in each height interval < 150 cm, with significantly more live touches in the 30–60 cm ($F = 10.1$, $P = 0.0029$) and 90–120 cm ($F = 4.49$, $P = 0.0404$) intervals.

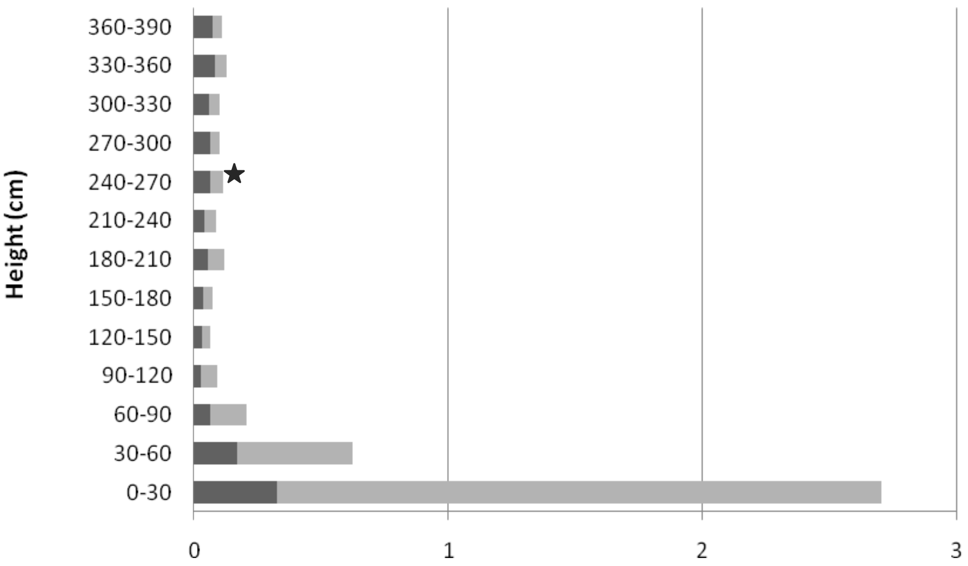
In the following wet season, the number of recorded touches increased dramatically, with an average of 6.4 and 7.6 in woodland and rehabilitated sites, respectively (Figure 3-6). The proportion of live touches more than doubled for both groups compared to dry season measurements, with an average of 5.4 (84%) live touches in woodlands and 5.2 (69%) in rehabilitated sites. Consistent with patterns observed in the dry season, in the wet season most material was found in the lower height intervals, in particular the 0–30 cm interval, and it was here that the large amount of dry season dead material was found to have been replaced by even higher levels of live material. Despite this, the rehabilitation averaged significantly greater amounts of dead material in this lowest height interval than woodland sites. Rehabilitated sites averaged significantly more live touches in the three tallest height intervals (from 300–390 cm) than woodland sites but still had a number of dead touches in all of the height intervals, as was the case in the dry season. This suggests that more canopy foliage had appeared at these levels in the wet season, but that the standing dead material was mostly still present.

Table 3-11 Select understorey characteristics in the preceding and subsequent wet seasons in relation to fire occurrence in 2000 and 2001 dry seasons, and fire severity in 2001 dry season (values are averages for the respective groups; standard errors of the mean are presented in parentheses)

		N (sites)	Understorey species richness		Litter cover (%)		Grass cover (%)		Weed cover (%)	
			Previous wet	Next wet	Previous wet	Next wet	Previous wet	Next wet	Previous wet	Next wet
2000 dry season	No fire	37	na	36.4 (1.2)	na	61.1 (5.8)	na	35.8 (2.9)	na	9.8 (2.4)
	Fire	5	na	44.0 (3.3)	na	54.3 (12.9)	na	38.7 (5.7)	na	6.7 (3.6)
	Analysis of Variance[1]			(np) KWstat = 4.0113, P = 0.0452		(n) F = 0.17, P = 0.6867		(sqrt) F = 0.28, P = 0.5995		(n) F = 0.21, P = 0.6459
	Significance[2]			**						
2001 dry season	No fire	22	37.5 (1.5)	37.9 (1.5)	51.8 (6.8)	69.7 (5.8)	28.9 (3.4)	25.5 (3.3)	14.3 (3.7)	10.4 (2.9)
	Fire	20	37.1 (1.9)	42.0 (2.2)	69.6 (8.1)	42.6 (6.5)	44.2 (3.3)	31.2 (2.5)	4.0 (1.1)	3.6 (1.3)
	Analysis of Variance[1]		(np) KWstat = 1.9940, P = 0.1579	(np) KWstat = 0.0701, P = 0.7912	(n) F = 2.85, P = 0.0989	(n) F = 9.83, P = 0.0032	(sqrt) F = 10.1, P = 0.0028	(sqrt) F = 2.85, P = 0.0990	(n) F = 6.42, P = 0.0153	(n) F = 4.38, P = 0.0428
	Significance[2]				*	***	***	*	**	**
2001 dry season	No fire	22	37.5 (1.5)	37.9 (1.5)	51.8 (6.8)	69.7 (5.8)	28.9 (3.4)	25.5 (3.3)	14.3 (3.7)	10.4 (2.9)
	Low severity	10	37.1 (3.0)	40.9 (3.4)	57.9 (10.6)	42.9 (10.4)	45.3 (4.9)	25.1 (2.8)	2.3 (1.1)	4.1 (2.0)
	Medium severity	5	36.8 (5.0)	43.8 (4.7)	87.8 (18.0)	40.9 (14.6)	43.8 (7.6)	33.3 (3.1)	3.6 (2.1)	1.5 (0.4)
	High severity	5	37.2 (1.6)	42.4 (3.7)	74.8 (16.1)	43.6 (9.9)	42.4 (6.1)	41.1 (5.0)	8.0 (2.5)	4.5 (3.4)
	Analysis of Variance[1]		(np) KWstat = 0.4945, P = 0.9201	(np) KWstat = 2.3476, P = 0.5035	(n) F = 1.90, P = 0.1463	(n) F = 3.12, P = 0.0370	(sqrt) F = 3.23, P = 0.0329	(sqrt) F = 2.13, P = 0.1125	(n) F = 2.27, P = 0.0957	(n) F = 1.48, P = 0.2356
	Significance[2]					**	**		*	

[1] Analysis of variance was conducted on untransformed data where possible (n), on transformed data (sqrt) where data were not normal or by the Kruskal-Wallis method where data were found to be non-parametric (np). [2] Subjective observations so marginal significance level nominated (P<0.1)

(a) Rehabilitated Sites



(b) Forest Sites

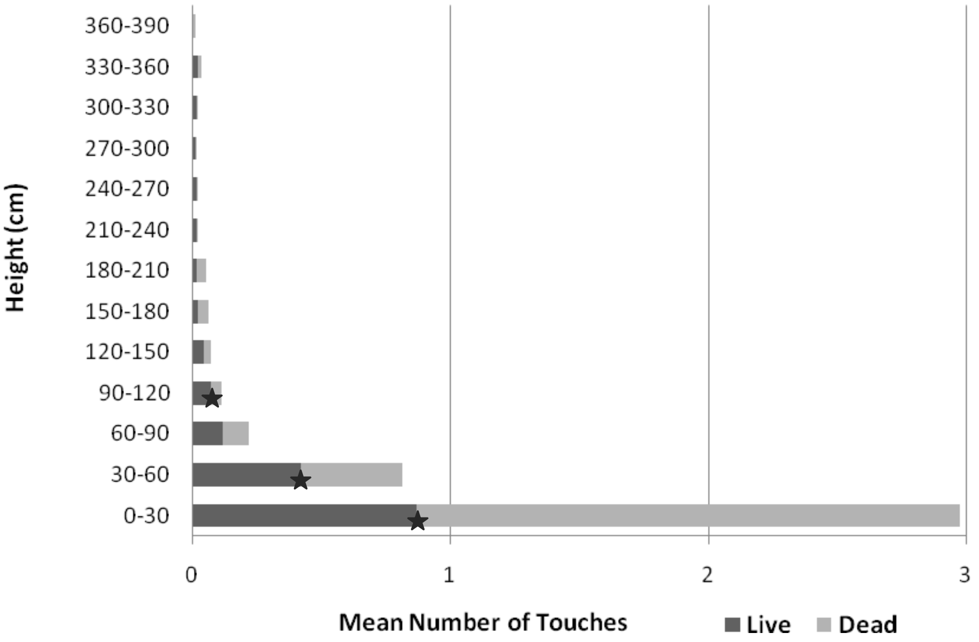
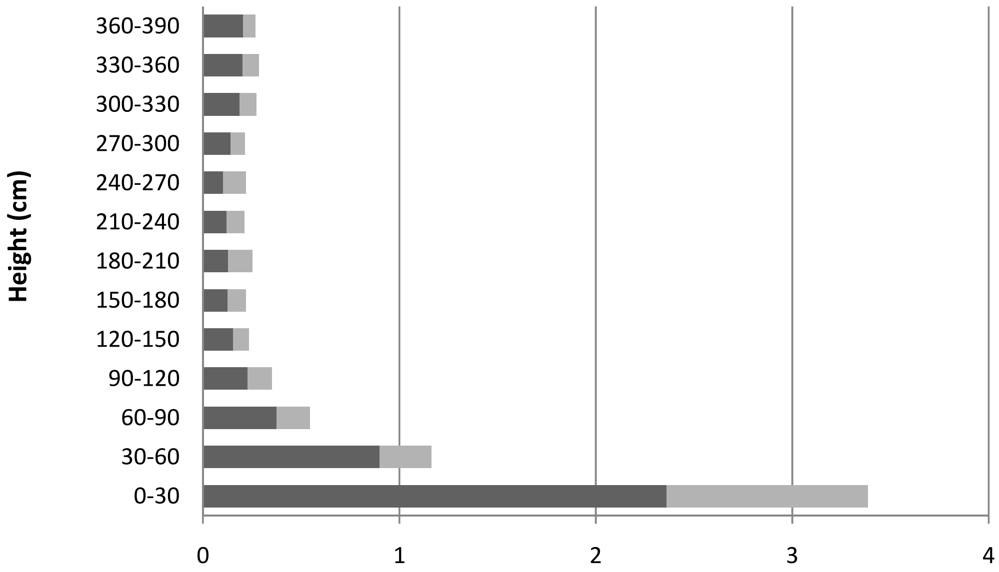


Figure 3-5 Vegetation structure as measured in the 2000 dry season using a modified Levy pole technique: (a) rehabilitated sites, and (b) woodland sites. Asterisks indicate significantly higher average number of touches compared to the other group of sites (woodlands vs rehabilitation)

(a) Rehabilitated Sites



(b) Forest Sites

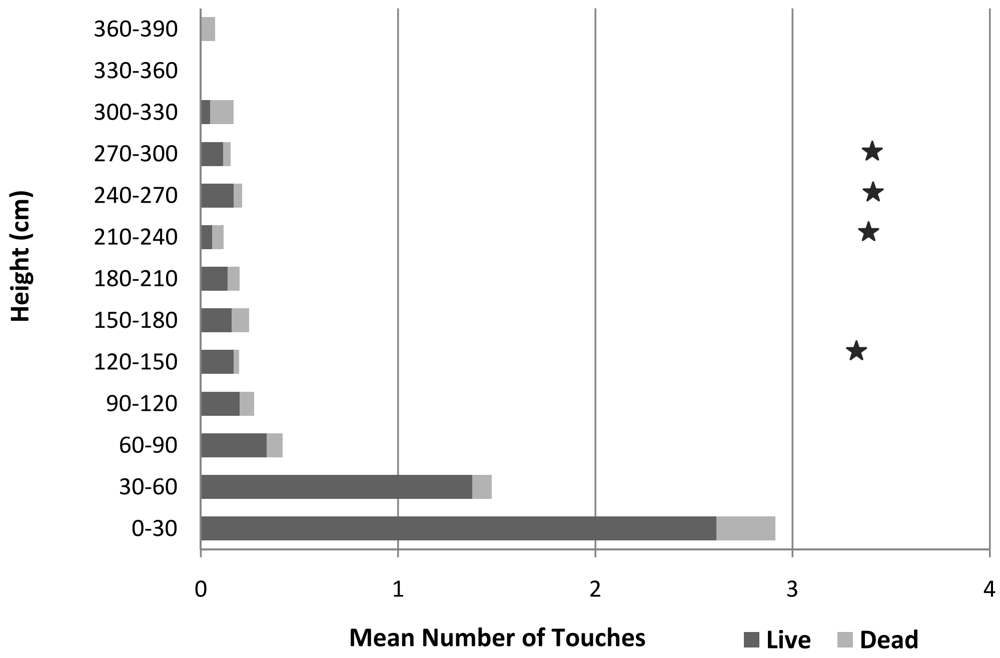


Figure 3-6 Vegetation structure as measured in the 2001 wet season using a modified Levy pole technique: (a) rehabilitated sites, and (b) woodland sites. Asterisks indicate significantly higher average number of touches compared to the other group of sites (woodlands vs rehabilitation)

3.3.1.6 Soil Characteristics

Topsoil pH was significantly greater in natural woodland than rehabilitated sites (6.6 ± 0.04 vs 6.4 ± 0.03, respectively), although all sites fell within the range 6.1–6.8 (Table 3-12). EC values all fell within 14 and 43 mS/cm, and were not significantly different between rehabilitated and woodland sites. Nor were there significant differences between rehabilitated and woodland sites in ammonium, nitrate, total phosphorus or available phosphorus.

With regard to exchangeable cations, the average concentration of the Calcium (Ca+) was significantly greater in soils from woodland sites than those from rehabilitated sites (64 ± 9.6 mg/kg and 25 ± 1.7 respectively). Magnesium and sodium concentrations in woodland soils (13 ± 1.7 mg/kg Mg and 6.9 ± 0.38 mg/kg Na) were also marginally higher than soils from rehabilitated areas (8.2 ± 0.63 mg/kg Mg and 7.5 ± 0.24 mg/kg K). Potassium was found at slightly lower average concentrations in woodland soils than rehabilitated sites (5.0 ± 0.62 and 6.6 ± 0.50 respectively). Being calculated from the sum of the exchangeable cations, the effective cation exchange capacity was almost twice as high in woodland soils as rehabilitated sites.

Average concentrations of the DTPA extractable micronutrients (manganese, iron, zinc and copper) were not significantly different between woodland and rehabilitation sites. Average organic matter content was also not significantly different between woodland and rehabilitated sites.

Table 3-12 Soil attributes of rehabilitated and natural woodland sites

Attribute	Unit	Rehabilitation (n = 34 sites[1])			Woodland (n = 9 sites)			Analysis of Variance[2]	Significance
		Avg.	SE	Range	Avg.	SE	Range		
pH (water)		6.4	0.03	6.1–6.7	6.6	0.04	6.4–6.8	(n) F = 14.1, P = 0.0005	**
Electrical conductivity (EC)	mS/cm	22.2	1.3	14.2–42.4	31.2	3.2	15.3–43.0	(np) KWstat = 6.0685, P = 0.0138	
Ammonium	mg/kg	1.1	0.06	0.35–2.0	1.2	0.17	0.69–2.0	(n) F = 1.41, P = 0.2420	
Nitrate	mg/kg	0.44	0.06	0.03–1.2	0.64	0.12	0.05–1.1	(np) KWstat = 1.36, P = 0.2440	
Total phosphorus	mg/kg	99	5.1	48–160	87	13	40–151	(n) F = 1.09, P = 0.3016	
Available phosphorus	mg/kg	0.81	0.29	0.07–9.0	0.18	0.04	0.09–0.45	(np) KWstat = 2.55, P = 0.1100	
Exchangeable Cations									
Calcium (Ca^{2+})	cmol/kg	25	1.7	12–51	64	9.6	26–107	(np) KWstat = 14.15, P = 0.0002	**
Magnesium (Mg^{2+})	cmol/kg	8.2	0.63	3.8–17	13	1.7	4.9–20	(np) KWstat = 7.38, P = 0.0066	
Sodium (Na^{+})	cmol/kg	7.5	0.24	5.1–10	6.9	0.38	5.4–9.3	(n) F = 1.44, P = 0.2375	
Potassium (K^{+})	cmol/kg	6.6	0.50	1.8–14	5.0	0.62	0.78–7.1	(n) F = 2.22, P = 0.1440	
CEC$_e$ (cation exchange capacity)	cmol/kg	47.4	9.9	22.7–92	88.9	22.3	37–143	(np) KWstat = 2.68, P = 0.0594	
DTPA Extractable Micronutrients									
Manganese (Mn)	mg/kg	98	6.6	31–168	109	12	49–150	(np) KWstat = 0.2888, P = 0.5910	
Iron (Fe)	mg/kg	11.7	0.65	5.72–26.2	17.9	2.31	8.07–26.6	(np) KWstat = 6.7465, P = 0.0094	
Zinc (Zn)	mg/kg	0.30	0.02	0.14–0.84	0.29	0.03	0.11–0.47	(np) KWstat = 0.1285, P = 0.7200	
Copper (Cu)	mg/kg	0.20	0.01	0.08–0.39	0.25	0.03	0.16–0.44	(n) F = 2.01, P = 0.1641	
Organic matter (loss on ignition)	%	4.45	0.23	2.37–8.62	5.09	0.63	2.08–8.04	(sqrt) F = 1.08, P = 0.3051	

[1] Based on 2001 dry season sampling data; [2]analysis of variance was conducted on untransformed data where possible (n) or transformed data (sqrt) or by the Kruskal-Wallis method where data distributions were non-parametric (np). Bonferroni correction: **0.01, P = 0.00058 for 17 tests; * 0.05, P = 0.0029

3.3.2 Rehabilitation of Different Ages—A Chronosequence Study

3.3.2.1 Univariate Analysis

Averages, standard errors, ranges and ANOVA results are presented for rehabilitation age groups and woodlands sites in Appendix B.

Species richness and the Shannon–Wiener diversity index did not differ significantly between rehabilitation ages nor woodland sites (Figure 3-7a & b; Appendix B–a). In fact, species richness was equally highest (50 species) in the oldest (19 years) and youngest (0.5 years) rehabilitated sites. This value was higher than that of the woodland sites, possibly due to the higher number of exotic species.

Canopy cover increased with age in rehabilitation from 0.5 to 7 years, but cover in sites 8–19 years of age varied independently of age, ranging between 37% and 61% (Figure 3-7c). This was comparable to woodland sites with an average 59% canopy cover.

Overstorey eucalypt density differed significantly between rehabilitation of different ages and woodland sites ($F = 6.50$, $P < 0.001$) (Figure 3-7d; Appendix B–b). Average eucalypt density in 0.5–6-year-old rehabilitation ranged from 0 to 133 (± 133) plants/ha while 7–15 year-old rehabilitation supported 333–1283 (± 217) eucalypts/ha. The three oldest rehabilitation sites (two 17-year-old sites and the 19-year-old site) supported 67–317 (± 250) stems/ha. The low densities in younger rehabilitation areas were partly a function of the definition of the overstorey as being greater than 4 m in height.

Overstorey acacia density was low in rehabilitation less than 3 years old, at 0–33 (± 33) stems/ha, compared to woodland sites which averaged 44 (± 36) stems/ha (Figure 3-7e). Overstorey acacia density dramatically increased in rehabilitation aged 3–11 years, with 233 (± 233)–725 (± 203) stems/ha. In older rehabilitation, average acacia densities were lower, ranging from 0 to 200 stems/ha, but were generally greater than the densities in woodland sites.

The density of species of 'other' trees in the overstorey differed significantly between rehabilitation of different ages and woodland sites ($F = 3.64$, $P = 0.0017$) (Appendix B–b). Rehabilitation aged 0–4 years and 13–19 years supported densities of 0–78 (± 65) stems/ha, and were comparable to woodland sites which averaged 48 (± 27) stems/ha (Figure 3-7f). Sites aged 6–12 years ranged from 67 to 442 (± 76) stems/ha.

Average overstorey height differed significantly between rehabilitation of different ages and woodland sites (F = 4.38, P = 0.0008) (Appendix B–c) and increased with site age (Figure 3-7g). Even after 19 years, average overstorey height (7.4 m) of the rehabilitation was 60% that of the woodland sites (12.7 ± 1.3 m). Dominant height (average height of the two tallest trees or shrubs > 2 m) differed significantly (KW Statistic = 33.6602, P = 0.0023) between rehabilitation of different ages and woodland sites (Appendix B–c). Dominant canopy height increased with age (Figure 3-7h). In fact, the tallest trees in the 15-year-old sites averaged 12.2 m, only 3.1 m less than the average dominant height of woodland trees.

Average overstorey stem diameter increased over time, with older rehabilitation sites having marginally greater DBHs than younger sites (5.7–12.3 ± 2.9 cm) (Figure 3-8a). However, all rehabilitation had smaller stem diameters than woodlands (15.7 ± 2.3 cm).

The densities of acacias and other non-eucalypt trees in the midstorey (2–4 m high) varied greatly within age groups (large standard errors) and showed no trend with age (Figure 3-8b). Acacia densities in all age groups were generally well above those found in woodlands. They were highest in 3–7 year old rehabilitation, but lower in the older rehabilitation (except the 19-year-old site). The density of ‘other’ trees in rehabilitation less than 4 years of age was below that of woodlands, but generally higher than that in older rehabilitation sites. The density of eucalypts in the midstorey was significantly different for rehabilitation of different ages and woodland sites (F = 3.62, P = 0.0018) (Appendix B–d). Densities increased with age of rehabilitation in sites aged 0–7 years, but were variable in older rehabilitation (Figure 3-8c). Densities of non-eucalypt non-acacia plants in the midstorey showed a variable response in relation to rehabilitation age (Figure 3-8d).

Average plant density in the understorey differed significantly between rehabilitation of different ages and woodland sites (F = 8.62, P = 0.0000) (Appendix B–e), but this was likely due to very high densities in one site (the 19-year-old site). When this site was removed, plant density showed no obvious trend with age, ranging between 10 and 20 plants m^{-2} across rehabilitation sites of all ages as well as woodland sites (Figure 3-8e).

Except for one 6-year-old site, understorey eucalypt cover in rehabilitation was similar in all age groups, and low compared to woodland sites. Understorey cover of ‘other’ (non-eucalypt, non–acacia) trees species was 300% higher in natural woodland than rehabilitated sites (Figure 3-8g), a highly significant difference (Appendix B–e). Although low in very young rehabilitation (0.5% in the 0.5-year-old site), the cover of other tree species did not appear to vary systematically with rehabilitation age, ranging between 0.8% and 10%. Understorey weed cover was almost zero in the 0.5-year-old site, much higher in 2–3 year old sites, and markedly lower in older rehabilitation and especially woodland (Figure 3-8h).

3.3.2.2 Multivariate Analysis

In order to explore the floristic relationships between natural woodland and rehabilitation sites, an initial unconstrained ordination (DCA) was performed on the 2000/01 species–site matrix, with detrending by segments and down-weighting of rare species (Figure 3-9). The first axis of the DCA was marginally longer than the rest, and explained 12.3% of total species (vegetation) variability. Axes 2–4 accounted for 7.0%, 5.8% and 3.3% of total species variability in the vegetation matrix, respectively. The woodland sites clustered together, relatively close to the origin. Rehabilitated sites did not separate into clusters, although some sites were closer to woodland sites in ordination space than others. As a group, rehabilitation sites had higher scores on each of the first two axes than the woodland sites.

A species–site biplot (Figure 3-10) of the DCA of the species–site matrix enabled examination of the correlations between sites and the more influential plant species. All the eucalypt species were positively correlated with the first ordination axis, but *Eucalyptus tetrodonta* was also negatively correlated with the second axis. The cover of several grasses (*Yakirra muelleri*, *Thaumastochloa pubescens*, *Sorghum stipoideum*, *Aristida holathera* var. *holathera* and *Heteropogon triticeus*) was positively correlated with the second axis and was negatively correlated with the densities of *Eucalyptus tetrodonta* (and cover), *Eucalyptus miniata* and *Corymbia polycarpa*. Giant spear grass (*Heteropogon triticeus*) was negatively correlated with the other grasses and correlated with the presence of *Eucalyptus tetrodonta*. The density of acacias (*Acacia aulacocarpa*, *A. auriculiformis*, *A. torulosa* and *A. latescens*) was also influential in the distribution of sites in ordination space, and correlated with high grass cover and low eucalypt density.

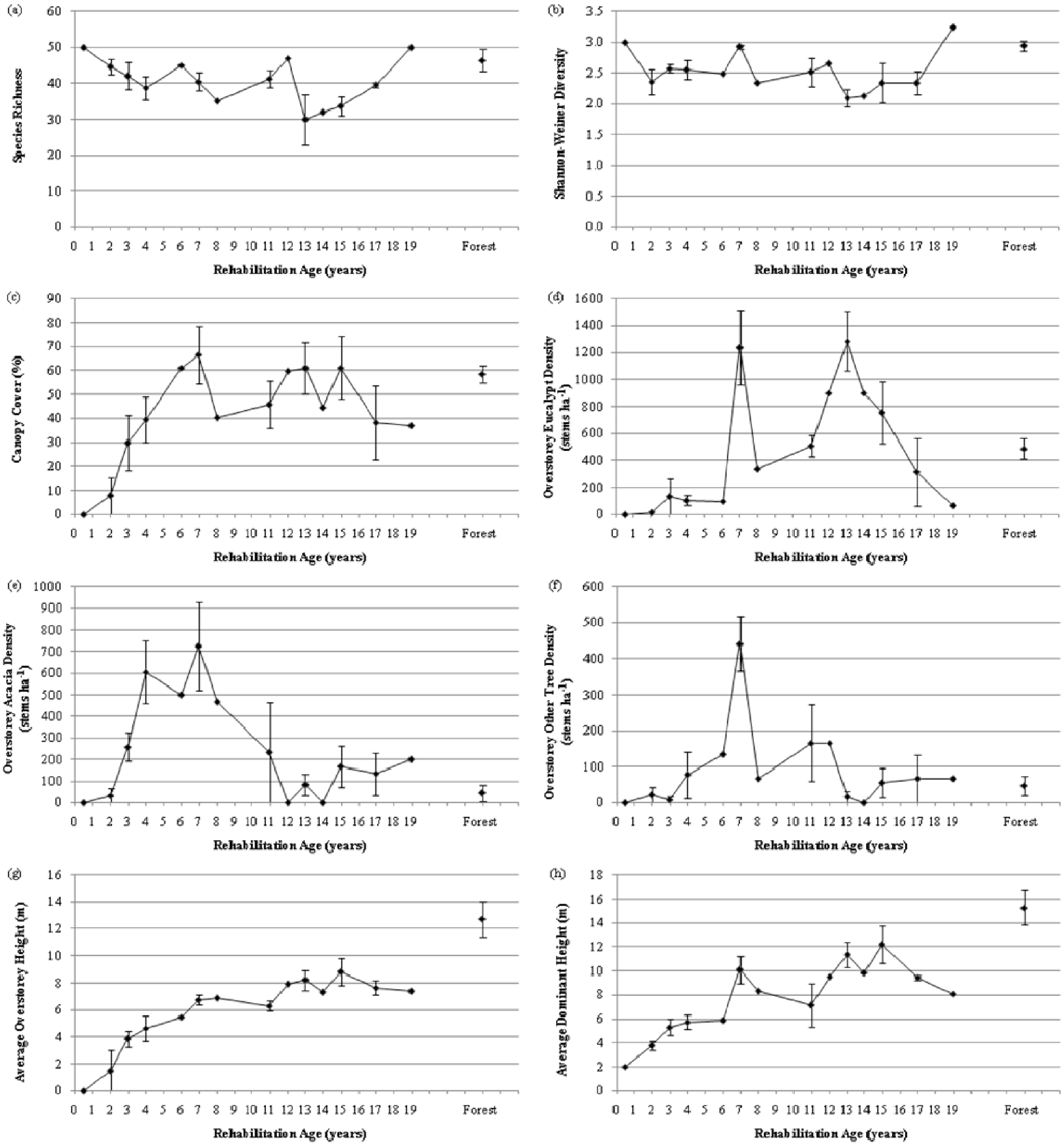


Figure 3-7 Vegetation characteristics of rehabilitated and natural woodland sites: (a) species richness; (b) Shannon–Wiener diversity index; (c) canopy cover; (d) overstorey eucalypt density; (e) overstorey acacia density; (f) overstorey ‘other’ tree density; (g) average overstorey height; and (h) average dominant height (top two trees). Values are means ± 1 SE

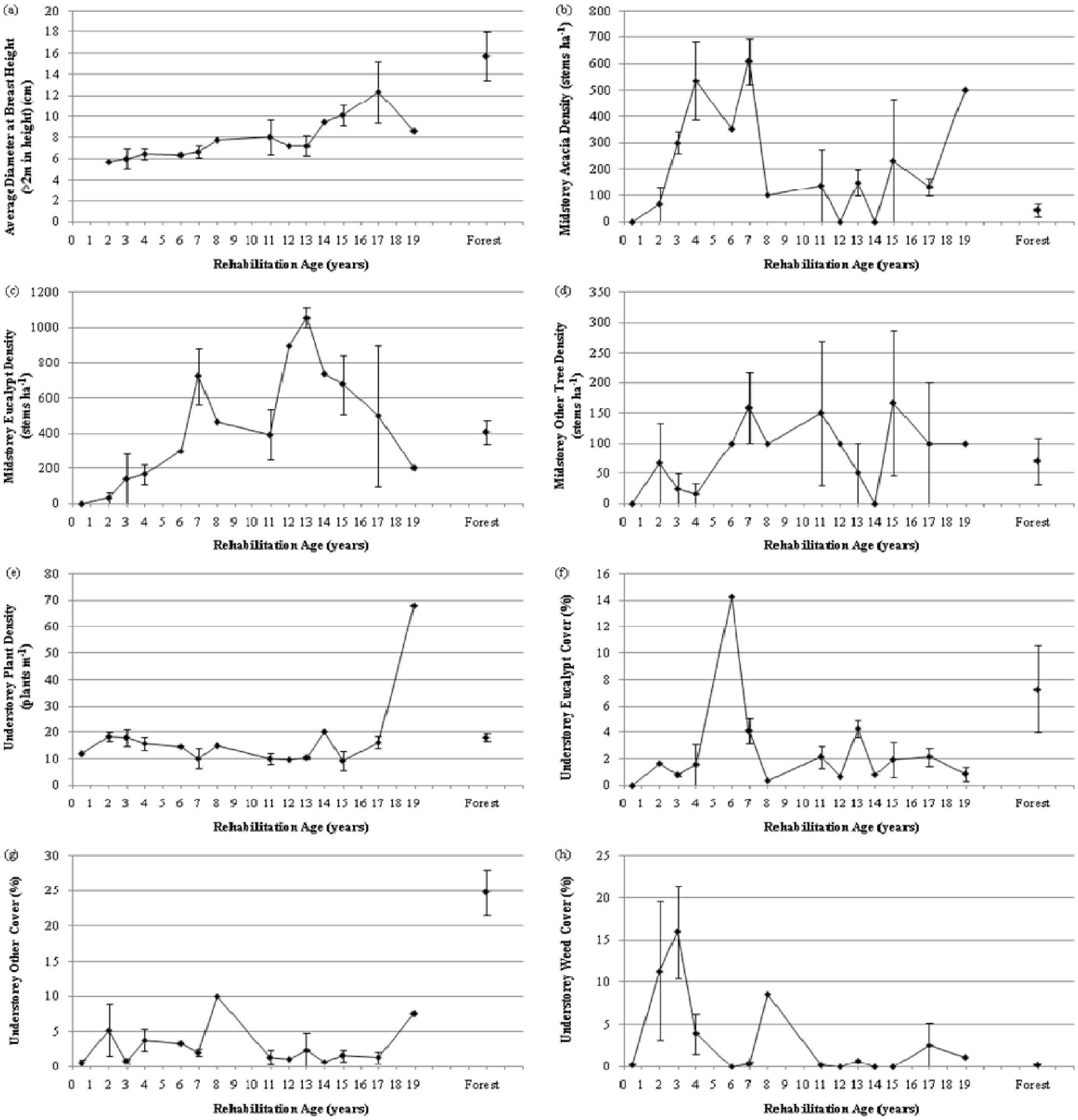


Figure 3-8 a-h Vegetation characteristics for rehabilitated and woodland sites: (a) average diameter at breast height (plants > 2 m high); (b) midstorey acacia density; (c) midstorey eucalypt density; (d) midstorey ‘other’ tree density; (e) understorey plant density; (f) understorey eucalypt cover; (g) understorey ‘other’ cover; and (h) understorey weed cover. Values are means ± 1 SE

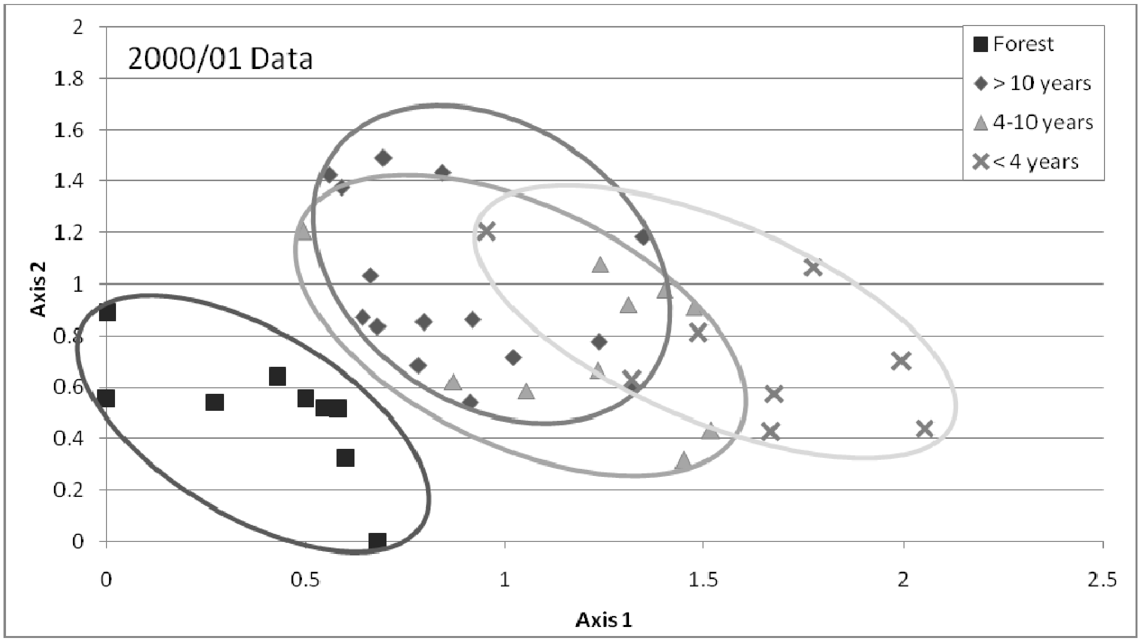


Figure 3-9 DCA ordination of all 42 sites of 2000/01 data (species–site matrix; down-weighted rare species) showing rehabilitation sites grouped by age groups (< 4 years, 4–10 years, > 10 years) and woodland sites

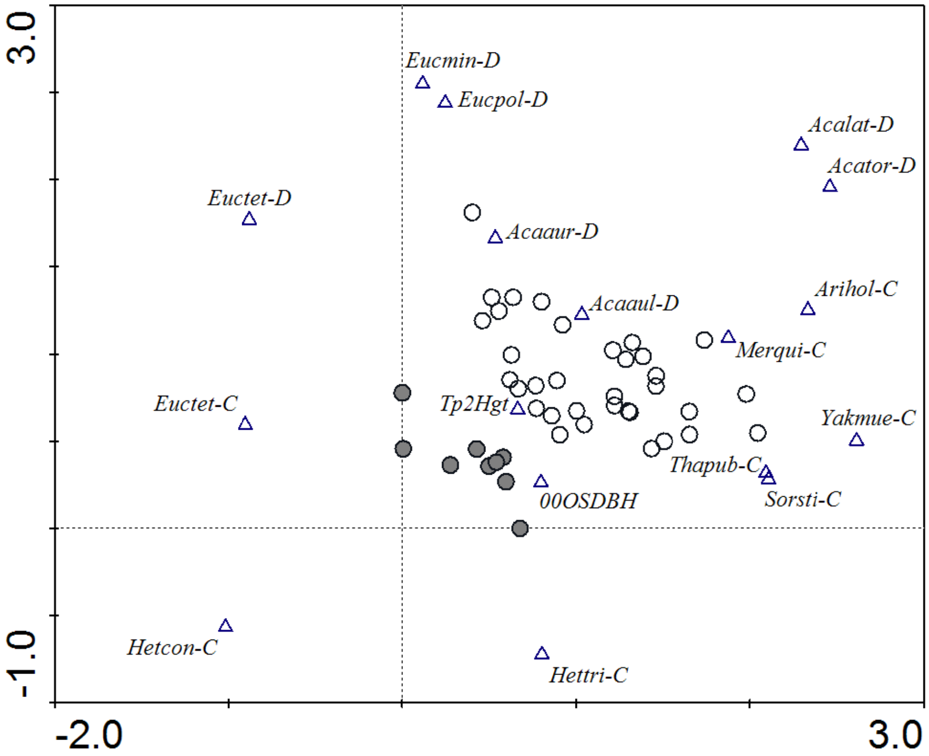


Figure 3-10 The species–sites (triangles and circles, respectively) bi-plot of the DCA of the species–site matrix (species with weight higher than 3% are shown). The woodland sites are represented by filled circles

3.3.3 The Characteristics of Rehabilitated Vegetation

3.3.3.1 Identification of Rehabilitation Groups

Classification using group-average clustering applied to the 2000/01 species–site matrix revealed seven distinct groups of sites (Figure 3-11). The woodland sites formed a cluster (Group A) with the lowest level of dissimilarity (< 50%) and included one 11-year-old rehabilitation site. The remaining rehabilitation sites fell into six groups, Groups B–G in increasing order of dissimilarity to the woodland sites, based on the composition and structural data in the matrix.

DCA analysis of the same data showed how the sites in Group B clustered closer to the woodland sites than sites in the other groups (Figure 3-12). Groups B, C and D were somewhat similar to each other and overlapped in ordination space. Groups E, F and G clustered further along the primary ordination axis (axis 1) than the other groups, and also overlapped slightly.

Four sites did not fit easily into the six main rehabilitation groups:

- F2-1989 was more similar to woodland sites than other rehabilitation sites (Group A);
- C-1992 was a highly weed-infested site with little similarity to other rehabilitation sites or woodland (Group I);
- F4-2000 was a very young site with no midstorey or overstorey development, and thus low in information content in the species–site matrix (Group J); and
- D-1989 had high acacia densities and cover as well as high grass loads (Group H).

These sites were classed as outliers and not included in the following comparative analysis. They are discussed further in Chapter 5.

3.3.3.2 Descriptions of Group Attributes

Vegetation characteristics of the seven groups are plotted in Figures 3-8 to 3-11. Detailed statistical summaries of these analyses are provided in Appendix C.

Groups B, C and D shared similar average site ages, ranging from 11.0 to 12.6 years (Table 3-13). Sites in Group E were on average 7.4 years old, and sites in Groups F and G were generally younger, averaging 3.0 and 2.3 years, respectively.

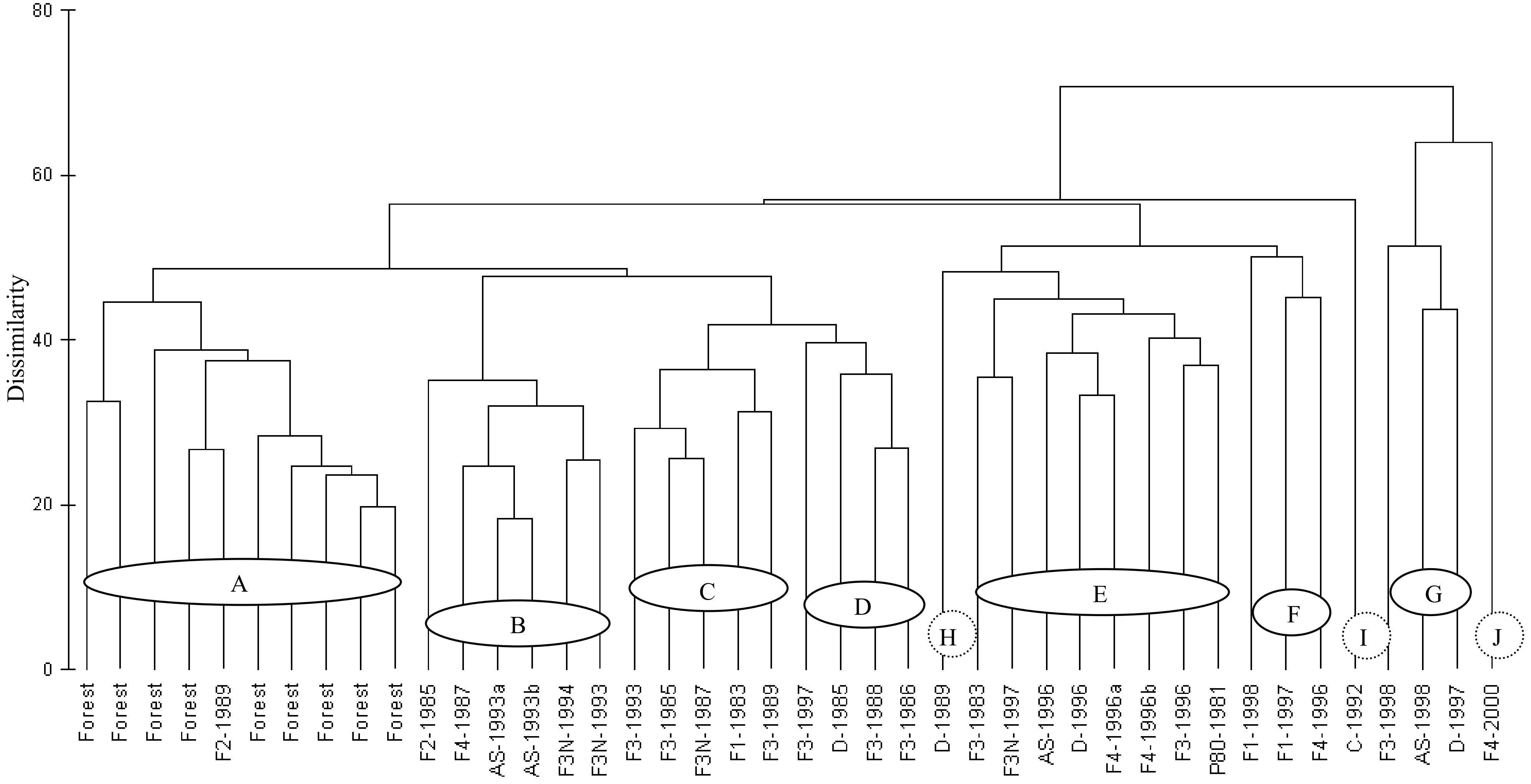


Figure 3-11 Dendrogram of sites using group-average clustering of Bray–Curtis dissimilarities calculated on the 2000/01 species–site data matrix (log [x + 1] transformation)

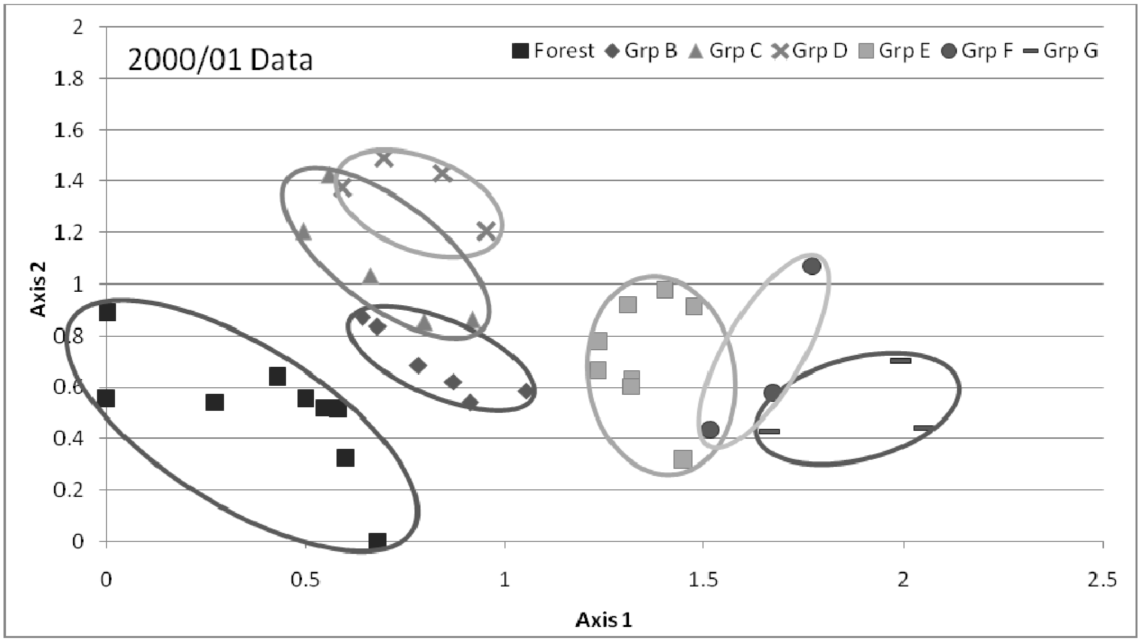


Figure 3-12 DCA ordination showing differences between rehabilitation groups and woodland sites (2000/01 species–site matrix; rare species down-weighted)

Table 3-13 Average age and number of sites of the six groups of rehabilitation sites

Group	Number of sites (n)	Average Age (years)
B	6	12.5
C	5	12.6
D	4	11.0
E	8	7.4
F	3	3.0
G	3	2.3

Species richness was highest in the woodland sites (average of 51 ± 2.7 species; Figure 3-13a) but not significantly so (Appendix C–a). Group B rehabilitation sites had a much lower average richness (39 ± 3.4 species. Of the rehabilitation groups, Group E sites had the highest richness (50 species), slightly lower than the average of the woodland sites. The woodland group also had the highest average Shannon–Wiener diversity (2.9 ± 0.1; Figure 3-13b), but Group E had at least one site with a value similar to that of the woodland sites (3.2).

Canopy cover was significantly lower (F = 12.1, P < 0.001) in Group G sites (average 3.3 ± 3.2%) compared to other groups (Figure 3-13c), and also very low in Group F (average 21 ± 1%). Group B sites averaged higher canopy cover (66 ± 8 %) than woodland sites (59 ± 4 %).

Dominant height differed significantly between groups (F = 31.5571, P = 0.0005; Appendix C–b). The woodland group had the largest range in dominant height (8–23 m) with an average of 13 ± 1.3 m (Figure 3-13d). This was higher than the maximum dominant height in the tallest rehabilitation group, Group D (maximum 11 m, average 7.9 ± 1.1 m). Groups F and G both had a maximum dominant height of less than 4 m.

Diameter at breast height (dbh) of overstorey trees did not differ significantly between the groups (Appendix C–b), even though woodland plots had a maximum dbh of 30 cm and averaged 16 ± 2.3 cm compared to averages of 7.3–8.2 cm in Groups B–E (Figure 3-14a). Groups F and G had very low stem diameters compared to other groups.

There was a significant difference in overstorey eucalypt stem density between groups (F = 6.19, P = 0.0001) (Appendix C–c). Woodland sites (Group A) averaged 489 ± 76 stems/ha, while Group C had the highest maximum and average density (1933 and 1133 ± 260 stems/ha, respectively) (Figure 3-14b). Groups B and D also had higher average overstorey eucalypt densities than woodland sites (744 ± 197 stems/ha and 817 ± 95 stems/ha, respectively). Groups E and F had very low numbers of eucalypts in the overstorey and Group G had none at all. Groups B and E had the highest average acacia densities in the overstorey (556 ± 168 and 517 ± 123 stems/ha, respectively) (Figure 3-14c). The average for woodland sites was lower than all other Groups (44 ± 36), including Group G which averaged 122 ± 122 stems/ha. Rehabilitation Group B had the highest maximum and average numbers of ‘other’ trees in the overstorey (600 stems/ha and 278 ± 98 stems/ha, respectively), even though at least one of these sites had no ‘other’ trees in the overstorey (Figure 3-14d). In fact, only Group C had ‘other’ trees in the overstorey at all sites. Group F also had quite high average ‘other’ tree densities in the overstorey, while woodland sites and Groups D and E had relatively low densities.

There was a significant difference in midstorey eucalypt density among groups (F = 11.4, P = 0.0000), with Groups B, C and D averaging 567 ± 109, 960 ± 89 and 729 ± 68 stems/ha, respectively (Appendix C–d). Woodlands averaged 489 ± 76 eucalypt stems/ha with a maximum of 900 stems/ha in the midstorey. Groups E and F, on the other hand, had only 63 ± 17 and 100 ± 84 eucalypts/ha, respectively, in the midstorey, and Group G had none (Figure 3-15a). The density of midstorey acacias differed significantly between groups (F = 3.65, P = 0.0026) (Appendix C–d). Groups E and B had the highest average densities, with 515 ± 104 and 483 ± 83 stems/ha, respectively (Figure 3-15b). Group C had a maximum of 783 stems/ha but averaged only 210 ± 147 stems/ha. Group G had higher average densities than the woodland sites and Group D, and only marginally fewer stems per hectare than Group F. Densities of 'other' trees in the midstorey of Groups B and C were higher than other groups, averaging 172 ± 64 and 200 ± 78 stems/ha, respectively (Figure 3-15c). Woodland sites had densities similar to Group F; Groups D and E had lower densities, and Group G had none at all.

Group E sites varied greatly in understorey plant density (8–68 plants/m^2). The average for this group was marginally higher than that of other groups, including natural woodlands (Figure 3-16a). Groups B, C and D had the lowest minimum and average densities compared to other sites.

Natural woodland sites had by far the greatest maximum cover of juvenile eucalypts in the understorey (29%) although the average (7 ± 3%) was much closer to that of the other groups (1–4%) (Appendix C–e; Figure 3-16b). Understorey cover of 'other' tree species differed significantly among the groups ($F = 10.1$, $P < 0.001$) (Appendix C–e). The woodland group averaged 25 ± 3% cover, compared to Group B, the next highest with 9 ± 4% cover. The other four groups all averaged less than 5% cover of understorey 'other' trees (Figure 3-16c). Understorey weed cover was highest in Groups D–G, with average values all above 6% and maximum values ranging between 18 and 27% (Figure 3-16d). Woodland sites and Groups B and C had much lower weed covers, with averages of less than 1% and no more than 1% weed cover at any one site.

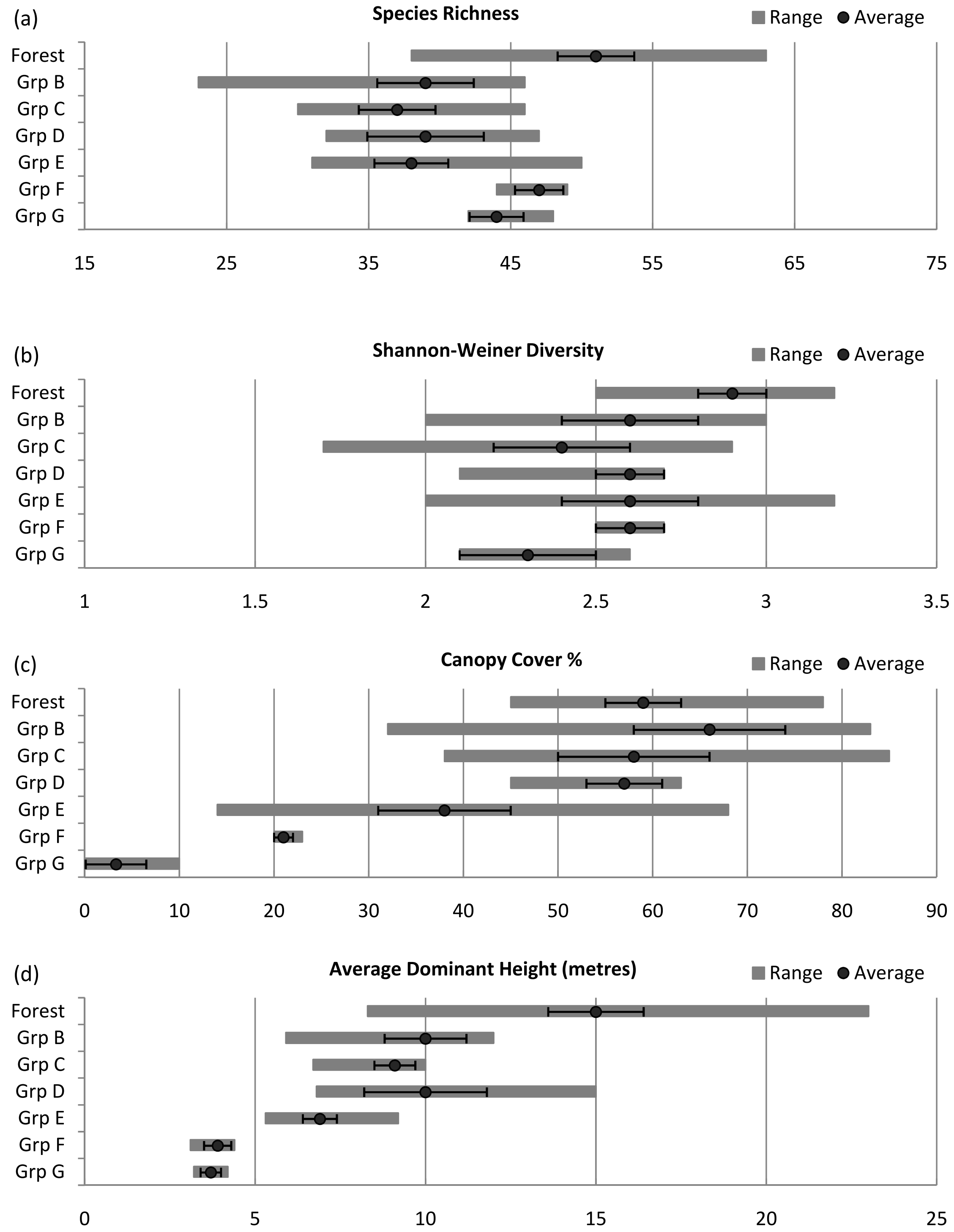


Figure 3-13 Vegetation characteristics of grouped sites in 2000/01: (a) species richness; (b) Shannon–Wiener diversity; (c) canopy cover; and (d) average dominant height (2000 dry season and 2001 wet season data). Lines (whiskers) represent standard errors

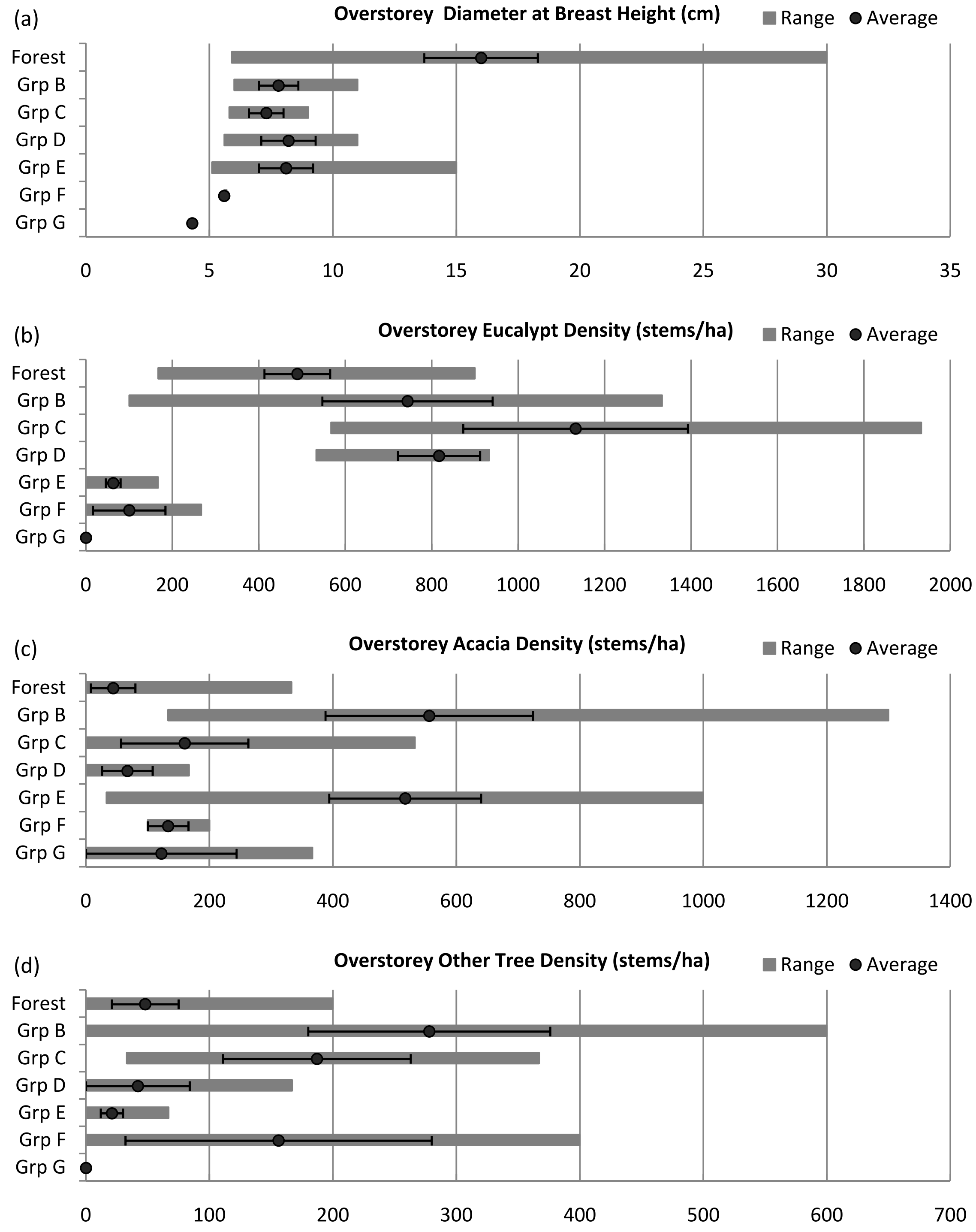


Figure 3-14 Vegetation characteristics of groups of sites in 2000/01: (a) overstorey diameter at breast height; (b) overstorey eucalypt density; (c) overstorey acacia density; and (d) overstorey ‘other’ tree density (2000 dry season data). Lines (whiskers) represent standard errors

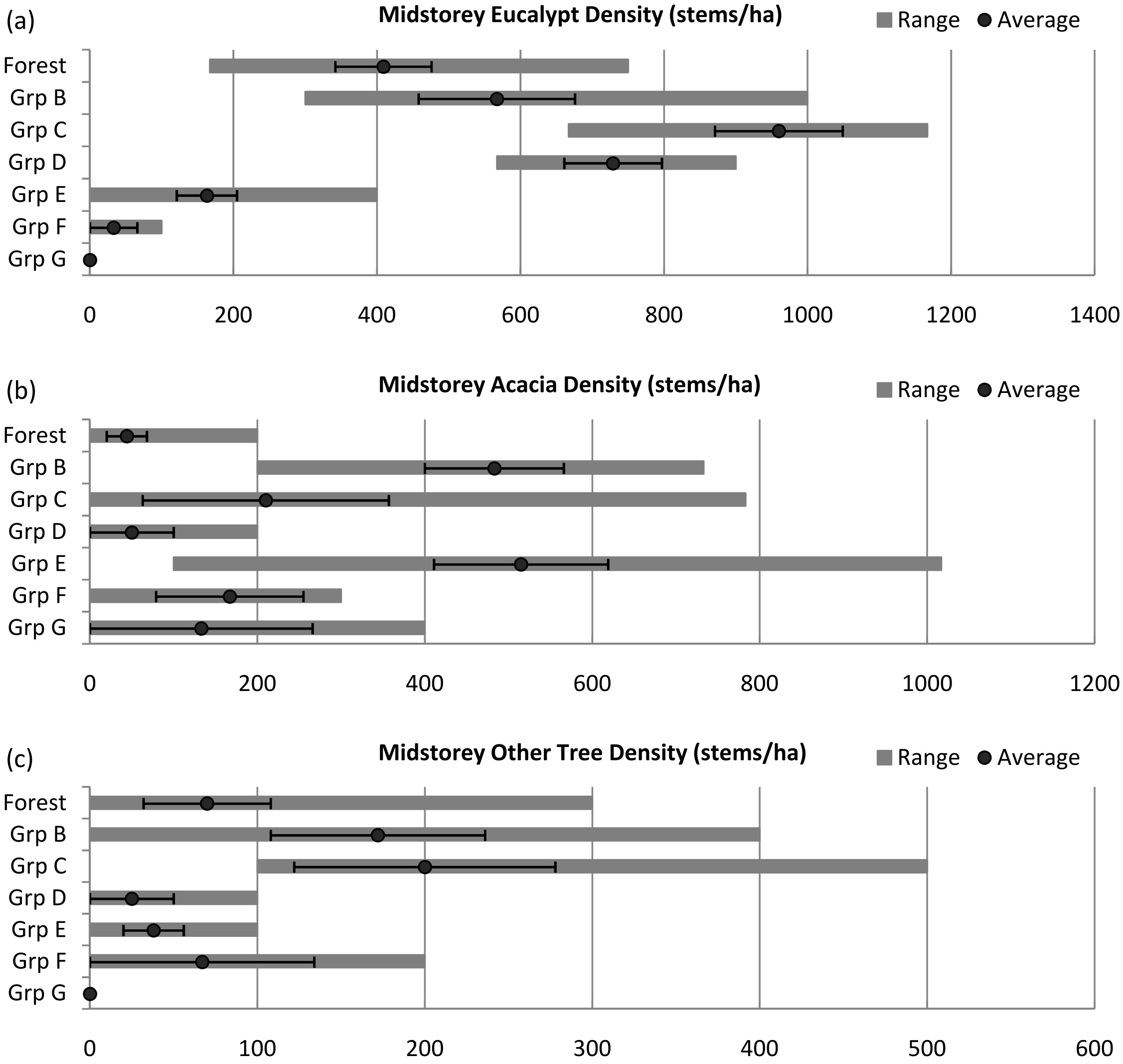


Figure 3-15 Vegetation characteristics of grouped sites in 2000/01: (a) midstorey eucalypt density; (b) midstorey acacia density; and (c) midstorey other tree density (2001 wet season data). Lines (whiskers) represent standard errors

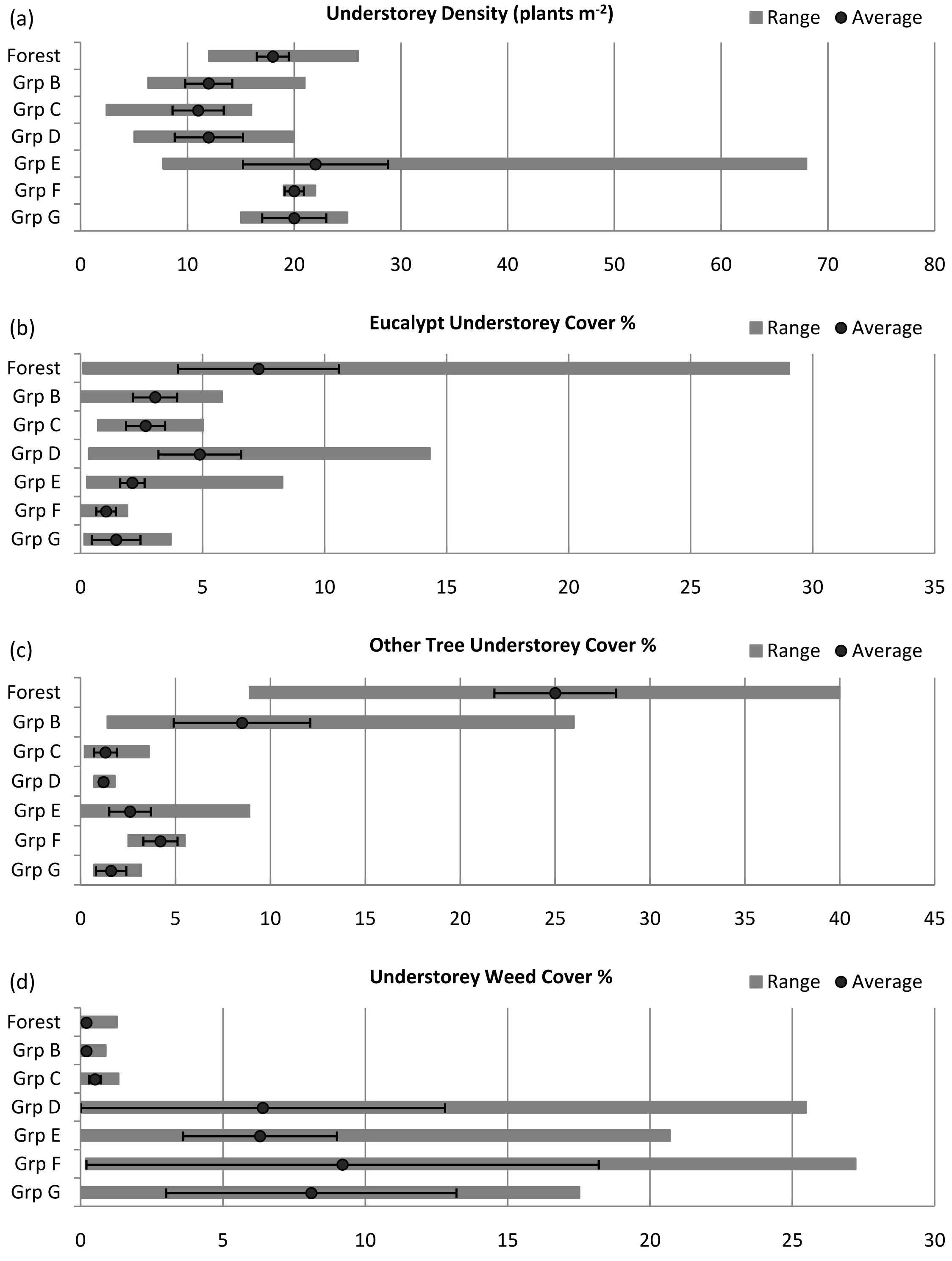


Figure 3-16 Vegetation characteristics of groups of sites in 2000/01: (a) understorey density; (b) understorey eucalypt cover; (c) understorey acacia cover; and (d) understorey other tree cover (2001 wet season data). Lines (whiskers) represent standard errors

3.3.4 Comparison of 2000/01 and 2001/02 Groups

Comparisons thus far have shown a number of significant differences in terms of floristic composition and structure between groups of rehabilitation and woodland sites, based on the 2000/01 sampling data. However, changes over time can be significant, especially in an environment where disturbances, such as fire, are common. Similarities between sites could change dramatically through time, depending on the vegetation characteristics that similarity is based on and the random occurrence of different disturbances among sites. For example, if two recently rehabilitated sites were similar in understorey composition or cover, a fire in one site could kill all the shrubs and leave the burnt site in a stable herbaceous state. On the other hand, older sites with similar overstorey densities are unlikely to be affected by burning, as the overstorey (> 4 m in height) is rarely impacted by the fires that normally occur in this environment.

A second set of sampling data was collected in 2001 and 2002. This information was used to explore the consistency of the relationships between sites studied in 2000/01 and highlight the short-term impacts of disturbance experienced over the course of 1 year, such as fire and cyclone-driven tree fall. Vegetation characteristics (such as composition or structural indices) that are resilient in the face of the short-term, transitory impacts of disturbance could be valuable criteria for measuring rehabilitation condition and development in the longer term.

3.3.4.1 Ordinations

A second unconstrained ordination (DCA) was performed on the 2001/02 species–site matrix, in the same way as described for the previous year's data in Section 3.3.2.2. The first axis of the DCA explained 12.5% of total species (vegetation) variability, while axes 2–4 accounted for 8%, 4.7% and 3.5% of total variability, respectively. Compared to the DCA of the 2000/01 data plotted by age group (Figure 3-9), sites in 2001/02 retained their overall pattern in ordination space, with woodland sites nearest the origin, and rehabilitation age generally decreasing with increasing distance from the origin (Figure 3-17). The woodland sites, in particular, retained their tight-knit relationship and position closest to the origin. Comparing the separate ordinations for each year, some movement of the Groups in ordination space was evident, as all groups had generally lower axis 1 values in 2001/02 compared to 2000/01 (Figure 3-18).

A third DCA ordination of species–site data for both years showed that sites within all groups except for Group F, were very closely associated for both years and this did not change between the two years (Figure 3-19). Group F was much less tightly clustered than the other Groups and moved considerably between the two sampling events (Figure 3-19d). These less stable sites convey important information about the dynamics of the system.

Canopy cover in 2001/02 differed significantly between groups ($F = 7.93$, $P < 0.001$) and also differed significantly from the previous year's values ($F = 12.88$, $P = 0.0049$). Groups B, C and D had canopy cover ranges and averages similar to that of woodlands (Figure 3-20a). Groups E and F averaged less than 20% cover and Group G canopy cover was extremely low. Canopy cover of all groups in 2001/02 was much lower than the previous year, including woodland sites, suggesting a drier season in winter 2001.

The density of overstorey eucalypts (Figure 3-20b), average dominant height (Figure 3-20c), midstorey eucalypt density (Figure 3-20d), acacia density in the midstorey (Figure 3-21a), and understorey eucalypt cover (Figure 3-21b) did not change significantly compared to the previous year (Appendix D–a & b), but all these variables still varied significantly among groups in 2001/02.

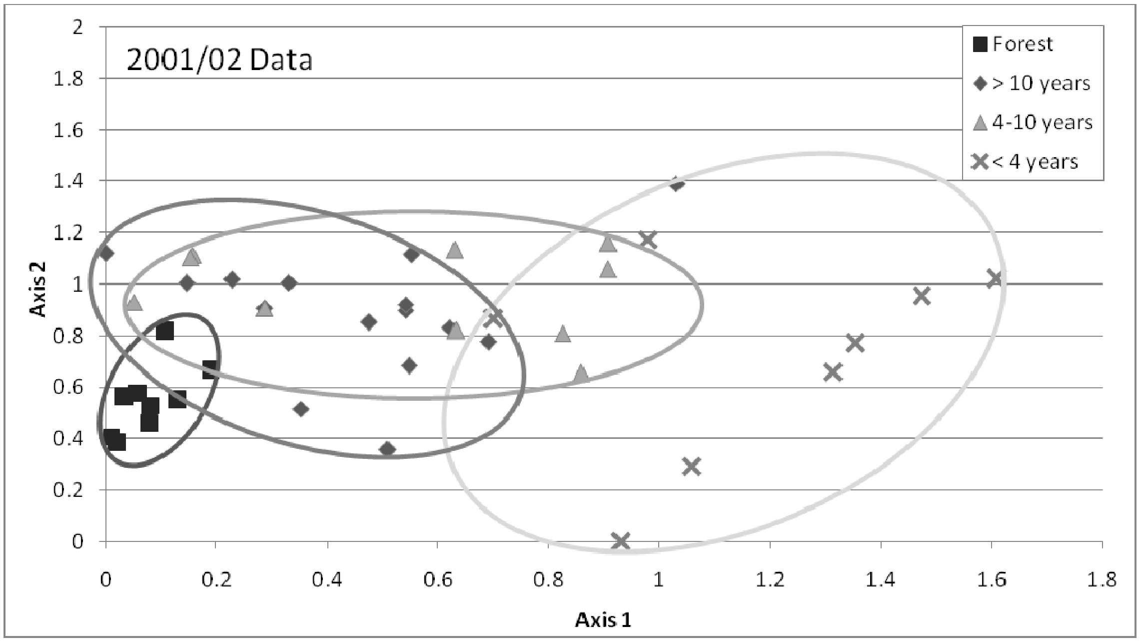


Figure 3-17 DCA ordination of all 42 sites, based on the 2001/02 data (species–site matrix; rare species down-weighted), showing rehabilitation sites grouped by age (< 4 years, 4–10 years, > 10 years) and the woodland sites

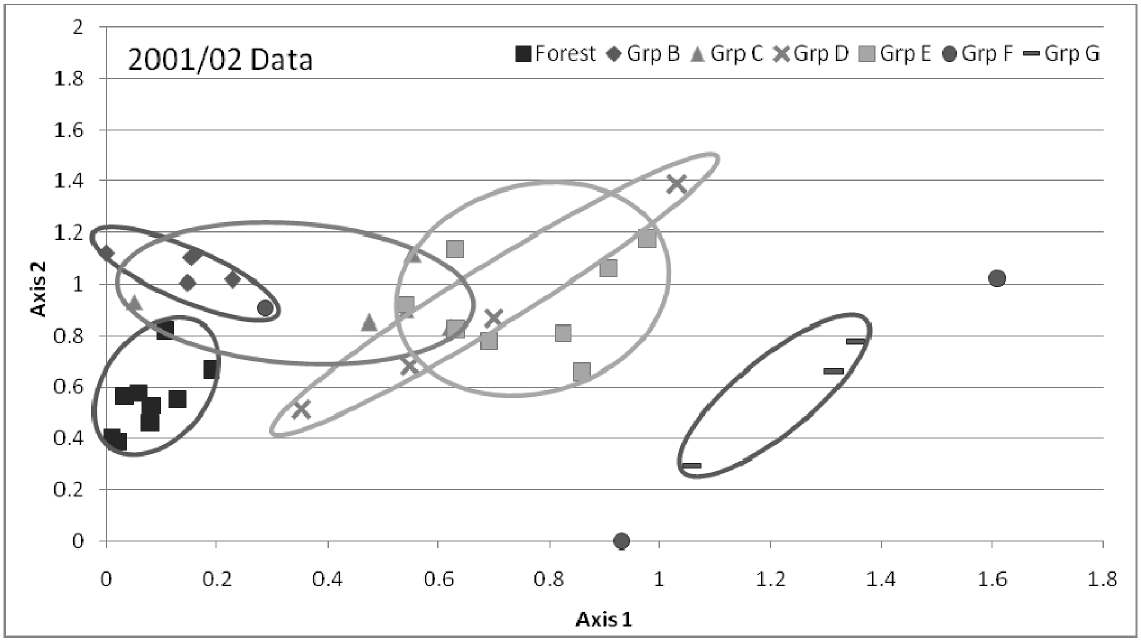


Figure 3-18 DCA ordination based on the 2001/02 species–site matrix (rare species down-weighted), but with sites assigned to the rehabilitation and woodland groups based on the previous year's analysis

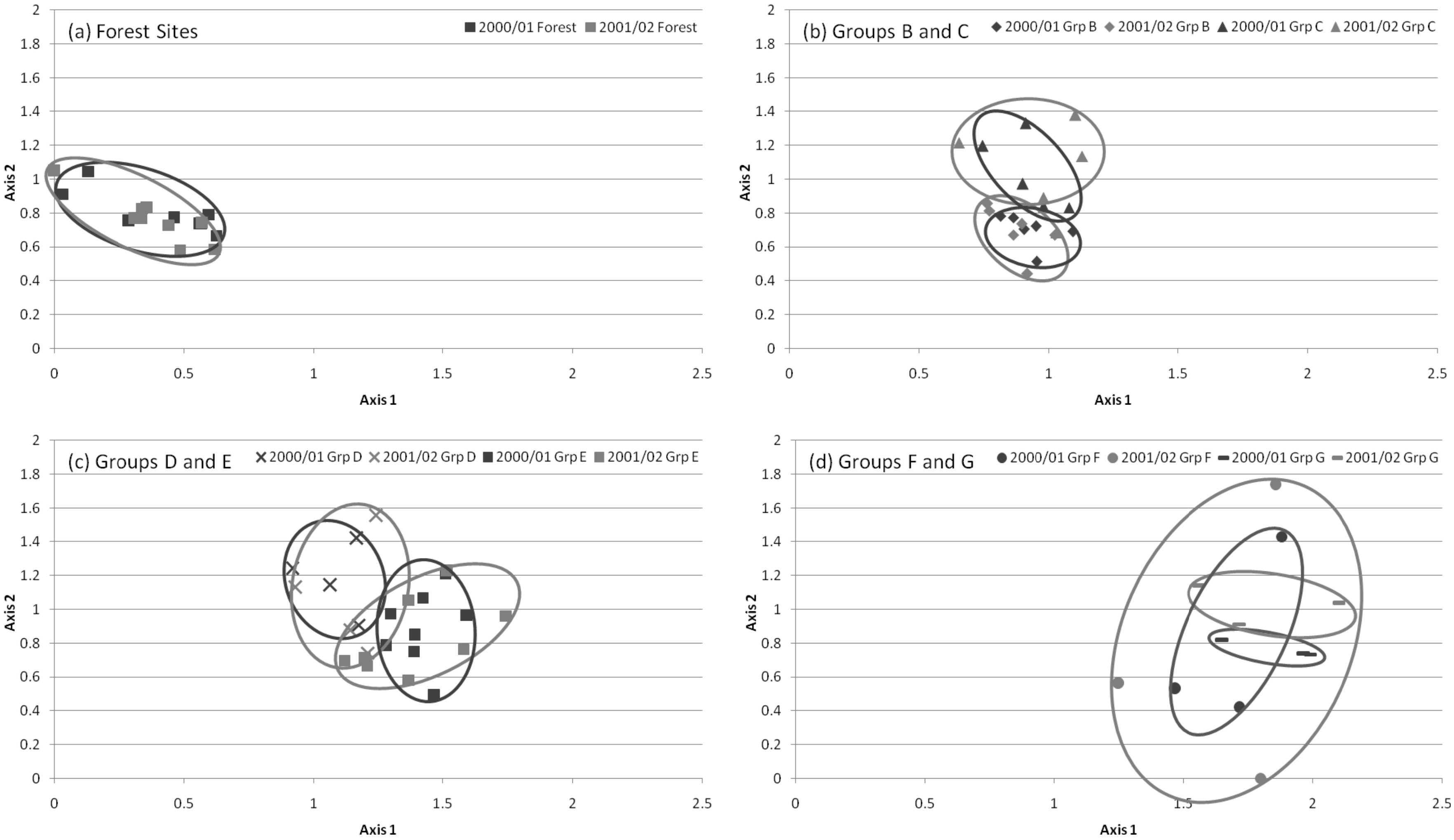


Figure 3-19 DCA ordination of 2000/01 and 2001/02 species–site data (down-weighted rare species) for (a) woodlands; (b) Groups B and C; (Groups D and E; and (d) Groups F and G

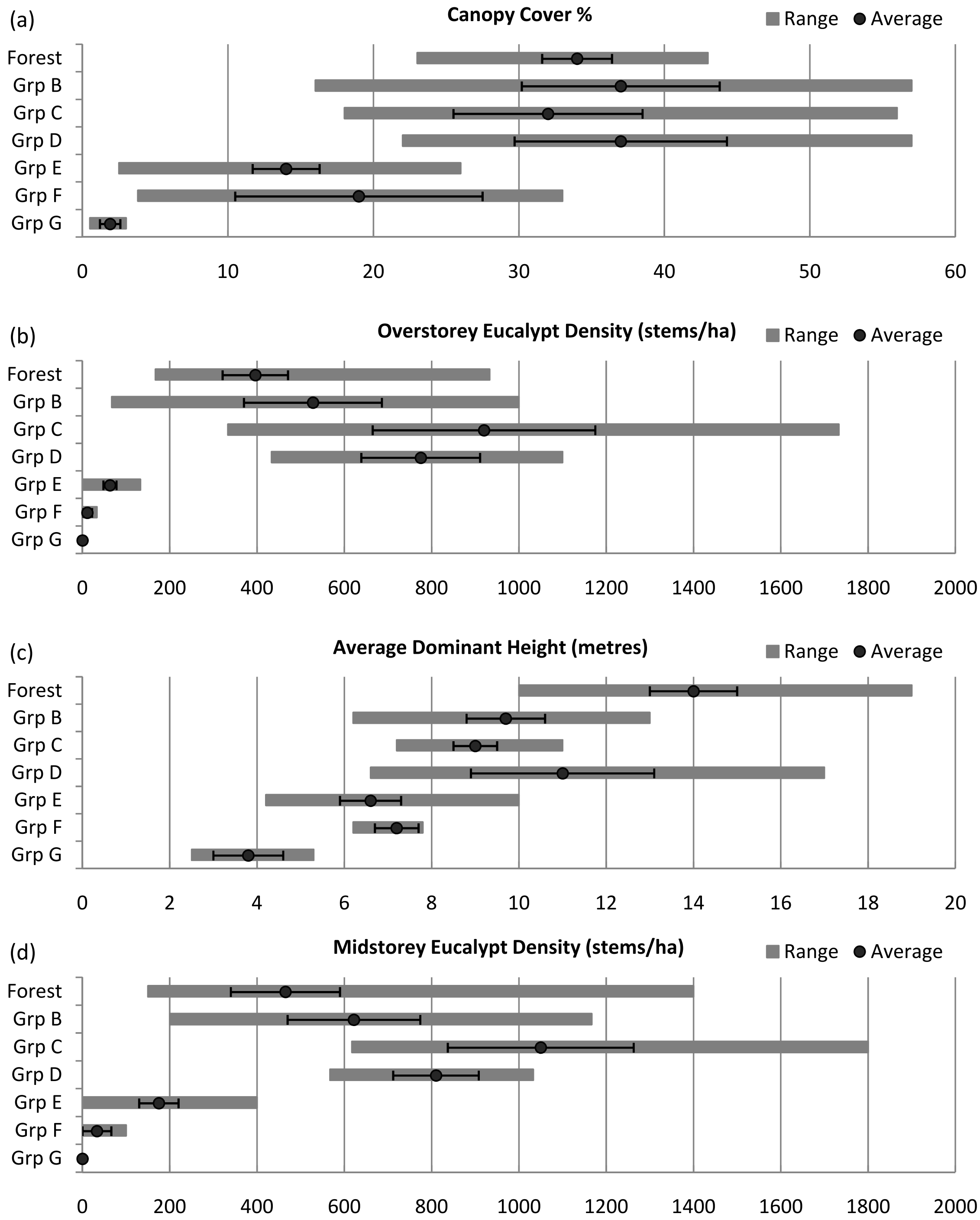


Figure 3-20 Characteristics of grouped sites in 2001/02: (a) canopy cover; (b) overstorey eucalypt density; (c) overstorey dominant height; and (d) midstorey eucalypt density (2001 dry season and 2002 wet season data). Lines (whiskers) represent standard errors

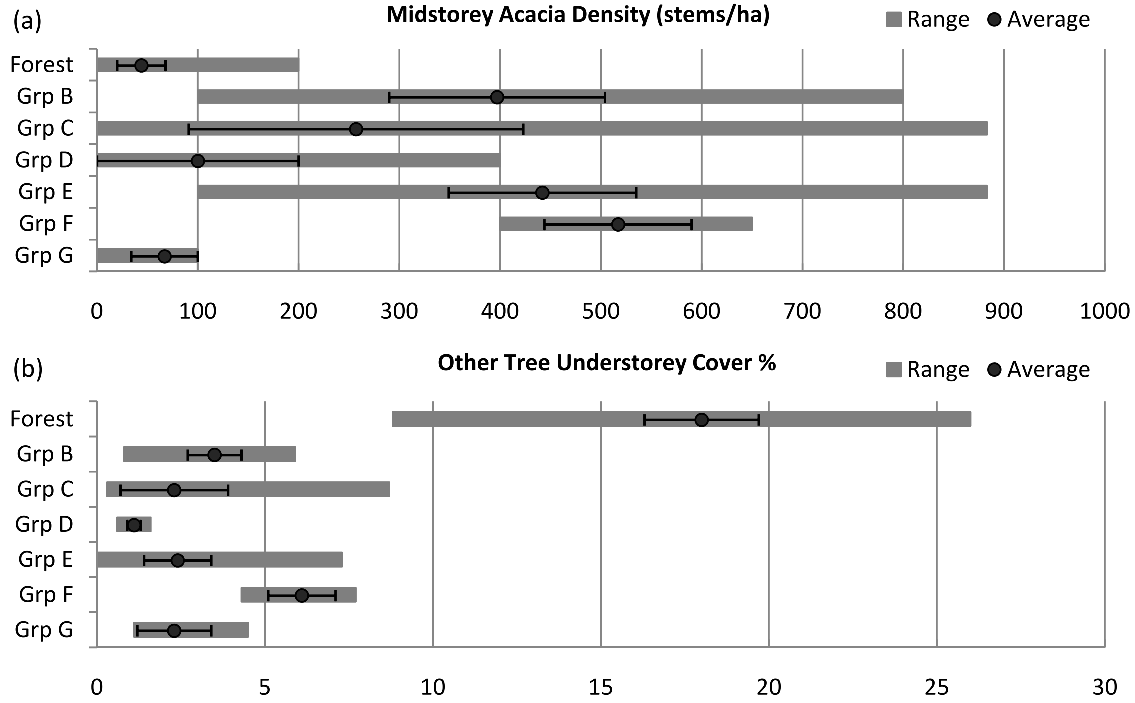


Figure 3-21 Characteristics of grouped sites in 2001/02: (a) midstorey acacia density; and (b) understorey density of other trees (2002 wet season data). Lines (whiskers) represent standard errors

3.4 Discussion

3.4.1 Natural Woodland and Rehabilitation—Key Differences

The natural woodlands of western Groote Eylandt are typical of the tropical savannas of northern Australia, in that they have are clearly stratified into distinct canopy, midstorey and groundstorey layers (Russell-Smith 1995). In particular, the canopy is dominated by *Eucalyptus tetrodonta* and *E. miniata* at densities between 167 and 900 stems/ha, with a dominant height averaging 15 m and densiometer canopy cover of 45–80%. Subcanopy species included ironwood (*Erythrophleum chlorostachys*), some tall acacia trees and red ash (*Alphitonia excelsa*). A sparse shrub layer consisted mostly of eucalypts but also other trees such as *Planchonia careya* and *Petalostigma pubescens*. The understorey was dominated by grasses (averaging 37% cover), including *Sorghum* sp. and *Heteropogon triticeus*. Weeds were rare (averaging < 1% cover). The above values for each attribute equate to end-point criteria for rehabilitation at GEMCO. It is advisable to recognise the range of values that exists for the woodland sites (Table 3-6), as this indicates the variability of these attributes in the natural environment, a variability which should be equally acceptable in a rehabilitated landscape.

In general, the GEMCO rehabilitation was composed of species similar to that of the native woodland, except for the exotic tree and shrub species that had been introduced as part of the seed mix or in forestry trials in the past, and also weed species that were opportunistically self-propagating within rehabilitation areas. The structure and relative dominance of species in the rehabilitation differed markedly from undisturbed woodland, as well. Acacia densities, in particular, were higher in all three vegetation strata in the rehabilitation compared to woodlands, with at least 7-fold, 6-fold and 2-fold increases in the overstorey, midstorey and understorey strata, respectively. Rehabilitated sites, on the whole, had significantly fewer species, lower average and dominant canopy heights, lower cover attributable to non-eucalypt and non-acacia tree species in the understorey, and higher weed cover than woodland sites.

High weed diversity and cover in rehabilitation compared to undisturbed woodland or forest sites is not surprising, and is similar to the situation reported for 9-year-old rehabilitation at the Narbarlek uranium mine, in Arnhem Land. Here, Bayliss *et al*. (2006) found that 11 grass weed species and 17 forb weed species made up 48% of all rehabilitation species (and 55% of total cover). Weeds were found to have a major impact on vegetation composition and probably on ecological function, as well.

Some species were only found in woodland plots, such as the fern *Cheilanthes contigua* or lily *Crinum uniflorum.* While this does not rule out their colonisation over a longer period of time, it suggests they are not able to recruit from the topsoil seed store or are unsuited to the rehabilitated environment. Such recalcitrant species may require special efforts for their introduction.

The regular fires in the region, affecting both woodland and rehabilitation sites, meant that litter generally did not build up at sites. This frequent burning also affected vegetation structure in the dry season, with greatly decreased numbers of Levy Pole touches, especially at lower heights where grasses and small herbs were removed by fire. Wet season values of grass cover and Levy Pole touches were consistently high, regardless of whether fire was experienced in the preceding dry season or not, highlighting the natural resilience of the understorey layer to recurrent fire. Fire is discussed in more detail in Section 3.4.5.

Levy pole measurements also showed that rehabilitation sites generally had more vegetation at heights above 1.5 m, reflected in the greater number of touches, both live and dead, at these upper height intervals in both wet and dry seasons. Due to the high acacia composition of many rehabilitation sites, the majority of the dead touches were senesced acacias, which provided standing trash that could potentially carry a fire above the grass layer. This differs from the low severity, patchy burns these systems are generally adapted to, and could inflict long-term damage to the midstorey and overstorey tree and shrub species.

Some acidification of the soil was observed in rehabilitated sites compared to woodland sites. This is a common feature of soils that have been seriously disturbed and replaced for rehabilitation, mixing the subsoils with the topsoil. The lowered pH level in rehabilitated sites, averaging 6.4, is not considered to be prohibitive to plant or microbial growth and thus no specific treatments, such as liming, are required (Handreck & Black 2002). Of all the soil chemical parameters measured, only calcium was significantly lower in rehabilitated soils compared to woodland sites. Despite this, fertiliser application to dramatically increase levels of nitrogen, phosphorus and potassium, is a standard feature of the rehabilitation technique at Groote Eylandt. Australian soils are acknowledged as being of low nutritional value (Isbell 1983) and while growth of some native species is improved with supplementary nutrition, other species are known to show symptoms of phosphorus toxicity even at low rates of phosphorus addition (Handreck & Black 2002).

3.4.2 Rehabilitation of Different Ages

Age has an obvious influence on woodland structure, as mature trees and shrubs are generally taller and have greater stem diameters than younger plants. Grasslands of different age, however, are unlikely to differ as markedly. Rehabilitated vegetation had a pronounced relationship with age, although other factors such as ecological assembly rules (Lockwood & Pimm 1999), disturbance and management history also had significant effects (these are explored in Chapter 4). Rehabilitation sites at GEMCO varied widely in vegetation characteristics, some being more similar to natural woodland than others. Ordination of the 2000/01 species–site data showed that older rehabilitated sites tended to be located closer to woodland sites in ordination space than younger rehabilitation.

Confounded with the age of rehabilitation, however, were idiosyncratic sets of disturbance and climatic histories which varied in time and space and likely affected rehabilitated sites in individualistic ways, for example:

- the timing, evenness and total amount of rainfall in the first wet season after rehabilitation establishment;
- the longer-term pattern of wet–dry seasonality at a particular age of rehabilitation; and
- the linkage between prolonged wet seasons producing high fuel loads and later, intense dry-season fires.

The increase in overstorey canopy cover with age in younger rehabilitation was directly related to the increasing height of plants. While increasing crown cover might suggest that the overstorey of older rehabilitation is developing towards the desired woodland structure, this variable does not discriminate between desirable and undesirable plant species, nor variations in plant density.

Overstorey eucalypt density increased with the age of rehabilitation although for very young sites, at least, this was an artefact of the definition of the overstorey (a minimum of 4 m in height). Rehabilitation sites aged less than 6 years and showed negligible increase in eucalypts over time. This result highlights the importance of the successful initial establishment of keystone species like eucalypts that are otherwise difficult to introduce to a site, unlike species with more aggressive colonisation strategies. It underlines the key role of initial floristic composition, as emphasised by Egler (1954) and also the potential role of complex ecological assembly rules in interpreting and predicting patterns of vegetation composition and function in developing rehabilitation (Lockwood & Pimm 1999).

Overstorey acacia densities were highest in rehabilitation aged 3–11 years and lower in older rehabilitation. Older rehabilitation had low numbers of acacias compared to other rehabilitated sites, and high eucalypt densities compared to natural woodland. This may be related to the relatively short lifespan of acacias (~ 10 years). Alternatively, it may reflect different establishment strategies or seed mixes in earlier approaches to rehabilitation. The overabundance of acacias in the middle-aged rehabilitation could have a significant effect on the development of such sites towards the proportions of overstorey species similar to those found in natural woodland.

Rehabilitation at Groote Eylandt was often dominated by acacia species. These can rapidly outcompete slower-growing, keystone species in the hostile, rehabilitation environment (pers. obs.). Comparison of acacia densities in rehabilitation of different ages confirmed this, up until approximately 11 years when they began to decline. Acacias were all grouped together in this analysis but included a range of life forms and species with different maximum lifespans, ranging from less than 10 years to over 50 years (Doran & Turnbull 1997). The shrubby acacias that were in high density in the rehabilitation, were generally short-lived species, such as *A. latescens*. This species started to senesce in less than 10 years. Acacia-dominated rehabilitation was characterised by even-aged stands; simultaneous senescence can lead to an ecosystem 'crash', with rapid release of nutrients and chemicals from leaf fall and an increase in light reaching the ground layer, both of which may favour aggressive grasses. A similar pattern of declining acacia densities was observed in older rehabilitated areas at Gove (Reddell *et al.* 1992). The senesced shrubs also remain for a period as standing trash and can increase the impact of a fire on any remaining mid- or overstorey plants by increasing flame height above ground level.

Other (non-eucalypt, non-acacia) species of tree in the overstorey were at conspicuously lower densities in the youngest and oldest rehabilitation than in woodland and sites aged 6–12 years. While this group of species consisted of a number of genera with different adaptive traits, early senescence (as seen in the acacias) was not a typical attribute. Thus, the apparent peak in these species' densities in rehabilitation of intermediate age was most likely due to different establishment techniques, especially seed mix, as much as any time-dependent, successional trend.

While average overstorey height increased with age of rehabilitation, even after 19 years no rehabilitated sites achieved more than 70% of woodland average height. As this measure was based on the average of the heights of all plants in the > 4 m stratum, it can misrepresent the canopy heights being achieved in rehabilitation of good structure and composition, but containing larger numbers of subdominant plants in the subcanopy. This issue did not arise in woodland sites as much, as they generally did not have a high proportion of trees in the subcanopy compared to the canopy. A better representation of the maximum vertical height of rehabilitated vegetation can be gained from the dominant height measure, which also increased with age, with some older sites reaching heights comparable with the woodland average.

Average overstorey stem diameters increased much more slowly than overstorey height, except for the older rehabilitation (> 13 years) where diameter increased markedly. This suggests that the eucalypts with the greatest diameters in the natural environment, are competing in the rehabilitation to attain a dominant height to the detriment of increasing trunk thickness. This is a general growth trait of many canopy eucalypt species (Jacobs 1955), one which has been manipulated through silviculture techniques for centuries to achieve tall, straight trunks in commercially grown forestry plantations. However, overly tall trees with too slender a trunk may be unstable and prone to breakage or windthrow from high winds. The rehabilitation data suggested that once a certain age and height is obtained, the dominant species are able to increase trunk diameter and thus their ability to persist.

The observed decrease in acacia densities in the midstorey of older rehabilitation compared to younger rehabilitation could be due to the relatively short life span of some of the species on site. Alternatively, it could be due to trees growing through the 2–4 m stratum into the overstorey (> 4 m) over time. Midstorey eucalypt density increased over time in younger rehabilitation, as younger plants achieved 2 m in height, and apparently decreased after 14 years. Again, this probably relates to the continuing growth of young eucalypts and their elevation into the overstorey.

Age of rehabilitation did not seem to influence the density of plants in the understorey, including grasses, nor understorey eucalypt cover. However, some understorey vegetation characteristics did vary among rehabilitation age classes and woodland. For example, there was much higher weed cover in young rehabilitation and much higher cover of ‘other’ tree species in natural woodland. Grasses, too, were found to occur at higher densities and levels of cover in areas with reduced plants in the upper strata. These patterns could be due to resource limitations, including light and space, with weeds and grasses generally thriving in high light conditions and subdominant woodland species, such as the ‘other’ tree species common to eucalypt woodlands, typically having higher shade tolerance (Walker & del Moral 2003). Weed cover peaked in 2–3-year-old rehabilitation, decreasing rapidly thereafter with increasing age as site capture progressed. Increasing site capture was evidenced by increasing density and cover of non-weed species in the groundstorey, increasing cover and plant height in the mid- and overstorey strata, and so on. This response of weeds and grasses, as well as acacias, to increased site capture by canopy species resulted in the negative correlation of a number of these species in ordination space with the dominant eucalypt species. Interestingly, however, *Heteropogon triticeus* (giant spear grass), a large, clumping native grass dominant in the woodland, showed a positive correlation with these overstorey species. This suggests that this grass species has compromised some aggressive traits (it is not found to dominate any rehabilitated sites) to become one of the more successful grasses in the mature eucalypt woodland environment.

The low proportion of juvenile eucalypts and other, non-acacia, woody species in the rehabilitation understorey is important. It highlights the even-aged nature of the rehabilitation, and has implications for the resilience to fire and long-term sustainability of these synthetic systems. As the rehabilitation overstorey develops and matures, however, recruitment from seed produced within the rehabilitation might occur. Also, the contribution of sprouts from lateral root extension may be significant for eucalypt recruitment. Thus, the density of eucalypts and other non-acacia woody species might increase in time in rehabilitation greater than 20 years of age, dependent only on the number of mature parent trees in the area.

3.4.3 Rehabilitation of Different Characteristics

Classification and ordination revealed seven distinct groups of sites, including woodland sites. Some 33 rehabilitated sites fell neatly into six groups, arbitrarily named Groups B–G in decreasing order of similarity to natural woodland, with only four outliers, including one site (Group A) that grouped with the woodland sites. It can be seen from the dendrogram of sites grouped according to Bray-Curtis dissimilarities, (Figure 3-11), Groups B, C and D (15 sites in total) were more similar to the woodland group (~ 50% dissimilarity), than Groups E, F, H and I (~ 60% dissimilarity; 13 sites) or Groups G and J (~ 70% dissimilarity; 4 sites).

The tight clustering and consistent positions of sites of all but one Group (Group F) in ordination space over the 2-year period indicates that the composition of the Groups was relatively stable, despite the fact that some sites were burnt in the dry season of the intervening year. Although the understorey data were collected in the wet seasons, the fact that the evidence of fires 6–8 months earlier was minor emphasises the resilience of the system to dry-season burning.

These Groups will be revisited in depth in Chapter 5.

3.4.4 Rehabilitation Characteristics Through Time

There was relatively little movement of the groups of rehabilitation and woodland sites in ordination space over the 2 years of sampling. This is despite some sites having been burnt in the intervening year, and others being impacted by cyclonic winds, causing stem breakage and wind throw in mostly shrubby acacias and grevilleas, thus reducing their density (pers. obs.).

Canopy cover did differ significantly between the two samples, including the woodland plots. This may be related to seasonally dry conditions causing lower foliage densities in the 2000 sampling round. All other significant characteristics that differentiated the six rehabilitation groups and woodland sites did not differ significantly between years, despite the aforementioned disturbances. This suggests that these measures are resilient to short-term changes and may be suitable criteria for monitoring rehabilitation success.

A number of univariate floristic measures used in this study indicated that rehabilitated areas were generally approaching the composition of the unmined woodland. However, the DCA output showed that rehabilitated areas were still distinct from the woodland. Although the rehabilitated vegetation generally moved towards the woodland sites with age, at no point did older rehabilitation come to lie within the ordination space occupied by the nine woodland reference sites.

3.4.5 Comment on The Observed Influence of Fire on Rehabilitated Vegetation Dynamics

Frequent fire is a natural feature of the tropical eucalypt woodland ecosystem and has resulted in some classic adaptations by plants. Fire also removes much of the ground layer material, including litter and vegetation, so that observations made during the burning season are likely to be limited for this strata, depending on the fire frequency. In fact, the impact of fire was the reason only wet season understorey data was included in this study. However, observations of the impacts of fire and the responses of vegetation are worthy of discussion.

Eucalyptus tetrodonta and *Eucalyptus miniata* sprout from lignotubers, epicormic buds and lateral roots in the field (Jacobs 1955 and pers. obs.; Figure 3-1). This adaptation is common in areas affected by frequent fires, enabling plants to survive even after above-ground parts have been killed (Gill 1981; Bond & Midgley 2001). While basal and epicormic resprouting in overstorey trees are clearly attributable to parent trees, sprouts from lateral roots may be mistaken as new seedling individuals in understorey assessment, as their origin is not obvious. That is, they, and possibly a number of other saplings in the adjacent area, may all rely on the same root system, and thus constitute a single plant. As the only way of determining the true origin of these plants is destructive, it must be acknowledged that a number of the seedlings counted as individuals may well be sprouts. Further investigations should determine what proportion of these seedlings are, in fact, resprouts or new individuals. With such information, revisiting the data presented here would be fruitful.

Understorey density and composition in the dry season was dramatically affected by fire. When the 2000 survey was conducted, uncontrolled fires occurred in the woodland and rehabilitation on and around the mining leases, affecting 5 of the 42 monitoring sites. In the 2001 dry season, 20 sites were burnt with fire intensities ranging from low severity, with patchy mosaic burns leaving some grasses and other vegetation behind and very low scorch heights, to high severity burns where all understorey vegetation was destroyed and scorch and flame heights on tree trunks or affecting the leaves of shrubs were observed up to 4–5 m above ground level.

During dry season monitoring events, some sites had obviously been very recently burnt, resulting in very low counts of grasses and most other species. Some species were not killed by the fires and recovered rapidly (e.g. perennial grasses such as *Heteropogon triticeus*), so that even 1 week after being burnt, a higher species count was obtained than immediately following the fire. It must be acknowledged that plant responses to fire affect the apparent composition of the vegetation, as species that survive but take longer to resprout are overlooked for some time. For these reasons, taking measurements repeatedly over a number of years, and in the appropriate season, in these fire-prone environments is the only way to ensure the maximum amount of information is obtained, as was conducted in this study.

3.4.6 Conclusions

In general, the GEMCO rehabilitation was composed of species similar to that of the native woodland, but the structure and relative dominance of species was markedly different compared to undisturbed woodland. Relative dominance was clearly linked to rehabilitation age. Rehabilitated sites, on the whole, had significantly fewer species, lower average and dominant canopy heights, lower cover attributable to non-eucalypt and non-acacia tree species in the understorey, and higher weed cover than woodland sites.

Rehabilitation was often dominated by acacia species and also high levels of grass cover, which affected their vegetative composition and structure, especially in the event of wildfires. Multivariate analysis of the sites suggested that there were six groups of rehabilitation, that shared common attributes distinct from the undisturbed woodland sites. Further analysis of the differences in the composition, structure and function of these groups in subsequent chapters (Chapters 4, 6 & 7) will explain the variability of rehabilitation at Groote Eylandt and how the groups compare with the target end point.

Chapter 4 Influence of the Environment and Management on Natural Woodland and Rehabilitated Vegetation

4.1 Introduction

Groote Eylandt rehabilitation practices were previously based on the traditional concept of Clementsian succession (Clements 1916), relying on an assumption that early colonisers, such as acacias, would give way over time to later successional species like eucalypts (B. Todd, pers. comm. 2001). This has led to older rehabilitation being dominated by acacia trees or large shrubs, or grasslands with only sparse, if any, eucalypts. In contrast, the initial floristic composition model of succession (Egler 1954) places greater importance on rehabilitation establishment methods, including soil handling and replacement, management of the topsoil seed store and the composition of applied seed. Early-establishment techniques can have a major influence on the starting point of the developmental trajectory. Environmental characteristics, such as soil substrate type, rooting depth and drainage, and disturbances through time can modify succession or cause the developmental trajectory to deviate.

4.1.1 Management of Succession for Rehabilitation

Wali (1999) showed that rehabilitation of surface-mined US coal sites in mixed grass prairie was significantly enhanced by judicious management. Compared to sites abandoned after mining and backfilling, sites which had been re-graded and provided with topsoil, fertiliser and a select seed mix showed rapid replacement of pioneer species, 3–5 times faster rates of leaching of (pioneer-produced) growth-inhibiting allelochemicals, and 5–8 times faster rates of mineralisation of growth-promoting ions. This comparison of abandoned and managed systems showed that, by following basic rehabilitation procedures (such as re-contouring and topsoil replacement), ‘the rehabilitation process can be achieved many decades sooner with human assistance’ (Wali 1999).

4.1.1.1 Site Preparation and Substrate Selection and Handling

Successful establishment of rehabilitation, and the initiation of a desirable successional trajectory from the outset, is the most effective way of managing rehabilitation. Establishment is intrinsically related to site preparation, substrate selection and substrate handling. In the wet–dry tropics, vegetation is commonly reintroduced to mined-out areas as both propagules in fresh topsoil and as seed applied directly using a range of methods. In some cases, supplementary planting of nursery-grown seedlings is used to increase the density of important species. While not all species in the pre-existing woodland re-establish from the topsoil seed store, spreading of fresh topsoil can result in the cost-effective establishment of many species (e.g. Tacey & Glossop 1980). Also, the natural attributes of topsoil (e.g. nutrients, organic matter and micro-organisms) can result in substantially improved establishment and development percentages for many species. The success of direct seeding can be variable, but in general, with effective topsoil handing techniques and the use of an appropriate seed mix dominated by framework species, good early establishment can be obtained (Reddell & Meek 2004).

Patterns of natural vegetation are generally dictated by characteristics of the soils upon which they are established. Thus, the importance of providing the most appropriate soil environment for establishment of rehabilitation cannot be understated. Substrate availability for rehabilitation is usually limited to those materials relocated as part of the mining process, including topsoil, subsoil and waste material (often low-grade ore). Once mining is complete, these materials are returned to the mined-out area, ideally in the same series of layers as they were found. In some instances, other waste products from the operation are available that may act as a useful substrate or amendment, for example the fines, or ‘sandtails’, generated from the manganese washing and grading process. In these cases, the potential toxicity and physical nature of the materials should be considered before they are utilised in the rehabilitation process.

Incorrect site preparation, including substrate handling, can significantly impact the success of rehabilitation activities. The stability of the final landform is integral to its long-term sustainability. Consideration of material erosivity and predicted surface hydrology should inform the designed elevation, slope gradient and drainage density (i.e. total length of watercourses per unit area) of the final landform (EPA 1998).

Handling of wet material by heavy machinery can result in high compaction which reduces rainfall infiltration (and therefore increases water runoff and erosion potential), reduces soil aeration, affects subsurface hydrology (i.e. drainage), and limits root penetration and long-term stability of larger trees and shrubs. Personal observations at Narbarlek, a rehabilitated uranium mine in Arnhem Land, Northern Territory, found that a high proportion of trees attaining heights near or above 4 m were falling over, revealing an unnaturally shallow root system. Ripping of the pit floor can improve the hydrological behaviour of the rehabilitated landform, including returning connectivity to surrounding landscapes. Hooper (1985), in an assessment of strategies for managing regenerated mined lands in northern Australia, found that small-scale depressions in the final landform developed denser patches of vegetation than the matrix, due to increased soil moisture collection and retention. Hooper concluded that landform design should aim for similar micro-scale variation to influence soil moisture and that this was ‘as important a tool as fire management in achieving growth and survival of the forest’.

Well-managed topsoil is valuable in rehabilitation for a variety of physical, chemical and biological properties, including its seed store, nutrients, organic matter and microbial properties (Tacey & Glossop 1980; Corbett 1999). An important physical property of topsoil is its ability to act as a medium for seed germination, root penetration and plant growth. Good physical structure should also provide for improved water holding capacity of the substrate. All reasonable efforts, especially in terms of timing and handling, should be made to conserve these attributes and avoid any later expenditure required to improve them.

In most scenarios, one of the most important features of topsoil is the seed bank, which contains seeds of far more species than can be harvested and sown in a standard rehabilitation process, including many groundstorey and other difficult-to-collect species. For example, Williams *et al.* (2005) found that tropical eucalypt savanna soil from north-eastern Australia contained between 58 and 792 seeds m^{-2} (to a depth of 5 cm) from a total of 53 species, with a predominance of grasses and forbs. Tacey and Glossop (1980) observed that the majority of the soil seed store in the jarrah forests of Western Australia affected by bauxite mining was contained in the upper 2 cm of the soil profile. Rehabilitation that focussed on immediately replacing the upper 5 cm of the soil profile (‘double-stripping’) to mined-out areas showed significantly greater seedling emergence and percentage of live plant and litter cover compared to other soil handling techniques (stockpiling and direct return of the top 40 cm profile) (Tacey & Glossop 1980).

However, species that rely on other modes of reproduction, such as persistence by resprouting after disturbance (Bond & Midgley 2001), are generally in reduced abundance in the soil seed store (Ward *et al*. 1997). In fact, seed banks of trees and shrubs were barely detected in the study of tropical eucalypt savanna soils by Williams *et al.* (2005).

For many years, the rehabilitation of disturbed mining land has generally involved the return of overburden followed by topsoil application prior to the establishment of vegetation. In a number of instances however, this approach has been found to result in high weed establishment due to grass and other weed seed stored in the topsoil seed bank. Reddell *et al*. (1994) found that the establishment of native vegetation (mainly *Eucalypt* and *Acacia* spp.) in straight overburden, with no added topsoil, can be very successful due to lack of competition from topsoil borne weeds. Naturally, there is a tradeoff with this approach with the loss of the naturally occurring native seed bank contained within topsoil, as well as the potential loss in water-holding capacity and nutritional value of the rocky overburden. However, in cases where competition from weeds significantly reduces revegetation success, these compromises may be acceptable.

The most important aspects of correct topsoil management, for maximising the seed store, are timing of stripping, depth of topsoil removed, direct placement of topsoil and disturbance after placement (Tacey & Glossop 1980). Correct management will ensure that the highest possible number of species is immediately present in the rehabilitation, maximising biodiversity and increasing the compositional similarity with the original vegetation. This ensures that that the regenerated ecosystem is immediately positioned to progress along the correct development path toward the desired end-point target.

4.1.1.2 Species Selection and Establishment

Species for rehabilitation are selected based on the target end land use (Section 1.2.1.1) and species selection focusses on those species considered to be integral to ecosystem composition and dynamics. These keystone species are generally long-lived K-strategy species (Section 3.1.1) and, in the savanna woodland, include the overstorey eucalypts (*Eucalyptus tetrodonta, E. miniata*) and other species contributing to the resilience and function of the ecosystem in the longer term. Unfortunately, another characteristic of these K-strategy species is that they are not particularly fecund, especially in suboptimal conditions, so that their establishment from only the topsoil seed store may not be competitive with other non-keystone, more opportunistic species.

Traditionally, ‘exotic’, pioneer species were considered valuable to the early stages of rehabilitation development for their soil stabilisation, especially grasses, or nitrogen-fixing abilities. Leguminous species often included pasture species (where this was a consideration of the rehabilitation targets) or, more recently native vegetation has become the target, acacia trees and shrubs. A number of the pasture species historically included in the rehabilitation seed mix are now self-colonising areas and are a weed problem (e.g. *Stylosanthes* spp.) Acacias also show a tendency to behave aggressively and out-compete more desirable species, leading to the failure of the rehabilitation to develop toward target end points. In fact, despite acacias being commonly used in many rehabilitation operations (e.g. Corbett 1999), they often become dominant and there is no evidence that these species have any role in initiating or facilitating any further, more desirable, successional development (Reddell & Meek 2004).

In many instances, management effort is required in the form of supplied seed or seedlings, in addition to the propagules provided by the topsoil resource, to ensure that a sufficient number and range of keystone species is able to establish in new rehabilitation. Many rehabilitation operations employ direct seeding as the preferred practice and have found that, as long as initial establishment is successful, this approach is more successful than planting seedlings (Corbett 1999). Planting seedlings has the advantage of avoiding many of the unpredictable aspects of germination in the field following direct seeding, and can provide greater reliability of plant survival and development. However, it can also be prohibitively costly and uneconomic for large-scale rehabilitation activities.

The benefit of direct seeding is that a measured amount of managed seed, with known provenance, viability and germinability, can be applied to a given area. This enables the seed mix to be tailored to achieve the targeted species density and keystone species richness. Limitations of directly applied seed exist, however, and include their susceptibility to:

- predation, especially by ants and termites;
- desiccation by exposure to wind and sun; and
- premature rainfall events triggering germination without follow-up rains.

Techniques to overcome these limitations include:

- soil scarification to produce microsites for shelter from wind and sun;
- use of water-retaining surface amendments such as woodchip mulch;
- timing of seed sowing to minimise risk of premature germination in response to early wet season rainfall events; and
- inoculation with spores of mycorrhizal fungi to improve effective nutrient uptake (Reddell & Zimmermann 2002).

4.1.2 Aims and Objectives of this Chapter

Identifying management and environmental influences that are correlated with good and bad rehabilitation outcomes can suggest causal relationships that, if correct, may be used to improve rehabilitation practice. In this chapter, ordination techniques were used to elucidate the relationships between rehabilitation establishment practices and environmental features, on the one hand, and the floristic composition and structure of the GEMCO rehabilitation on the other. The specific objectives were to:

- compare rehabilitation vegetation patterns with a range of environmental and management history variables; and
- identify significant environmental and management determinants of the structure and function of the rehabilitation assemblages.

4.2 Methods

4.2.1 Species–Site Data

The species–site matrix for 2000/01 was used as described in Section 3.2.2.3 (Table 3-5).

4.2.2 Environmental Data

4.2.2.1 General Site Variables

Age

Rehabilitation sites included in this study ranged in age from 0.5 to 19 years since rehabilitation. Undisturbed woodland sites were of indeterminable age, thus these sites were assigned an arbitrary value of 100 years for the purpose of analysis.

Quarry Location

Site selection for this study focussed on ‘quarries’, being the various satellite mining areas spread around the GEMCO mining lease. Both rehabilitation and natural woodland sites were sampled in each quarry wherever possible (Table 4-2). This ensured that variability in the rehabilitation and control or analogue sites across the lease would be sampled. Including ‘quarry’ as a geographic or landscape factor in analyses recognised the potential effect of a complex array of features, including (1) variability in overburden (e.g. sand, loam or red and white clay) across the lease; (2) variability due to final substrate profile after backfilling; and (3) variation in localised rainfall.

Table 4-1 Number of sites in each ‘quarry’ (Figure 2-6)

Quarry	Number of sites		Quarry	Number of sites	
Code	Rehab.	Woodland	Code	Rehab.	Woodland
Q-Misc	1	3	Q-F2	2	0
Q-AS	4	1	Q-F3	9	1
Q-C	1	1	Q-F3N	4	0
Q-D	4	2	Q-F4	5	0
Q-F1	4	1			

4.2.2.2 Rehabilitation Treatment (Management) Variables

Topsoil

Fresh topsoil contains organic matter, microbes and a seed bank; these resources are maintained at near-optimal concentrations when the material is relocated immediately after stripping and ‘direct returned’ to an area awaiting rehabilitation. Approximately 53% (i.e. 18) of the 34 rehabilitated sites sampled had received direct return topsoil (‘Top1’ in Table 4─2). Some rehabilitated sites had not received topsoil of any sort above the backfilled overburden material (Top0). This was the case with 26% (i.e. 9) of the 34 rehabilitated sites, plus the nine woodland sites which were not subjected to any rehabilitation treatments. Seven sites (21% of rehabilitated sites) received stockpiled topsoil (Top2), which generally has reduced value in terms of organic matter, microbes and viable seed. Stockpiled topsoil can also have the additional problem of containing a weed seed store.

Seed Mix

Mined-out areas rehabilitated in different years potentially received different seed mixes, depending on the rehabilitation targets of the day and other factors. For rehabilitated sites sampled in this study, the seed mixes applied can be summarised as follows and are listed in Table 4─2:

- An all exotic mix of pasture grasses and leguminous herbs such as *Chloris gayana*, *Stylosanthes humilis* and *S. scabra* (Seed5);
- Seed of the main overstorey native plant species (*Eucalyptus tetrodonta*, *E. miniata* and *Corymbia polycarpa)*, with exotic grasses maintained for soil stability and organic matter accumulation (Seed4);
- Mostly local native plant species plus some ‘exotic’ south-eastern eucalypt species such as *Eucalyptus alba*, *E. papuana*, *E. bigalerita*, *E. ferruginea*, *E. camaldulensis*, *E. tereticornis* and *E. tintinnans* (Seed3);

- Seed of the main overstorey eucalypts and various acacias, some non-local, for their nitrogen-fixing properties and ability to rapidly colonise a site (Seed2);
- A more diversified local native seed mix including a number of subcanopy and midstorey trees and shrubs such as *Planchonia careya*, *Terminalia ferdinandiana* and *Petalostigma banksii* (Seed1).

Deep Ripping

Deep ripping following the backfilling earthworks is a standard practice and only five rehabilitated sites were recorded in the GEMCO rehabilitation database as not having been ripped (Table 4─2).

Fertiliser

In addition to the woodland sites, four areas of rehabilitation had not received any fertiliser at establishment or later (Fert0). The majority of sites (21) had been fertilised with superphosphate at the rate of 300 t/ha (Fert1); eight sites had received 300 t/ha of a custom-made, complete fertiliser containing nitrogen (12%), phosphorus (14%) and potassium (10%) (Fert2).

Remediation

Rehabilitated areas that were identified as lacking in the locally dominant eucalypt species were sometimes nominated for follow-up remedial management, usually in the form of hand-planted eucalypt seedlings. Eight of the 33 rehabilitated sites were recorded as having received supplementary eucalypt plantings (Rem1) while the remainder, and of course the woodland sites, had received no additional inputs (Rem0) after broadcast seeding.

4.2.2.3 Topsoil Chemistry, Soil Surface Cover and 1 m Soil Profile

Topsoil Chemistry

Topsoil sampling was undertaken as described in Section 3.2.1.2 and topsoil chemistry analyses were undertaken as described in Section 3.2.2.1. For statistical analysis of the topsoil chemistry data, pH, electrical conductivity (EC) and organic carbon were normally distributed and not transformed; all other topsoil chemistry variables were log (x + 1) transformed (Table 4-4).

Table 4-2 Code, description and number of sites for each environmental variable category of 'rehabilitation treatment'

Variable	Variable Code	Description	Number of Sites Rehab.	Number of Sites Woodland
Topsoil	Top0	Nil topsoil applied after backfilling	9	9
	Top1	Fresh topsoil placed by direct return	17	0
	Top2	Topsoil stockpiled prior to use	7	0
Seed Mix	Seed1	Good all native mix; extra midstorey species, acacias, local overstorey eucalypts	6	0
	Seed2	Average all native mix; few midstorey species, acacias, local eucalypts	15	0
	Seed3	Average all native mix with added local and exotic eucalypts (with or without exotic grasses)	6	0
	Seed4	Average native mix with exotic grasses (*Chloris gayana*, *Cynodon dactylon*, annual rye grass)	5	0
	Seed5	Exotic pasture species (incl. grasses and legumes)	1	0
Ripped	Rip0	Not ripped	5	9
	Rip1	Ripped to approx. 1 m deep	28	0
Fertiliser	Fert0	Zero fertiliser applied	4	9
	Fert1	300 t/ha superphosphate applied	21	0
	Fert2	300 t/ha NPK (12:14:10) applied	8	0
Remediation	Rem0	No remediation work	25	9
	Rem1	Remedial planting of eucalypt seedlings	8	0

Table 4-3 Codes and descriptions for each soil chemistry (environmental) variable

Code	Variable	Unit	Statistical format
pH	pH	-	not transformed
EC	Electrical conductivity	mS/cm	(log + 1) transformation
Cu	Copper	mg/kg	(log + 1) transformation
Fe	Iron	mg/kg	(log + 1) transformation
Mn	Manganese	mg/kg	(log + 1) transformation
Zn	Zinc	mg/kg	(log + 1) transformation
AvP	Available phosphorus	mg/kg	(log + 1) transformation
TotP	Total phosphorus	mg/kg	(log + 1) transformation
Ca	Calcium	mg/kg	(log + 1) transformation
Na	Sodium	mg/kg	(log + 1) transformation
Mg	Magnesium	mg/kg	(log + 1) transformation
K	Potassium	mg/kg	(log + 1) transformation
NO3	Nitrate (NO_3^-)	mg/kg	(log + 1) transformation
NH4	Ammonium (NH_4^+)	mg/kg	(log + 1) transformation
OrgC	Organic carbon	%	not transformed

Soil Surface Cover

Measurements of litter cover and depth were made in the wet season (Table 4─5), as measures in the dry season were significantly influenced by frequent fires, which can remove a large proportion of the accumulated material. The proportion of the soil surface covered by other material, such as small pisolitic pebbles, fallen timber or disturbed by animal activity, was also recorded (Table 4─1).

Soil Profile (to 1 m)

The uppermost 1 m of soil in sampled sites was either quite sandy or contained a lot of clay, possibly due to the changed profile after mining (Table 4-4). Upper profiles were separated into a number of groups, including brown, sandy earths (Soil1), white or yellow sands (Soil2), clay and sand together (Soil3), red or orange clays and lateritic clay (Soil4) and sandtails (Soil5), the fine waste material left after processing of the manganese ore (Figure 4-2).

The soil texture of the upper 1 m of soil was also assessed in relation to the proportion of gravel or pisolitic material. Just under 40% of rehabilitated sites and 80% of woodland sites had high proportions (approx. > 20 %) of gravel in the top 1 m of the profile (Gravel in Table 4-4).

Table 4-4 Codes, descriptions and numbers of sites in each level of each environmental variable describing the upper 1 m of soil profile

Variable	Variable Code	Description	Number of Sites	
			Rehab.	Woodland
Soil Type	Soil1	Brown, sandy earths	10	5
	Soil2	Sand (white, yellow)	1	3
	Soil3	Clay with sands	5	1
	Soil4	Red/orange clay and lateritic clays	16	0
	Soil5	Sandtails	1	0
Gravel	Gravel	Greater than moderate proportion (20%) of gravel and pisolites	12	7

4.2.2.4 Vegetation-Derived Measures

Select vegetation descriptors were used in analysis as supplementary variables and overlain on the ordination plots. These variables are listed in Table 4─5 below. Values for basal area and plant densities were normalised prior to analysis.

Table 4-5 Codes, descriptions and number of sites for each soil surface cover (environmental) variable

Variable	Variable Code	Description (unit, transformation)	Number of sites	
			Rehab.	Woodland
Litter Cover	LitCov	Wet season litter cover (%; not transformed)	34	9
Litter Depth	LitDep	Wet season depth of litter overlying soil surface (cm; log [x + 1] transformation)	34	9
Surface Cover	Rock	Large rocks or smaller lateritic pisolites (%; not transformed)	31	3
	Log	Fallen timber (%; not transformed)	33	8
	Dist	Soil disturbed by animal (foraging & burrowing) activity (%; not transformed)	7	3

Figure 4-1 Typical rehabilitated soil surface of small rocks, pisolites and leaf litter (Plot: F3-3.2)

Figure 4-2 One-metre soil cores for (a) AS-93a.1, with brown sandy soil at 0–40 cm and increased white clay content at 40–80 cm depth (Soil1); (b) F3-89.2, showing change from lateritic clays to sandy and finally brown (loamy) earths at the surface (Soil4); (c) F3N-26.3, with high lateritic clay content throughout (Soil4, Gravel); and (d) F3N-97.1, with 0–100 cm sandtails profile (Soil5)

Table 4-6 Code and description for each vegetation measure (n = 42)

Variable	Variable Code	Description (unit, transformation)
Diversity	Divers	Shannon–Wiener diversity index (not transformed)
Species Richness	SppRich	Species richness (not transformed)
Canopy Cover	CanCov	Canopy cover (%; not transformed)
Basal Area	BA	Overstorey & midstorey basal area (normalised)
Acacia Density	OSacacia	Density of acacias > 2 m in height (normalised)
‘Other’ Density	OSother	Density of woody plants > 2 m other than eucalypts or acacias (normalised)
Grass Cover	Grass	Understorey native grass cover (%)
Exotic Cover	USexotic	Understorey exotic herb and grass cover (%)

4.2.3 Multivariate Analysis

The multivariate methods of classification and ordination were utilised to explore the relationships between sites, and a range of management and environmental variables. An unconstrained DCA was performed as described in Section 3.2.2.3. The length of the longest axis was 2.045 units suggesting that unimodal ordination methods may not be optimal but, as the data set contained a large number of zero values, the unimodal approach was preferred (ter Braak & Šmilauer 2002). A species–site bi-plot aided visual interpretation of the relationships. Environmental variables were projected onto the DCA ordination.

A constrained ordination, canonical correspondence analysis (CCA), was performed to examine directly the variation explained by environmental variables (Lepš & Šmilauer 2003). Forward selection was used to reduce the number of environmental variables to the most meaningful while still explaining the species composition patterns. CCA bi-plots of sites and environmental variables were created to visually display relationships. T-value bi-plots were constructed, including van Dobben’s circles, to display species significantly correlated with those environmental and management variables determined by CCA and forward selection as significant to vegetation structure and composition.

4.3 Results

The floristics and structure of rehabilitated sites, and that of the unmined woodland, were considered in relation to environmental attributes and management history.

4.3.1 Unconstrained (DCA) Ordination and Projected Environmental Variables

An initial unconstrained ordination (DCA) was performed on the species–site matrix as shown in Figure 3-9. Environmental variables were projected onto the DCA ordination (Figure 4-3 and Figure 4-4). A strong negative correlation was apparent between the age of sites and axes 1 and 2. While some rehabilitated sites had not received topsoil, fertiliser, nor been ripped, the fact that all nine woodland sites were also in these categories meant that these environmental variables (Top0, Fert0 and Rip0) were highly correlated with the undisturbed woodland sites. Calcium and electrical conductivity were highly correlated with each other, and negatively correlated with the first axis as well as available and total phosphorus, zinc, potassium and manganese. Sodium, potassium and total and available phosphorus were positively correlated with the second axis, and were negatively correlated with pH, iron, calcium and nitrate.

Litter depth was positively correlated with the first axis, while gravel substrates and surface litter cover were strongly negatively correlated with the second axis. Variables describing the dominant material in the 1-m subsoil profile were also related to vegetation composition and structure, with Soil2 (sandy substrate) being strongly negatively correlated with the first axis, Soil4 (red and lateritic clays) being strongly positively correlated with the second axis, and Soil1 (brown, sandy earths) negatively correlated with the second axis.

Age was strongly correlated with the vegetation ordination, but perhaps only because the woodland sites were arbitrarily given a high age (100 years). Plotting the sites by age (Figure 3-9), however, showed that young rehabilitation was least similar to natural woodland sites, and that rehabilitation of increasing age was successively more similar to woodland sites.

4.3.2 Constrained (CCA) Ordinations

Following exploration of the species–site matrix using DCA, a constrained (CCA) ordination was performed to directly extract the variation explained by environmental variables. Forward selection was used to reduce the number of environmental variables to the most meaningful while still explaining the species composition patterns. Age was the most important factor (Lambda1 = 0.17; Table 4-7) influencing vegetation composition and structure. After selecting age as the highest ranking marginal effect, several other variables were found to be significant ($P < 0.05$) as conditional effects: litter depth, direct return topsoil (Top1), seed mix 2 (Seed2), litter cover, and superphosphate application (Fert1). These five variables, with age, made up the model.

A CCA plot (Figure 4-5) showed that the woodland sites clustered together and were positively correlated with the first axis and negatively correlated with the second axis. The species most associated with this part of ordination space were generally absent in the rehabilitation, and included *Hakea arborescens*, *Erythrophleum chlorostachys*, *Buchanania obovata*, *Ampelocissus acetosa* and *Tacca leontopetaloides*. Species correlated with the non-woodland sites included the grasses *Thaumastochloa pubescens* and *Yakirra muelleri* and the large shrub *Acacia holosericea*.

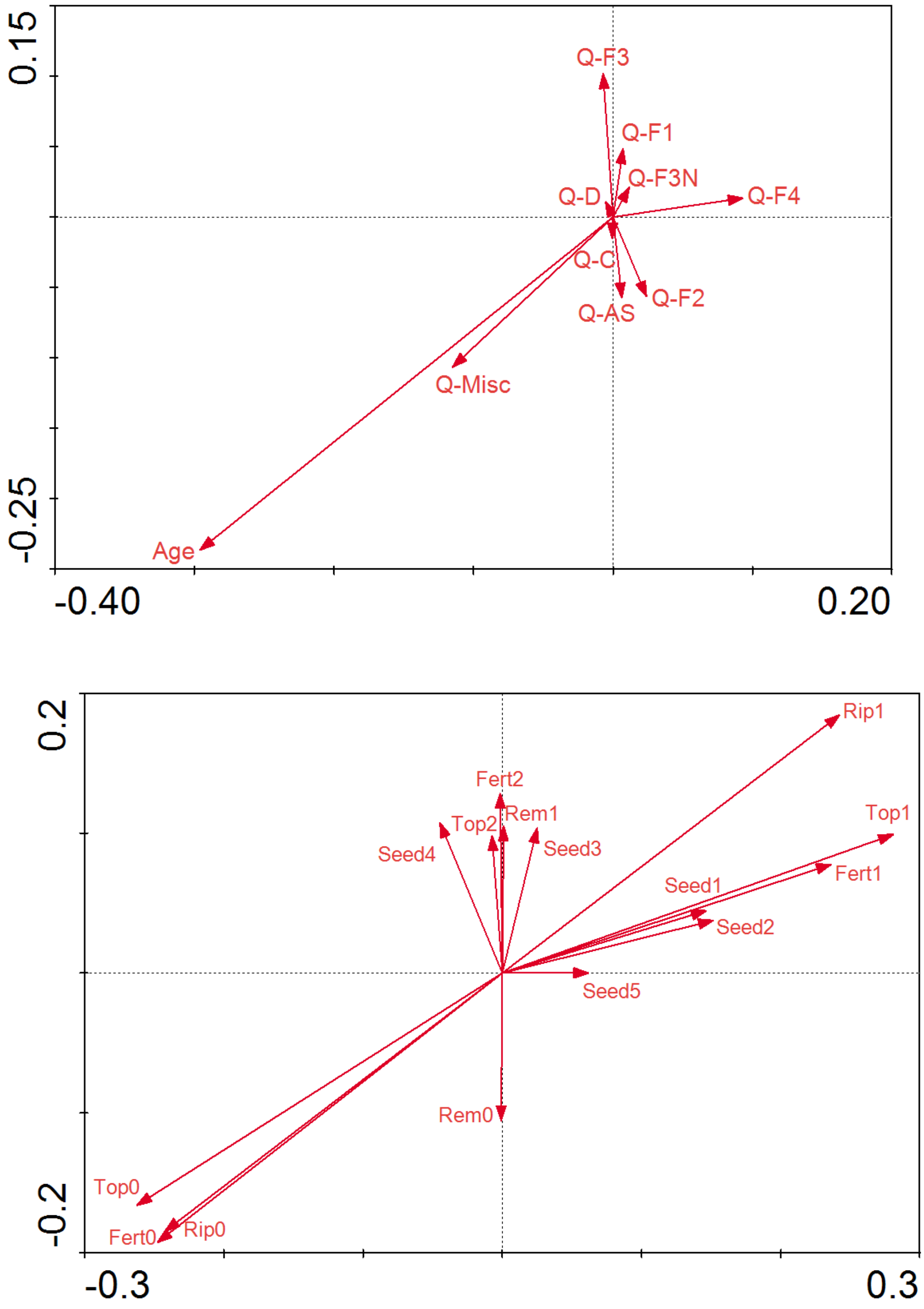


Figure 4-3 A retrospective projection onto the DCA ordination of the environmental variables of (a) age and quarry location; and (b) treatment. Codes are explained in Table 4—1 and Table 4—2

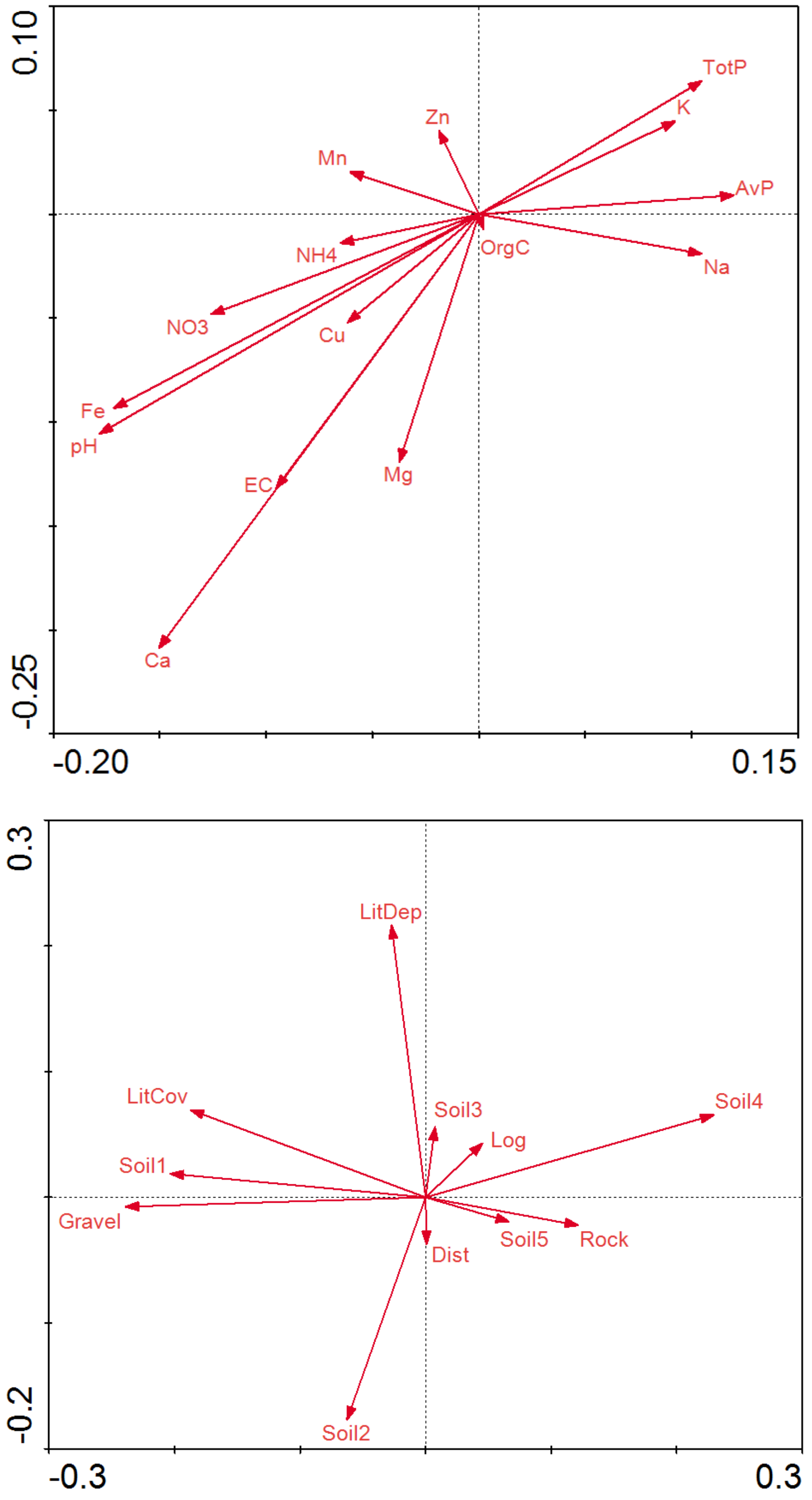


Figure 4-4 A retrospective projection onto the DCA ordination of the environmental variables of (a) soil chemistry; and (b) soil surface cover and structure. Codes are explained in Table 4─3, Table 4─4, and Table 4─5

Table 4-7 Conditional and marginal effects for significant ($P < 0.05$) variables in the CCA of the species–site matrix (ME, marginal effects; CE, conditional effects; λ, eigenvalues)

Variable	ME λ	CE λ	P	F
Age	0.17	0.17	0.002	3.99
Litter Depth	0.09	0.08	0.004	2.03
Topsoil 1	0.11	0.07	0.002	1.80
Seed Mix 2	0.08	0.06	0.010	1.65
Litter Cover	0.08	0.06	0.040	1.56
Fertiliser 1	0.10	0.06	0.018	1.47

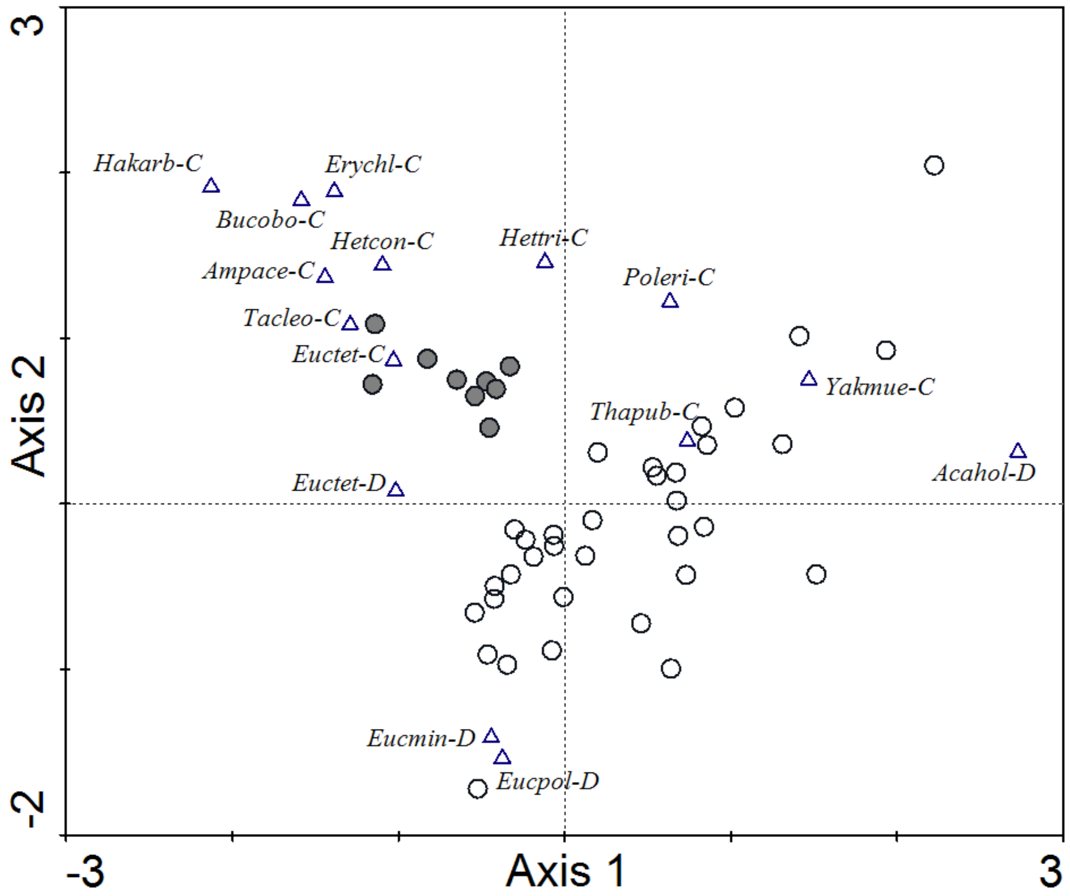


Figure 4-5 A species–sites (triangles and circles, respectively) bi-plot of the CCA of the species–site matrix (species with greater than 30% fit are shown) (the woodland sites are represented by filled circles). Species codes are listed in Appendix D

Environmental variables appeared to have an important association with the ordination of the sites, with age in particular being significant (Figure 4-6). The quarry location variable, Q-Misc, included three woodland sites and Pole80 (the 19-year-old site), so the apparent strong correlation with age was likely to have been an artefact of the coding method. Otherwise, Quarry location did not appear to have a great influence on the vegetation of the rehabilitation sites.

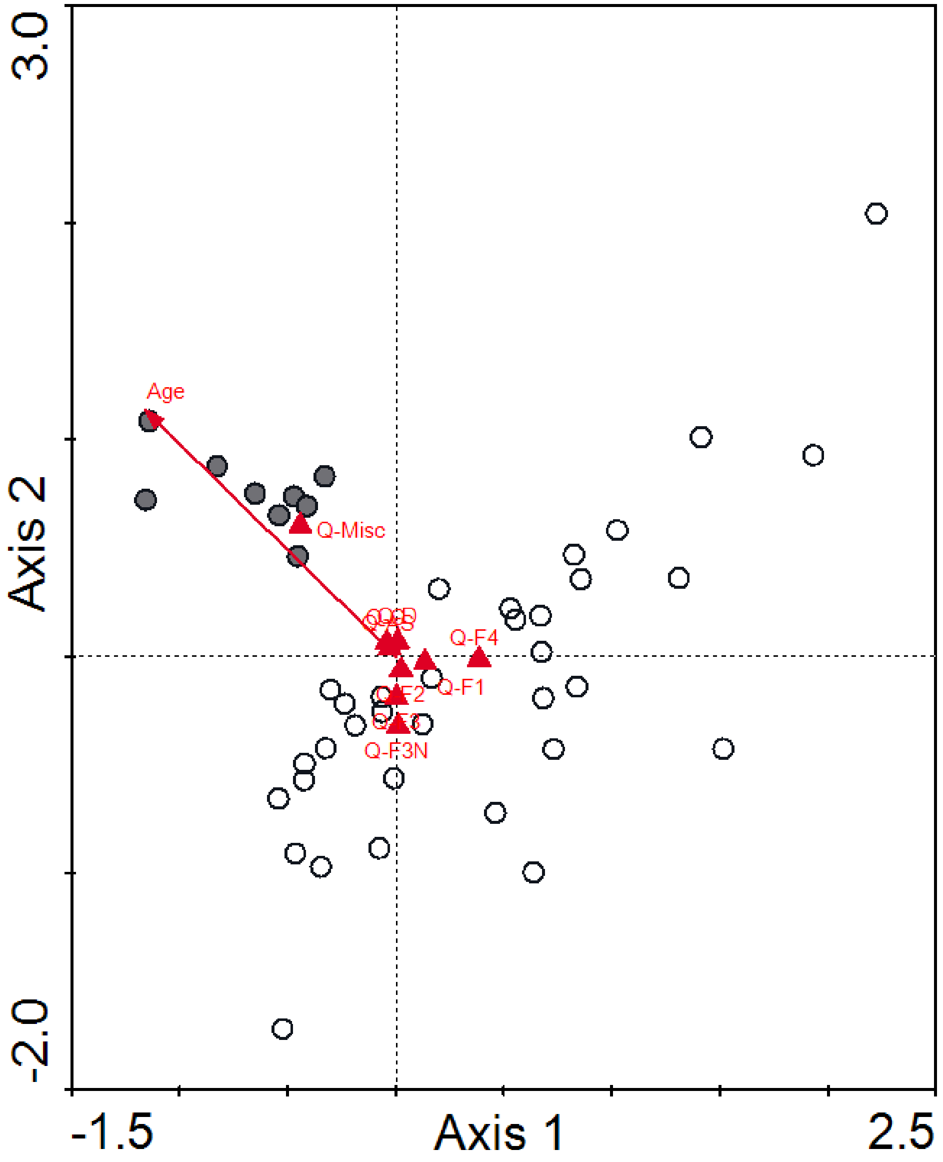


Figure 4-6 CCA bi-plot of sites and environmental variables of age and quarry (filled circles are woodland sites, open circles are rehabilitation). The scalar environmental variable, Age, is represented by a red arrow and categorical values for the Quarry variable appear as filled triangles. Codes are explained in Table 4—1

None of the woodland sites received any of the rehabilitation establishment treatments (ripping, topsoil, seed, fertiliser or remediation planting). This strongly influenced the apparent effect of these variables on site location in ordination space and the correlations between these variables and the woodland sites (Figure 4-7). Ripping had a strong negative correlation with the first ordination axis, and was correlated with the direct return of topsoil (Top1) and use of superphosphate (Fert1).

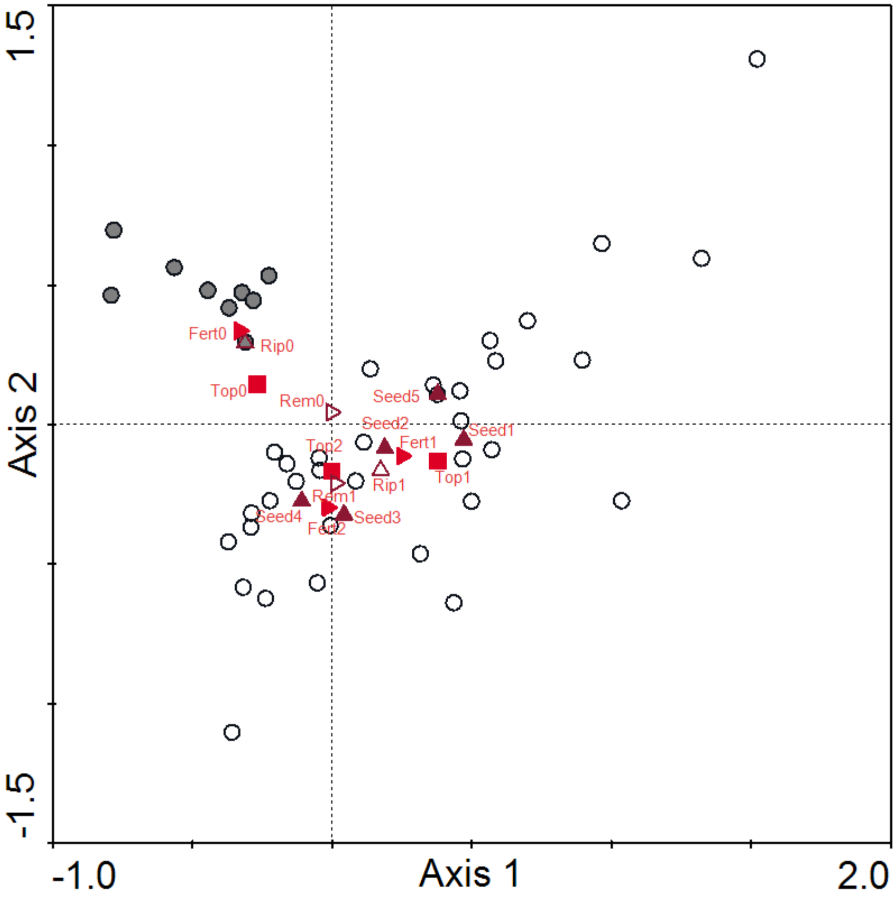


Figure 4-7 CCA bi-plot of sites and environmental treatment variables (filled circles are woodland sites, open circles are rehabilitation). Categorical values of the treatment variables are represented as follows: fertiliser = filled right triangles, topsoil = squares, remediation = open right triangles, ripped = open up triangle, seed = filled up triangle. Codes are explained in Table 4–2

Of the topsoil chemistry, pH and calcium were most strongly correlated with the woodland sites, while phosphorus, potassium and sodium were negatively correlated with those sites (Figure 4-8).

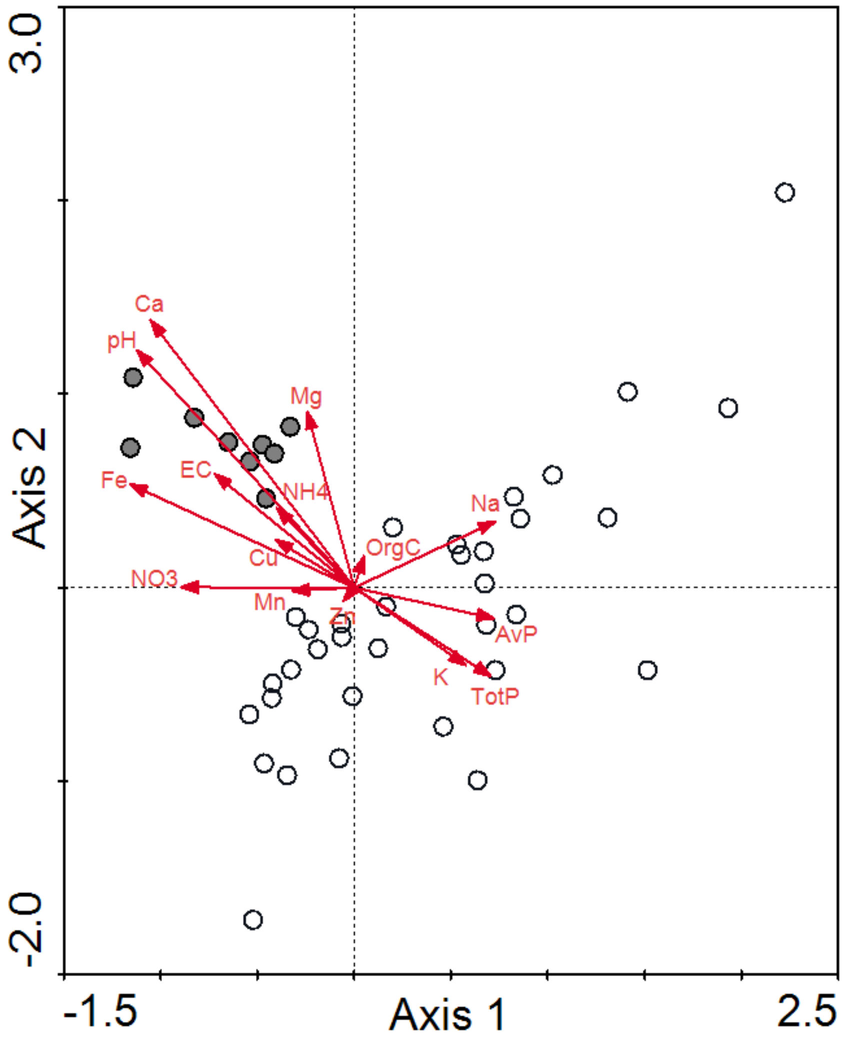


Figure 4-8 CCA bi-plot of sites and environmental variables of topsoil chemistry (filled circles are woodland sites, open circles are rehabilitation). Codes are explained in Table 4–3

The CCA of sites and soil surface characteristics (Figure 4-9) showed that soil gravel content and a sandy topsoil substrate were weakly correlated with woodland sites. Litter cover and litter depth were negatively correlated with both the first and second axes, and appeared to align well with the main axis of variation in the vegetation of the rehabilitation sites.

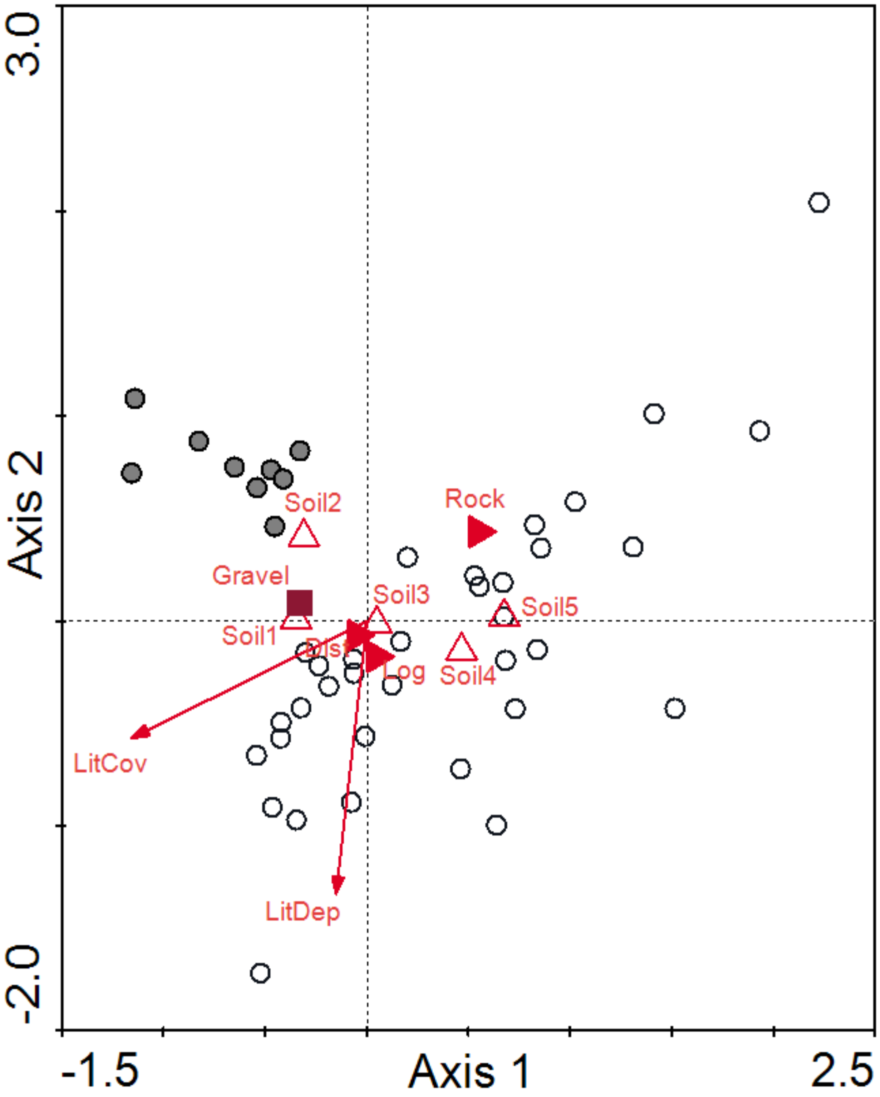


Figure 4-9 CCA bi-plot of sites and environmental variables for soil surface cover and profile structure (filled circles are woodland sites, open circles are rehabilitation). Categorical values of the profile structure variables are represented as follows: soil type = open up triangles, gravel = filled square, and surface cover = filled right triangles. Codes are explained in Table 4─4 and Table 4─5

Site age was significant in explaining vegetation structure and composition (Table 4-7). A t-value bi-plot identified 14 species that were significantly correlated with site age (Figure 4-10), including *Eucalyptus tetrodonta,* the two *Heteropogon* spear grasses, and four subcanopy tree species such as *Buchanania obovata* and *Erythrophleum chlorostachys* (ironwood). Seven species were negatively correlated with age, including *Eucalyptus miniata, Corymbia polycarpa*, the weedy vine *Passiflora foetida* and *Acacia auriculiformis*.

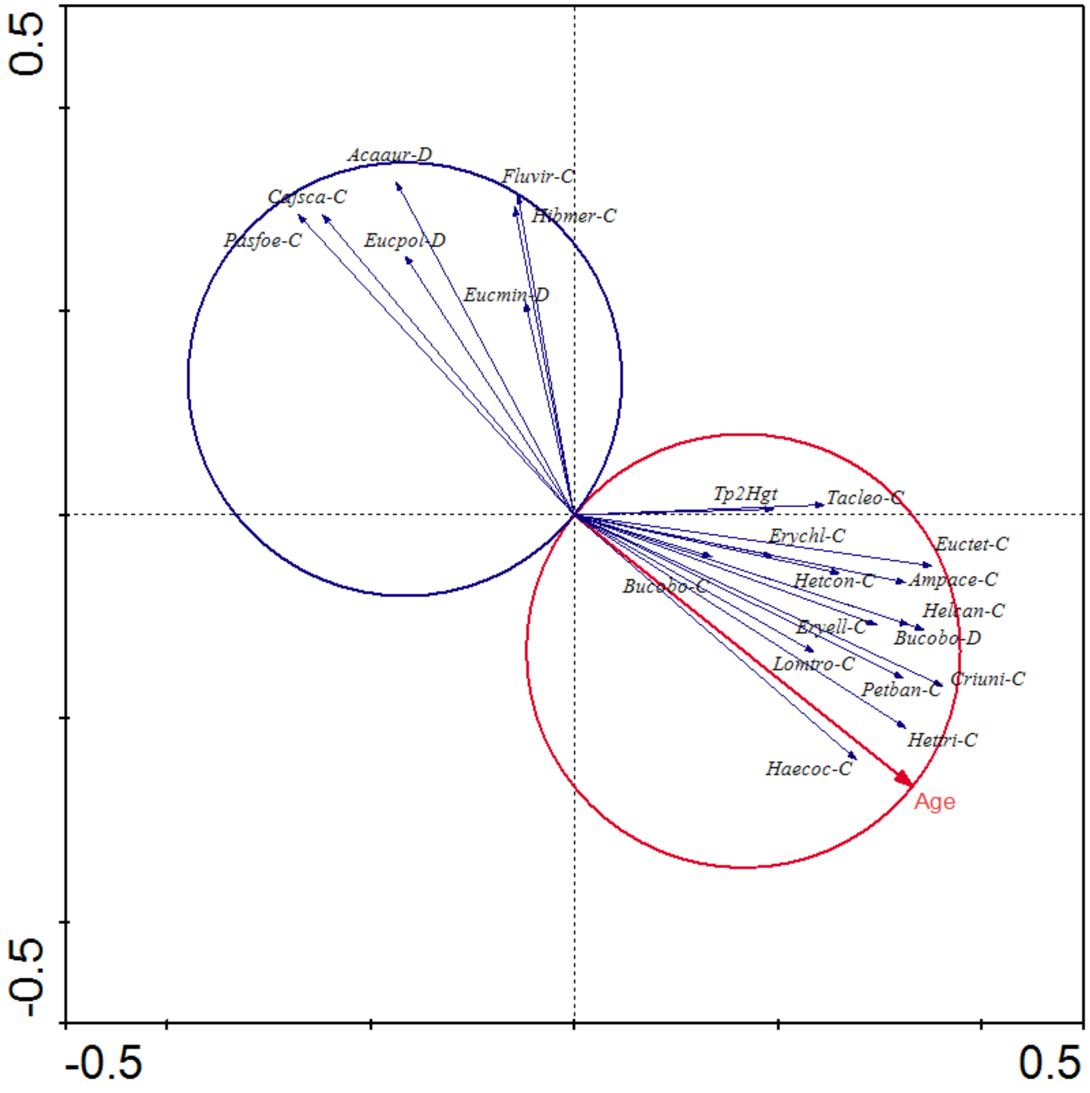


Figure 4-10 A t-value bi-plot of significant correlations between site age and species composition and structure. Species codes are listed in Appendix D

The use of direct return topsoil also appeared to have a significant influence on vegetation composition and structure. The grass *Yakirra muelleri* was the only species significantly correlated with direct return topsoil, while *Eucalyptus miniata* was negatively correlated with this variable (Figure 4-11).

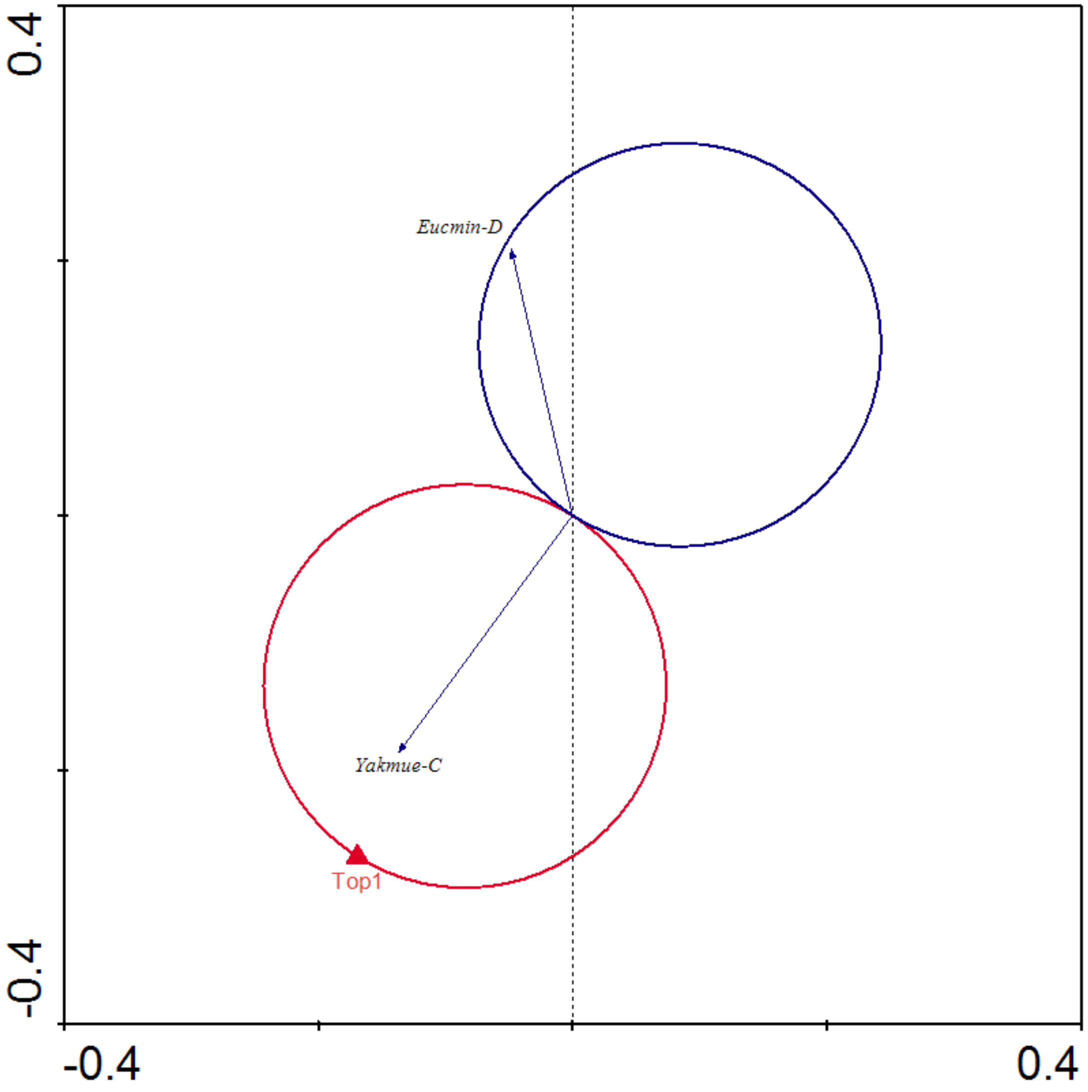


Figure 4-11 A t-value bi-plot of significant correlations between use of direct return topsoil (Top1) and vegetation composition and structure. Species codes are listed in Appendix D

Litter depth appeared to have a significant impact on vegetation composition and structure and was significantly positively correlated with *Eucalyptus miniata*, *Hibiscus meraukensis* and *Flueggia virosa*, and negatively correlated with *Yakirra muelleri* (Figure 4-12).

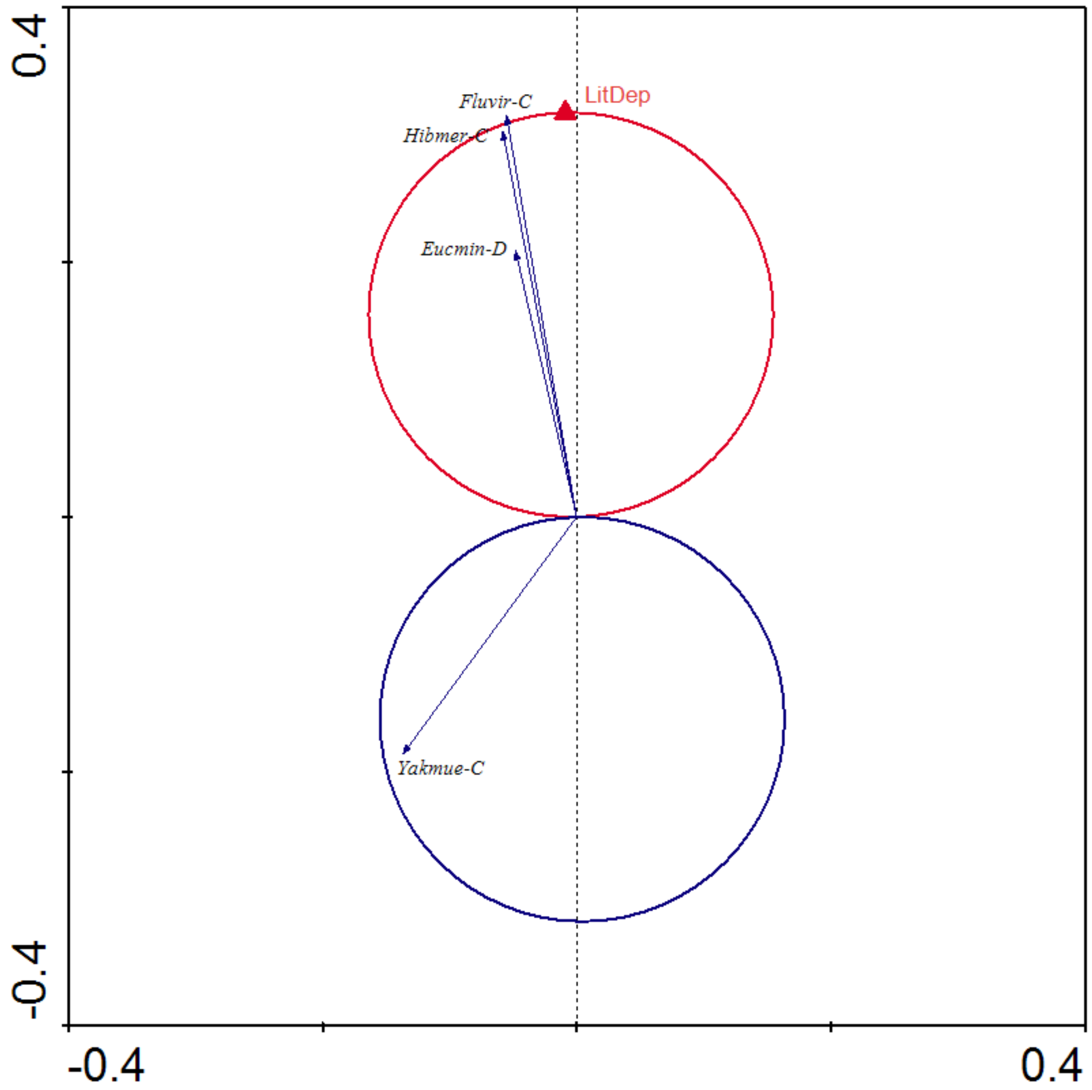


Figure 4-12 A t-value bi-plot of significant correlations between litter depth (LitDep) and species composition and structure. Species codes are listed in Appendix D

Superimposition of selected vegetation measures as supplementary variables revealed further patterns in the structure and composition of the vegetation (Figure 4-13). Shannon-Wiener diversity was correlated with increasing age and woodland sites, and was negatively correlated with high percentages of exotic species (including weeds and exotic grasses) in the understorey as well as the density of other woody species (non-eucalypt and non-acacia species above 2 m in height). Overstorey canopy cover and the density of acacias over 2 m were exactly correlated, and in fact shared the one 'vector arrow' in the ordination diagram. Both measures were also correlated with basal area, litter cover and, to a lesser degree, litter depth and were negatively correlated with understorey grass cover.

Sites are represented in Figure 4-13 by coloured circles to indicate their age. From this, it is evident that most younger sites were correlated with grass cover, in particular *Yakirra muelleri*, *Thaumastochloa pubescens* and *Sorghum stipoideum*. Sites of intermediate age, that is 4–10 years, were spread between younger and older sites, however, they were the most common sites correlated with the density of overstorey 'other' trees and shrubs and the understorey cover of exotic species including grasses. Sites older than 10 years were most correlated with litter depth and basal area and, to an extent, overstorey acacia density and canopy cover.

4.4 Discussion

Six environmental or management variables were significantly related to the vegetation composition and structure of the natural woodland and rehabilitated sites. Age had an obvious influence on the overall structure of woodland vegetation, as older trees and shrubs were generally taller and had greater trunk diameters, amongst other things. Areas of non-woodland vegetation, however, such as grassland sites, differed in more ways than simply due to age.

The correlation of litter cover and depth with canopy cover, acacia density in the overstorey and site basal area, was expected as these measures indicate high standing biomass and increased litter fall compared to other rehabilitation and even woodland sites. The negative correlation of these measures with grass cover also suggested that sites with these characteristics are less frequently burnt and may accumulate more litter than sites that have higher grass (fuel) loads and are more regularly burnt. Interestingly, woodland sites were not correlated with litter cover and depth. This suggests that these sites had intermediate levels of litter cover and depth, possibly a result of being more frequently burnt, or that nutrient cycling and biological decomposition in these sites was more active compared to rehabilitated sites resulting in a reduction in accumulated litter.

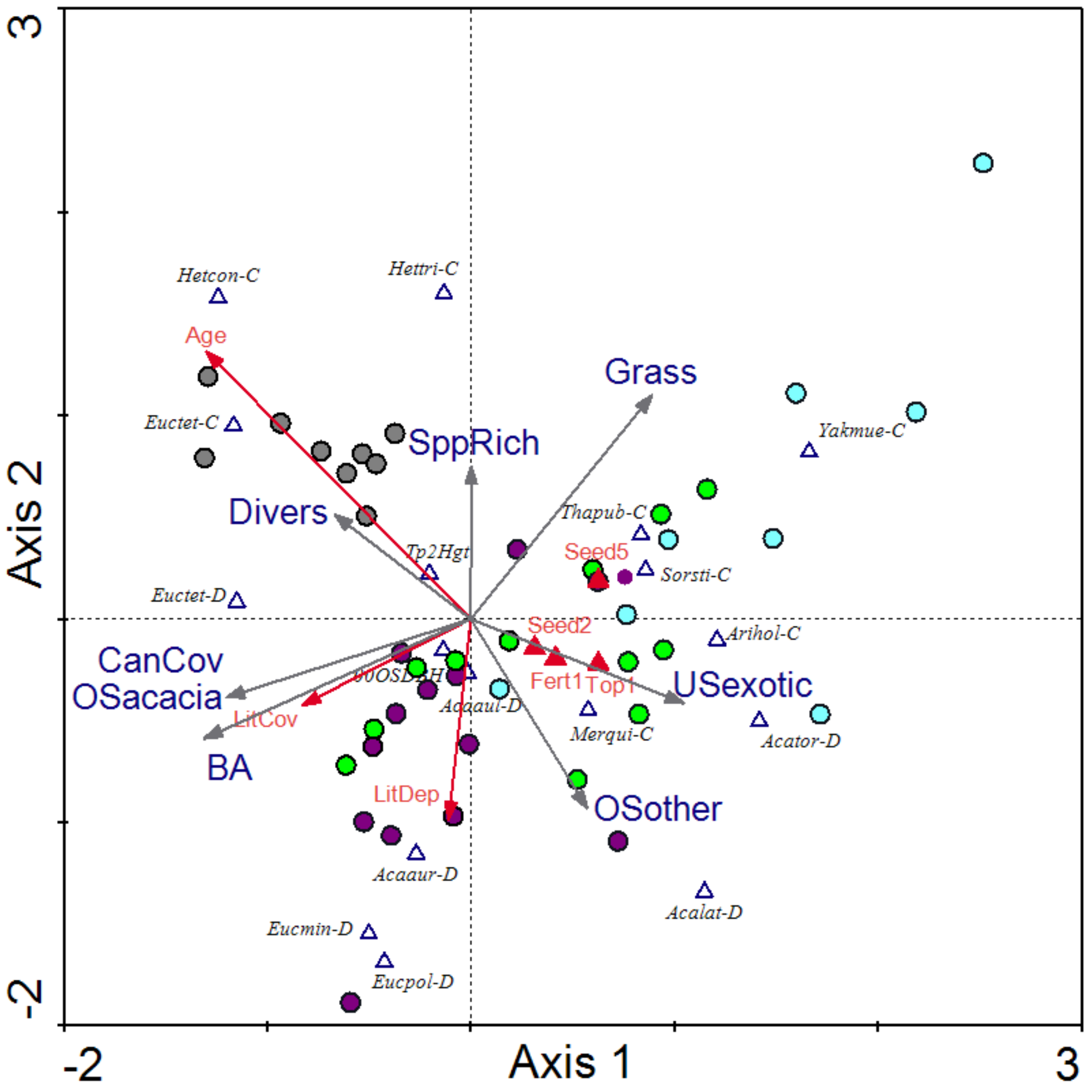


Figure 4-13 A triplot of species, sites, significant environmental variables and select vegetation measures as supplementary variables. Woodland sites are represented by grey filled circles, and rehabilitated sites by blue (< 4 years), green (4–10 years) and purple (> 10 years) circles

Older sites, despite having received the earlier seed mixes generally containing the exotic species and fewer local native species, were more similar to woodland sites than younger rehabilitation sites. This may be related to the contribution provided to the initial vegetation composition by the topsoil seed store or it could be an indication of successional development through time as a result of colonisation of rehabilitated sites by local species leading to better composition and structure than initially provided, or a combination of these.

Topsoil return and fertiliser application were correlated with the presence of exotic species in the understorey. Since the native flora is adapted to low levels of nutrients (Specht & Specht 1999), application of fertiliser could favour establishment of eutrophic, exotic species over local native species. Experiments involving reduced and zero use of fertilisers in rehabilitation would be interesting to see whether adequate native regeneration with minimal weed invasion can be achieved.

The negative correlation of grasses with eucalypt cover, as well as overstorey acacia density, canopy cover, overstorey basal area, litter cover and litter depth, was not surprising. It is likely to reflect the influence of competition for resources, especially space, light and water. That younger sites were also positively correlated with understorey grass cover, and negatively correlated with the other variables just listed, supports the notion that younger sites had higher levels of grass cover and less woody and litter cover. The latter are the result of increased biomass, especially in the form of well-developed trees and shrubs.

There is an apparent progression through time of sites trending towards the woodland and older rehabilitation sites, moving away from younger sites with high grass covers towards older sites with increased basal area, canopy cover and acacia density in the midstorey and overstorey. It is this last aspect, that of high acacia densities, that is a major problem in rehabilitation at Groote Eylandt (Section 2.3), possibly preventing such sites from moving more quickly towards woodland sites through increases in density and cover of *E. tetrodonta*.

Chapter 5 Options for Management of Rehabilitation and Succession at GEMCO

5.1 Introduction

The success of ecosystem rehabilitation in a mining context can be heavily influenced by factors relating to the initial disturbance of an area to be mined, in particular clearing, soil stripping and subsequent soil storage and handling activities. Upon completion of mining, the approach taken to re-create the landform, including substrate availability and reinstatement of a suitable growing medium profile, also influences rehabilitation success (EPA 1998). The subsequent establishment of vegetation on this re-created landform, including species selection, seed quality and dispersal, timing, and the use of fertilisers also has a significant bearing on the final outcome of the rehabilitation process (EPA 1995).

The major problems encountered in mine site rehabilitation on Groote Eylandt can be divided into establishment (management) techniques, such as substrate handling and seed mix composition, and post-establishment factors including variations in weather, especially rainfall, destruction by fire and competition from weeds and other aggressive species.

The majority of sclerophyll communities in Australia are fire-prone (Gill 1981), and the plants of the forest and woodland communities of tropical north Australia have a range of adaptations to cope with the almost annual fire regime (Stocker & Mott 1981). Furthermore, the disturbance associated with surface mining often leads to a proliferation of annual and perennial weed species. Before the relinquishment of leases associated with rehabilitated sites, it is critical to demonstrate that these areas are resilient to further disturbances such as fire, weed invasion or the outbreak of dieback (EPA 1995). For example, Alcoa of Australia, after defining its completion criteria for rehabilitated bauxite mines in the jarrah forest, proposed that these criteria could then be assessed under five time categories in a process of staged completion. The main element assessed 10 to 15 years after the establishment of vegetation is whether the area can be integrated into the broad-scale fire management regime of the bioregion (Elliott *et al.* 1996).

So, a range of processes can act as threats, or negative transitional drivers, that affect rehabilitation development. Conversely, these same factors can potentially be harnessed to actively redirect the development of substandard rehabilitation towards the desired successional state or trajectory. There exists a range of opportunities to impose post-establishment management techniques to, for example, remove dominant undesirable species, increase overall species richness or reduce the risk of damage due to uncontrolled fire. Some of the earliest management activities, such as soil selection, can be those most influential on the ultimate trajectory of vegetation development.

Substrate selection in particular has the potential to dramatically influence the early development of rehabilitated vegetation. Topsoil, that is known to have beneficial attributes like native seed store, organic matter and nutrients, can also contribute negatively through the introduction of seed of aggressive species, like grasses, to the rehabilitation area. These species may outcompete the more desirable, sown keystone species for limited resources in the harsh, early establishment environment. A large scale field trial at Comalco, at Weipa on Cape York Peninsula, found that the density of native trees and shrubs was higher on subsoil only and stockpiled soil treatments (Short 1994). Another study at Weipa found that competition from volunteer grasses, rather than any influence from reduced quality or quantity of soil organic matter, was the key limiting factor limiting establishment of sown native plants (Schwenke 1996).

5.1.1 Management Intervention Options

The idea of 'managing succession' is really the facilitation of succession, with the aim of accelerating progression through the developmental (seral) stages, as well as controlling the direction of this progression to ensure it moves toward the desired end point. Management activities that can impact a number of aspects of vegetation succession include:

- Appropriate planning to enable timely and effective rehabilitation activities;
- Substrate selection, handling and preparation (Section 4.1.1.1);
- Species selection and vegetation establishment (Section 4.1.1.2); and
- Ongoing maintenance, including retreatment of areas, weed control, and fire management.

However, active management takes time and effort and is contrary to the common final rehabilitation target of a 'sustainable' system, requiring no more inputs (e.g. management) than similar natural systems. The gradual removal of management activities (e.g. weed control) should be strategically planned and carefully monitored.

Management intervention or remediation targets may aim to improve a number of issues, including where:

- rehabilitation has failed (e.g. due to fire, harsh winds, excessive heat or lack of water infiltration);
- certain species have failed while others have developed satisfactorily (thus total re-establishment of the area is not warranted); and
- there is lack of colonisation by species that so not recruit from seed.

Just as there is an array of rehabilitation scenarios that may warrant management intervention, there is a range of options for the rehabilitation practitioner to consider.

5.1.2 Aims and Objectives of this Chapter

This chapter examines the management interventions available at Groote Eylandt; in particular, it aims to:

- Identify possible management options available to GEMCO management to effect transitions toward a desirable trajectory, or maintain rehabilitated vegetation within a desired trajectory or set of states; and
- Investigate one of these management treatments, that of topsoil return, to determine the optimal substrate mix for vegetation rehabilitation at Groote Eylandt.

5.2 Management Options

Management options to influence transitional sequences and improve the quality of rehabilitation on Groote Eylandt are many, but are generally focussed on three key process stages:

- Disturbance and substrate handling (Table 5-1);
- Vegetation establishment (Table 5-2); and
- On-going management, such as weed and fire control (Table 5-3).

Of the many activities with the potential to impact on rehabilitation success (Table 5-1, Table 5-2 and Table 5-3), some may be expected to have a greater influence than others, or provide good outcomes for relatively little effort or cost, and thus may be more suited to improving techniques. While much can be learned from the rehabilitation experiences of other mining operations (and disturbance-driven native ecosystems), site-specific investigations are required to produce the best outcomes.

Options with particular potential at GEMCO were identified as being:

1. Soil handling techniques to maximise germination and establishment of keystone species;
2. Reduction in competition from woody weeds, e.g. *Acacia* species;
3. Reduction in damage due to late season burns through early-season controlled burns;
4. Introduction of non-seeded species to mature rehabilitation through topsoil inoculation; and
5. Impacts of topsoil handling on the topsoil seed store.

These options were investigated through a program of field experiments undertaken as part of this research. Unfortunately, only the first of the investigations was successful and is reported in detail in this thesis (Section 5.3). The other four investigations failed in their establishment due to a range of factors including lack of direction and supervision of field activities, logistical constraints due to operational machinery and personnel availability, and uncontrollable climatic factors. Even having failed, however, the details of these investigations provided in Section 5.4 provide useful information for future research.

Table 5-1 Potential impacts and transitional sequences in rehabilitation vegetation (key life form groups) expected in response to various disturbance and substrate handling activities

Activity	Potential Impacts and Transitional Sequences
1. Clearing	- Only above ground vegetation removed, so keystone species re-establish rapidly, mostly from below ground resources such as lignotubers, with species richness comparable to pre-disturbance community - Potential for grasses to take advantage of increased space and light resources but unlikely to persist once canopy species attain sufficient height
2. Stripping	- Soil moved too wet resulting in overly compacted soil surface making establishment of keystone species difficult - Plants establish but fail to develop due to restricted rooting depth from shallow soil profile, unripped mine floor, or compacted substrates. May result in stunted vegetation, susceptible to felling by strong winds (e.g. Bassett *et al*. 2005) - Soil stripped after grass seed shed will likely have a higher proportion of these and pose a greater risk of high grass competition with more desirable keystone species. Could utilise pre-clearing burning or early stripping to reduce grass seed load in soil (e.g. Schwenke 1996)
3. Substrate selection	- Fresh topsoil relocated at time of first rains so that seed and vegetative propagules are able to propagate, resulting in good initial species diversity, establishment and ultimately growth - Fresh topsoil more likely to contain seed of overly competitive species that prevent sown keystone species from establishing, which are known to not establish well from seed (e.g. Schwenke 1996) - Stockpiled or no topsoil results in revegetation of simple composition, perhaps slower early growth due to lower initial nutrient availability. Should develop well but species diversity will take years to increase (e.g. Tacey & Glossop 1980) - Stockpiled soil can contain high loads of weed seed in its outer layer, and can introduce a weed problem from the outset of rehabilitation if used without treatment - Application of islands or strips of fresh topsoil in existing rehabilitation areas could ameliorate problems due to low species diversity, especially in the understorey, or bad nutrient cycling due to absence of mycorrhizae or rhizobia
4. Cultivation methods	- Scarification of soil surface removes any crusting and creates microsites for seed to shelter: results in improved seed germination and establishment, improves longer term site nutrient and water capture and retention, increases likelihood of healthy developing revegetation - Scarification or ploughing can remove growth of more aggressive species, such as grasses, present and germinating from the soil seed store – only if after initial wet season rains, decreasing competition and increasing chances of keystone species establishing and developing

Table 5-2 Potential impacts and transitional sequences in rehabilitation vegetation (key life form groups) expected in response to various management activities relating to vegetation establishment

Activity	Potential Transitional Sequences
1. Species selection	- Inclusion of keystone species provides for likely development of structurally and functionally sound ecosystem, which will then persist in time and recruit new species thus gradually returning toward original biodiversity levels - Seed mix with too many competitive species, such as grasses or acacias, may outcompete keystone species and result in vegetation community dominated by aggressive, relatively short-lived species that is not similar to original woodlands nor sustainable in the long-term - In potentially seasonally inundated areas, inclusion of a wider variety of species, such as melaleucas, would ensure recruitment and persistence
2. Seeding details	- Incorrect picking, storage or preparation of seed could reduce viability and germination percentages resulting in too few of the keystone species in an area. Low densities encourage aggressive colonisers like grasses to establish an potentially outcompete those keystone plants that are present, or increase risk of fire due to increased fuel loads - Incorrect seeding rates of keystone species can result in too few keystone plants establishing leaving the area exposed to invasion by more aggressive species, or too many stems of keystone species resulting in masses of tall, thin trees susceptible to felling by strong winds and termites, but self-thinning (mortality over time) should result in a reduction in stems per area over time
3. Seeding activities	- Uneven seed distribution can leave bare areas prone to erosion or available for colonisation by aggressive grasses and weeds, or over-seed and result in too high density
4. Fertiliser	- Use of fertiliser with high nitrogen content can increase initial growth but result in reduced drought tolerance for survival through the dry season due to increased leaf:root ratio increasing plant mortality over time - High nitrogen fertiliser also favours rapid growing species such as grasses and weeds, which could outcompete more desirable keystone species - High phosphorus fertilisers have been found to elicit strong positive growth responses from native plants (excl. Proteaceae), although they are usually provided in a mineral form which are prone to rapid leaching especially in high rainfall areas like the north Australian subtropics, reducing their influence over time - Inorganic or slow-release fertilisers would be most beneficial (but can be difficult to distribute with broadcast seed) and would increase growth through at least the first couple of growing seasons, resulting in higher more healthy vegetation

Table 5-3 Potential impacts and transitional sequences in rehabilitation vegetation (key life form groups) expected in response to various on-going, post-establishment management activities

Activity	Potential Transitional Sequences
1. Weed management.	- Eradication of grass weeds, with relatively short lived seed, can be achieved by repeat chemical treatment before seed set and results in a reduction in competition and fire risk so that existing keystone species can be relieved from their suppressed state and grow to dominate the community - Woody weeds, often have longer lived seed, and chemical treatment is less successful unless applied prior to annual seed set, for many successive years. Physical removal of the plants as well as the seed-bearing layer of the soil is one option but removes all other vegetation as well, effectively returning the system to the start of the trajectory requiring fresh application of the desired seed mix
2. Fire management	- In good quality rehabilitation, dominated by overstorey eucalypts, a cool season fire should be prescribed at an age when the eucalypts fire-resistant appendages, like lignotubers , are sufficiently developed and the canopy of the plant is above the likely fire flame height. This should not have a negative effect on the eucalypts themselves but may affect some component of the understorey if they have not been subject to fire previously. A shift in species composition could be expected but is not necessarily a bad thing as fire is bound to be a regular disturbance in this environment and species present must be resilient to this. In fact, early dry season prescribed burns are a common vegetation management tool in the tropical savannas designed to reduce the grass fuel load and mitigate any effects from more severe late dry season fires - Fire in young rehabilitation, which is yet to develop mature fire resistance, can result in outright removal of the slower growing keystone species, and likely favour the more rapidly developing species that either have masses of seed in store, have some fire resistant traits, or have grown in height above the fire prone layer. This dramatically shifts the vegetation composition and structure away from the desirable keystone species and it is unlikely that any will be naturally recruited in future as there is no existing seed store nor no below ground material from which to sprout - Fire could be used as a tool to remove weeds that are not able to respond aggressively to the event (e.g. Holmes *et al*. 2000). Unfortunately, most successful weeds in the wet/dry tropics of Australia are able to take advantage of the effects of fire and not only survive but are generally promoted by it, e.g. gamba grass
3. Remedial planting	- A lack of keystone species can be directly addressed by supplementary planting of the appropriate species. These mature seedling have an advantage in that they are likely to establish and grow rapidly and contribute to the composition and resilience of the system immediately - Remedial planting is also a technique to introduce recalcitrant species which have been identified as desired components of rehabilitation that would otherwise be unlikely to recolonise on their own

5.3 Establishment Field Experiment: Substrate Handling and Preparation

5.3.1 Background

Preliminary rehabilitation results on Groote Eylandt suggest that many understorey and overstorey species are being outcompeted in the early stages of rehabilitation development by weeds and grasses or are not readily colonising rehabilitation areas voluntarily. Of those plants that do establish, many experience less than optimal growth due to inadequate substrate selection and handling techniques negatively impacting on physical, chemical and biological attributes. Past rehabilitation has used various combinations of available media, including topsoil (a sandy lateritic earth), bare subsoil, stockpiled topsoil, mixed topsoil and subsoil, mixed topsoil and overburden, and sandtails with varying success. Topsoil and subsoil have already been described for Groote Eylandt (Section 2.1.3), and the sandtails medium is described in Section 2.2.4.

Whilst substrate selection is sometimes dictated by availability (e.g. timing or proximity), a proven difference in the effectiveness of the various media would enable more considered planning to be undertaken. The following study aimed to assess the suitability of the various substrates available to improve the establishment and initial development of revegetation.

5.3.2 Methodology

An experiment was established to investigate the effects on germination and subsequent development of new rehabilitation of various substrate combinations, including freshly stripped topsoil and subsoil (double stripped and spread as two distinct layers), a single-stripped topsoil/subsoil mix, overburden only, and sandtails.

In January 2001, a 1-ha mined-out area in F1 Quarry was backfilled with overburden and returned to approximately 50 cm below natural surface level. The area was then covered by the four substrates to a depth of approximately 50 cm in rows of roughly 25 x 100 m (Figure 5-2), leaving a level final profile. The area was deep ripped to a depth of 0.5–1 m (Figure 5-3). Scarification of the area was delayed by 3–4 weeks later which unfortunately resulted in a number of already resprouting material being re-disturbed.

This treatment was intended to be replicated in an adjacent mining area (C-quarry), but machinery availability and wet season rainfall prevented this from being established. This reduced the replication for this experiment and resulted in pseudo-replication, based on replicated monitoring quadrats within single soil treatments. While not the preferred situation, the experiment was considered worth continuing with.

A native seed mix was applied by hand to the prepared area on 23 February 2001 and consisted mainly of overstorey tree species, especially eucalypts. The seed mix was calculated to achieve a target final in-field composition and density and took into account germination percentages and the results of viability assays (M. Lord, GEMCO, pers. comm. 2002). The seed mix was notable in that it contained no acacias, which were formerly a significant component of most seed mixes at GEMCO but had led to a woody weed problem in some rehabilitated areas.

Table 5-4 Native seed mix applied to substrate trial areas

Species	Common Name	Rate (g/ha)
Eucalyptus tetrodonta	Darwin stringybark	108
Eucalyptus miniata	Darwin woollybutt	172
Eucalyptus polycarpa	Bloodwood	8.5
Grevillea pteridifolia	Fern leaf grevillea	18
Alphitonia excelsa	Red ash	20
Petalostigma pubescens	Quinine tree	83
Melaleuca leucadendra	Weeping paperbark	4
Terminalia carpentariae	Wild peach	71
Erythrophleum chlorostachys	Cooktown ironwood	20
Cycas angulata	Cycad	125
Pandanus spiralis	Screw palm	125
Buchanania obovata	Green plum	65

Fertiliser was not applied to the rehabilitation area, as had been the practice in previous years, as this had been observed to encourage competition from weeds including grasses and was thought to be of relatively little benefit to the desired native species.

Three 10 x 10 m plots (as were used in the long-term monitoring program, Section 3.2.1.1, including the four 2 x 2 m quadrats for understorey assessment in each plot) were established within each of the treatment areas (i.e. 12 plots overall) and these were assessed for a range of vegetation measures during the following 18 months (Figure 5-2). As the vegetation did not exceed 2 m in height during the 18 months, data collection consisted only of plant density, composition and cover for the four 2 x 2 m quadrats in each plot. Corner photos were also taken at each data collection.

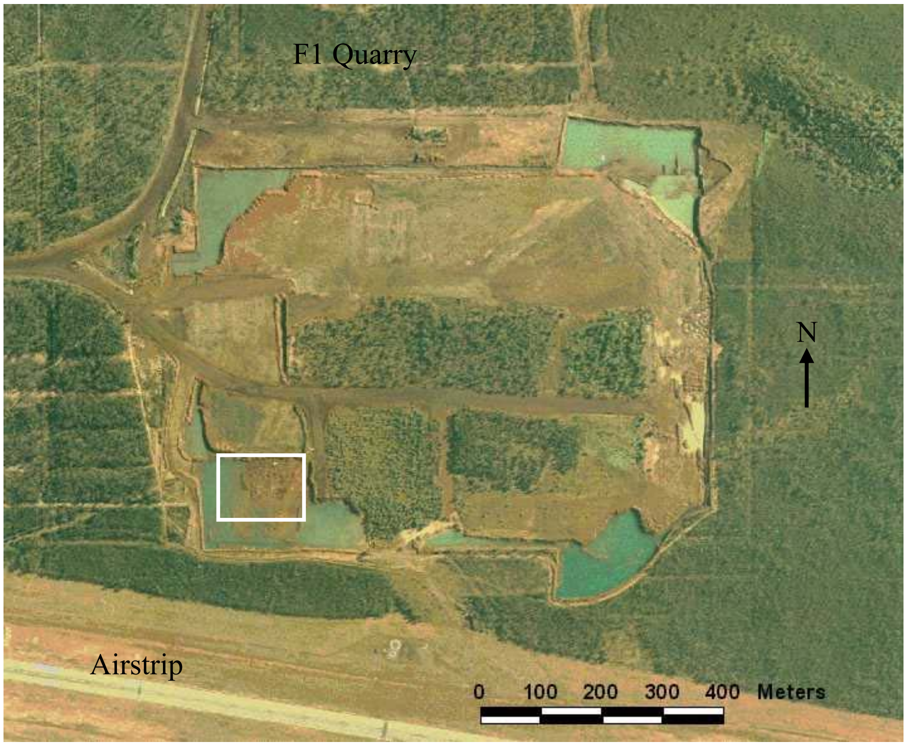


Figure 5-1 Location of Substrate Trial in F1 Quarry (white outline) (this image was taken before the finish of mining in this area and backfilling of the 1-ha area)

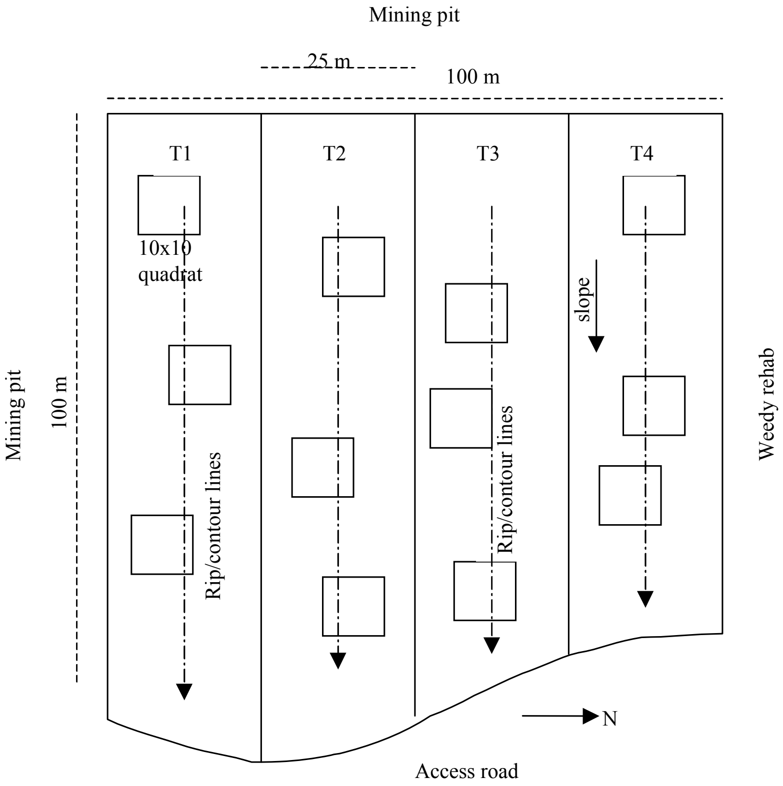


Figure 5-2 Experimental design of F1 substrate experiment: T1 = Topsoil – direct return; T2 = Topsoil / subsoil mix; T3 = Subsoil only; T4 = Sandtails only

Figure 5-3 Substrate trial after ripping, viewed from the south east, with the direct-return topsoil treatment in the foreground

Average wet season rainfall for Groote Eylandt (based on 68 years of meteorological records for Angurugu township) is 1280 mm. Total rainfall for the 2000/2001 wet season was 1530 mm, slightly above average, with approximately 700 mm falling in the 2 months after seeding of the substrate trial area (Figure 5-4). This above-average rainfall was due in part to the passing of Tropical Cyclone Winsome just off the northwest coast of Groote Eylandt on 11 February and the influence of two other cyclones in the region, TC Wylva and TC Abigail (Figure 5-5). The 2001 dry season lasted approximately 6 months between May and November. The 2001/2002 wet season was dramatically below average, with only 780 mm falling for the entire season. Of this, 525 mm occurred in the 3 months before the second survey in February. A further 255 mm fell on 36 rain days, mostly during March, of the following 144 days before the 18-month survey in July 2002.

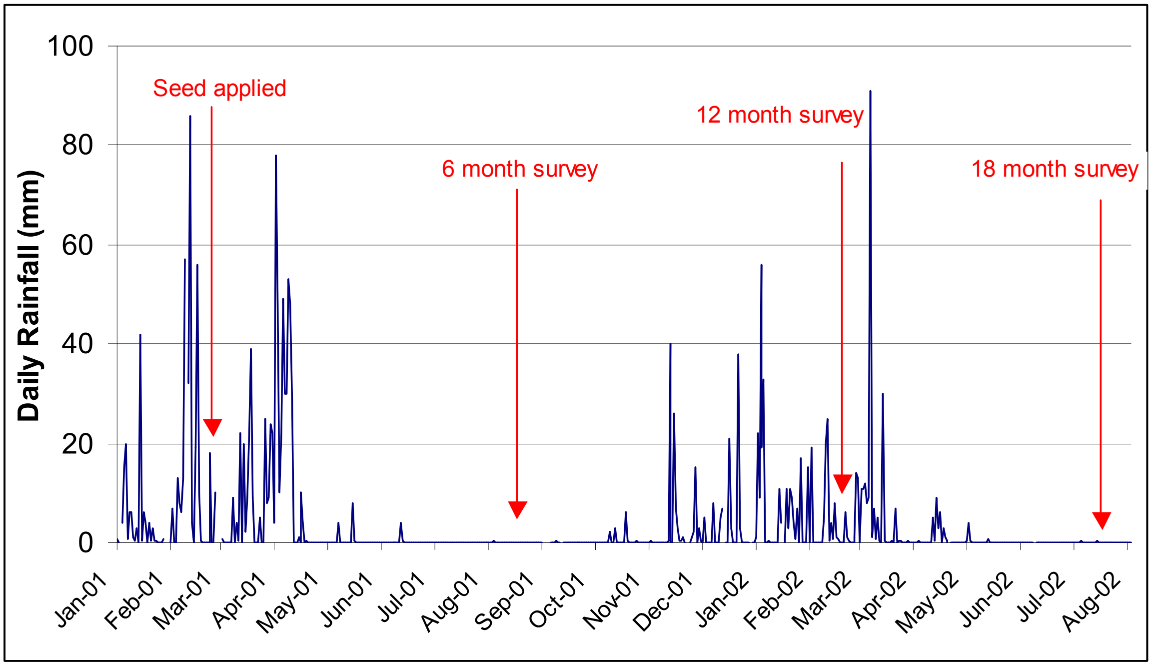


Figure 5-4 Daily rainfall (mm) at Groote Eylandt Airport from January 2001 to August 2002. Red arrows indicate dates of seed application and surveys of the substrate experiment

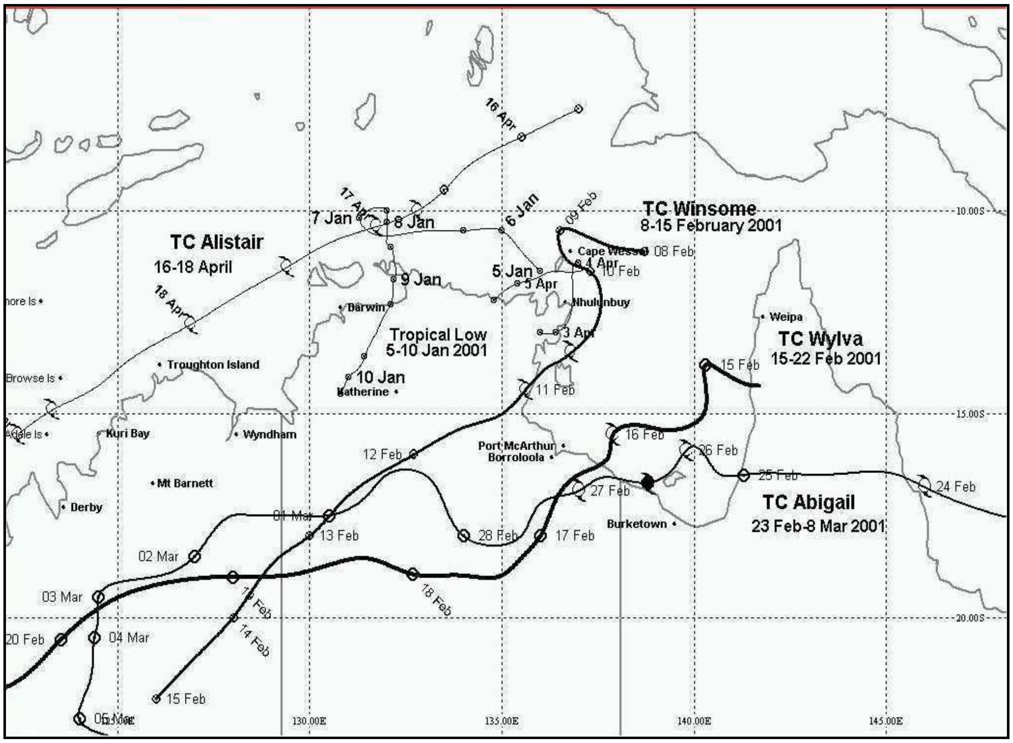


Figure 5-5 Tracks of tropical cyclones and lows affecting rainfall at Groote Eylandt in early 2001 (BOM 2002)

5.3.3 Data Collection and Analysis

In February 2001, composite samples of each substrate were collected from four locations within each 10 x 10-m quadrat. A subsample of each composite sample was removed, dried, sieved to 2 mm, and returned to the University of New England for analysis. Soil samples were analysed for pH, Electric Conductivity (EC), organic matter (loss on ignition), exchangeable bases (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}), ammonium and nitrate, micronutrients (Mn, Fe, Zn, Cu) and P (total and available) as described in Section 3.2.2.1.

Air-dry moisture content was estimated for topsoil samples of all soil treatments. Replicates of composite samples, each weighing approximately 3–5 kg, of the surface 10 cm of each substrate type were collected mid-morning on a humid day (after some rain the day before) in February 2002. These samples were immediately taken to the GEMCO geological laboratory and weighed before and after drying in a fan-forced oven. The difference in the two weights of each sample represents the water content lost through the drying process. This weight, in proportion to the assayed soil volume, provided a measure of the moisture-holding capacity of the substrate.

Having been sown with native seed in February 2001, the site was first surveyed 6 months later, in August. Two further surveys were made, one in the wet season on the 24 February 2002 (12 months after seeding) and another in the middle of the 2002 dry season, on 18 July (18 months after seeding).

Counts of species from the four 2 x 2 m quadrats in each plot were used to calculate total and average species richness and densities of each species. Estimates of projected foliage cover (%) were made for all individual plants. For some analyses, species were grouped into life form groups: eucalypts, non-eucalypt woody species, grasses, and non-grassy forbs.

Soil and vegetation measures were summarised as averages, standard errors and ranges. They were further assessed for significance within and between treatments using single-factor analysis of variance (ANOVA) with the *Statistix*^{TM} software package. The vegetation data were further analysed across time using repeated-measures ANOVA. To satisfy the normality assumptions of ANOVA, data were transformed (ln) for soil calcium and potassium concentrations. Nonparametric data were analysed using the Kruskal-Wallis test, for concentrations of soil nitrate, magnesium, sodium, cation exchange capacity, manganese, copper and organic matter. A Bonferroni correction was performed to correct for alpha inflation due to the multiple comparisons. Mean values are presented in the text with standard errors in parentheses.

5.3.4 Results

Despite obvious differences in texture, the three treatment substrates did not differ in soil moisture content (F = 2.62, P = 0.1230), although the sandtails substrate had a marginally lower moisture-holding capacity than other substrates (Figure 5-6).

Samples of soil from the four different treatments had remarkably different chemical characteristics, and were significantly different in terms of electrical conductivity, nitrate concentrations and calcium concentrations (Table 5-5). All treatments had similar pHs, averaging between 6.4 and 6.6 pH units. The topsoil and subsoil/topsoil treatments had significantly greater electrical conductivity (F = 13, P = 0.0004), averaging 24 and 27 mS/cm, respectively, compared to the subsoil and sandtails substrates, which averaged 12 and 11 mS/cm, respectively. Nitrate concentration in subsoil was significantly less than that of the other substrates (F = 9.12, P = 0.0020). Total phosphorus concentrations were highest in sandtails, averaging 260 mg P/kg, and less than half that in other soils. Available phosphorus was very low in all soils, with averages ranging from 0.02 to 2.5 mg P/kg, with the higher concentrations being found in the in the subsoil/topsoil mix.

The exchangeable cations were found at higher concentrations in the topsoil and, to a lesser degree, the topsoil/subsoil treatment (Table 5-5). Levels of calcium, in particular, were significantly lower in the sandtails treatment (F = 54.1, P = 0.0000), averaging 3.9 mg Ca/kg , than other treatments, which ranged between 16 and 33 mg Ca/kg. Concentrations of micronutrients were generally lower in the sandtails and subsoil treatments, as were proportions of organic matter, but the differences were not significant (after Bonferroni correction).

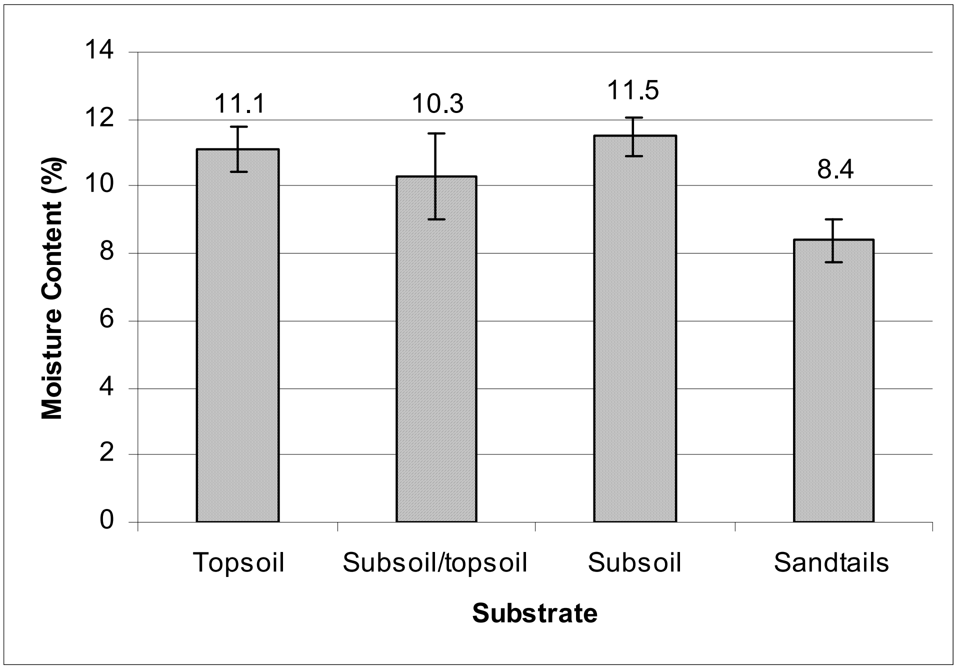


Figure 5-6 Soil moisture content of the topsoil, topsoil/subsoil, subsoil and sandtails substrates

A total of 61 native plant species were identified in the rehabilitation (plus 2 exotic weed species). Of these, only two (3.2%) were eucalypts, 19% were grasses (Poaceae), 19% were non-eucalypt shrubs and trees (including acacias) and just over 55% were non-grass herbs (including forbs, sedges, lilies and vines).

Of the 12 species supplied in the seed mix, only five were recorded in any plots, including *Petalostigma pubescens, Melaleuca leucadendra, Erythrophleum chlorostachys* and two of the three eucalypts, *Eucalyptus tetrodonta* and *E. miniata.* This means that less than 10% of species

Table 5-5 Select attributes of topsoil, subsoil, topsoil/subsoil and sandtails substrates

Attribute	Unit	Topsoil		Subsoil/Topsoil		Subsoil		Sandtails		Analysis of Variance[2]
		Avg (SE)	Range	Avg (SE)	Range	Avg (SE)	Range	Avg (SE)	Range	
pH (water)		6.4 (0.05)	6.4-6.6	6.5 (0.4)	5.7-7.6	6.6 (0.3)	5.9-7.3	6.4 (0.08)	6.3-6.7	n.s.
Electrical conductivity (EC)	mS/cm	24 (1.7)	21-29	27 (4.1)	18-36	12 (0.5)	11-14	11.2 (0.8)	9.0-12.9	F = 13.0, P = 0.0004**
Ammonium	mg/kg	0.75 (0.20)	0.40-1.2	1.1 (0.11)	0.8-1.2	0.73 (0.05)	0.63-0.85	0.96 (0.13)	0.66-1.17	n.s.
Nitrate	mg/kg	0.67 (0.08)	0.58-0.90	0.59 (0.16)	0.19-0.96	0.06 (0.01)	0.05-0.08	0.20 (0.07)	0.02-0.37	F = 9.12, P = 0.0020*
Total Phosphorus	mg/kg	88 (6.45)	77-106	122 (10)	103-143	84 (11)	63-107	260 (69)	177-466	n.s.
Available Phosphorus	mg/kg	0.74 (0.36)	0.06-1.73	2.5 (1.0)	0.6-5.3	0.02 (0.01)	0.01-0.03	0.06 (0.02)	0.001-0.10	n.s.
Exchangeable Cations										
Calcium (Ca^{2+})	mg/kg	33 (1.8)	30-37	24 (4)	14-32	16 (1.2)	14-19	3.9 (0.5)	2.4-4.8	(ln trans) F = 54.1, P = 0.0000***
Magnesium (Mg^{2+})	mg/kg	9.4 (1.6)	6.2-13	7.3 (0.5)	6.4-8.6	6.1 (1.8)	2.9-9.5	4.1 (0.54)	3.0-5.5	n.s.
Sodium (Na^{+})	mg/kg	7.8 (0.36)	6.9-8.4	6.5 (0.6)	5.4-7.6	8.2 (0.4)	7.2-9.3	6.2 (0.19)	5.7-6.5	n.s.
Potassium (K^{+})	mg/kg	6.3 (0.74)	4.8-7.9	4.2 (0.9)	2.6-6.8	4.9 (0.2)	4.5-5.3	2.5 (0.90)	0.40-4.8	n.s.
CEC_e	$Cmol_c$/kg	0.29 (0.02)	0.25-0.33	0.22 (0.02)	0.17-0.27	0.18 (0.012)	0.15-0.21	0.09 (0.007)	0.07-0.10	n.s.
DTPA Extractable Micronutrients										
Manganese (Mn)	mg/kg	97 (9.2)	82-121	87 (5)	76-102	96 (36)	33-166	74 (4.5)	63-85	n.s.
Iron (Fe)	mg/kg	14 (1.7)	9-17	14 (1.7)	10-17	12 (4)	5-20	6.3 (0.15)	6.0-6.6	n.s.
Zinc (Zn)	mg/kg	0.3 (0.06)	0.2-0.4	0.2 (0.01)	0.16-0.22	0.10 (0.004)	0.09-0.11	0.28 (0.07)	0.12-0.44	n.s.
Copper (Cu)	mg/kg	0.2 (0.03)	0.1-0.3	0.3 (0.07)	0.1-0.5	0.07 (0.03)	0.02-0.12	0.07 (0.01)	0.04-0.1	n.s.
Organic matter (loss on ignition)	%	4.3 (0.53)	3.2-5.6	4.9 (0.6)	3.4-6.2	4.2 (0.4)	3.5-5.0	3.7 (0.28)	3.3-4.5	n.s.

[1]Based on 2002 dry season samples; [2]Analysis of variance was conducted on untransformed data where possible or transformed data (ln) or by the Kruskal-Wallis method where data were found to be non-parametric (n). Bonferroni correction: ***0.001 P = 0.000063, **0.01 P = 0.00063, *0.05 P = 0.0031 for 16 tests. P > 0.0031 = non-significant (n.s.)

were introduced as sown seed. Volunteer tree or shrub species included *Clerodendron floribundum*, *Hakea arborescens* and *Exocarpus latifolia*. These were most common in the topsoil-containing treatments, supporting the notion that they were introduced as part of the soil seed store.

Species richness varied significantly among treatments both within and between surveys. In all three surveys, the topsoil and topsoil/subsoil treatments had significantly greater species richness than either the straight subsoil or sandtails treatments, which, in turn, differed significantly from each other (6 months: F = 29.4, P = 0.0001; 12 month: F = 105, P = 0.0000; 18 month: F = 30.4, P = 0.0001). By 12 months, the species richness of all treatments had more than doubled, except the subsoil treatment which increased by 57%.

The effect of the wet season on species richness was apparent in all treatments, except the sandtails, declining at the subsequent 18-month survey. Of particular note were the topsoil treatment species richness, which decreased by 30%, and the topsoil/subsoil richness, which decreased by 23%. Species richness was significantly different when compared across both surveys for treatment (F = 139.02, P = 0.0000), time (F = 133.33, P = 0.0000) and treatment x time (F = 22.22, P = 0.0003). In total, 25 species were found in the initial dry season survey, 49 species were recorded in the wet season survey, and this had declined to 39 species by the following dry season survey.

Eucalyptus tetrodonta was the most frequent species, occurring in 10 of the 12 plots (83%), 6 months after seeding, and in nine of 12 plots by 18 months. Eucalyptus miniata occurred in 42─58% of plots across the sampling period.

Very few weeds were observed over the 18 months. Only a single *Sida cordifolia* plant, which persisted for 12 months at a subsoil/topsoil treatment plot, was recorded. One *Hyptis suaveolens* plant appeared in a subsoil treatment plot by the 12-month survey and a single plant of this species was also recorded from each of two topsoil/subsoil plots at the 18-month survey. These may have invaded from the adjacent rehabilitation area which was dominated by *Acacia holosericea* with a dense *H. suaveolens* understorey.

Despite no acacias being included in the applied/sown seed mix, a few (n = 8) plants were observed during the experiment on all substrates. With such low numbers, these were not analysed separately, but rather included in the 'non-eucalypt woody' species group for the purpose of further analysis.

Establishment after 6 months, as measured in August 2001, was significantly greater in treatments including topsoil (i.e. topsoil and topsoil/subsoil) as measured by total plant densities (F = 10.1, P = 0.0042) (Figure 5-7). The topsoil/subsoil treatment had the highest density of 1.9 plants per square metre (pm^{-2}), which was significantly greater than the subsoil treatment (0.958 pm^{-2}) and sandtails (0.104 pm^{-2}), although not significantly greater than the topsoil treatment (1.375 pm^{-2}) (Figure 5-7). The species with the highest average density (pm^{-2}) across all treatments was the grass *Schizachyrium fragile* (0.33 pm^{-2}) followed by *Eucalyptus tetrodonta* (0.21 pm^{-2}). Grasses were the main reason for the high plant densities in the topsoil-containing treatments, and grass cover was significantly greater on the topsoil and topsoil/subsoil sites (F = 6.72, P = 0.0141) than other treatments. Densities of eucalypts were significantly lower in these treatments (F = 4.06, P = 0.0500) and did not contribute to total site densities much at all.

By the next wet season, 12 months after seeding, the topsoil and topsoil/subsoil treatments continued to support significantly higher plant densities than the subsoil and sandtails treatments (F = 45.2, P = 0.000), although again this was predominantly due to a significantly higher level of grass cover at these sites (F = 10.0, P = 0.0044). The overburden-only treatment had significantly greater eucalypt cover than all other treatments, including the sandtails treatment (F = 4.91, P = 0.0320). Three grass and one sedge species dominated in terms of average density across treatments. In descending order, these were *Eriachne ciliata* (2.37 pm^{-2}), *Thaumastochloa pubescens* (0.99 pm^{-2}), *Schizachyrium fragile* (0.80 pm^{-2}) and *Fimbristylis densa* (0.42 pm^{-2}). *Eucalyptus tetrodonta* was the eighth most common species (0.10 pm^{-2}), equal with the herb *Heliotropium ventricosum*, and the grass *Paspalidium rarum*, but remained the most abundant woody species.

Eighteen months after seeding, average grass cover in the topsoil and topsoil/subsoil treatments had increased dramatically, to 29 and 26%, respectively, which were significantly greater (F = 9.08, P = 0.0059) than grass cover in the subsoil and sandtails treatments (2 and 0.5%, respectively). Eucalypt cover had increased on all treatments, especially the subsoil treatment which averaged 11% cover compared to 2–4% cover for other treatments. Eucalypt density was greater in subsoil for all three measurement periods, including at 18 months (Figure 5-7). By this stage, *Eriachne ciliata* which had been dominant 6 months earlier, was not found at all.

However, grasses maintained the highest densities, with *Schizachyrium fragile* (2.14 pm^{-2}), *Thaumastochloa pubescens* (1.13 pm^{-2}) and *Ectrosia leporina* (0.89 pm^{-2}) dominating. *Eucalyptus tetrodonta* was still the most dense woody species but with the eighth highest density overall.

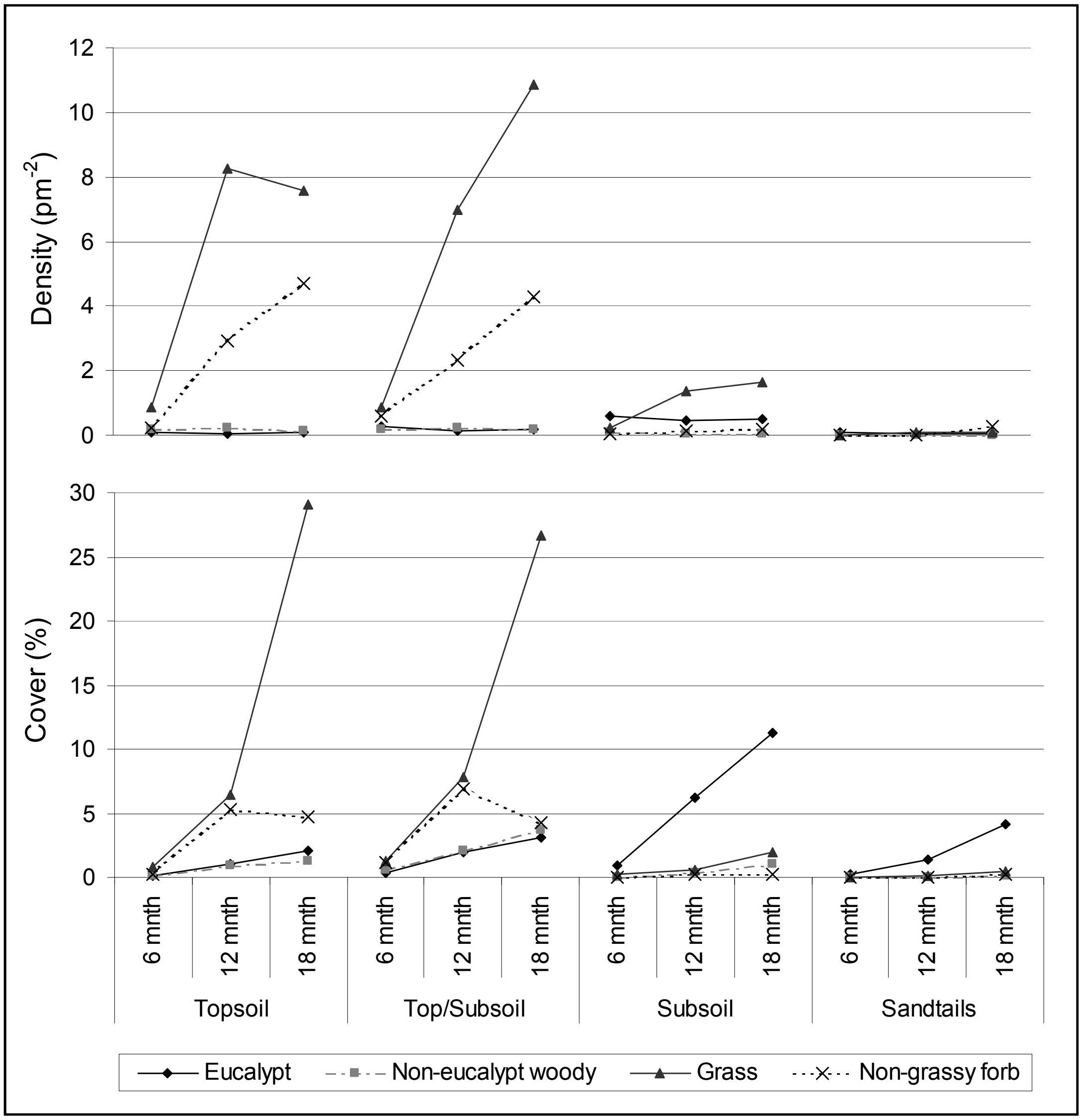


Figure 5-7 Average density and cover for each treatment by age and life form

Repeated-measures ANOVA showed that eucalypt density was significantly different with respect to time and treatment but not time x treatment. Grass density and cover increased markedly by 12 months in all treatments and were significant for treatment, time and treatment x time.

Non-eucalypt woody species comprised 20% of species and included acacias, *Melaleuca* spp., ironwood, *Petalostigma* spp., and *Hakea arborescens*. However, they were present at very low densities and cover values. There were no significant differences between treatments, ages or treatment x age, although there were marginally higher densities and cover in the topsoil containing treatments.

The density and cover of non-grassy forb species were not significantly different between treatments at 6 months, but had increased significantly by 12 months, when the topsoil-containing treatments had significantly higher densities of these species than other treatments (density: F = 27.8, P = 0.0001; cover: F = 24.5, P = 0.0002). By 18 months, density and cover of the non-grassy forb species in topsoil-containing treatments had declined slightly, but remained significantly higher than other treatments.

5.3.5 Discussion

All material used in this trial was taken from fresh sources, so that the potential negative effects of stockpiling, such as weed contamination, decreased nutrient content, low biological activity, and decreased native seed store, were avoided. This was confirmed by the low numbers of weeds that established in this trial, confirming that using fresh material can avoid (in the short term at least) the introduction of weeds into young rehabilitation. Low weed establishment may also have been related to the lack of fertiliser applied to the trial, which potentially reduced the aggressive growth of any weeds present.

Soil chemical and physical analysis confirmed that topsoil generally contained higher concentrations of exchangeable cations and micronutrients. Subsoil mixed with topsoil also had elevated levels of these nutrients compared to straight subsoil. Sandtails was generally much lower in all of these, except for zinc which was present in concentrations comparable to the other substrates. Interestingly, the subsoil had the lowest levels of ammonium, nitrate, total and available phosphorus while sandtails had remarkably high levels of total phosphorus but very low levels of available phosphorus.

Organic matter was not greatly different even between the topsoil and subsoil substrates, and was typical of the shallow, highly weathered soils typical of savanna woodlands and forests of the wet─dry tropics. Sandtails has less organic matter than the other substrates which can be linked to the lower moisture-holding capacity of this substrate compared to the other materials.

Topsoil appears to be only marginally more valuable in terms of chemical composition and plant nutrition compared to the other substrates. There is no obvious reason why subsoil, or a mix of the two, should not support vegetation equally well. Sandtails has marginally lower concentrations of most nutrients, except for total phosphorus, although its lower organic matter content and moisture-holding capacity may be less favourable for vegetation establishment and development in this harsh environment where water availability is often a limiting factor to growth and survival.

In terms of vegetation establishment and growth, only five of the 12 sown species were recorded in any treatments over the 18 months of assessment. These made up less than 10% of all recorded species, but importantly included the two dominant eucalypt species, *Eucalyptus tetrodonta* and *E. miniata.* This result is concerning as species selected for inclusion in a broadcast seed mix generally represent the most desirable keystone species and are considered critical to the initial establishment of successful rehabilitation. It is interesting that other species commonly found in rehabilitated areas, such as *Alphitonia excelsa* and *Grevillea pteridifolia*, did not appear to have germinated from the sown seed nor to have been supplied as part of a topsoil seed store, as they were not recorded in the trial at all.

Failure to germinate when supplied as seed, or from a freshly returned topsoil seed bank, suggests that further research is required into some of these species to ensure correct seed management techniques and identify recalcitrant traits which need special management, for example pre-sowing treatments such as scarifying.

The remaining 90% of species recorded, including grasses and sedges, were volunteers, introduced either in the substrate or via another dispersal mechanism (e.g. wind). Grasses appeared to be the most successful among these species as they were significantly more abundant than non-grass forbs in both the topsoil/subsoil mix and straight topsoil. Furthermore, as the sandtails substrate (and to a lesser extent the subsoil) are likely to have no seed store, any volunteers appearing in this substrate can be considered to have been introduced by dispersal (or contamination during preparation of the substrates). These volunteers included four grasses and

Acacia holosericea (likely wind-blown from the adjacent *A. holosericea* and *Hyptis suaveolens*-dominated rehabilitation area).

As early as 6 months after sowing, the negative influence of grass competition on eucalypt establishment was evident, with the topsoil and topsoil/subsoil treatments both having significantly higher grass cover but lower eucalypt densities than the other treatments with no seed store. In fact, eucalypts consistently made up the highest proportion of cover in both subsoil and sandtails treatments, compared to grasses, non-eucalypt woody species and non-grassy forbs.

The overwhelming presence of grasses in the topsoil-containing treatments suggests that these species were a major component of the topsoil seed store, or at least were the life form best able to take advantage of the freshly laid out rehabilitation area, free from canopy suppression and competition from other established vegetation as would be found in an undisturbed woodland environment. Acacias were conspicuously absent compared to older rehabilitation at GEMCO, being present in very low numbers on all four substrates, including sandtails. This reflects their relatively low abundance in the natural woodland community and highlights the artificially high numbers found in existing rehabilitation. As they were not included in the seed mix, their presence at all exemplifies their ability to persist through soil handling, soil seed bank dilution and to recruit in a material unlikely to have had a seed store at all (sandtails).

The results of this trial suggest that topsoil is important for the establishment of eucalypt-dominated vegetation in rehabilitated areas, but not for the traditional reasons of nutrition, target species seed store, and water-holding capacity, nor even its role as a substrate to support the establishment and growth of seedlings (e.g. Tacey & Glossop 1980). The main influence of topsoil was negative, through provision of a seed store dominated by aggressive native species, in particular grasses, that outcompeted the more desirable eucalypt species.

Management opportunities to remove this potentially disastrous start for rehabilitation include utilising subsoil as the only substrate to support establishment of the dominant, keystone species supplied in a broadcast seed mix. This requires some work in itself as less than half of the sown species established at all in this trial, regardless of substrate. Recognising the important role of the topsoil seed store in increasing diversity, by providing forbs and non-keystone woody species in addition to grasses, islands or strips of topsoil could be strategically placed across new rehabilitation so that these species are at least present and have the potential to colonise the wider area with time.

Although this trial did not assess the need for fertiliser, there was no obvious nutritional distress after 18 months of growth for the larger woody species, namely eucalypts. As traditional fertiliser applications at Groote Eylandt are usually undertaken within this time (either at sowing or 3–6 months after the event), fertiliser does not appear to be required. In fact, while fertiliser applications may increase the growth of desirable rehabilitation species, it also increases the chances of weeds, grasses and other aggressive competitors taking over.

5.4 Unsuccessful Experiments

Conducting research on rehabilitation on operational mine sites, utilising operational equipment and personnel, poses a range of difficulties which must be carefully planned, managed and overcome. Four of the five investigations into management options failed to produce any results, due to a range of factors including lack of direction and supervision of field activities, logistical constraints due to operational machinery and personnel availability, and uncontrollable climatic factors. Despite this, the details of these investigations are provided here as they provide an important focus for future investigations (Section 7.3.3).

5.4.1 Acacia Thinning Experiment

5.4.1.1 Background

High densities of non-keystone species, such as acacias, are believed to aggressively compete with more desirable eucalypt species and result in failed rehabilitation. These high acacia densities may have arisen via a number of pathways, based on either poor establishment techniques or post-establishment disturbance. A seed mix with a high number or proportion of competitive species or low viabilities of more desirable species may create this scenario. Alternatively, uncontrolled fires at an inopportune time (e.g. when only 1─2 species is sufficiently resilient) may result in a near-monoculture of species which quickly take over and dominate the site.

With no additional disturbance, this system would develop to a point where the law of self-thinning would apply and plant mortality would increase. Gradually, this may result in a reduction of overall density, and open up the understorey to colonisation by other species as well as propagules of the overstorey species. A long time frame would be required before a multi-aged stand with diverse understorey, mid-storey and overstorey components would develop.

Disturbance, especially by fire, is a more likely scenario, and this may have catastrophic impacts on the system, which is likely to have a high fuel load of litter at ground level and standing wood at middle and upper levels. The closed canopy of high density eucalypt stands also carries fire rapidly between trees with a higher intensity than the usual low intensity, ground-level trickle fires of these tropical savannah woodlands and forests.

Thinning is the silvicultural practice of removing neighbouring trees to increase the basal area and height of the remaining trees. Thinning in forestry typically is undertaken to achieve three benefits: to create structural diversity within the stand, improve wildlife habitat or stimulate growth of remaining trees. In forests where biodiversity values are important, a technique of variable density thinning has been developed, where an area is thinned unevenly creating a mosaic of areas of cover, and open areas for light-loving plant species including forage for wildlife (e.g. grass; USDA Forest Service 2005). Also, several studies have shown that the risk of a devastating crown fire can be lowered if fuel loads are reduced and small-diameter trees are removed (e.g. Fule *et al*. 2001).

Some areas of GEMCO rehabilitation have detrimentally high tree densities. These sites have typically very low species richness, especially in the mid- and ground-layer, likely caused by the competitive nature of the dominant overstorey acacias. The sites also have high fuel loads in litter as well as standing trash, and are at high risk of severe fire. Standing trash is particularly evident in areas where overstorey acacias have started to senesce. An investigation of the effects of thinning of overstorey acacia trees on understorey diversity and fuel loads was proposed for such an area of acacia-dominated rehabilitation.

5.4.1.2 Methodology

Two areas of approximately 50 x 50 m (Figure 5-8) were cleared of the dominant acacias in the midstorey and overstorey in an experiment to assess the effects of this on development (in response to decreased competition for light and other resources) of various components of the understorey, which was low in density, cover and biodiversity. Clearing was undertaken using chainsaws and handsaws by members of the GEMCO rehabilitation crew, in August 2001. Thinned material was mulched on site and used on supplementary plantings of seedlings of the major eucalypts that were also made in the area. Two areas (50 x 50 m) adjacent to these cleared areas were marked out as controls, making a total of 4 x 50 x 50 m plots. Measurements of these were not to be undertaken for a year, when differences in development were expected to emerge.

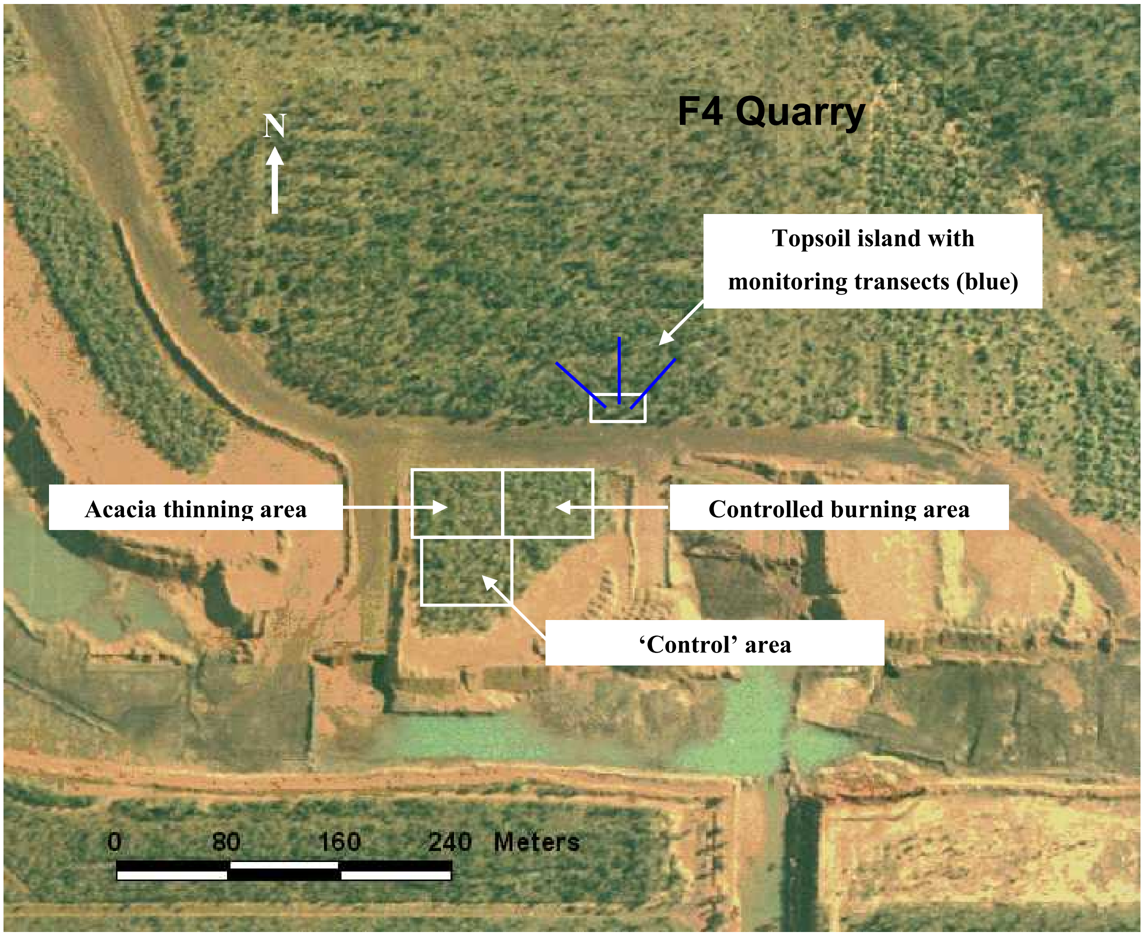


Figure 5-8 Locations of Block A sites of investigations into acacia thinning, controlled burning and topsoil inoculation in F4-Quarry rehabilitation

5.4.1.3 Outcomes

Unfortunately, the two thinned plots of 50 x 50 m were burnt by a wildfire in the following dry season leading to significant disturbance. The fire effects eclipsed any changes in understorey diversity, density or fuel loads resulting from the thinning treatment and so the experiment was discontinued. Other issues associated with this trial that should be considered when planning future experiments include:

- The 50 x 50 m plot size was relatively small and edge effects likely confounded some of the effects of decreased overstorey (larger plot size recommended);
- Machinery used during thinning, mulching, and planting caused major disturbance of the site (increased supervision and minimal disturbance by personnel and machinery recommended); and
- Supplementary plantings with mulch also took up considerable space and removed litter and other understorey plants (trial focussed on key aim uncomplicated by other factors recommended).

5.4.2 Controlled Burning Experiment

5.4.2.1 Background

Rehabilitation efforts on Groote Eylandt are frequently hindered by the effects of weeds and grasses through competition for space, light and nutrients, and devastation by fire encouraged by high fuel loads. One way of reducing the damage to young desired understorey plants from uncontrolled dry season fires is prescribed burning. Prescribed burning is widely practised by fire management professionals and indigenous custodians throughout the Top End. Such burns would ideally occur in the early dry season or at a suitable time of day and with appropriate wind and weather conditions later in the dry season. This would remove the fuel load of mature wet season weeds and grasses with a controlled, low intensity fire with less impact on desired plants than uncontrolled fires.

5.4.2.2 Methodology

A site of acacia-dominated rehabilitation with a high grass fuel load in F4-Quarry, adjacent to the acacia thinning trial, was selected for the burning trial (Figure 5-8). The area was adjacent to one of the 50 x 50 m areas that were used for the acacia-thinning trial, to enable the two methods to be compared between themselves and with an adjacent unmanipulated (control) area.

Estimates of fuel load and vegetation structure were made prior to burning at three randomly selected points (Figure 5-9). A 0.5 x 0.5 m quadrat was placed at each random point. Three litter depth readings were taken within the quadrat, using a litter gauge as described in Section 3.2.1. Percent cover of litter (dead grass, leaves and non-standing woody trash) within the quadrat area was also estimated. All litter within the quadrat was bagged, oven dried (60° C for 8 hours) and weighed. Standing vegetation was assessed using the Levy Pole method (Section 3.2.1).

The burning exercise was conducted early on the morning of 19 September 2001 by the GEMCO rehabilitation crew under the supervision of the Environmental Co-ordinator. An informal report on the exercise indicated that the temperature at this time was relatively low, with a slight, persistent dew drop on the vegetation and a fairly calm wind. Flame height was observed to remain below 1 m and the fire was restricted to the experimental area. Rate of spread of the fire was estimated by timing the movement of fire front between strategically placed metal discs (Figure 5-10). Three transects of 5 discs, separated by 10-m intervals, were established within the area for the controlled burning experiment.

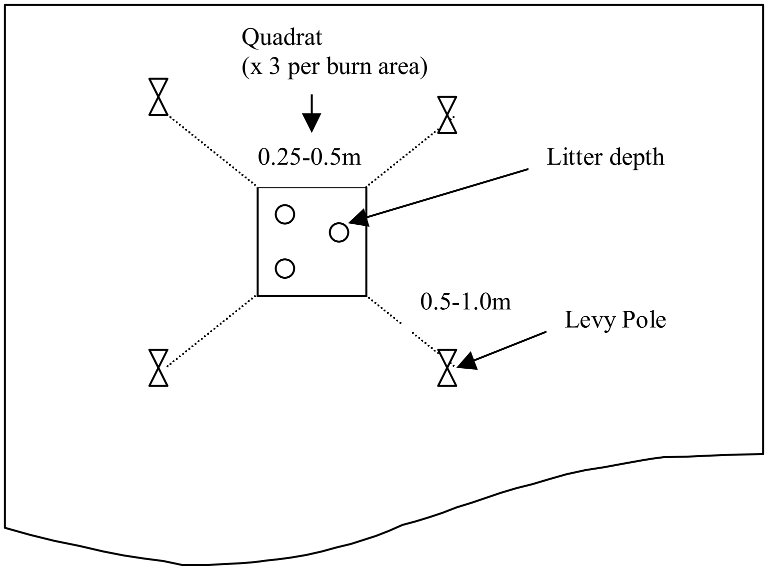


Figure 5-9 Diagram of sampling layout for fuel estimations

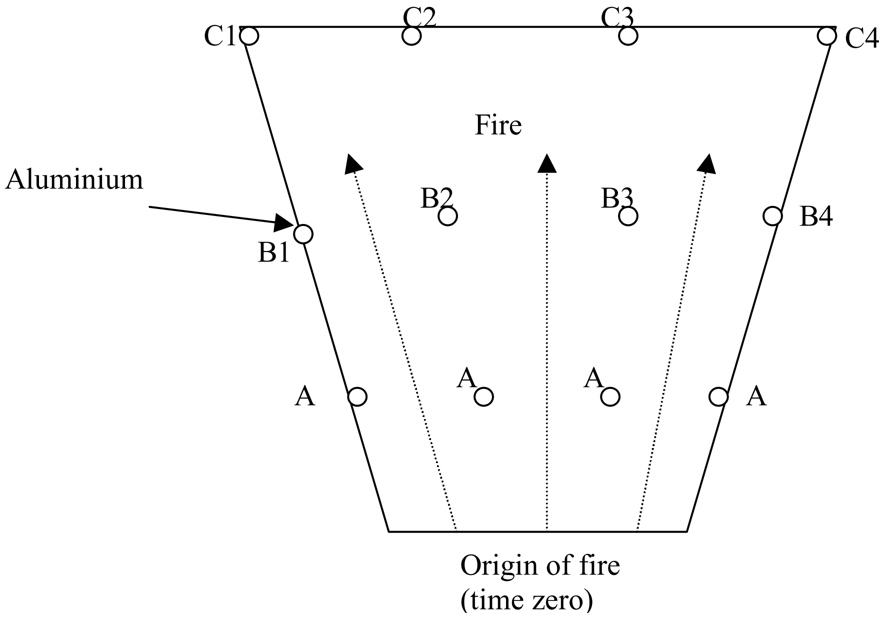


Figure 5-10 Layout of metal discs for the measurement of the rate of spread of the fire front

5.4.2.3 Outcomes

The fuel load was calculated as approximately 6.9 t/ha. The fire took between 68 and 80 minutes to travel the 50 m from the burn front, averaging 0.024 m/sec for the whole area. The controlled burn was incomplete, with much of the plot only partially burnt, while the adjacent control area which was also intended to act as the control for the acacia thinning trial was partially burnt.

Discussions on the practicality of the exercise after the failed attempt determined access issues were the main problem. It is thought that a larger area would be required for any future trials, one where a fire break in the form of a cleared track was able to be established prior to the burn.

5.4.3 Topsoil Islands Experiment

5.4.3.1 Background

One commonly encountered problem in rehabilitation is a lack of understorey species richness or a composition favouring some species, such as grasses, over others. This is generally considered to be the result of using a substrate containing little or no stored seed (e.g. subsoil only or stockpiled topsoil) or perhaps due to a fierce fire early in development, killing all young understorey plants. It would be expected that, over time, a number of understorey species would find their way into such areas (through dispersal by insects, animals and wind). However, at GEMCO this seems to have been limited by the isolation of many rehabilitation sites from unmined forest areas. One opportunity for facilitation of this colonisation process would be the establishment of fresh topsoil islands underneath the existing canopy which would then act as a seed source for growth and further dispersal of a range of understorey species.

To test this idea, topsoil islands were established underneath an area of mature rehabilitation in the expectation that seeds in the spread topsoil would germinate in the following wet season, and develop into mature understorey species. These could then act as a source of future seed for further spread into the rehabilitation area.

5.4.3.2 Methodology

In early August 2001, around 40 m^3 of fresh topsoil from B-Quarry was dumped and thinly spread (<15 cm depth) over an area of 12-year-old rehabilitation in F4-Quarry, where a good *Eucalyptus miniata* overstorey had developed but was lacking in understorey. This was done using a small dozer and bobcat for spreading the material out as thinly as possible, while avoiding existing plants of any significance (e.g. young pandanus, cycads, *Clerodendrum* spp.). Once spreading was complete the area of topsoil covered around 25 x 25 m. Three 40-m transects were set up radiating out from within the island (Figure 5-11), using fence droppers at 10-m intervals, and the occurrence of any vegetation within an area 1 m either side of this transect was recorded. Also, canopy cover was measured at three places along each transect. This survey was repeated 6.5 months later (the final monitoring opportunity).

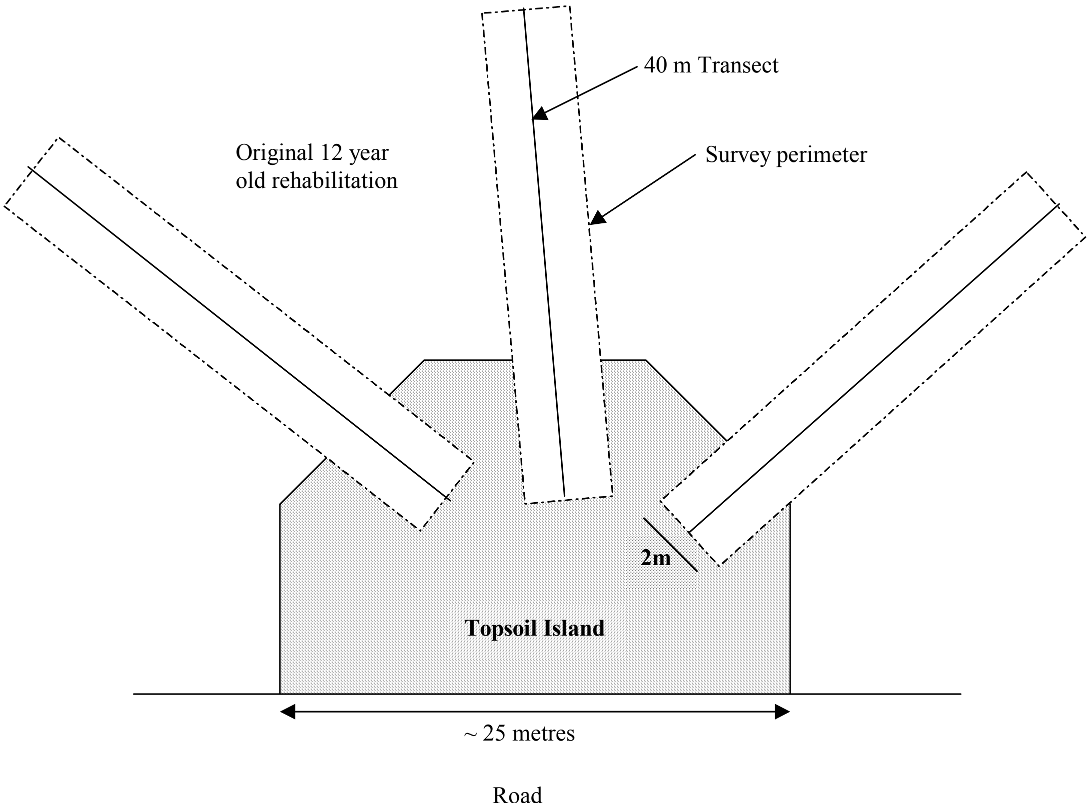


Figure 5-11 Layout of transects for monitoring of the Topsoil Island trial in F4 Quarry (not to scale)

5.4.3.3 Outcomes

This trial was intended to be established in two separate areas, to provide a replicate for assessment of the treatment. However, for a variety of reasons, this was not possible and only one area was established. Due to the delay in establishment of this trial (due to operational priorities other than rehabilitation trials), follow-up monitoring was undertaken only 6.5 months afterwards and no significant results were observed in any of the variables measured. This trial is more likely to produce results over a longer timeframe than was possible here and may need to be adopted in an on-going GEMCO monitoring program as conclusive results may take several years to emerge. Also, replicated treatments should be established for experimental rigour.

5.4.4 Topsoil Seed Bank Experiment

5.4.4.1 Background

The contribution of the topsoil seed bank to rehabilitation can be affected by soil handling practices, such as stockpiling and direct return. However, in the savanna woodland typical of northern Australia, where keystone overstorey species rely heavily on vegetative methods for reproduction, it may be the case that the seed store does not contain significant numbers of these species. Rather, the seed store is generally dominated by grasses and forbs (Williams *et al.* 2005). To determine the potential contribution to species richness in rehabilitation by the topsoil seed store, an experiment was undertaken. Samples were also taken of stockpiled and direct returned topsoil to quantify the effect on this seed store of soil handling techniques.

5.4.4.2 Methodology

Multiple, composite samples were collected of the top 10 cm of soil from undisturbed forest sites and freshly returned rehabilitation areas, as well as material from approximately 40 cm deep within a 2-year-old topsoil stockpile. These samples were sieved to remove large clumps of rock and gravel, and air-dried (in trays in a covered shed on site) before being packaged and freighted back to the University of New England for germination and monitoring in the Ecosystem Management glasshouse. Soil was placed at 5 cm depth in germination trays.

Germinants were counted as they emerged, and species were to be identified as they were able to be differentiated (or through specimens sent to the Herbarium once the planned 6 week conclusion of the experiment was reached).

5.4.4.3 Outcomes

The timing of this experiment was unfortunate. Mid-winter in Armidale was cold, the glasshouse was not temperature-controlled, and snow penetrated the glasshouse and settled on the treatment trays. Very little germination was observed over a period exceeding 6 weeks and the experiment failed. Seed of species adapted to the tropical environment of northern Australia could not be expected to germinate under such cold conditions. Future efforts at this valuable exercise should be established either on-site, at co-operative universities or research institutes in the tropics, or only in temperature-controlled facilities in southern states.

Chapter 6 The GEMCO Rehabilitation Succession Model

6.1 Introduction

Rehabilitated landscapes develop by passing through a series of states (or 'seres'), representing a successional trajectory (Westoby *et al*. 1989). One or more trajectories can result in a mature system with composition, structure and function similar to that of the natural woodland ecosystem. States along these trajectories are considered desirable (assuming that the natural woodland is the defined end point for the rehabilitation). Other trajectories exist that can result in vegetation types that do not meet the rehabilitation aims, and these trajectories, and the states that exist along them, are undesirable (Westoby *et al*. 1989).

A potentially complex set of transitions or drivers, relating to time, natural disturbances ('events' *sensu* Westoby *et al*. 1989) and management interventions ('actions' *sensu* Westoby *et al*. 1989), influences the direction of change in the developing rehabilitation, and therefore the desirability of the trajectory. Some states are ecologically stable in the sense that they are likely to persist indefinitely while others are intermediate or transient, en route to one or other stable states (Westoby *et al*. 1989). At Groote Eylandt, the natural woodland is ecologically stable. However in the rehabilitation, almost all states are transient, as there is continuous maturation of the vegetation community toward, hopefully, a state similar to the natural woodland. Some rehabilitation may have crossed a threshold and become stable in a deviant state, such as a grassland that is frequently burnt. Such a disturbance regime prevents further colonisation by other plant life forms. Once a threshold is crossed, management interventions are required to redirect the vegetation back toward the desired successional trajectory. Further disturbances (natural or unwitting), however, can drive the developing rehabilitation into new states, potentially crossing further thresholds.

Understanding the path that a rehabilitated site has taken to arrive at its current state is important in informing management about particular sets of disturbances or transitions to be facilitated or avoided, depending on whether the site is in a desirable or undesirable condition. Regardless of the path taken to reach a particular state, it is likely that similar rehabilitation sites (in terms of vegetation composition and structure) will have the same potential for management to influence their future development and ultimate success.

Knowledge of the nature of rehabilitation development over time, and the response of vegetation to different disturbances or drivers, enables the compilation of a successional state-and-transition model (Westoby *et al*. 1989). Such a model can be applied proactively to ensure management is focussed on priority issues that minimise management inputs and maximise rehabilitation success in the long term.

The passage of time is the most obvious causal factor, or 'driver', in succession. That is, in the absence of other influences (such as disturbance), rehabilitation will develop and mature, hopefully approaching the target ecosystem. Depending on the ecosystem in question, these passive transitions may involve a complex series of interspecific and intraspecific interactions, including seral replacement due to competition or senescence. For example, early dominance by aggressive acacias or grasses may prevent slower-growing eucalypts from establishing at the desired density (Reddell *et al*. 1992; Short 1994; Section 3.3.1.2) Another example early in succession is high grass cover that could carry a fire and destroy immature canopy species, which may not have had sufficient time to develop fire resistance, such as lignotubers or thick, fibrous bark (Williams *et al*. 1999; Section 3.3.1.2).

Disturbance is the most dramatic driver, causing vegetation to move from one state to another. In tropical savanna ecosystems, such as the eucalypt woodlands and forests of Groote Eylandt, fire is the most common disturbance (Williams & Lane 1999). Other disturbances include wet-season inundation and flooding, dry-season drought, high winds (including cyclones) and herbivory (Reddell & Meek 2004). These drivers vary in effect, frequency and intensity and, therefore, so does their influence on the development of rehabilitation. Vegetation in different states of development may also respond to drivers in different ways, for example resilience to fire. The characteristics of the dominant plants that shape the ecosystem response to disturbance are 'vital attributes' in the sense of Noble and Slatyer (1981) (see discussion in Section 1.2.3).

The vital attributes of the rehabilitation on Groote Eylandt that are responsible for determining vegetation transitions in response to disturbance are the methods of persistence through disturbance of the dominant plant species and life forms (Noble & Slatyer 1981). The prevailing environmental conditions at establishment also influence the outcome (Section 4.3). It is possible to classify each species or life form using vital attributes. With a knowledge of the age or duration of critical life stages of each species, successional 'replacement sequences' can be modelled for any combination of dominant species or life forms in response to particular disturbance regimes (Noble & Slatyer 1981). Replacement sequences can be reinterpreted as states and transitions, so that the range of potential trajectories, and the relationships between them, can be represented in simplified form, such as a state-and-transition model.

The data presented in previous chapters were used to construct a model of successional trajectories that identifies sites heading towards the desirable end-point ecosystem and others on deviant trajectories. Several ecosystem variables were used to identify such sites. A state-and-transition model was developed to show the various successional states that can be identified in rehabilitation and the factors precipitating transitions between states. Thresholds were also identified where management inputs are required to relocate an unacceptable vegetation state back on a desired trajectory. The characteristics of the desirable states were used to define technical assessment criteria for evaluating the success or otherwise of rehabilitation.

The resulting state-and-transition model of the rehabilitation at Groote Eylandt enables the early identification of vegetation states, prediction of desirable and undesirable transitions, and appropriate management interventions to redirect vegetation towards, or facilitate development along, desired successional trajectories.

6.1.1 Aims and Objectives of this Chapter

This chapter aimed to develop a practical succession model for rehabilitation at Groote Eylandt and identify a suitable set of values as interim and completion assessment criteria. The specific objectives of this chapter were to:

- classify recognised groups of rehabilitation at Groote Eylandt as desirable or undesirable states;
- examine the underlying properties of the rehabilitation states, including vital attributes of key species groups, to identify important transitions and management interventions that explain the likely successional pathways available to desirable and deviated states; and
- to develop a GEMCO state-and-transition succession model of vegetation rehabilitation at Groote Eylandt.

6.2 Methods

Based on the results of Chapters 3 and 4, which identified six groups, or states, of rehabilitation (B to G, plus woodlands), states were assigned to one of two main categories, ‘desirable’ or undesirable’, depending on their similarities to the target woodland ecosystem (Section 3.4.3).

The constrained ordination (CCA), as presented in Section 4.3.2, was repeated for rehabilitated sites only (i.e. no woodland sites). Bi-plots were used, with rehabilitation sites grouped by successional state (S1 to S7 and D1 to DXX) and plotted against environmental variables, to help explain the origins of particular rehabilitation groups and states.

The key plant genera and life forms influencing the succession of rehabilitation at Groote Eylandt include acacias, eucalypts and grasses. The vital attributes of these dominant plant groups were used to derive a successional ‘species type’ classification of each, in the manner of Noble and Slatyer (1981). These vital attribute (VA) classifications were used to create replacement sequences for three key rehabilitation scenarios, with fire and time as the key transitional drivers, the differences being the relative proportions of the key life forms of eucalypts, acacias and grasses. These scenarios were:

- ‘normal’ proportions of key life forms;
- dominance by grasses; and
- high densities of acacias.

These sequences formed a vital attributes model that provided additional information on the ecological processes underlying succession in the rehabilitated environment. They contributed to the understanding of observed states of rehabilitation and suggested additional states that had not been observed as part of this research.

Measurements and observations were combined to determine the catalogue of rehabilitation states, and vital attributes modelling, literature, observations and ecological intuition were combined to produce a catalogue of transitions between states in response to passage of time, natural drivers (e.g. fire) and management interventions. These individual transitions between particular states were compiled to form an overall state-and-transition model for the development of rehabilitation at Groote Eylandt.

6.3 Results

6.3.1 Vital Attributes Modelling

6.3.1.1 Vital Attributes of Main Life Forms

Eucalypts

The characteristics of eucalypt species used in rehabilitation on Groote Eylandt include:

- relatively long-lived and slow-growing species (Brooker & Kleinig 1994);
- although prolific seeders, they rely mostly on vegetative reproduction in the fire-adapted ecosystems of Groote Eylandt (Reddell & Zimmermann 2002);
- fire and competition results in a cohort of suppressed juveniles that persist in the understorey (Reddell *et al*. 1992);
- during the establishment phase, fire-sensitive juveniles (sj) develop their fire-resistance (rj) after 2─3 years, prior to maturation (Williams *et al*. 2003b);
- once established, they are resistant to fire and dominate the site and reduce the potential for aggressive, early colonising species to establish (Walker & del Moral 2003); and
- a vital attribute classification as species type 'UI' (after Noble & Slatyer 1981; Whelan 2002; Table 6-1).

Table 6-1 Derivation of the eucalypt 'species type' (after Noble & Slatyer 1981; Whelan 2002)

Vital Attribute Group	Biological Mechanism	Vital Attribute	Species Type
Method of Persistence	Able to survive fire both as suppressed juveniles and mature trees by resprouting from lignotuber (juveniles) or epicormic buds beneath the bark of trunks and limbs (mature trees); seedlings establish from seed held in tree canopy whenever there is a gap in understorey, but particularly after fire	U	UI
Conditions for establishment	Intolerant of competition from adults	I	

Acacias

The acacias of Groote Eylandt rehabilitation have the following characteristics. They:

- are often relatively short-lived (< 20 years) (Doran & Turnbull 1997);
- are often susceptible to fire as adults (Cowie & Finlayson 1986);
- have a large seed bank in the soil, which germinates in response to fire (Cavanagh 1980);
- are aggressive, early colonisers that can rapidly capture a site and exclude other, slower-growing species (Setterfield *et al*. 1993); and
- have a vital attribute classification as species type 'SI' (after Noble & Slatyer 1981; Whelan 2002; Table 6-2).

Table 6-2 Derivation of the acacia 'species type' (after Noble & Slatyer 1981; Whelan 2002)

Vital Attribute Group	Biological Mechanism	Vital Attribute	Species Type
Method of persistence	Long-lived seed store which is not destroyed by fire	S	SI
Conditions for establishment	Aggressive early colonisers, intolerant of competition from adults	I	

Native Grasses

Native grasses in rehabilitation have the following characteristics:

- highly dispersive seeds, carried by wind, water and animal vectors (Ashwath *et al*. 1994);
- many perennials are able to resprout after fire from underground rhizomes (Tothill 1969); and
- a vital attribute classification of species type 'DT' (after Noble & Slatyer 1981; Whelan 2002; Table 6-3).

Table 6-3 Derivation of the perennial grass 'species type' (after Noble & Slatyer 1981; Whelan 2002)

Vital Attribute Group	Biological Mechanism	Vital Attribute	Species Type
Method of persistence	Dispersal mechanism can bring propagules to site at any time	D	DT
Conditions for establishment	Able to establish at any time	T	

6.3.1.2 Hypothetical Replacement Sequences

Vital attribute data for these life forms are summarised in terms of species type and life stages in Table 6-4. From these key pieces of information, a hypothetical replacement series was developed for fire as the key disturbance to a range of scenarios with different proportions of the key life forms of eucalypts, acacias and grasses. For each scenario, and later in this chapter, the dominant life form in any sere or state is highlighted in bold font.

Table 6-4 Vital attribute data for main life forms (after Noble & Slatyer 1981)

	Species	Life stage (years)
	type	0 10 30 70 200 ∞
Acacia	SI	----m--------l--------e
Eucalypt	UI	---------m----------------------le
Grass	DT	--m-----------------------------------le

m = time taken to reach reproductive maturity; l = longevity of the species population in the community; e = time taken to reach local extinction

Replacement Sequence in Response to Recurring Fire

Early in rehabilitation development, all three life forms are present only in their juvenile forms (Figure 6─1a). A fire at this stage would remove the non-fire-resistant woody juveniles (SI_j and UI_{sj}) and leave only juvenile grasses (DT_j). If 1 year passes without fire, the grasses will have reach maturity (DT), although the woody species remain as juveniles. Fire at this stage would also result in only juvenile grasses. After 5 years without fire, the acacias reach maturity (SI) and the eucalypt juveniles have developed fire-resistance (UI_{rj}). Fire at this stage would kill the fire-susceptible, mature acacias, but would promote germination of the soil seed-store of acacia, creating a stand of juvenile grasses, juvenile acacias and fire-resistant juvenile eucalypts. Depending on the frequency or severity of the fire, this system would either continue developing towards the mature eucalypt-dominated woodland, become an acacia-dominated grassland (if fires recur within 10–20 years, which is very likely on Groote Eylandt) or would develop into a grassland if the mature acacias eventually died out in the absence of fire. With regard to the original unburnt rehabilitation, which still contains eucalypts, only after approximately 5–10 years of fire exclusion are mature plants of all three life forms present, as well as a suppressed, juvenile cohort of eucalypts (UI_{rj}). Now that mature, fire-resistant eucalypts are present, a fire would only reduce acacias and grasses to new cohorts of juvenile recruits, but would otherwise leave the system intact (i.e. the system is relatively resilient to fire once the eucalypts are mature). As the juvenile acacias and grasses mature, the system returns to its prior status. If, however, the vegetation is burned again before the acacias have matured, it may shift to a system without acacias, but retaining juvenile grasses and juvenile and mature eucalypts. If the original system is protected from fire for over 20 years, a system of mature grasses and eucalypts with a suppressed juvenile eucalypt cohort could be expected, as the acacias will have senesced with no fires to promote new recruitment from the soil seed store. Should fire protection continue for 50 years after the senescence of the acacias, the wattles would be lost from the site as their seed would have expired in the soil seed bank. If fire exclusion continued for hundreds of years, there is a chance that the mature and juvenile eucalypts would die out and a grassland would remain.

In reality, eucalypt savanna systems are highly unlikely to evade burning for such long periods of time, remaining in a fire-resilient cycle in response to recurrent fire with grasses reduced to juveniles following fire, but quickly maturing, and suppressed juvenile eucalypts ever-present (Figure 6─1a). The understorey eucalypts may progress into the subcanopy if fire is absent for long enough that they can grow beyond the reach of flames and scorching heat, but only if competition from mature trees is relieved through gap formation (e.g. trees uprooted in a cyclone).

The replacement sequence shows how fire too early in the development of rehabilitation can result in the removal of the keystone woody life forms (eucalypts), and leave a system with little or no likelihood of developing toward the final target of eucalypt-dominated savanna woodland (Figure 6─1a). What is particularly interesting in this replacement sequence is the presence of multiple pathways that end in the same, mature, fire-resilient, eucalypt-dominated savanna ecosystem. While one pathway results from the passing of time, another involves repeated fire, indicating the potential for fire to be used pro-actively in rehabilitation to facilitate development towards the mature ecosystem. Figure 6-2 shows a 4-year-old site, developing over 18 months, losing a number of early shrubs to fire, but a couple of eucalypts persisting through this event and continuing the develop. It is worth noting the major loss of understorey biomass caused by the fire followed by the rapid return of grasses and other species in just over 6 months.

The above replacement sequence assumes that natural proportions of the key life forms are present. Several serious deviations from these sequences could occur should the proportions or characteristics of the key life forms be changed. For example, should the native grasses be present at very high densities, they may outcompete the eucalypts early on, and may support a fire earlier and of higher intensity than would normally be the case. If the native grasses are replaced by aggressive, fire-promoting grasses such as *Andropogon gayanus* (gamba grass), the canopy of the mature eucalypts in vegetation protected from fire for over 10 years would not necessarily be resilient to the higher intensity fire that would result. In this case, the vegetation may regress to a grassland (Figure 6─1b). In these scenarios, even the usual fire-resistant strategies of the eucalypts may be compromised by higher intensity fires.

Another example would be the case of high densities of juvenile acacias early in site development out-competing eucalypts, which remain suppressed until the acacias have senesced. This may result in a prolonged juvenile stage in the eucalypts, during which they may have reduced fire resilience. In these fire-prone ecosystems, this may cause increased early mortality of eucalypts (Figure 6─1c), leading to a long-term reduction in the density of eucalypts.

In reality, it is unlikely that fire could ever be excluded practically on a large scale from rehabilitation for over 20 years. Thus, further consideration of the vegetation sequences or stages elucidated here will only include those where fire is excluded for less than 20 years.

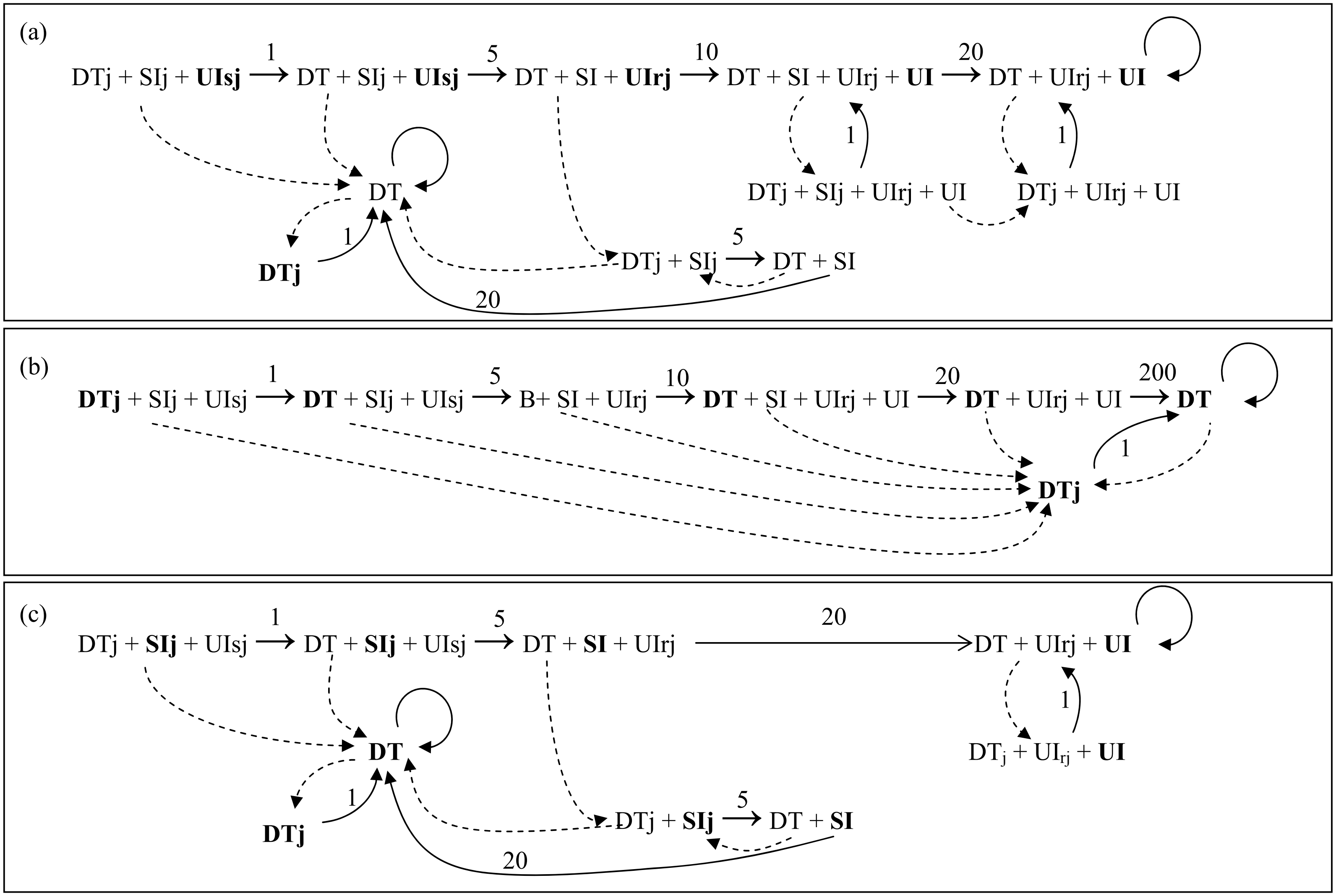


Figure 6-1 Replacement sequence of the key life forms of grass (DT), acacias (SI) and eucalypts (UI) for (a) natural proportions of key life forms; (b) grass dominance; and (c) acacia dominance. Bold indicates dominance, dashed and solid lines represent transitions with and without fire respectively, numbers represent years with no fire, and lowercase ‘sj’ indicates a fire-sensitive juvenile form and ‘rj’ a fire-resistant juvenile form

Figure 6-2 Development over 18 months with fire (1996—97 rehabilitation in D-quarry)

6.3.2 Catalogue of States

Analysis of hypothetical replacement sequences based on vital attributes of key life forms in the previous section suggested several different stages or developmental states that could be expected in rehabilitation on Groote Eylandt (Section 6.3.1.2). In rehabilitation with an appropriate composition of the key life forms at establishment, four distinct states exist along the successional trajectory toward mature eucalypt woodland. However, fire in any of the first three of these states has the potential to divert the rehabilitation in an unfavourable direction, resulting in undesirable outcomes. Protection of these states from fire for 3–5 years (Williams *et al.* 2003b) should see development of a fire-resilient, eucalypt woodland, which is able to withstand recurrent fires (i.e. the target rehabilitation state). At least two undesirable outcomes are possible if fire occurs too soon (within 3–5 years). If the composition at the outset of rehabilitation is incorrect, or differential establishment success results in dominance by non-eucalypt species such as fire-promoting grasses or acacias, undesirable states can be expected. From the sequences presented in Section 6.3.1.2, a further eight undesirable states have been identified.

Sites analysed in this study were found to form seven distinct groups, based on ordination and classification of floristic and structural data, including woodlands. Four of these groups correspond to hypothetical states identified from first principles using the vital-attributes approach. The woodland sites formed one distinct group and, as the target vegetation type, can be considered the endpoint of the developmental trajectory. Three groups are similar to the target ecosystem and are therefore collectively termed ‘desired states’ (Groups B, C and D). The other three rehabilitation groups are sufficiently different to the target vegetation type to be termed ‘undesirable states’ (Groups E, F and G). Four sites did not fit any of these groups, and thus represent other rehabilitation states at Groote Eylandt (groups A, H, I and J, albeit represented by single sites only).

In addition to these quantitatively sampled and derived groups, observations of the rehabilitation at Groote Eylandt by Grant and Duggin (2000) and personal observations generated several other potential states that could be quantitatively defined with further field measurements and continuing refinement of the data set, including increasing the number of field sample sites. Three of these proposed states were added to complete the successional trajectories, as well as highlight the need to continue monitoring and improving the succession model of rehabilitation at Groote Eylandt. Altogether, and in addition to natural woodland, 24 vegetation states are known to exist in the rehabilitation on Groote Eylandt, including 8 desirable states and 16 undesirable states (Table 6-5).

Through development of the catalogue of states (Section 6.3.2), potential drivers that could influence development of each state and facilitate transitions among states were identified, including ten passive transitions and 20 management interventions (Table 6-6).

The identified states, transitions and management interventions are presented in a set of schematic diagrams (Figure 6-3 to Figure 6-5). In these diagrams, all of the states identified as existing, or potentially existing, in the Groote Eylandt rehabilitation are oriented along an x-axis, which represents development, and a y-axis which represents any one or a combination of ecosystem attributes. A shaded section of the graph represents the desired trajectory, and the acceptable states are shown as a sequence of states progressing from the origin (0, 0) toward the target Sx community. The trajectory is shown as a wide band to indicate the potential for a range of attribute values within states. Deviated states are arbitrarily located in the space around this trajectory, with grass-dominated communities being shown below the desired trajectory and acacia-dominated communities above it. Other deviated states are positioned more for clarity than certainty about their relative location with respect to other states and trajectories.

Figure 6-3 shows the likely transitions for the states resulting from the passage of time without disturbance (T7) or a sequence of natural fire events (T7; typically regular, low-intensity burns). Circular arrows indicate a stable state in the absence of any other disturbances. Transitions due to the passage of time suggest that a number of multiple trajectories exist, including for deviated states. Some deviated states are shown as possibly returning to the desired trajectory without any management intervention or other disturbances, but this is generally reliant on prolonged periods without fire which is highly unlikely. In this environment, fire is likely to be a regular event in all states except those at very early stages of development, which likely have very little vegetative cover to carry a fire. Without active control of fire in rehabilitated areas on Groote Eylandt, the most likely transitions to occur in the absence of other management interventions are those shown as resulting from the natural fire events (dashed arrows in Figure 6-3).

Table 6-5 Summary list of measured, observed and hypothetical rehabilitation states on Groote Eylandt. VA codes are explained in Figure 6-1

	Description	Measured (No. of sites; Group)	Observed (not measured)	Hypothetical (VA code)
Desirable				
S0	Bare ground, prior to revegetation	–	✓	–
S1	Very early-stage development eucalypt woodland (all seeded—keystone species present)	1; Group J	–	$\mathrm{DT}_j+\mathrm{SI}_j+\mathbf{UI}_{\mathbf{sj}}$
S2	High-diversity, very early-stage rehab. (volunteer species in addition to seeded species)	–	–	–
S3	Early-stage development eucalypt woodland	–	–	$\mathrm{DT} + \mathrm{SI}_j + \mathbf{UI}_{\mathbf{sj}}$
S4	Early–middle-stage development eucalypt woodland	6; Group B	–	$\mathrm{DT} + \mathrm{SI} + \mathbf{UI}_{\mathbf{sj}}$
S5	Middle-stage development eucalypt woodland	5; Group C	–	–
S6	Middle–late-stage development eucalypt woodland	4; Group D	–	–
S7	Late-stage development eucalypt woodland	1; Group A	–	$\mathrm{DT} + \mathrm{SI} + \mathrm{UI}_{rj} + \mathbf{UI}$
Sx	Mature eucalypt woodland	9; Group A	–	$\mathrm{DT} + \mathrm{UI}_{rj} + \mathbf{UI}$
Undesirable				
D1	Very early-stage rehabilitation; understorey only, eucalypts absent	–	✓	–
D2	Very early-stage rehabilitation with high proportion of grasses	–	✓	–
D3	Very early-stage rehabilitation dominated by acacias	–	–	$\mathrm{DT}_j + \mathbf{SI}_{\mathbf{j}} + \mathrm{UI}_{sj}$
D4	Grassland (juvenile grasses present after fire)	–	✓	DT_j
D5	Weed-dominated community, minor presence of other life forms only	–	✓	–
D6	Early-stage development of eucalypt woodland with high proportion of grasses	–	–	$\mathbf{DT} + \mathrm{SI}_j + \mathrm{UI}_{sj}$
D7	Early-stage development of eucalypt woodland dominated by acacias	3; Group G	–	$\mathrm{DT} + \mathbf{SI}_j + \mathrm{UI}_{sj}$
D8	Middle-stage development of eucalypt woodland with high proportion of grasses	1; Group I	✓	$\mathbf{DT} + \mathrm{SI} + \mathrm{UI}_{sj}$
D9	Middle-stage development of eucalypt woodland dominated by acacias	8; Group E	–	$\mathrm{DT} + \mathbf{SI} + \mathrm{UI}_{rj}$
D10	Middle-stage rehabilitation, dominated by non-eucalypt woody species and weeds	3; Group F	–	–
D11	Eucalypt-acacia woodlands with high stand density	1; Group H	–	–
D12	Juvenile grass and acacia community present immediately after fire	–	–	$\mathrm{DT}_j + \mathbf{SI}_j$
D13	Mature grass and acacia community	–	–	$\mathrm{DT} + \mathbf{SI}$
D14	Mature eucalypt woodland with high proportion of grasses	–	–	$\mathbf{DT} + \mathrm{SI}+ \mathrm{UI}_{rj} + \mathrm{UI}$
D15	Stunted eucalypt woodland or swamp species dominant	–	✓	–
D16	Mature eucalypt woodland with sparse understorey	–	✓	–

Stages: very early, 0–1 years; early, 1–3 years; early–middle, 3–5 years; middle, 5–10 years; middle–late, 10–20 years; late, > 20 years

Table 6-6 Summary list of passive transitions and management interventions

	Description
Passive Transitions	
T1	Area unprepared, grass seeds reach site and colonise
T2	Area unprepared, weeds reach sites and colonise
T3	Roots fail to penetrate or substrate saturated
T4	Time, natural recruitment
T5	Time, no natural recruitment
T6	Fire (natural regime, i.e. once every 2─3 years)
T7	Time (with no fire)
T8	Invasion by weeds
T9	Invasion by grass
T10	Unnaturally intense fire (e.g. extra high fuel load)
Management Interventions	
M1	Fresh topsoil, good cultivation, native seed applied, weeds and grasses controlled
M2	Fresh topsoil, good cultivation, no seed applied, weeds and grasses controlled
M3	Stockpiled topsoil or subsoil, no seed applied, close to woodland
M4	Stockpiled topsoil or subsoil, no seed applied, far from other vegetation
M5	Use of stockpiled topsoil or subsoil, otherwise good rehab. practice
M6	Insufficient ripping or backfilling, otherwise good rehab. practice
M7	Any substrate, native seed applied, nearby weeds and grasses not controlled
M8	Fresh topsoil, native seed applied, bad germination, weeds and grasses not controlled
M9	Extra seed supplied
M10	Protect from grass and weeds
M11	Protection from fire
M12	Prescribed (controlled) burn
M13	Cultivation/herbicide to remove grasses; extra seed/plants supplied
M14	Cultivation to remove acacias; extra seed/plants supplied
M15	Plant seedlings; protect from weeds and fire until mature
M16	Herbicide/cultivate to remove weeds; extra seed/plants supplied
M17	Clear/thin dominant woody shrubs or trees
M18	Topsoil (sieved soil) seed store, and/or seed mix, as islands or strips
M19	Clear vegetation and re-rip ground; extra seed/plants supplied
M20	Planting of recalcitrant species

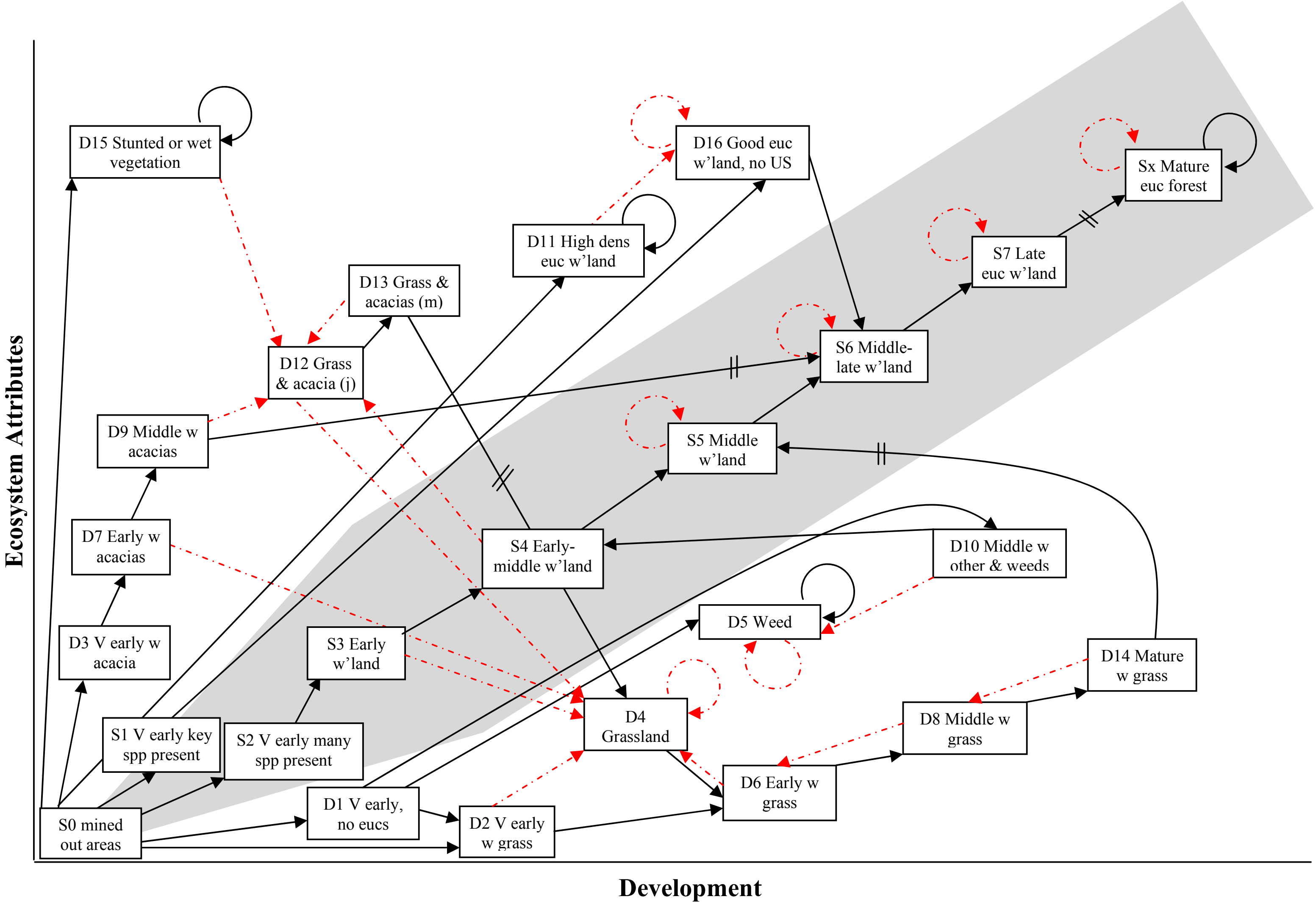


Figure 6-3 Groote Eylandt rehabilitation states and transitions for time without disturbance (black solid arrows) and natural fire events (red dashed arrows). The shaded area represents the desired successional trajectory. Double line separators represent extended periods of time. Abbreviations: v = very, w = with; US = understorey. Descriptions of states and transitions are in Table 6-5 and Table 6-6

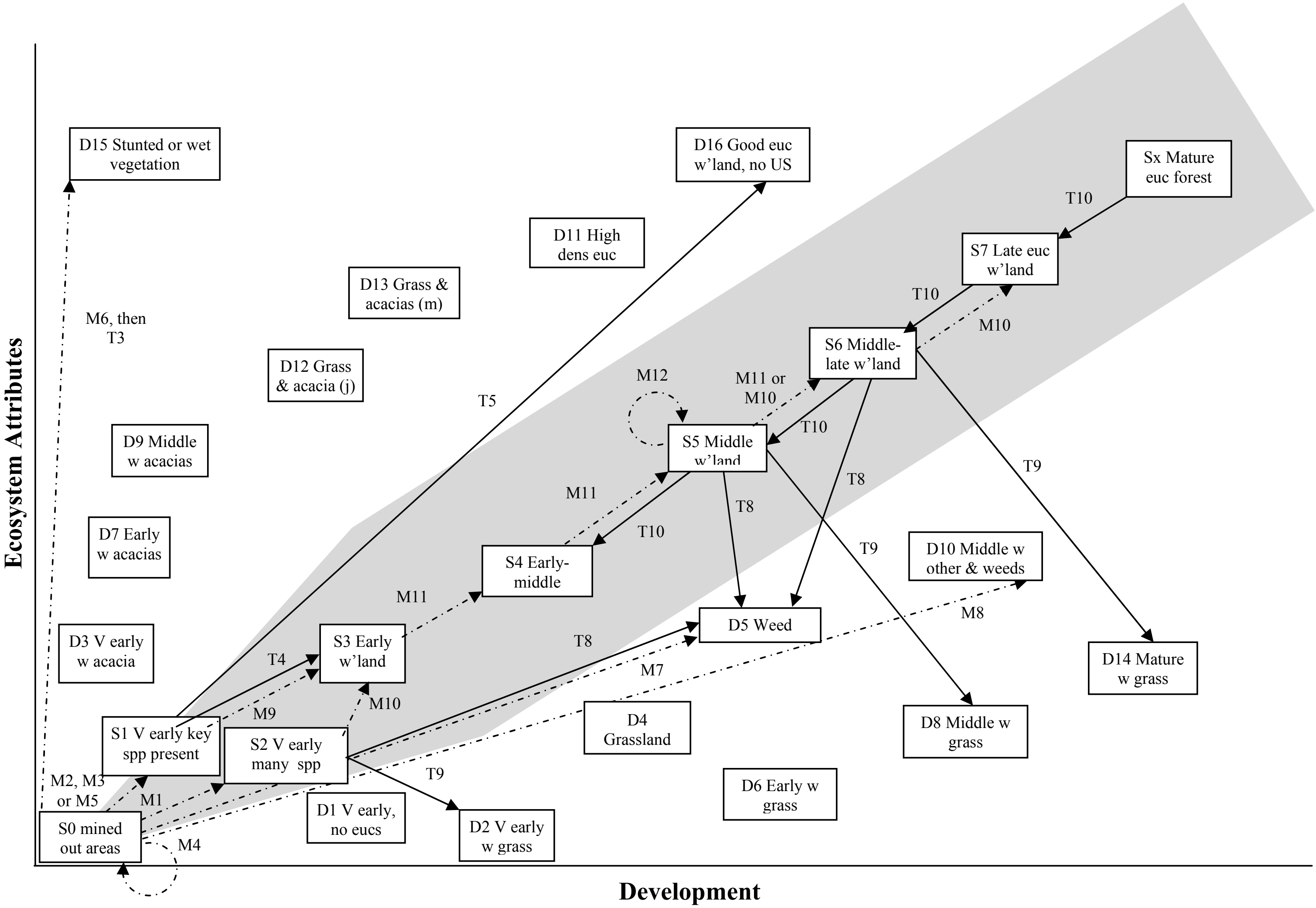


Figure 6-4 Passive transitions (solid arrows; excluding time and fire) and management interventions (dashed arrows) with the potential to affect desirable states. The shaded area represents the desired successional trajectory. Descriptions of states and transitions are in Table 6-5 and Table 6-6

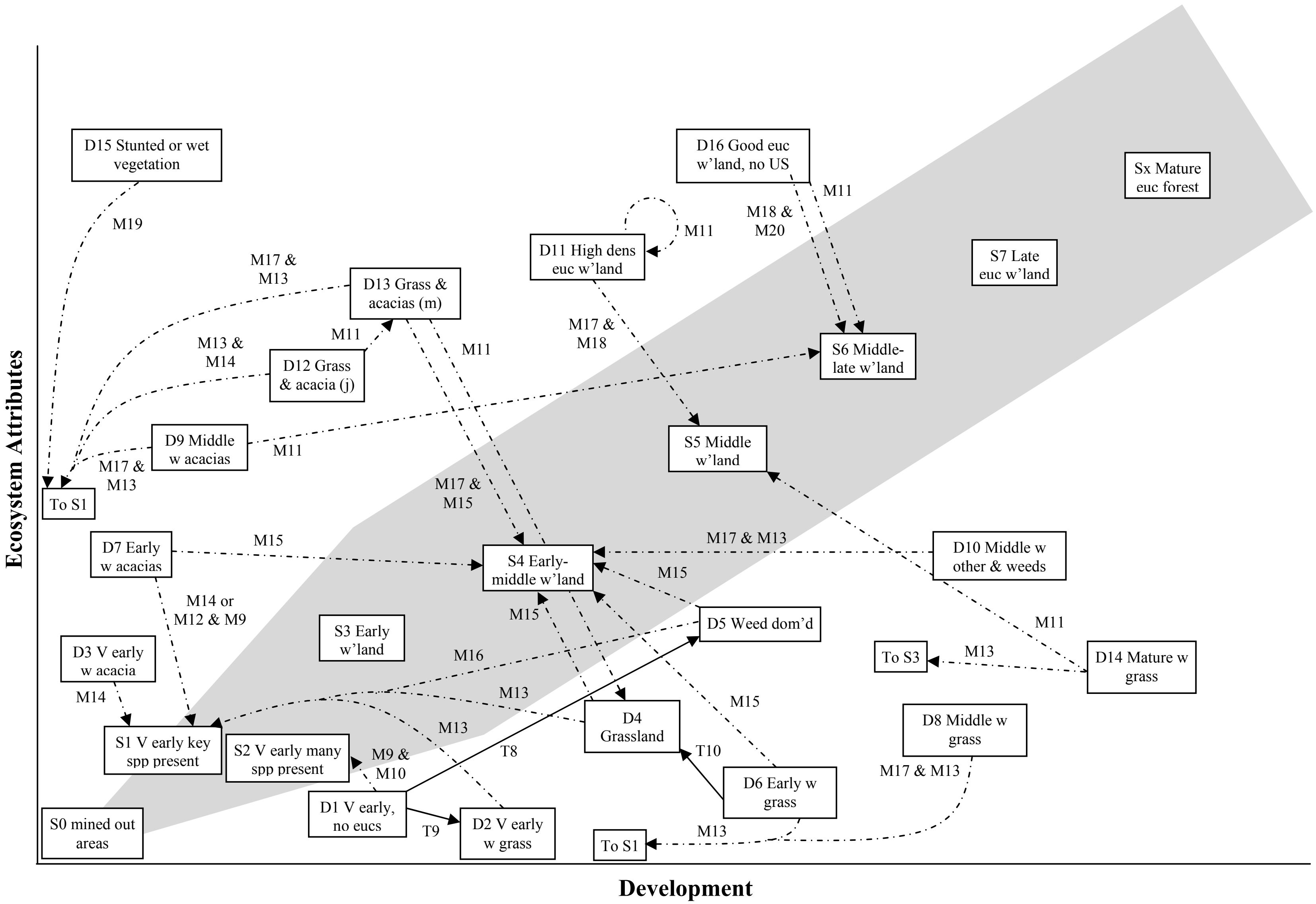


Figure 6-5 Passive transitions (solid arrows, excluding time and fire) and management interventions (dashed arrows) with the potential to affect undesirable states. The shaded area represents the desired trajectory. Description of states and transitions are in Table 6-5 and Table 6-6

A number of other transitions and management interventions have been suggested (Table 6-6) and these are shown in Figure 6-4 and Figure 6-5 for desirable and deviated states, respectively. The suggested management interventions redirect the deviated sites back toward the desired trajectory.

The following sections present each observed or proposed state in terms of the following:

1. Description: general floristics, structural and other developmental attributes;
2. Method of identification: vital attributes model, study data or observation;
3. Quantifiable indicators (if derived from study data);
4. Photographic image (if available); and
5. Discussion of potential transitions and subsequent development.

6.3.2.1 Desirable States

The plant succession linking the 'desirable' states (S0–Sx) in Table 6-5 is the standard developmental rehabilitation trajectory, where development correlates with time. Forgoing undesirable disturbance, sites in these states are expected to continue along this trajectory towards the target native woodland ecosystem (Sx). That is, these states are transient in that they should undergo passive transitions through time from one to the next, in the direction of the target ecosystem which is a stable state.

State S0—Mined-out areas, prior to revegetation activities

This state represents the 'origin' of rehabilitation succession at Groote Eylandt and is essentially a blank canvas, with each rehabilitation activity, including earthworks and seeding, having a critical bearing on the success of the rehabilitation outcome. This state could undergo many potential transitions that could result in desirable or undesirable states (Figure 6-6).

Time, in the absence of other drivers (including active rehabilitation interventions), would see colonisation of the area by plants introduced by wind, water and animal-borne seed. Depending on the distance of the site from mature eucalypts, this could see the site progress towards S1, but over a longer period than with active rehabilitation. The transition from S0 to one of several desirable trajectories is mostly dependent on two sets of management activities. These relate to disturbance and substrate handling (Table 5-1) and vegetation establishment (Table 5-2). Appropriate substrate selection, preparation and seed mix application should see a site progress through the early stages of the desired trajectory (e.g. to S1). There are, however, several opportunities for the trajectory to deviate from the outset. With no active rehabilitation, sites are liable to move to undesirable states, such as D4 if grasses colonise (T1; Figure 6-6) and dominate, or D5 if weeds dominate the site (T2). Active rehabilitation (very early management intervention) has the potential to initiate development of the vegetation toward the desirable state, S2 (M1; Figure 6-6), through the use of fresh topsoil, appropriate site preparation, use of a native seed mix (e.g. Table 2-1) and control of grass or weed threats (Section 5.1.1; Table 5-3). Rehabilitation activities lacking any of these components (e.g. failure to use an appropriate native seed mix, M2), or the use of stockpiled (as opposed to fresh) topsoil or subsoil lacking a seed store (M3 or M5), could see the sites move to S1, which is of lesser quality than S2, but nevertheless likely to develop along the desired trajectory given time and access to supplied seed or natural recruitment (e.g. from undisturbed woodland nearby). Suboptimal site preparation, coupled with no seed mix and little likelihood of natural recruitment (M4) could see the site remain relatively barren at S0.

Insufficient ripping of the soil profile to relieve compaction and improve drainage and root penetration (M6), followed by standard rehabilitation practices, may see desirable early vegetation (S1) develop, but as trees and shrubs mature, they may be subject to waterlogging or their roots may fail to penetrate to sufficient depth for anchorage or to access soil moisture in the late dry season (T3). This could result in D15, with stunted vegetation or a community more suited to wet conditions (e.g. a *Melaleuca*-dominated teatree swamp) than the target well-drained woodland ecosystem.

Failure to control grasses and weeds in the early stages of rehabilitation (M7), when they threaten slower growing keystone species (i.e. eucalypts), can result in undesirable states. In particular, a weed (D5, D10) or grass (D14, D8) dominated system could result, with few or any of the desired woody species, depending on the availability of a natural seed store (M8).

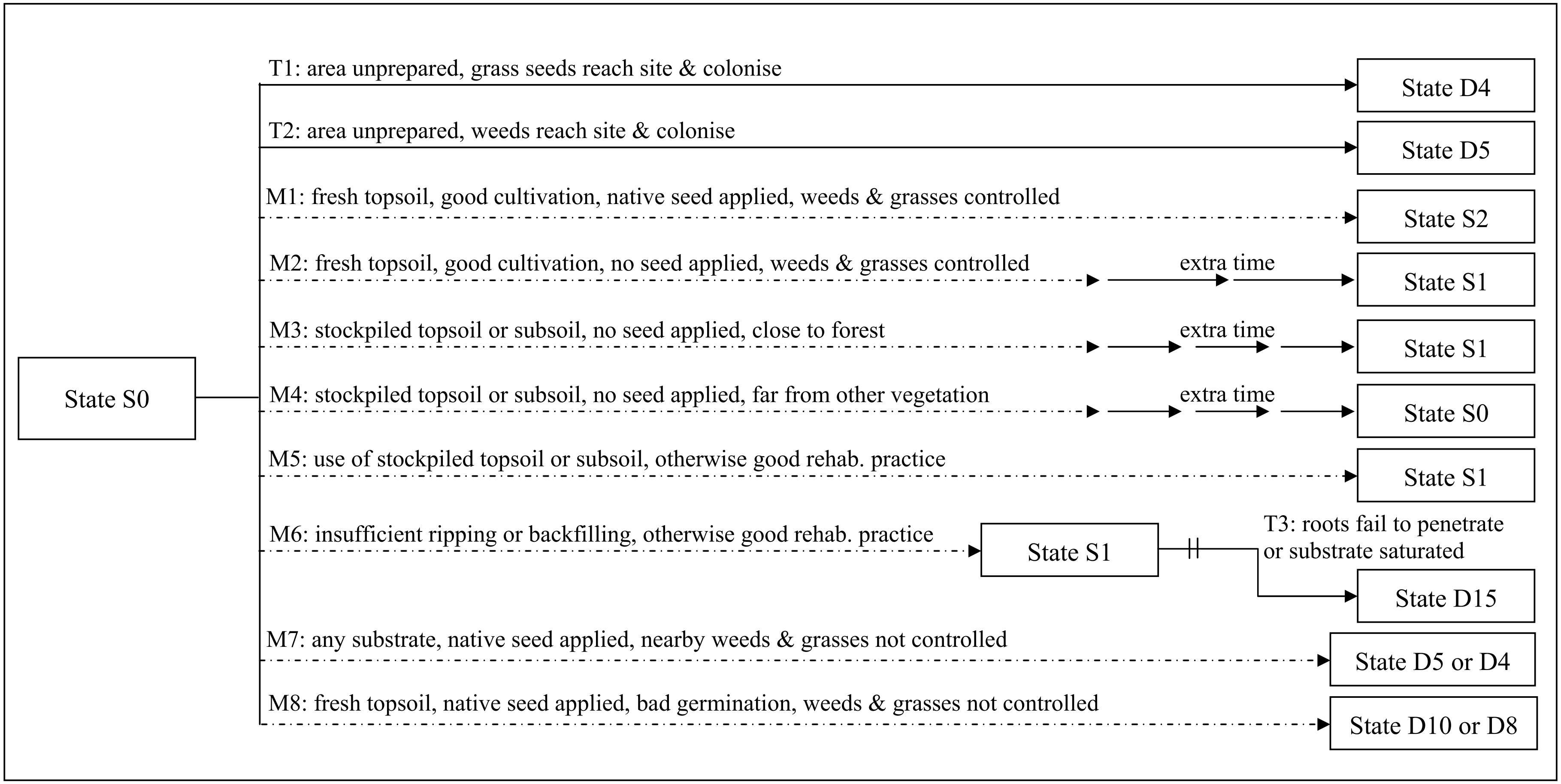


Figure 6-6 Potential transitions (T; solid arrows) and management interventions (M; dashed arrows) at rehabilitation establishment (state S0). Multiple arrows represent extended period of time

State S1—Very early-stage development of eucalypt woodland

This state can be described as juvenile rehabilitation, showing good early establishment of woody species, particularly eucalypts, good diversity in general, reasonable grass cover and an absence of weeds (Figure 6-7). This state was identified in the VA model ($DT_j+SI_j+\mathbf{UI_{sj}}$; Figure 6-1) as well as in the field where it was represented by the single site constituting Group J (site F4-2000; Figure 6-21a).

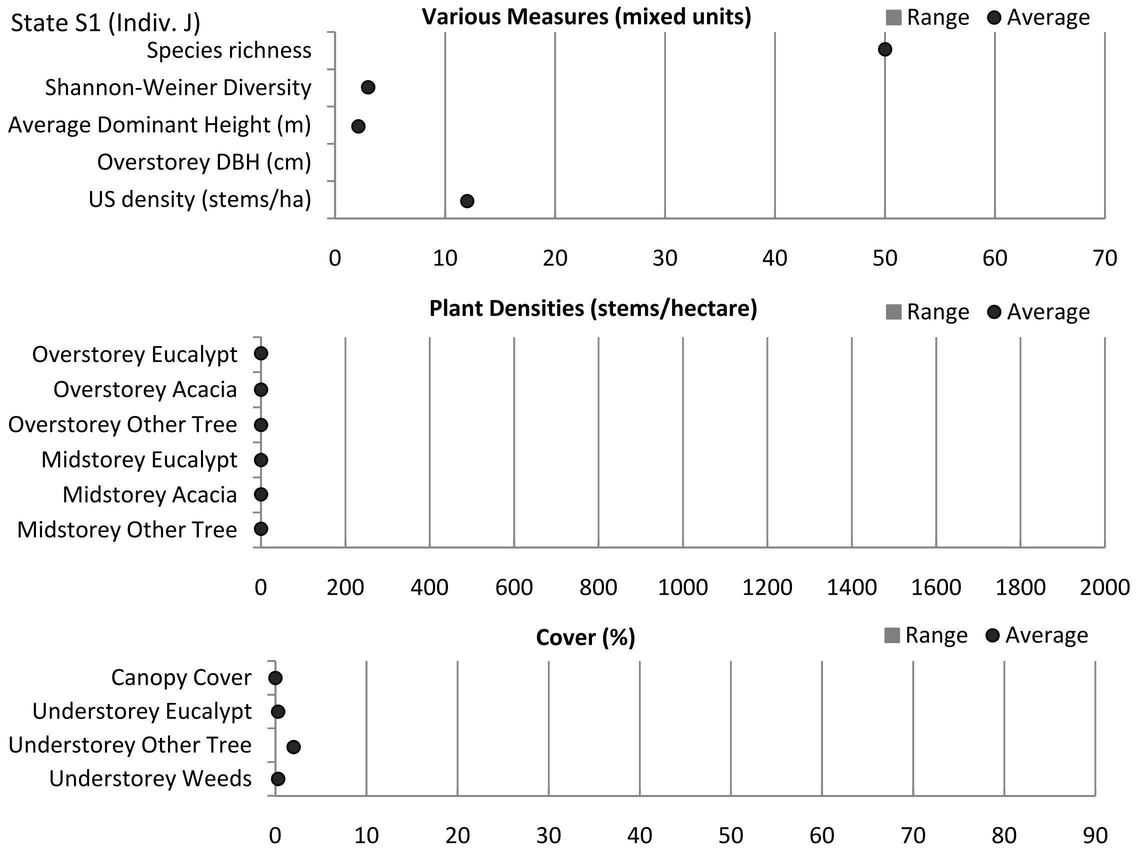


Figure 6-7 State S1: vegetation characteristics (2000 dry season and 2001 wet season data)

Sites in this state are unlikely to be subjected to wildfire as there is relatively little vegetative cover and therefore little fuel present. Fire (T6; Figure 6-8) would, however, likely cause this site to regress to something similar to the pre-existing unrehabilitated state (S0) as eucalypts and acacias, and perhaps even grasses, would be eliminated. Sites with the potential for natural recruitment of keystone and other target woodland species (e.g. sites adjacent to undisturbed woodland) are likely to improve with time (T4) to resemble the more mature, desirable rehabilitation state S3. If, however, the sites are isolated with little potential for significant recruitment over time, the site may develop a good eucalypt overstorey but relatively little diversity, especially in terms of understorey (T5), typical of state D16. Management intervention in the form of additional supplied seed (e.g. as broadcast seed or strategically applied fresh, sieved topsoil: M9), should see understorey diversity increase and a more diverse, desirable ecosystem (S3).

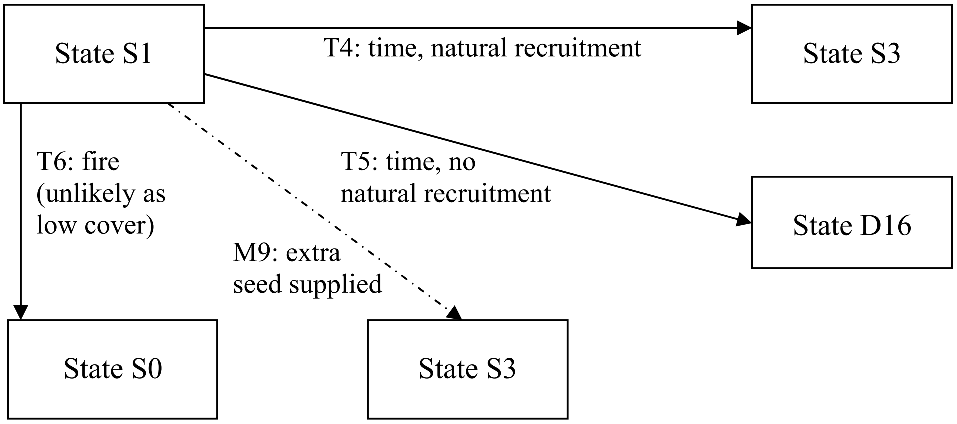


Figure 6-8 State S1: potential transitions, management interventions and alternate states

State S2—Very early-stage development of high-diversity eucalypt woodland

This is juvenile rehabilitation that shows good early establishment of woody species, particularly eucalypts, high diversity including many volunteer species typical of the target woodland and originating from the topsoil seed store, reasonable grass cover and an absence of weeds. This state is anticipated to occur after optimal topsoil handling, providing fresh soil with a good seed store of non-seeded species. No sites sampled in this study were this state, but it has been observed at other mines in north-eastern Australia and is anticipated to be achievable at Groote Eylandt with improved soil handling practices.

S2 sites are unlikely to burn as they would have relatively low cover and litter levels. As for state S1, however, fire (T6; Figure 6-9) would return sites in this state to something resembling the pre-rehabilitation state, S0. In the absence of weed or grass dominance, this state should develop (T7) along the desired trajectory to S3. Invasion by weeds (T8) or grass (T9), however, would divert it to the deviant states, D5 or D2, respectively. Active protection from weeds and grasses (M10), such as control of weeds in adjacent open or rehabilitated areas, would provide increased assurance that S2 sites would move to S3 in a reasonable time.

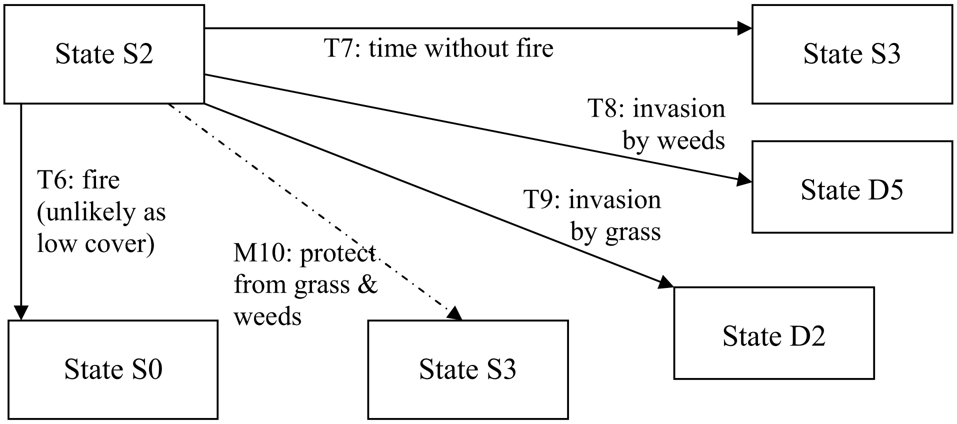


Figure 6-9 State S2: potential transitions, management interventions and alternate states

State S3—Early-stage development of eucalypt woodland

This state is characterised by relatively little overstorey (> 4 m) and a complex midstorey, consisting mainly of eucalypts (*Eucalyptus tetrodonta* and *E. miniata*). The understorey is variable in cover with low leaf litter, moderate grass cover and few, if any, weeds. This state was identified in the vital attributes model as DT + SI_j + $\mathbf{UI_{sj}}$, meaning that only the grasses have matured and have a seed store or developed the ability to resprout after fire. Acacias and the dominant eucalypts are present only as fire-sensitive juveniles (sj). This state has good proportions of the main life forms and should be relatively resistant to increased dominance of grasses or weeds in the absence of disturbance. It was not sampled and was not observed in the Groote Eylandt rehabilitation.

Time without fire (T7; Figure 6-10), which may require active protection (M11) should see sites in this state develop along the desired trajectory to S4. Uncontrolled fire (T6) would kill the juvenile acacias and eucalypts and result in the deviant grassland state, D4.

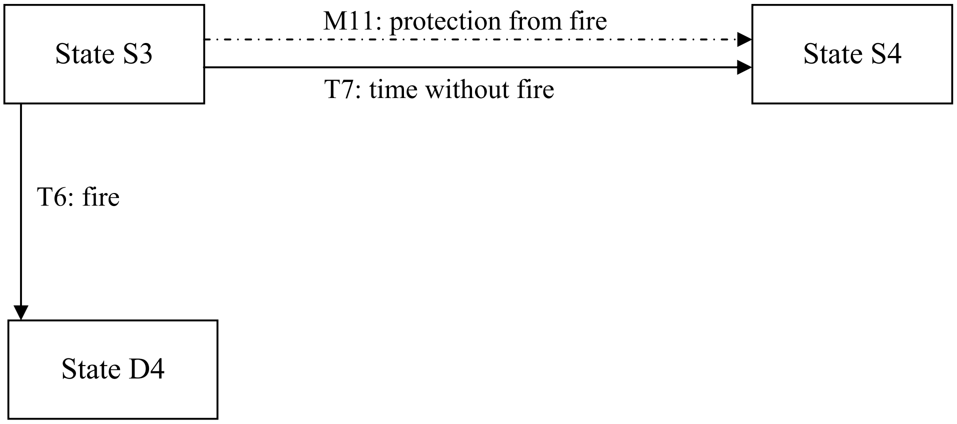


Figure 6-10 State S3: potential transitions, management interventions and alternate states

State S4 — Early–middle-stage development of eucalypt woodland

Over time, tree heights and plant cover increases and competition leads to changes in understorey composition (Figure 6-11). The woodland overstorey becomes dominated by eucalypts while the understorey increases in richness with age and decreases in grass and weeds with increasing canopy cover. Sites in this state have a well-developed canopy and high densities of eucalypts, acacias and other trees in the overstorey and midstorey. Overstorey trees are generally over 6 m in height but only approach half the height (12 m) of mature woodland trees.

This state equates to the VA-based community, DT + SI + $\mathbf{UI_{sj}}$, which contains reproductively mature grasses and acacias, but only juvenile, potentially fire-sensitive eucalypts, although the latter are the dominant life form. Group B matches this state (Figure 6-21b), which is dominated by appropriate proportions of the main life forms, and is thus relatively resistant to increases in grasses or weeds (in the absence of fire and other disturbances).

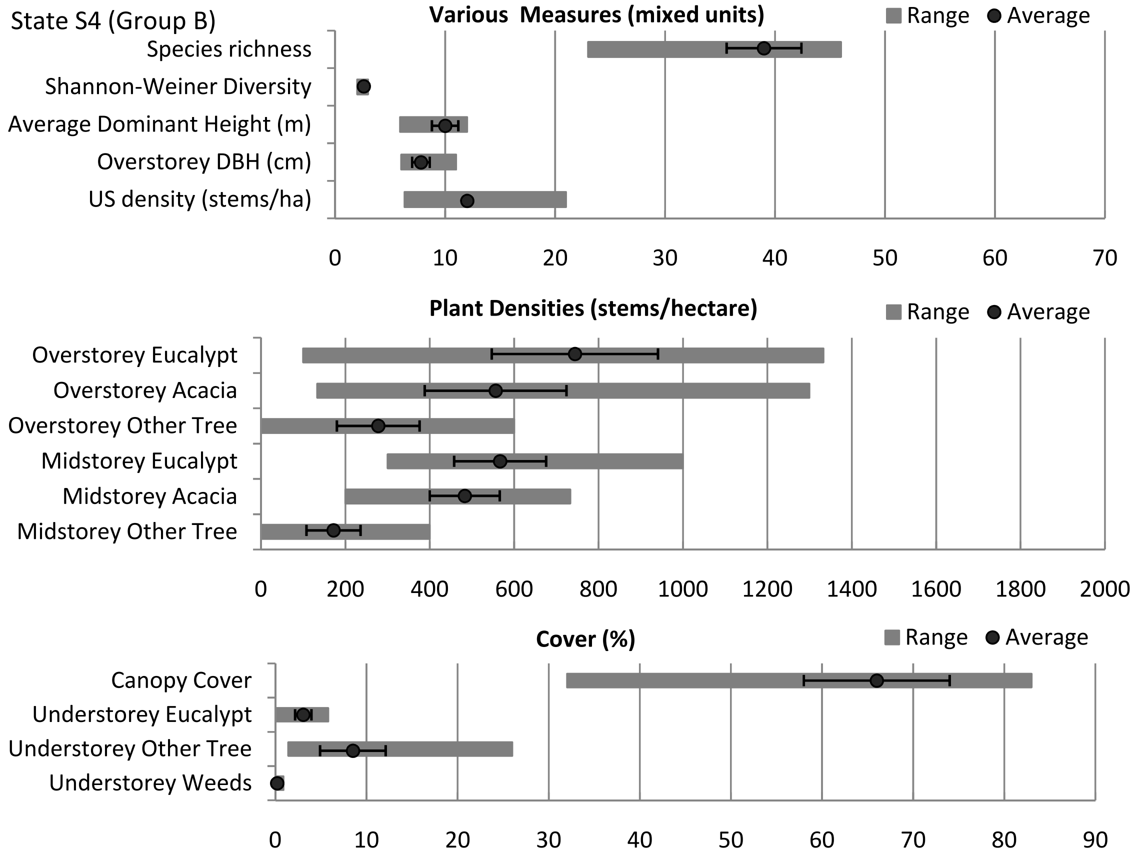


Figure 6-11 State S4: vegetation characteristics (2000 dry season and 2001 wet season data)

This transient state should mature into S5 in the absence of fire (T7; Figure 6-12), perhaps requiring active fire suppression as the key management intervention in the fire-prone rehabilitation and savanna ecosystems of Groote Eylandt (M11). A fire (T6) in this state is likely to kill the juvenile eucalypts and mature acacias, resulting in state D12, a grass-dominated system with many juvenile acacias (Figure 6─1).

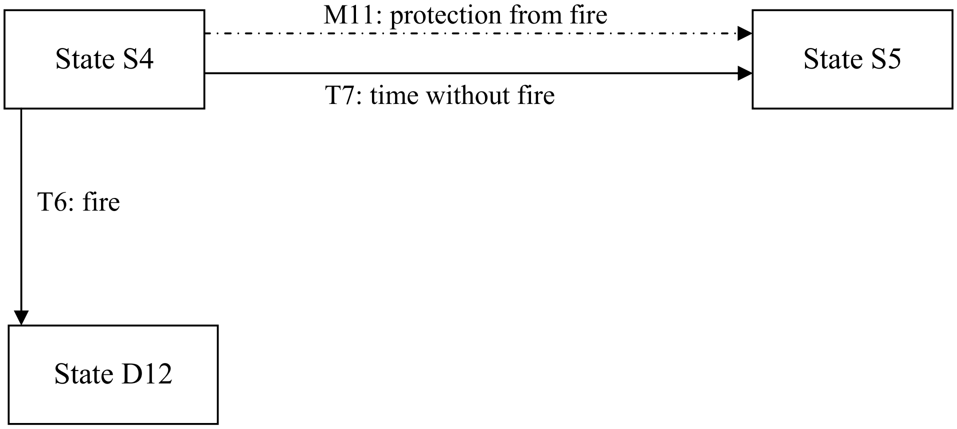


Figure 6-12 State S4: potential transitions, management interventions and alternate states

State S5—Middle-stage development of eucalypt woodland

State S5 is characterised by very high overstorey and midstorey eucalypt densities, and high canopy cover (Figure 6-22a). Species of other woody trees also occur in the overstorey and are present at high densities in the midstorey (Figure 6-13). S5 sites generally have a low understorey plant density, including low weed cover. This state corresponds to Group C, as identified by classification and ordination analyses (Section 3.3.3).

This state is dominated by mature eucalypts and is thus resilient to recurrent fire (of natural intensity) and likely to develop along the desired successional trajectory to state S6, the middle–late-stage eucalypt-dominated woodland (Figure 6-14). Rehabilitation in this state could contain some fire-sensitive subdominant species, as sites have likely been protected from fire throughout their development. This is the earliest state where planned fire (M12) could be introduced as a management tool to prove the fire resilience of the system in a controlled situation using early-season, low-intensity burns so that impacts are minimised.

Pressure from weeds (T8) or grasses (T9) would increase susceptibility to fire and other disturbances, threatening to divert S5 sites to states D5 or D8, respectively. Weed and grass control should be applied as a management activity where these life forms are a potential threat.

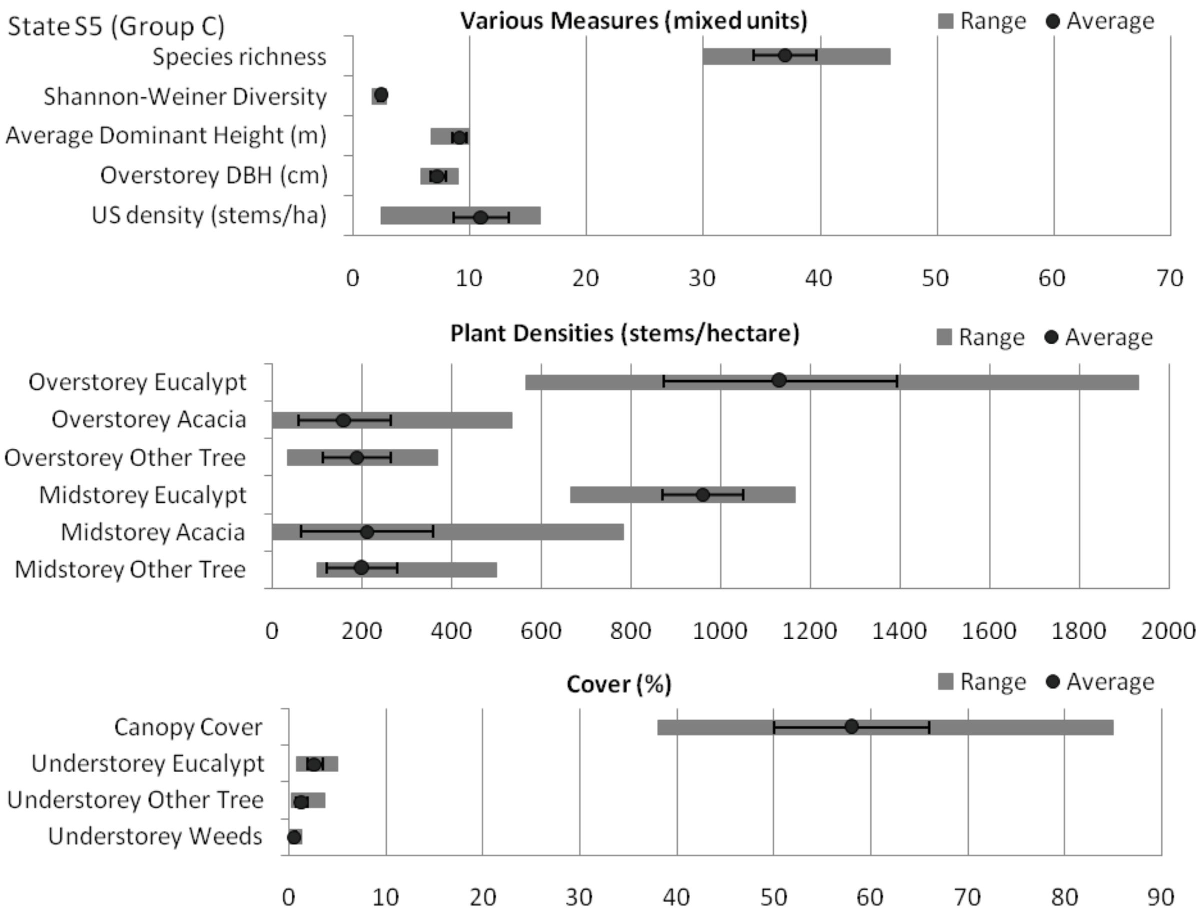


Figure 6-13 State S5: vegetation characteristics (2000 dry season and 2001 wet season data). Lines (whiskers) represent standard errors

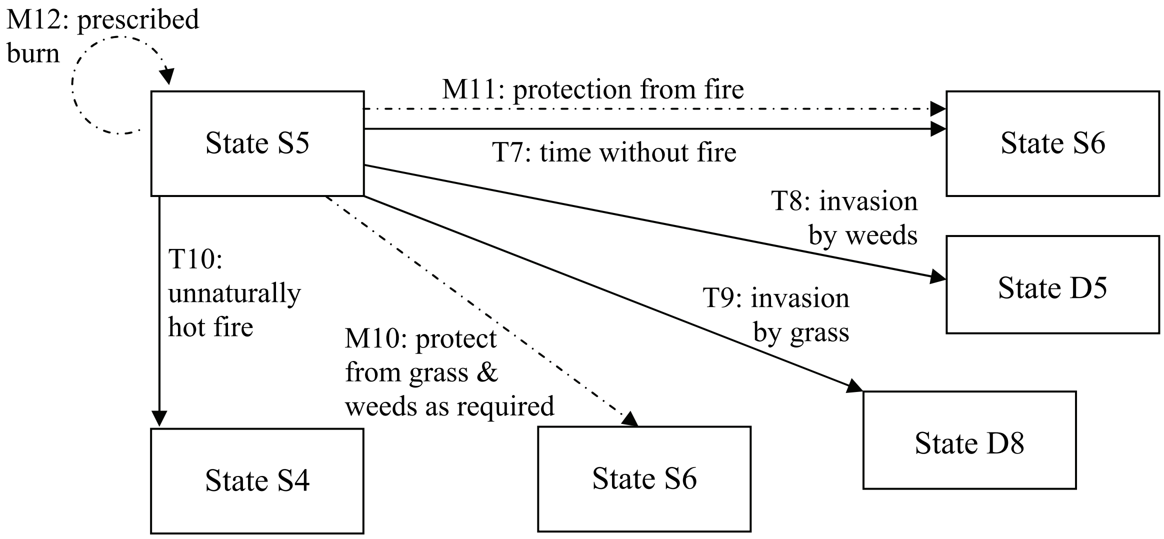


Figure 6-14 State S5: Potential transitions, management interventions and alternate states

State S6—Middle–late-stage development of eucalypt woodland

This state is characterised by high heights and densities of eucalypts in the overstorey and midstorey, but a lack of other woody species in these strata (Figure 6-22b). Acacias are found at low density in the midstorey, and understorey plant density is generally low, although weeds are present in the understorey (Figure 6-15). Sites in Group D belong to this state.

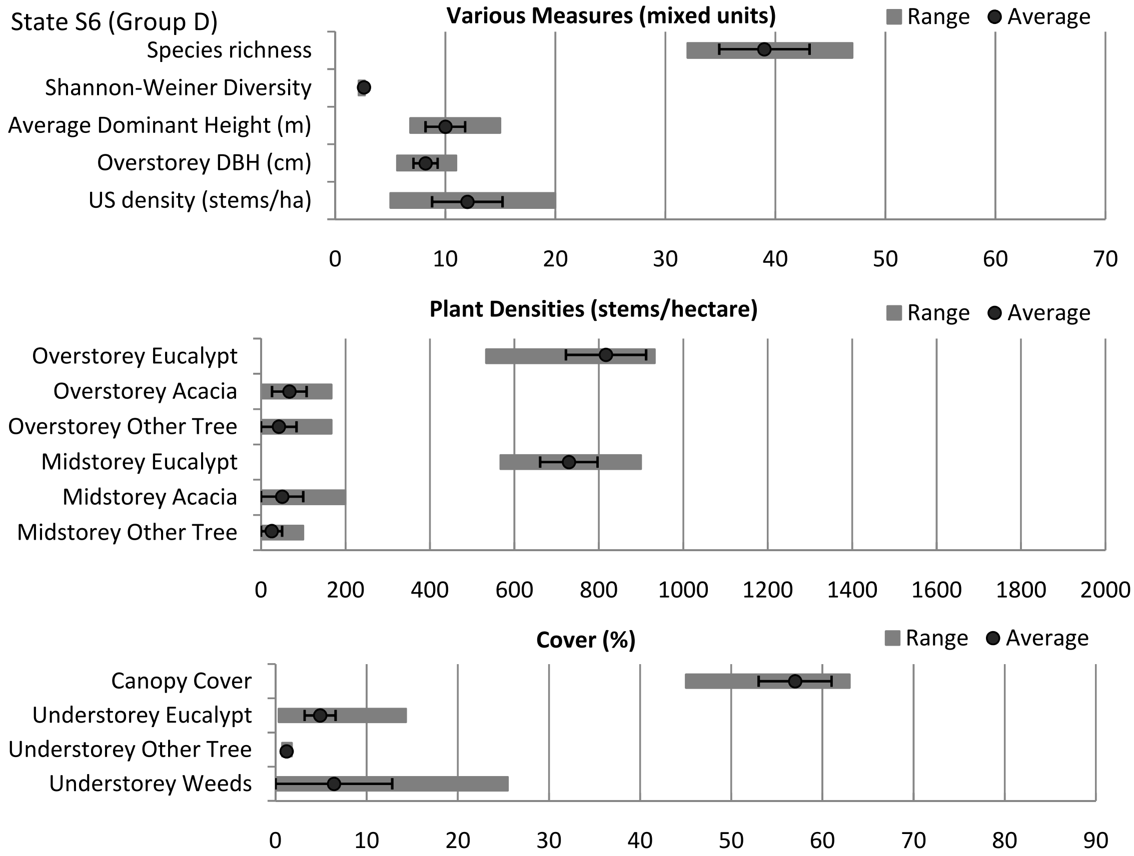


Figure 6-15 State S6: vegetation characteristics (2000 dry season and 2001 wet season data)

This mature woodland state is likely to contain only fire-resistant species as it will have been already burnt, ideally by a low-intensity, prescribed fire, and be resilient to uncontrolled, even late dry-season burns (T10; Figure 6-16). Thus, even in the event of a low to medium-intensity fire (T7), this state should develop toward the more mature S7. S6 should be resistant to invasion by weeds or grasses as well, as there should be good canopy cover and a high level of resource use by the mature plants present. However, should sites in this state be threatened by weeds (T8) or fire-promoting grasses (T9), control measures (M10) may be required to prevent it degrading to the deviant states, D5 or D14, respectively.

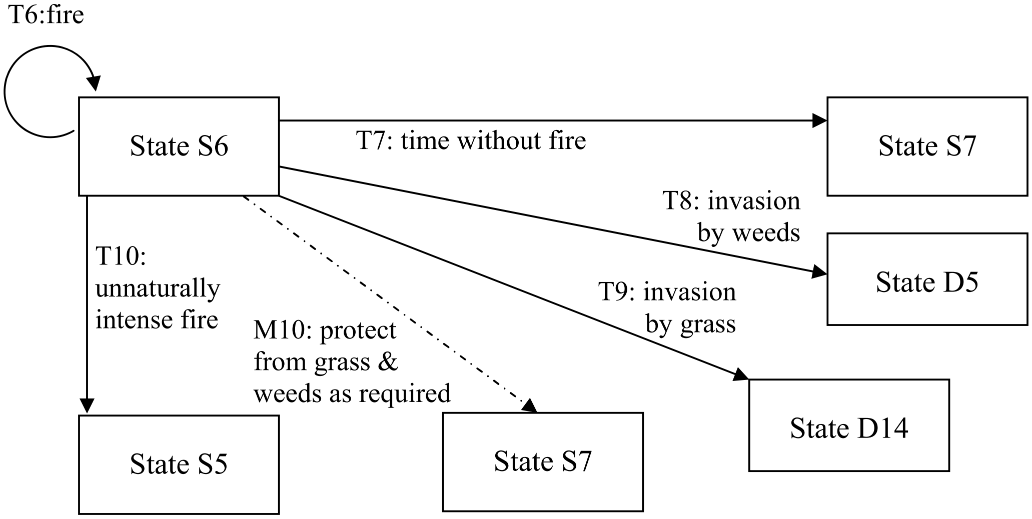


Figure 6-16 State S6: potential transitions, management interventions and alternate states

State S7—Late-stage development of eucalypt woodland

This state is mature woodland dominated by eucalypts with many juvenile seedlings in the midstorey and understorey (Figure 6-17). The understorey has high species richness including some grasses and very few weeds. This state was identified in the vital attributes model as DT + SI + UI_{rj} + **UI** and is represented by the individual site in Group A (site F2-1989; Figure 6-23a).

Sites in this state are resilient to fire, resistant to invasion by weeds and non-native grasses, and are comprised of mature eucalypt woodland with complex attributes including vertical structure and habitat values (e.g. hollows and logs). Resilience to fire means that even a harsh fire (T10; Figure 6-18) will maintain the state in its current, stable condition. This state would be an appropriate 'completion stage' or relinquishment standard for rehabilitation, as it should continue to develop over time (T7) toward the target eucalypt woodland ecosystem (state Sx).

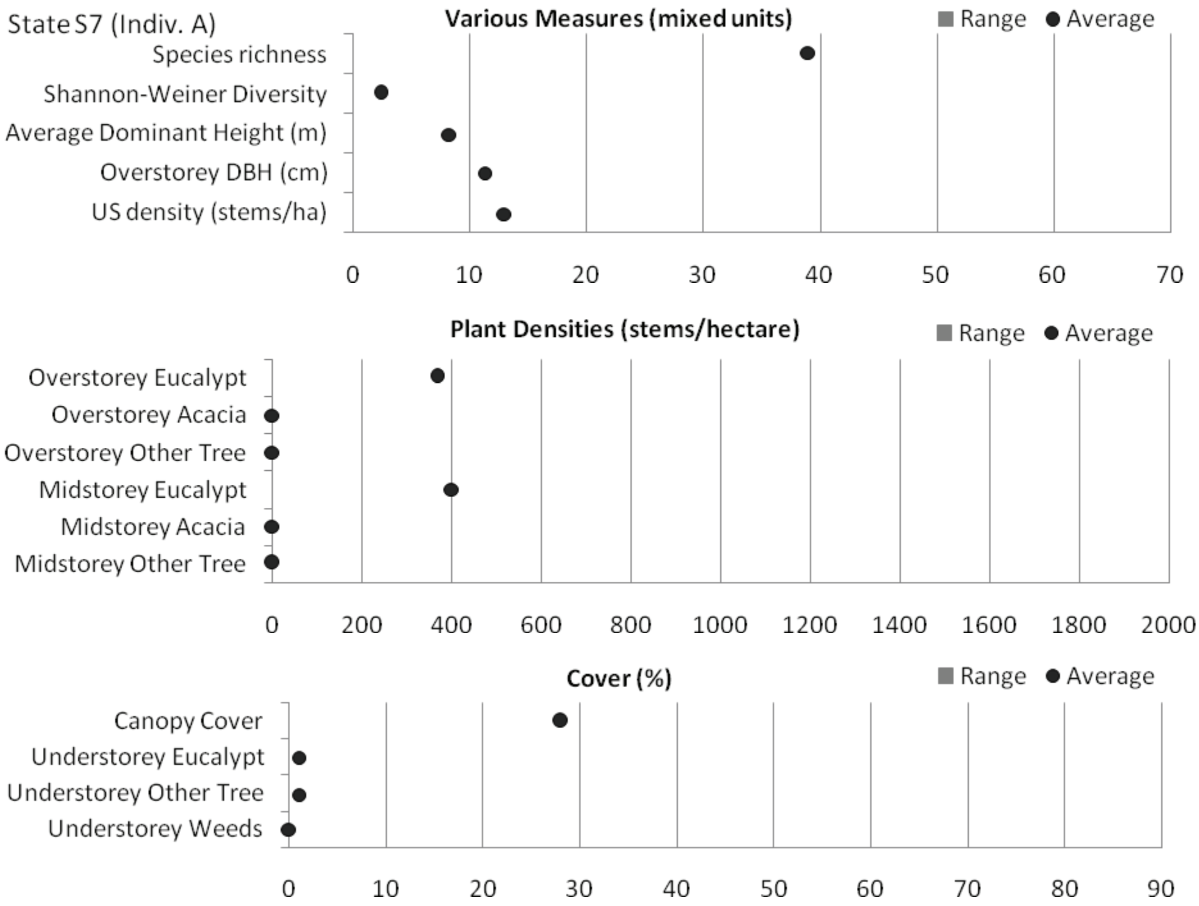


Figure 6-17 State S7: vegetation characteristics (2000 dry season and 2001 wet season data). Lines (whiskers) represent standard errors

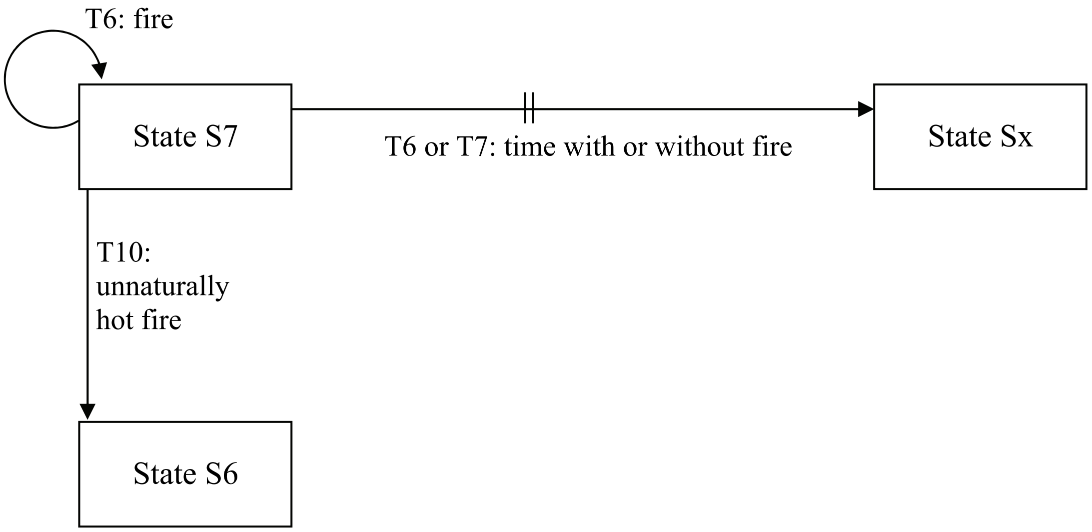


Figure 6-18 State S7: Potential transitions, management interventions and alternate states

State Sx (Woodland Group)—Target ecosystem, eucalypt woodland

After an undefined period of time, the Groote Eylandt rehabilitation should mature to resemble the composition, structure and function of the surrounding native woodland (Figure 6-19). This system is resilient to regular fires, although leading to periodic changes in cover (Figure 6-20). The overstorey is dominated by eucalypts with many juvenile overstorey species suppressed in the diverse understorey. Understorey cover is dominated by grasses with no weeds. This state was recognised in the vital attributes model as DT + UI_{rj} + **UI** and was represented by the group of undisturbed woodland sites (Figure 6-23b).

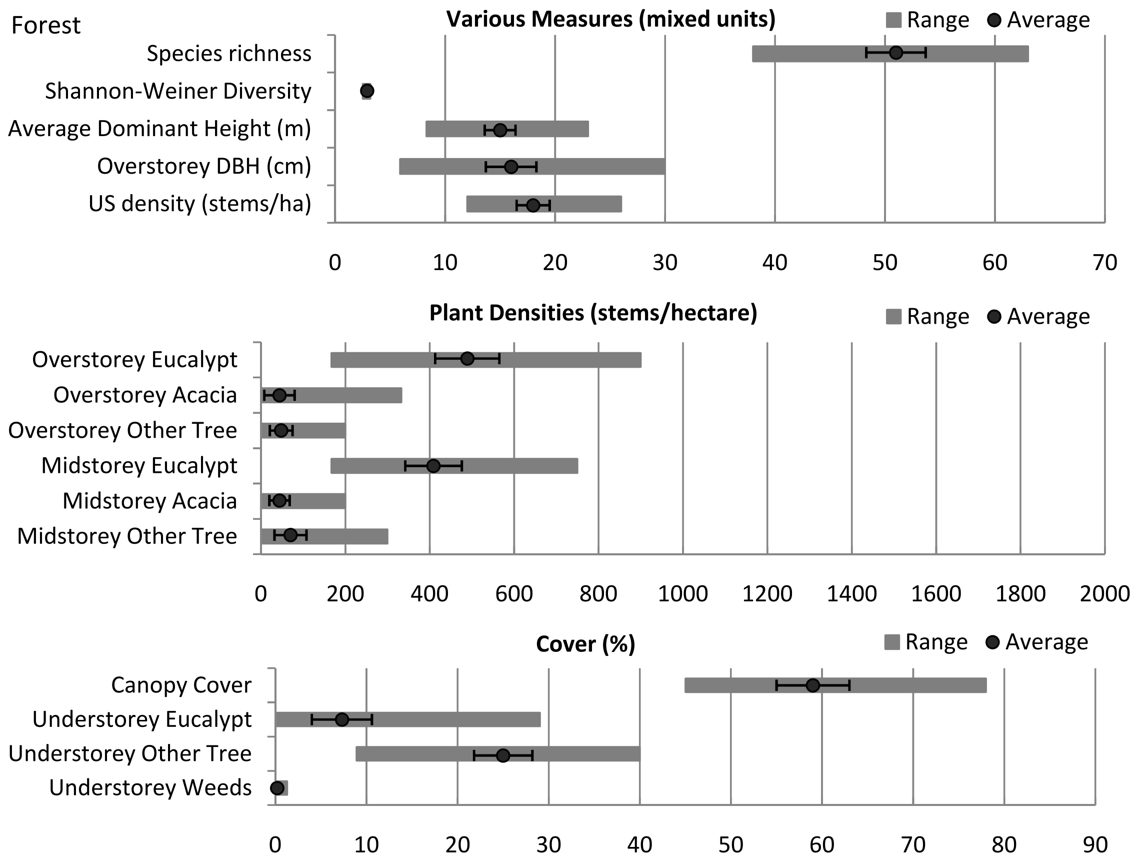


Figure 6-19 Woodland group: vegetation characteristics (2000 dry season and 2001 wet season data)

Sites in this state are resilient to the regular fires (T6; Figure 6-20) common in eucalypt woodland savanna. In fact, regular fires maintain the composition and proportions of plant species in the configurations observed in savanna ecosystems of Groote Eylandt. Time with and without fire (T6 and T7 respectively) is anticipated to maintain this state in its stable condition (Sx). If an unnaturally hot fire were to occur (T10), for example some fire-promoting grasses penetrated into the understorey of the woodland, there is a change that this would cause the woodland to regress to something more like S7.

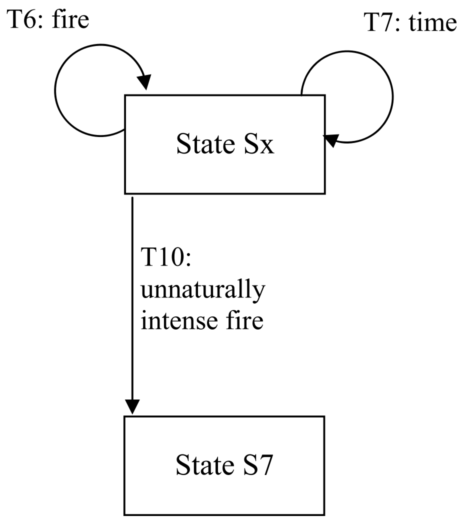


Figure 6-20 State Sx: potential transitions, management interventions and alternate states

Figure 6-21 Representative sites for a) state S1 (Site F4-2000, plot 2, Feb. 2001) and b) state S4 (Site F3N-1994, plot 1, Feb. 2002)

Figure 6-22 Representative sites for a) state S5 (Site F1-1983, plot 3, Feb. 2002) and b) state S6 (Site D-1985, plot 1, Feb. 2002)

Figure 6-23 Representative sites for a) state S7 (Site F2-1989, plot 3, March 2003) and b) state Sx (Site B, plot 3, Feb. 2002)

6.3.2.2 Undesirable States

Undesirable states include sites that have attributes that preclude their likely development towards the desired mature eucalypt woodland ecosystem in any reasonably short timeframe without active intervention. These states sit outside the 'desired' successional trajectory, and their relative locations or positions are determined by their configuration (composition and structure) and developmental status, which may not be necessarily related to time.

State D1—Very early-stage rehabilitation with understorey only, eucalypts absent

This state features juvenile rehabilitation, possibly with some woody species and good diversity, but an absence of eucalypts. It is unlikely to develop into a eucalypt woodland. This state was observed by Grant and Duggin (2000) and me in rehabilitation at Groote Eylandt and elsewhere (pers. obs.). While there are a number of potential trajectories that could result in this state, common influences include insufficient or bad quality of seed of keystone species and early 'false-start' rainfall that initiates germination but is followed by dry periods and high temperatures, causing high mortality.

Sites in this state are prone to invasion by weeds (T8; Figure 6-24) or increased dominance of aggressive grasses (T9), leading to states D5 or D2, respectively. Without eucalypts and other keystone canopy and subcanopy species to develop canopy closure and dominate the site, aggressive colonisers (*r*-strategists), such as grasses and acacias, are more likely to dominate and preclude colonisation by keystone species. In this early stage of development, cover and fuel loads should be low so the risk of damaging fire is also low. In the absence of fire and any management intervention (T7), sites in state D1 should develop into the mature but equally deviant state, D10. Should a fire occur (T6), D1 sites would effectively return to the original S0 state, requiring a repeat of the full rehabilitation treatment to initiate development along the desirable trajectory. Management intervention, to protect a D1 site from over-dominance by grass or weed species (M10) and supplying seed of the target rehabilitation species (especially eucalypts; M9), could see it develop into the desired S2 state.

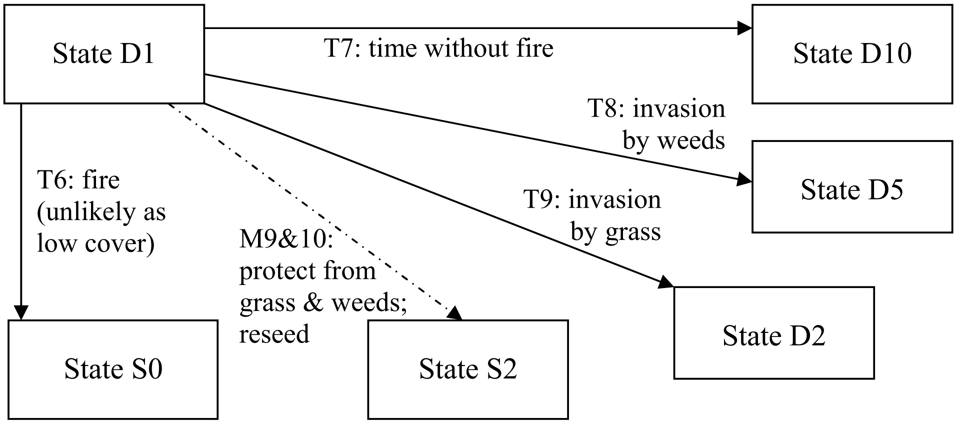


Figure 6-24 State D1: potential transitions, management interventions and alternate states

State D2—Very early-stage rehabilitation dominated by grasses

Sites in this state are typified by low stature and cover, good diversity of keystone rehabilitation species but an over-riding dominance of grass species, potentially fire-promoting exotic grass species. A number of areas were observed to be in this state (Figure 6-45a). While fire is unlikely, given the low cover early in development, its occurrence (T6; Figure 6-25) could reduce D2 sites to D4, a grassland community. Without management intervention or fire (T7), D2 sites would mature into state D6. Management intervention may require mechanical cultivation or chemical treatment to control the dominant grasses and the supply of additional seed or seedlings (M13) to reinitiate development of the system and move it to a desirable S1 state.

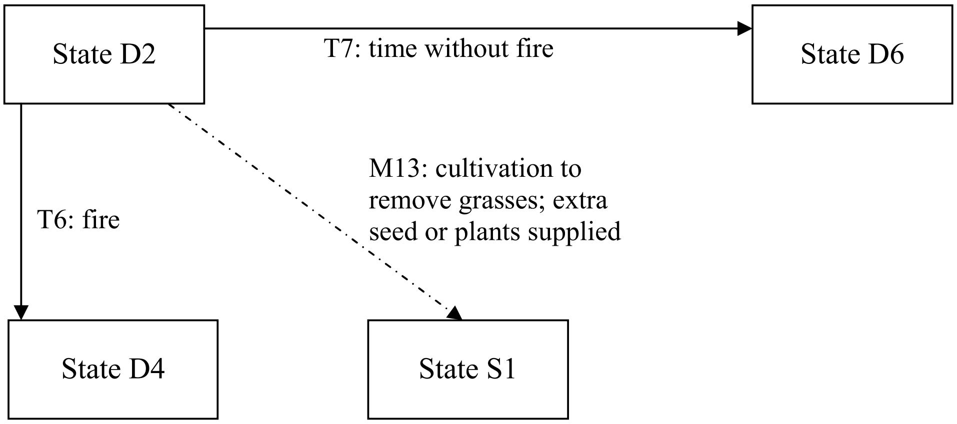


Figure 6-25 State D2: potential transitions, management interventions and alternate states

State D3—Very early-stage rehabilitation dominated by acacias

Rehabilitation with a high establishment density of *Acacia* species compared to other more desirable species (such as eucalypts, ironwoods, cocky apple, *Brachychiton* sp.) could be included in this state. This state was identified from first principles as $DT_j + \mathbf{SI_j} + UI_{sj}$, using the vital attributes model (Figure 6-1). Fire is unlikely in sites at such an early developmental stage. Over time (T7; Figure 6-26), sites in this state would develop into a mature acacia-dominated community, state D7. Management intervention to relieve the acacia dominance, for example physical cultivation to remove the juvenile acacias followed by reseeding with the rehabilitation seed mix (M14), should see D3 sites return to the early stages of the desired successional trajectory (S1).

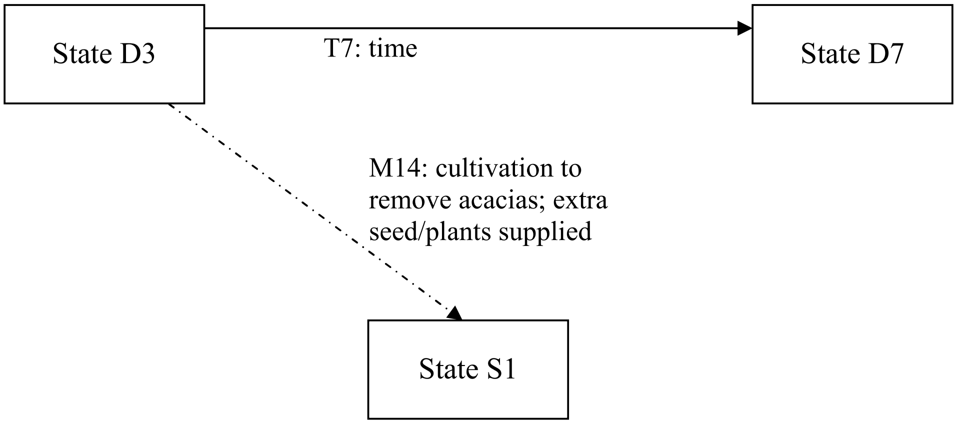


Figure 6-26 State D3: potential transitions, management interventions and alternate states

State D4—Grasslands (occasionally with some weeds)

This state is identified by a dense cover of grasses and weeds although scattered acacias are often present. The subsequent high grass fuel load makes these sites prone to recurrent fires. The lack of eucalypts, high levels of grass competition and repeated burning limit the successful development of this state. This state was identified in the vital attributes model as DT_j and was observed in the rehabilitation at Groote Eylandt by Grant and Duggin (2000) and me (pers. obs.).

In the absence of intervention, sites in this state are likely to be subject to repeated fires that will maintain grass dominance and prevent the establishment of other life forms (Figure 6-27). Should fire be excluded for some time (T17), the state is likely to develop further along this undesirable trajectory to state D6, a grass-dominated system containing some woody or herbaceous species. Management intervention is required to redirect this state to the desired trajectory, for example use of herbicides to control the grass followed by reseeding or planting with target rehabilitation species (M13) to reinitiate development at state S1. A more strategic approach may be to plant mature seedlings through the grass and protect them from competition from weeds or grasses (e.g. with mulch or herbicide) and fire, until they reach a height and stem diameter beyond the topkill threshold of fire and create a canopy that reduces light and the ability of the grass layer to dominate (M15). This scenario may require active management for several to many years, but will likely result in rehabilitation of a desirable state (S4).

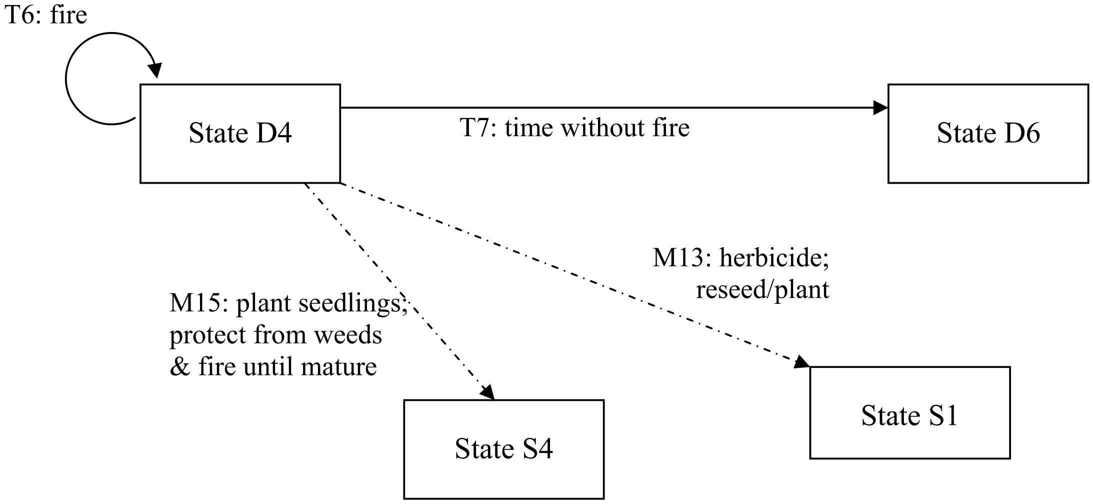


Figure 6-27 State D4: potential transitions, management interventions and alternate states

State D5—Weed-dominated community

Sites in this state have become dominated by weeds (e.g. siratro and passiflora; see Table 3-7) with only a minor presence of other life forms at various developmental stages (Figure 6-45b). The aggressive nature of the weeds prevents significant recruitment or establishment of other, more desirable species in the absence of favourable disturbance or management intervention. Most weeds that are able to persist in these fire-prone environments have strategies such as the ability to resprout after fire (e.g. passiflora and hyptis) or high reproductive rates that result in large seed stores (e.g. hyptis). This state was observed in a few rehabilitation areas on Groote Eylandt (Grant & Duggin 2000; pers. obs.).

This state is stable in response to both fire (T6; Figure 6-31) or its absence (T7). Management interventions to control the weeds and introduce more desirable species (M16 or M15) should return sites in this state to the desirable trajectory, specifically to states S1 or S4, respectively.

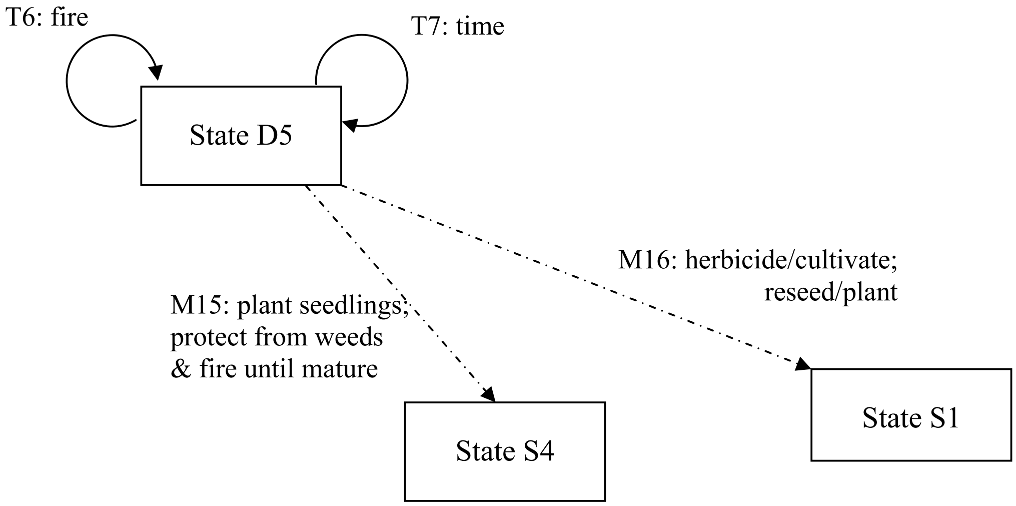


Figure 6-28 State D5: potential transitions, management interventions and alternate states

State D6—Early-stage development of eucalypt woodland with a high proportion of grasses

The key components of the target woodland are present, most importantly eucalypts, however the understorey is dominated by high grass cover, potentially including exotic, fire-promoting grasses. This state was identified in the vital attributes model as $\mathbf{DT} + \mathrm{SI}_j + \mathrm{UI}_{sj}$ (Figure 6-1).

The grass dominance of this state negatively affects site development as well as response to fire. In the absence of fire (T7; Figure 6-29), the system is likely to develop toward state D8, with more mature trees and shrubs in a grass-dominated matrix. The more likely scenario is that a fire (T6), especially a high-intensity fire (T10), will destroy the immature acacias and eucalypts, diverting development to a D4 grassland state. Management interventions must remove the high grass competition and fuel load and increase the proportion of more desirable woody species. Use of herbicides or cultivation is one option which, if followed by seeding or seedling plantings (M13), could see the state redirected to the desired trajectory (S1). Strategic plantings and ongoing protection against competition and fire (M15) is an alternative option, as it is with states D4 and D5, but the fire-promoting nature of the grasses in this state means that such an approach is risky and would require substantial efforts in fire protection to successfully return sites in this state to S4.

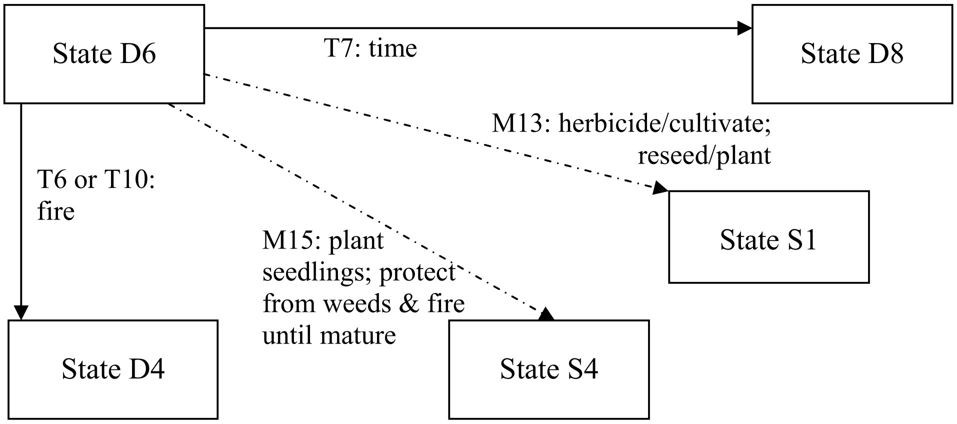


Figure 6-29 State D6: potential transitions, management interventions and alternate states

State D7—Early-stage development of eucalypt woodland dominated by acacias

This state is dominated by acacias and has very low canopy cover of trees, a low height of the dominant woody plants (acacias) and a moderate cover of understorey weeds (Figure 6-30). This state was identified in the vital attributes model as DT + $\mathbf{SI}_j$ + UI_{sj}, and sites in Group G (Section 3.3.3; Figure 6-46a) were identified as being in this state.

Sites in this state are likely to develop further along the undesirable trajectory to state D9 in the absence of fire (T7; Figure 6-31). Should fire occur (T6), it is likely that the immature acacias and eucalypts will be killed and the system will regress to a grassland (D4). Management interventions such as cultivation to control the acacias followed by reapplication of seed or seedling plantings (M14) should return D7 sites to an early state on the desired trajectory (S1). As the acacias are juvenile and fire-prone in this state, burning is an option as a management tool (M12) to remove them from the system before they establish a persistent seed store. Follow-up seeding (M9) should return treated sites to S1. Strategic planting of mature seedlings and their protection from competition from weeds (M15), for example by thinning the young acacias, should see sites in this state progress to S4.

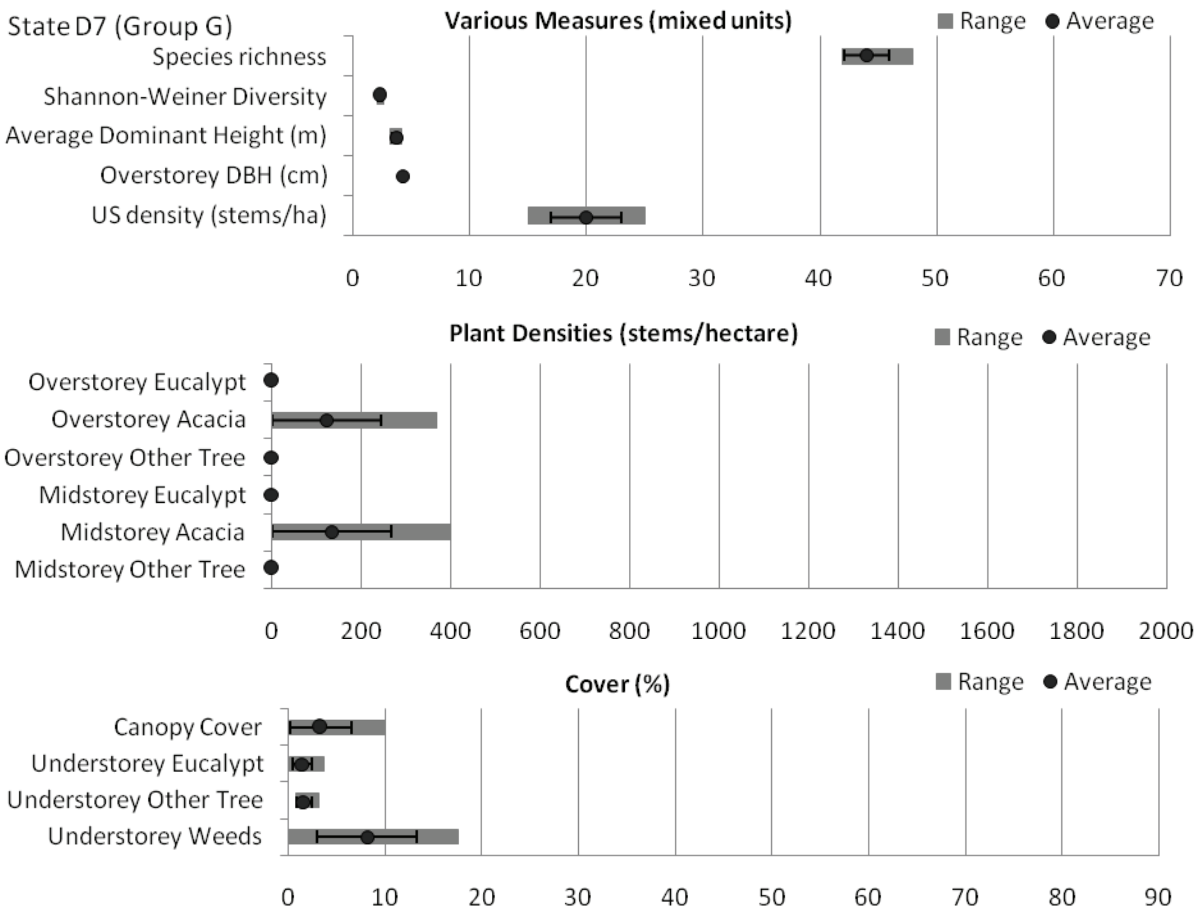


Figure 6-30 State D7: vegetation characteristics (2000 dry season and 2001 wet season data). Lines (whiskers) represent standard errors

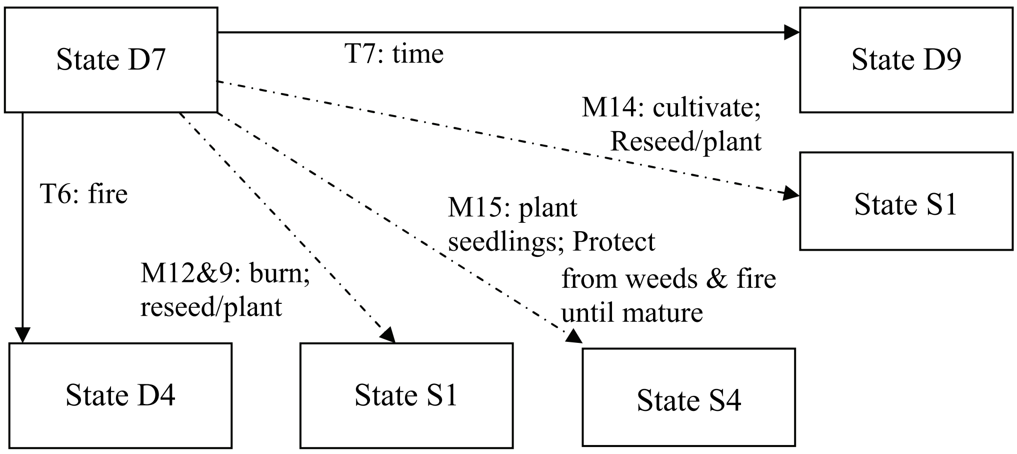


Figure 6-31 State D7: Potential transitions, management interventions and alternate states

State D8—Middle-stage development of eucalypt woodland with a high grass biomass

This state is identified by a good overstorey of eucalypts, with more than 300 stems/ha, but also acacias and high fuel loads resulting from grasses, litter and dead acacias (Figure 6-32). The main issue with this state is that the proportion of grasses is unnaturally high and potentially destructive, due to the fire-promoting nature of the grassy understorey. This state was identified in the vital attributes model as **DT** + SI + UI_{sj}, (Figure 6-1) and in the field as the lone site in Group I (site C-1992). This state was also observed during the initial assessment of Grant and Duggin (2000).

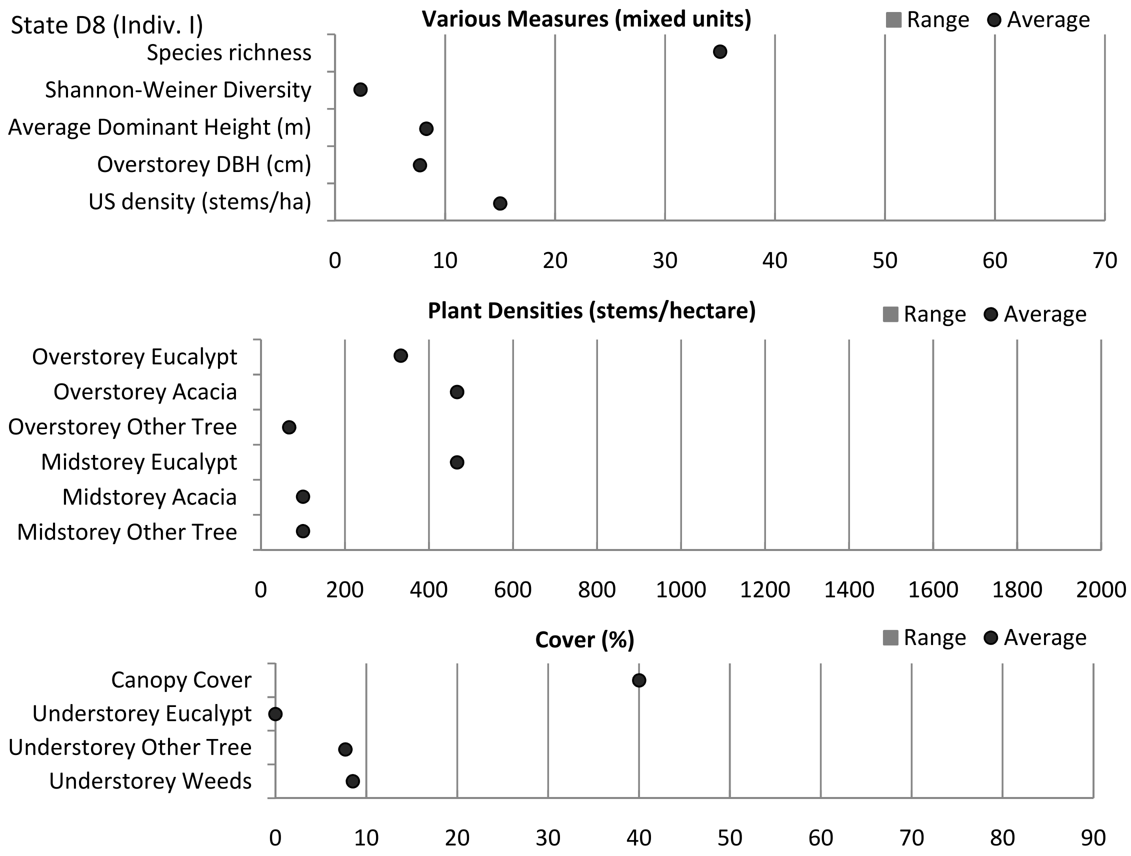


Figure 6-32 State D8: vegetation characteristics (2000 dry season and 2001 wet season data)

In the absence of fire (T7; Figure 6-38), sites in this state are likely to develop along an undesirable trajectory to state D14. Fire (T6) would kill the juvenile eucalypts and result in a grass-dominated system with juvenile acacias present (D6). Management interventions to clear or thin the dominant acacias in the midstorey or overstorey (M17) and reduce the dominance of the grasses (cultivation or herbicide), followed by planting or resowing of the target species

(M13), would restore the condition of sites in this state to the early stage of the desired developmental trajectory (S1).

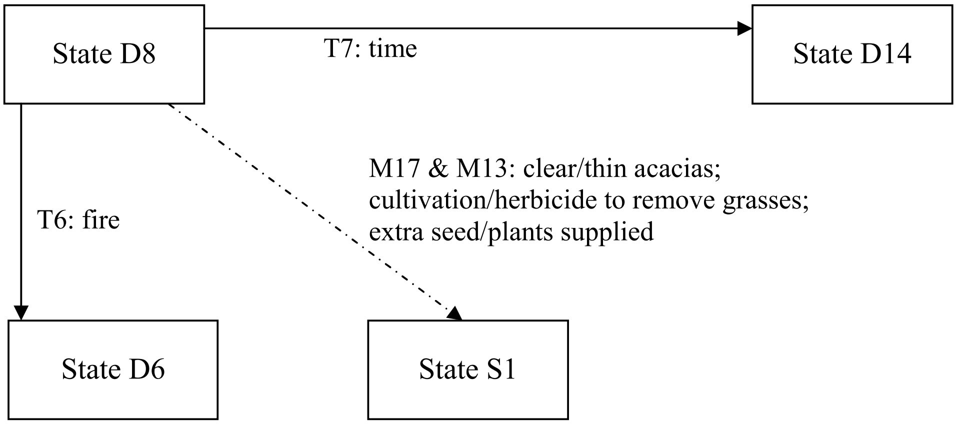


Figure 6-33 State D8: potential transitions, management interventions and alternate states

State D9—Middle-stage development of eucalypt woodland dominated by acacias

Sites in this state have high species richness compared to other deviated rehabilitation states (Figure 6-34). Overstorey and midstorey acacia densities are high, but eucalypts and other woody species in these strata are in lower than target densities. These sites have a large range in understorey plant densities and a moderate cover of understorey weeds. This state was identified in the vital attributes model as DT + **SI** + UI_{rj} and corresponds to Group E (Section 3.3.3; Figure 6-46b).

Being dominated by mature acacias, sites in this state are likely to move to the deviant state, D12, in response to fire (T6; Figure 6-35), as the fire-resistant acacia seed store will germinate after fire and produce a cohort of juvenile acacias amongst the grass understorey. Management should remove the chance of fire (M11), in which case the mature acacias will reach their maximum lifespan and senesce, leaving the grasses to dominate the system (S6), as acacia recruitment from seed in the absence of fire is likely to be limited. To redirect the system to the initial stage of the desired trajectory (S1), the acacias will need to be removed or thinned (M17), any excess grasses or other weeds controlled, and the desired species resown or replanted (M13).

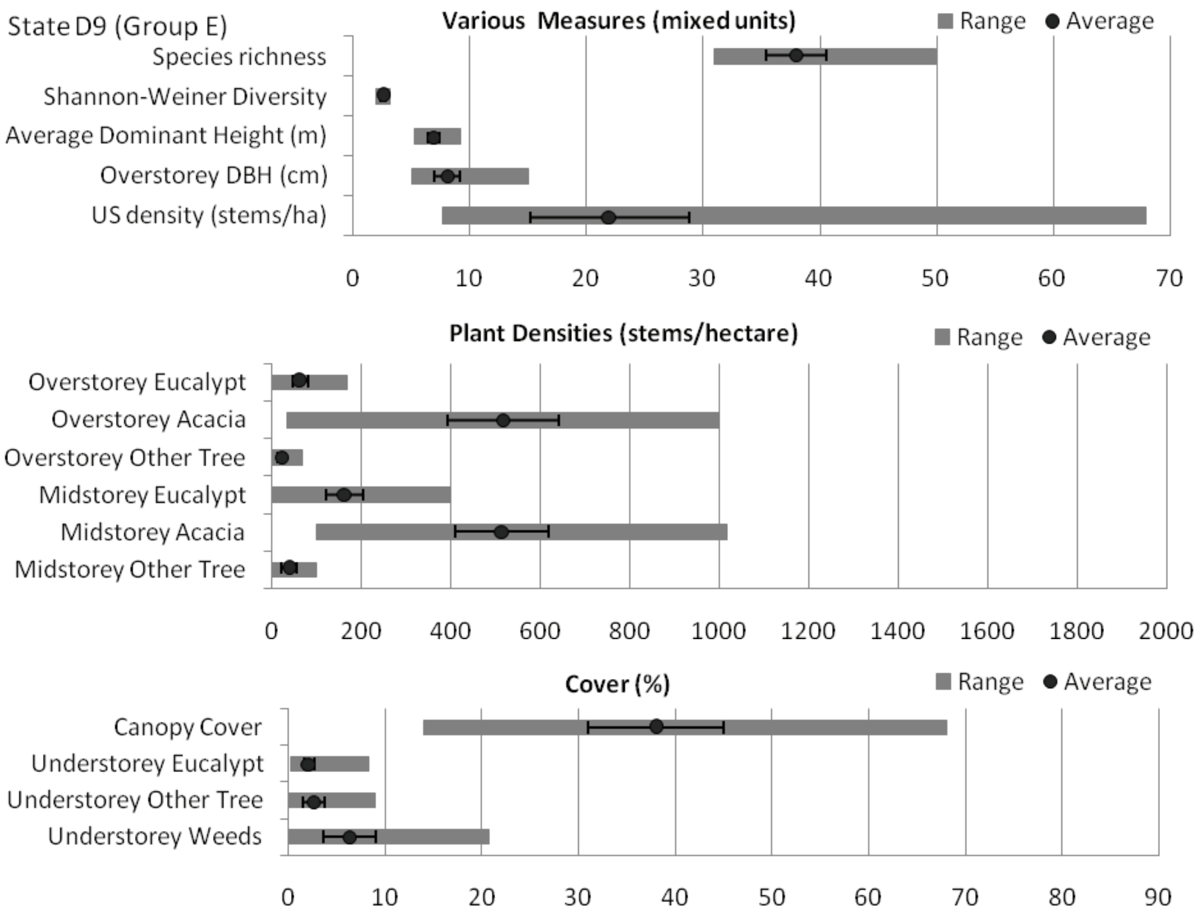


Figure 6-34 State D9: vegetation characteristics (2000 dry season and 2001 wet season data). Lines (whiskers) represent standard errors

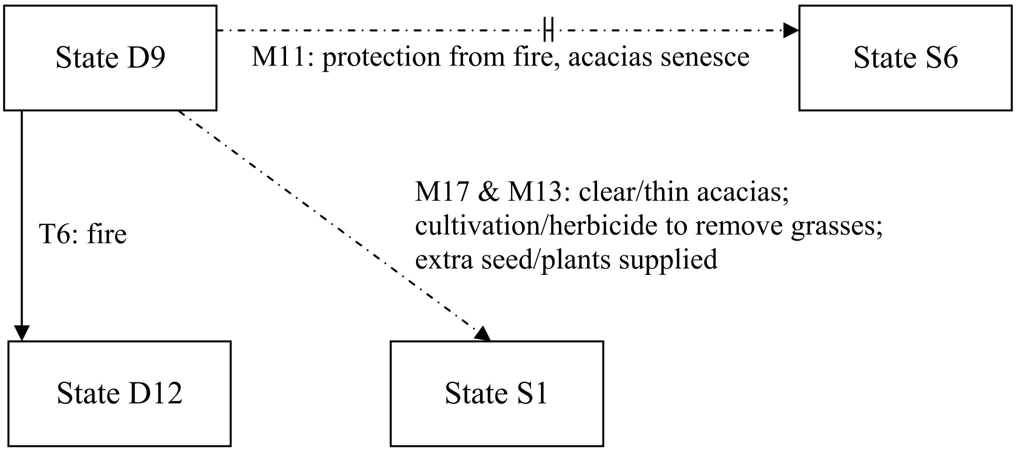


Figure 6-35 State D9: Potential transitions, management interventions and alternate states

State D10—Rehabilitation dominated by non-eucalypt woody species and weeds

This state is identified by the dominance of non-eucalypt tree species (such as *Clerodendrun floribundum*, *Trema tomentosa* and *Grevillea* spp.) in the overstorey and midstorey (Figure 6-36). Sites in this state generally have a low canopy cover, a low height of the dominant woody stratum and a low density of eucalypts in the overstorey and midstorey. There is often a moderate cover of understorey weeds. This state was represented by Group F sites (Section 3.3.3; Figure 6-47a).

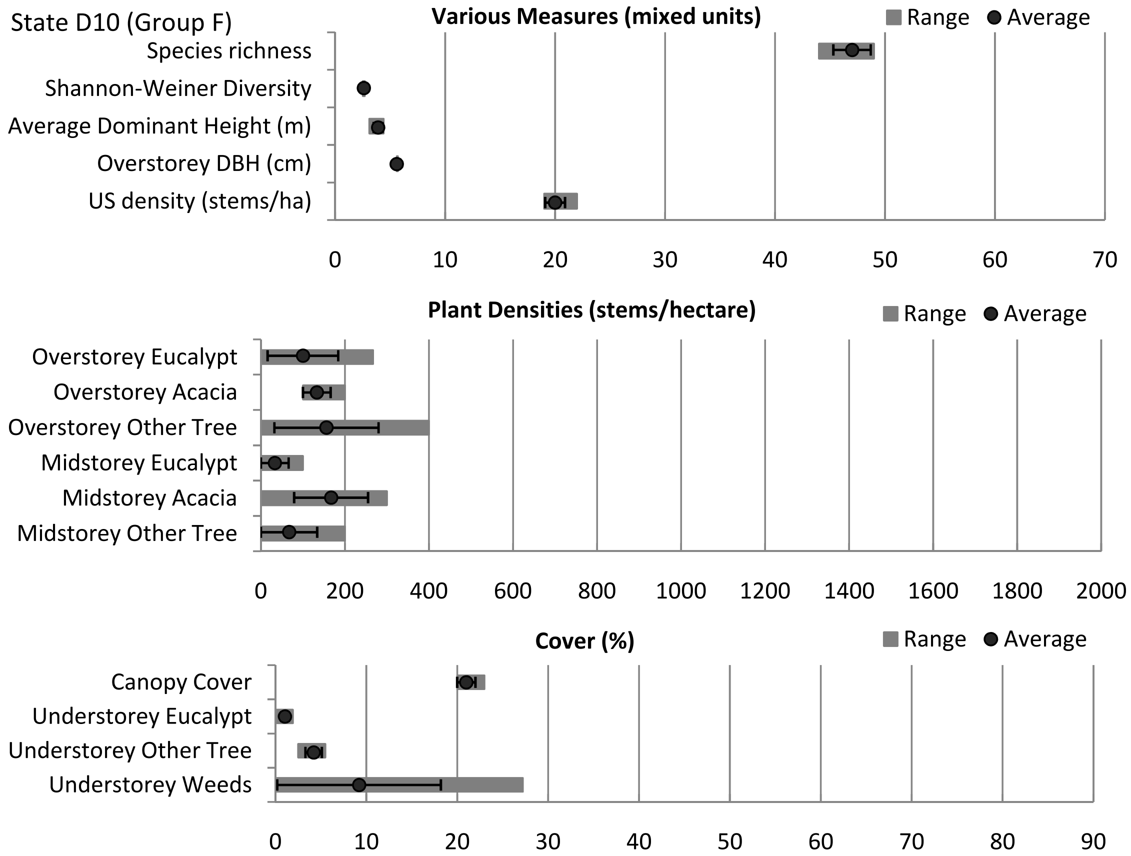


Figure 6-36 State D10: vegetation characteristics (2000 dry season and 2001 wet season data)

In the absence of fire over a prolonged period (T7, although only likely through considerable management effort: M11; Figure 6-37), sites in this state have the potential to develop into an intermediate eucalypt woodland through natural recruitment of eucalypts. Fire (T6), on the other hand, would cause regression to the weed-dominated state, D5. Management intervention would be required to redirect sites in this state back toward the desired trajectory, for example thinning of the woody overstorey (M17) to release any eucalypts in the understorey, and control of weeds by herbicide application followed by reapplication of the rehabilitation seed mix or seedlings (M13).

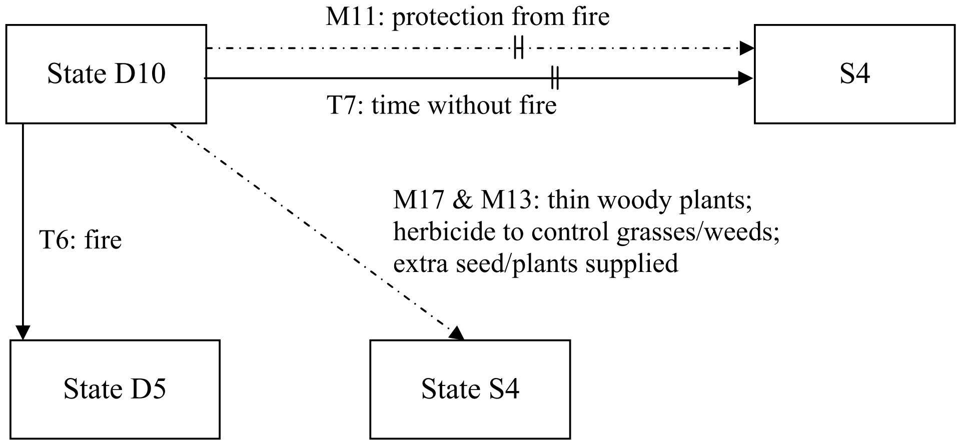


Figure 6-37 State D10: potential transitions, management interventions and alternate states

State D11—Eucalypt–acacia woodlands with high stand density

This state is eucalypt woodland with high densities of eucalypts and midstorey acacias, which are unlikely to self-thin and therefore may impede understorey development (Figure 6-38). The main limitations to this state developing into the desired end point are poor understorey development and diversity, which is not likely to increase because of the dense overstorey. This state was recognised in the field study as Group H (individual site D-1989) (Section 3.3.3; Figure 6-47b).

Sites in this state will develop into D16 if subject to fire (T6; Figure 6-39). An absence of fire, which would most likely require active and sustained management (M11), would maintain the state in its condition. Another intervention would be required to return D11 sites to the desired developmental trajectory, for example thinning to reduce competition (M17) and introduction of diversity through seed-laden or sieved topsoil, or application of a rehabilitation seed mix (M18). These activities could result in mature woodland rehabilitation with moderate woody plant densities and diversity (state S5).

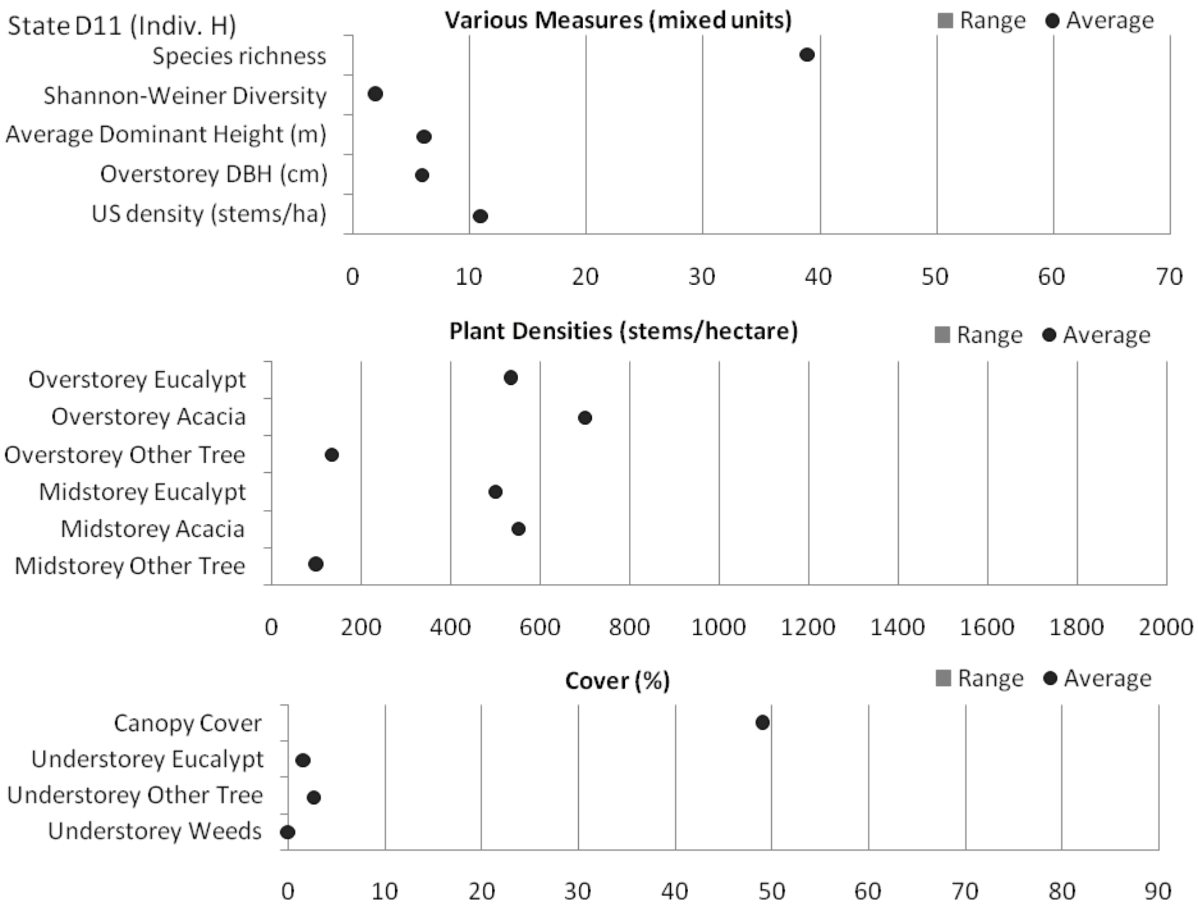


Figure 6-38 State D11: Vegetation characteristics (2000 dry season and 2001 wet season data). Lines (whiskers) represent standard errors

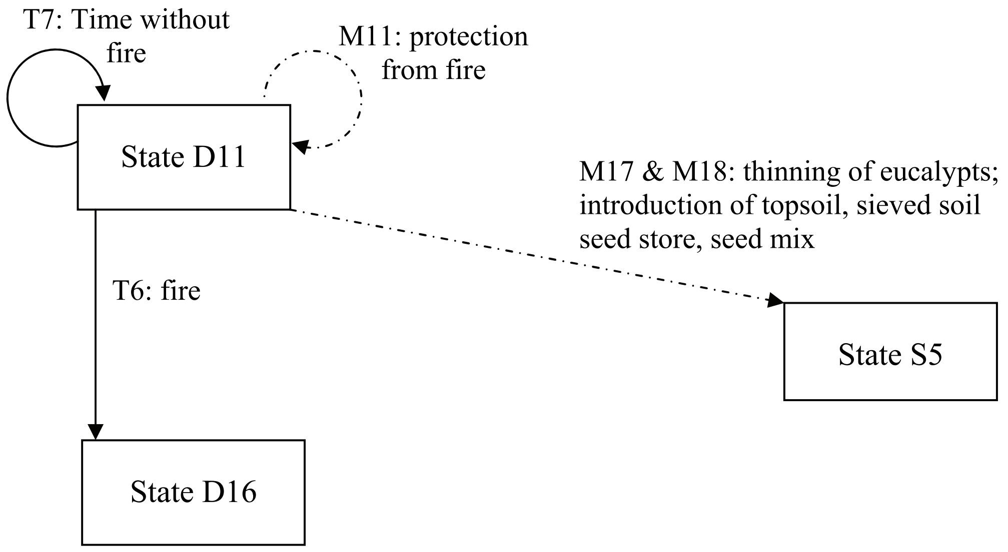


Figure 6-39 State D11: Potential transitions, management interventions and alternate states

State D12—Post-fire, juvenile grass and acacia community

This state is an ecosystem recovering from fire or other disturbances and dominated by juvenile acacias (regenerating from the soil seed store) and grasses. This state was identified in the vital attributes model as DT_j + $\mathbf{SI}_j$ (Figure 6-1).

Sites in this state would be reduced to grassland in the event of fire (T6; Figure 6-40). Management intervention to prevent fire (M11) may see D12 sites develop into a mature acacia state with a grass understorey (D13). To bring D12 back to the desired trajectory (e.g. S1), cultivation to remove the juvenile acacias (M14) and grasses (M13) followed by additional seed, would be required.

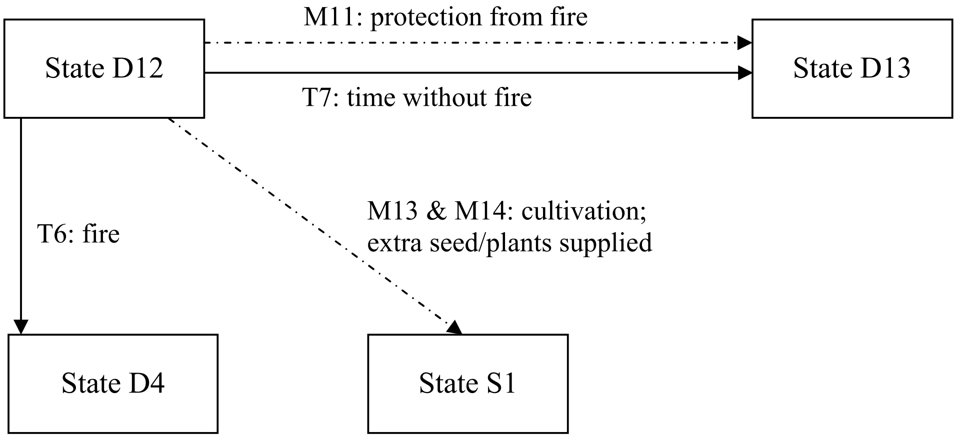


Figure 6-40 State D12: potential transitions, management interventions and alternate states

State D13—Mature grass and acacia community (2–20 years without fire)

This state is dominated by mature acacias with a grass understorey. There are few, if any, eucalypts or other woody species due to prolonged competition. This state was identified in the vital attributes model as DT + **SI**.

Fire (T6; Figure 6-41) in a D13 site would return it to D12 with juvenile grasses and acacias. Exclusion of fire for over 10 years, only possible in this environment with management intervention (M11), would see the mature acacias senesce and the sites become grasslands (D4). Two management interventions would return the system to the desired trajectory (S1): removal of the dominant acacias and grass by thinning or clearing, and cultivation or chemical treatment (M17 and M13, respectively). More intensive management, through clearing or thinning of acacias (M17) followed by planting of mature seedlings and protection from competition and fire until woody plants were resistant to these threats (M15), would drive the transition to S4.

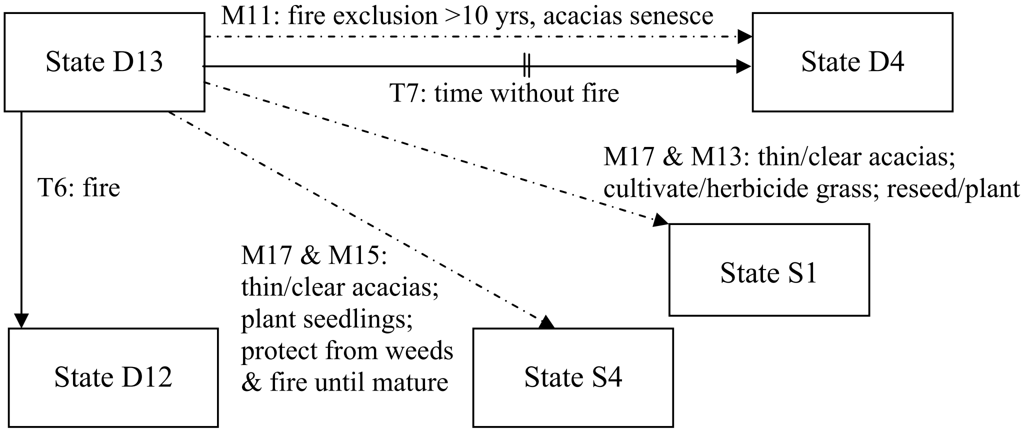


Figure 6-41 State D13: potential transitions, management interventions and alternate states

State D14—Mature eucalypt woodland with overly high proportion of (fire-promoting) grasses

This state is characterised by a mature overstorey dominated by local eucalypts, potentially high diversity in the middle stratum, but with a high biomass of grasses in the understorey. This state was identified in the vital attributes model as **DT** + SI+ UI_{rj} + UI.

The high grass biomass in these sites means that fire is likely (T6; Figure 6-42), resulting in the transition to D8. Management intervention to protect sites from fire for a prolonged period (M11) could see them improve in the direction of the desired trajectory (to S5), given the mature nature of the overstorey. A more immediate intervention would involve reducing the grass cover by cultivation or herbicide application, followed by resowing with the rehabilitation seed mix, or a subset of understorey seed or seedling plantings (M13). This treatment could return this state to S3.

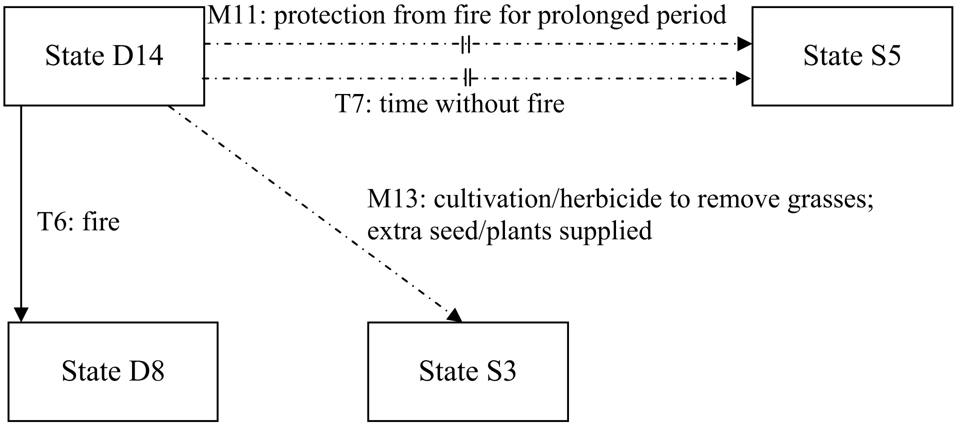


Figure 6-42 State D14: potential transitions, management interventions and alternate states

State D15—Stunted eucalypt woodland (growth limited by rooting depth) or swamp species dominant (due to poor drainage and lack of ripping)

Sites in this state are characterised by the presence of short or stunted woodland eucalypts or the dominance of woody perennials tolerant of seasonally waterlogged substrates (e.g. *Pandanus* species or *Melaleuca* trees and shrubs). This state has been observed in rehabilitation at Groote Eylandt and other operations in the wet–dry tropics of northern Australia (pers. obs.). It is most likely a symptom of inadequate site preparation prior to rehabilitation (e.g. insufficient ripping to reinstate drainage and allow deep root penetration, or too little material backfilled so that the resulting land surface is lower, closer to the groundwater table and subject to run-on from adjacent land).

With no additional disturbance or intervention (T7; Figure 6-43), this state is likely to persist indefinitely. Fire (T7) may occur, however, in which case D15 sites may develop into state D12. Active management intervention could, however, return this state to the desired trajectory with a combination of clearing and correction of the substrate problem (e.g. re-ripping the ground, followed by an appropriate rehabilitation seed mix or seedling plantings: M19).

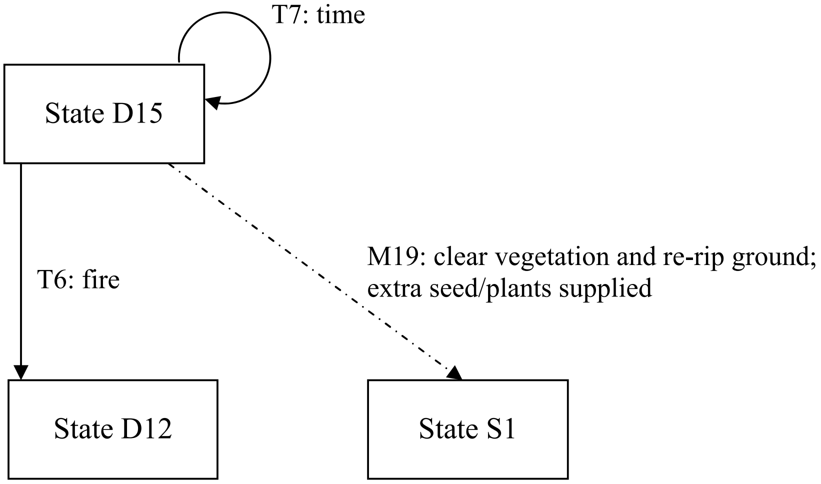


Figure 6-43 State D15: potential transitions, management interventions and alternate states

State D16—Eucalypt woodland with a sparse understorey

This state is eucalypt woodland with acceptable tree densities but a sparse understorey. This state was observed in rehabilitation at Groote Eylandt (Figure 6-48; Grant and Duggin 2000) and elsewhere (pers. obs.).

Sites in this state are still prone to burning, despite the sparse understorey, due to abundant litter from the overstorey canopy trees. In this case (T6; Figure 6-44), sites are likely to remain relatively stable and not progress or develop into any other state. Protection from fire (M11), however, could see the understorey cover and diversity improve with time until the state has developed toward the desired trajectory (S6). Active facilitation of this transition could be brought about by supplementation of the understorey with seed or vegetative propagules from freshly relocated topsoil (or sieved topsoil for a cost-effective alternative: M18). This material could be placed in islands or strips through the rehabilitation to introduce additional species. If required, recalcitrant species could be raised in the nursery and planted out individually during the early wet season (M20). These interventions would see sites in this state develop into S6, given sufficient time.

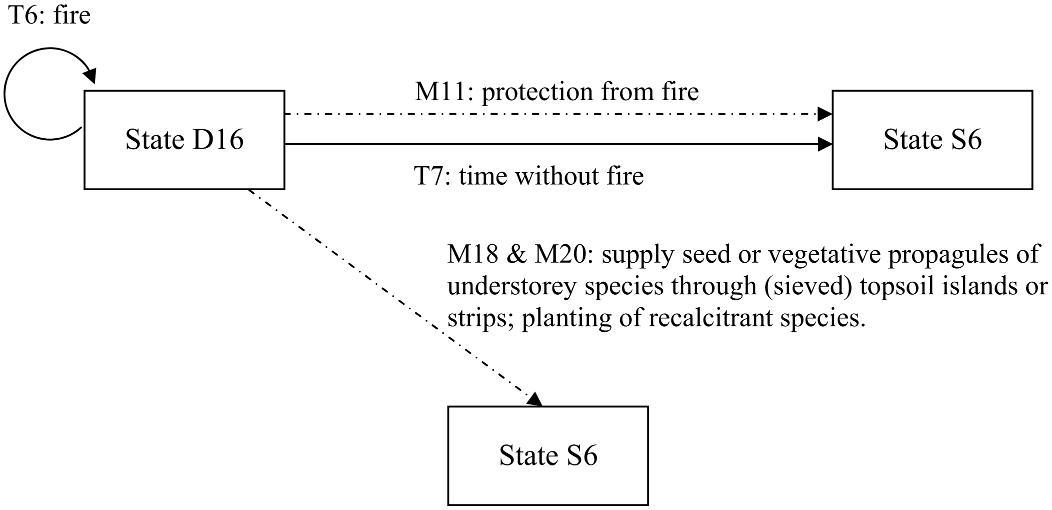


Figure 6-44 State D16: potential transitions, management interventions and alternate states

Figure 6-45 Representative sites for a) state D2 (Quarry C, October 2002) and b) state D5 (Quarry F3N, Feb. 2002)

Figure 6-46 State Representative sites for a) state D7 (Site F3-1998, plot 1, Feb. 2002) and b) state D9 (Site F3-1983, plot 3, Feb. 2002)

Figure 6-47 Representative sites for a) state D10 (Site F4-1996, plot 2, Feb. 2002) and b) state D11 (Site D-1989, plot 1. Feb. 2002)

Figure 6-48 Representative site for state D16 (Quarry F4, Feb. 2002)

6.3.3 Relationship Between Environmental Variables and Rehabilitation States

A constrained ordination (CCA) was performed to summarise the variation explained by environmental variables. Age of rehabilitation was strongly correlated with the ordination of the successful rehabilitation states (Figure 6-49). Quarry location did not appear to have much influence on this ordination.

There was a positive correlation with the exotic pastures species seed mix (Seed5) and the deviated states, particular those in State D9 and D10 (Figure 6-50). Sites of more mature successful rehabilitation (i.e. S5 and S6) appeared to be weakly correlated with seed mixes containing native species (Seed4 and Seed1), remedial planting of eucalypts (Rem1) and, surprisingly, stockpiled topsoil (Top2). Successful intermediate rehabilitation (S4) was correlated with seed mixes containing only native species (Seed2 and Seed3).

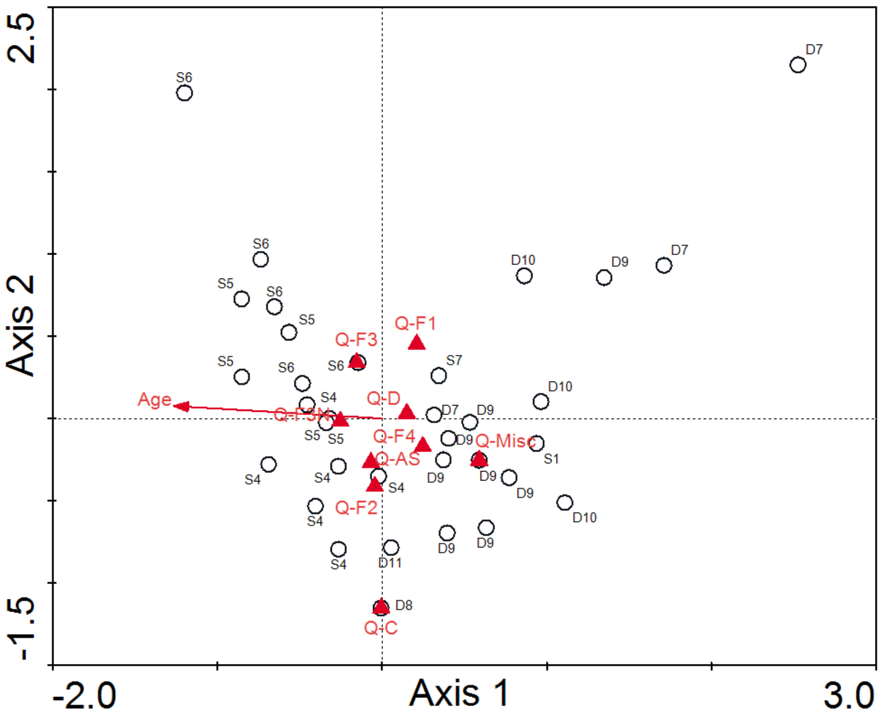


Figure 6-49 CCA bi-plot of rehabilitation sites (labelled by successional state as described in Table 6-5) and environmental variables of age and quarry. Sites labelled S are examples of successful rehabilitation states, while sites labelled D are representative of deviant states. The scalar environmental variable, Age, is represented by a red arrow and categorical values for the Quarry variable appear as filled triangles. Codes are explained in Table 4-1

Successful mature rehabilitation (S5 and S6) was weakly positively correlated with soil pH levels and negatively correlated with soil magnesium, calcium, potassium, and available phosphorus concentrations (Figure 6-51). Intermediate successful rehabilitation (S4) was positively correlated with soil concentrations of nitrate and iron, and negatively correlated with sodium and zinc levels.

Unsuccessful rehabilitation in States D10, D9 and D7 were strongly correlated with the level of rock on the soil surface (Rock; Figure 6-52), and negatively correlated with litter cover and litter depth. Successful states (S4 in particular) were correlated with litter cover and litter depth.

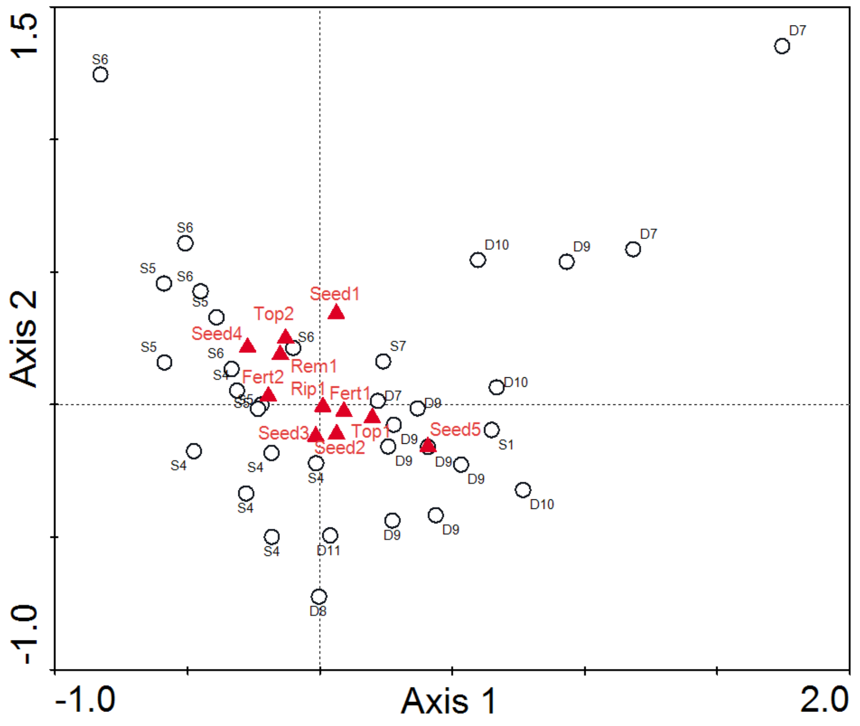


Figure 6-50 CCA bi-plot of rehabilitation sites (labelled by successional state as described in Table 6-5) and environmental variables. Categorical values of the treatment variables are labelled with codes which are explained in Table 4—2

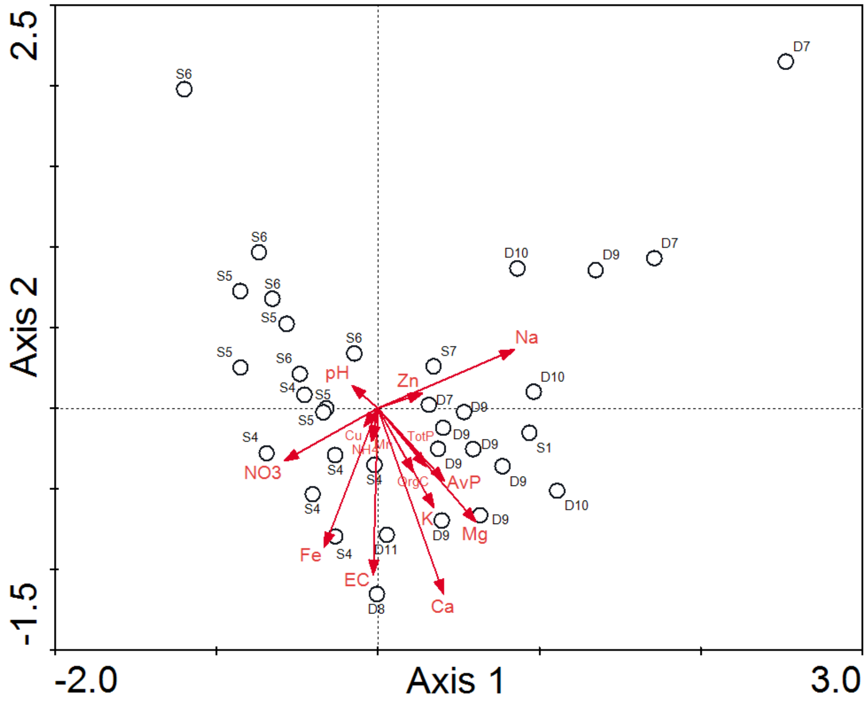


Figure 6-51 CCA bi-plot of rehabilitation sites (labelled by successional state as described in Table 6-5) and topsoil chemistry variables. Codes are explained in Table 4—3

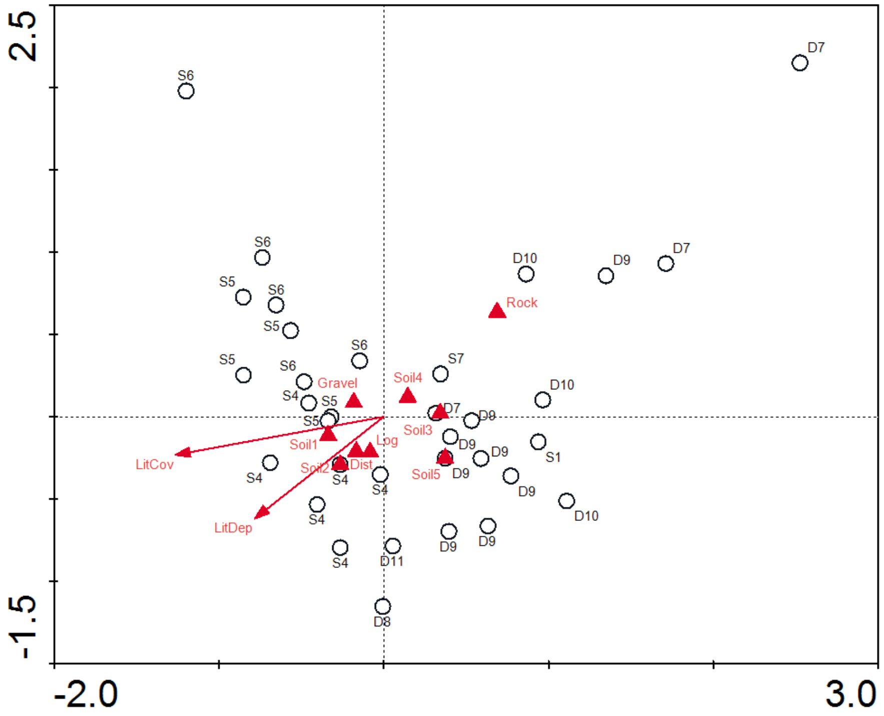


Figure 6-52 CCA bi-plot of rehabilitation sites (labelled by successional state as described in Table 6-5) and environmental variables for soil surface cover and profile structure. Categorical values of the profile structure variables are labelled with codes which are explained in Table 4-4 and Table 4─5

6.4 Discussion and Conclusions

The dynamics of the rehabilitation at Groote Eylandt are complex. The key transitional drivers are time, fire and interspecific competition between keystone species and grasses, weeds and acacias. Management activities at the outset of the rehabilitation process have a major bearing on the successional trajectory followed. For example, ordination analysis found correlations between unsuccessful rehabilitation and high levels of rock on the soil surface, perhaps due to the physical impediment by a rock cover of plant establishment or perhaps the rocks (often low-grade manganese-containing pisolites) had a chemical toxicity affecting vegetation. This suggests that material containing high levels of rocks should not be utilised in the surface layer of the rehabilitated soil profile. Successful rehabilitation was correlated with seed mixes of native species, remedial planting of eucalypt seedlings and stockpiled topsoil. While the former factors are readily recognisable as likely to contribute to good rehabilitation establishment and subsequent development, the stockpiled topsoil correlation is surprising. It may be that competition from aggressive species, such as grasses, is decreased following a reduction in the topsoil seed store due to stockpiling, leading to improved establishment of sown keystone species.

Management interventions also provide a method, sometimes the only method once a developmental threshold has been crossed, to redirect deviant sites back to states along the desired successional trajectory or pathway.

The potential rate of change in developing rehabilitation (i.e. plant growth rates, entry of new species, changes in absolute cover and biomass, and relative proportions of the biomass of each species) is greatest early in succession soon after plant establishment, the rate of change generally decreasing with increasing maturity of the system. The stage in succession when change is most rapid and when there is the greatest likelihood of the rehabilitation embarking on the desired trajectory or deviating on to an undesirable trajectory, is in the site preparation or establishment stage of rehabilitation (Section 5.3.1). As a result, early (0–3 years) management interventions are generally less intensive in terms of cost and effort than later opportunities.

Time is particularly relevant for tracking the development of successful rehabilitation, as development of the woody overstorey in particular (e.g. increased stem diameter and height) should increase directly with age. Age was correlated in the ordinations with successful sites, probably due to the inclusion of structural measures in the site-species matrix used in the analysis.

Time is less relevant when looking at unsuccessful rehabilitation, that has deviated from the desired trajectory. For these sites, and these ‘deviated trajectories’, time is not necessarily the common factor, as sites may have arrived in that state via a number of different trajectories, each potentially taking different lengths of time. For example, a 15-year-old rehabilitation site subjected to repeat burning may resemble a grassland and have more in common with a 3-year-old rehabilitation site dominated by grasses than with another 15-year-old site with different species structure or composition. Thus, for undesirable rehabilitation, developmental stage should not be assumed to be correlated with age.

Early identification of desirable and undesirable vegetation development enables management opportunities to be enacted when they are most cost-effective. More mature, deviated sites are a continued pressure on adjacent areas of newer rehabilitation. In particular, they are a source of weeds or introduced grasses that readily colonise these areas.

The introduction of fire into developing rehabilitation by prescribed burning, once eucalypts are likely to be fire-resilient, is important. This would ensure that the species composition and structure is that of the fire-resilient mature woodland and that later uncontrolled fires will not cause large changes. In other words, it increases confidence in the resilience of the system and supports withdrawal of ongoing management, such as active exclusion of fire. These steps are required prior to considering rehabilitation relinquishment.

While the basis of the proposed management interventions in the GEMCO rehabilitation succession model may be sound, some are likely to be unrealistically difficult to implement, such as prolonged exclusion of fire to rehabilitation dominated by grasses. Others, especially mechanical approaches such as clearing, may be more useful in larger areas requiring retreatment. Some techniques, such as chemical control may be very costly and may be limited to strategic application in appropriate circumstances. As several interventions are proposed for most states, the choice is up to the practitioner. Adaptive application of the proposed interventions should result in improved outcomes over time, as well as the identification of new opportunities.

The Groote Elyandt state-and-transition (S&T) model is similar to that developed for other ecosystems elsewhere. The complexity encountered in the early stages of the model is attributable to the nature of rehabilitation of severely disturbed areas. Models developed for natural systems, are generally much more simple and have a more steady rate of change throughout the trajectory (e.g. the northern speargrass eucalypt woodlands model of McIvor & Scanlan 1994). The Groote Eylandt model is only similar to the model developed specifically for rehabilitated ecosystems by Grant (1997, 2006), which influenced the collaborative research described here.

The succession model developed for rehabilitated vegetation after bauxite mining by Alcoa in Western Australia (Grant 2006) recognised five desirable and nine undesirable states of vegetation development, and six undesirable transitions, including 'ripping shallow or off contour, unblasted caprock, or inadequate soil return', wildfire, and 'spring prescribed burn'. While some of these transitions are related to certain states due to their occurrence in the rehabilitation timeline (i.e. site preparation activities generally affect the S0 State), it appears that in Grant's (2006) model, other transitions are only selectively recognised (at a particular time). For example, wildfire (undesirable transition T4) is suggested to affect only desirable rehabilitation between 5 and 15 years of age (state S3). This model does not recognise that this transition could affect younger or older desired vegetation or 'deviated' states. In fact, most deviated states in this model appear to be stable and unlikely to develop into alternate states without management manipulation.

The use of time as the *x*-axis in the Alcoa model (Grant 2006) is potentially confusing. The implication that site age necessarily has a major influence on the relationship of deviant states to the desired states and to each other is inappropriate. As argued for the GEMCO rehabilitation, stand age and stage of development are not necessarily related, especially in vegetation with undesirable characteristics such as stunted growth or dominance by a grass understorey subjected to repeated, intense fires. This is why the *x*-axis in the Groote Eylandt model describes developmental stage in relation to progression along the desired trajectory.

Once rehabilitation assessments are regularly made (through monitoring; Section 7.3.2), and the management interventions are routinely implemented, older rehabilitation areas in undesirable states should improve and be relocated back on the desired trajectory. Implementation of the recommended interventions, particularly earlier in the rehabilitation process, should see fewer older areas in undesirable states, and more areas on the desired trajectory. Once the older undesirable rehabilitation is dealt with, the Groote Eylandt model could be simplified to focus on any recurring undesirable transitions and developmental deviations, and the management manipulations required as a result. In the future, these will hopefully be concerned with rehabilitation establishment treatments and managing the disturbance regime.

Developing the GEMCO vital attributes – state-and-transition (VAST) model has confirmed concerns regarding the complexities of these systems. Variability in fire frequency and intensity is one of potentially many factors that could confound such an endeavour. Some of the information in the VA model is also difficult to assess, such as which key species should be included as representative of successional states or have the capacity to direct community succession at critical thresholds. Westman and O'Leary (1986), in their attempt to derive a VA replacement sequence for post-fire succession in coastal sage scrub, found that the vital attributes model was useful as it dealt with species individualistically in terms of their response to disturbance and acknowledges the potential for frequent disturbances, in particular fire. On the other hand, the VA method shows promise for developing replacement sequences for other disturbances that could potentially impact on rehabilitation at Groote Eylandt, such as cyclones or low-rainfall or short wet seasons. While not as frequent a disturbance as fire, these events have the potential to affect rehabilitation and need to be better understood and managed to reliably achieve best-practice rehabilitation outcomes.

The GEMCO VAST model developed here is limited by the range of states and ages assessed: insufficient sites less than 4 years of age were included in fieldwork so this section of the model lacks quantitative description of most of the young states. Despite this, many states, young and old, were able to be identified or predicted. Indeed, the model is potentially too complicated for the rehabilitation practitioner to use as a decision-making tool for management. Chapter 7 addresses this issue by presenting a simplified version of the model. Nevertheless, the information contained in the rehabilitation model for Groote Eylandt will be immediately useful for the assessment and management of older rehabilitation, particularly deviant sites. This was an important concern for the operation at the outset of this research. The VAST model and associated catalogues of sites and transitions will also enable quantification of the mine-wide status of the existing rehabilitation, and will indicate what, if anything, is required to manage or redirect rehabilitation development on a stand-by-stand basis.

Chapter 7 Synthesis and Conclusions

7.1 Introduction

This chapter synthesises the findings of the thesis in light of the broader aims of the research as well as the objectives of each component of the study. Recommendations for management at the GEMCO mining operation are presented, including a preliminary S&T model and proposed interim and completion assessment criteria for the desirable rehabilitation states. Finally the broader implications of the research for theory and practice are discussed and recommendations for further research are presented.

7.2 Summary of Results

The first data chapter (Chapter 3) described the *Eucalyptus tetrodonta* woodland of western Groote Eylandt and compared a range of vegetation parameters with those of 42 rehabilitated sites. GEMCO rehabilitation was found to be composed of some of the same species as the native woodland, but the structure, dominance and relative abundance of species was markedly different (Section 3.3.1). Although rehabilitation had fewer species overall, these sites tended to have more exotic species and higher densities of acacias in all strata compared to native woodland sites. Midstorey and overstorey structural development in rehabilitated sites corresponded to site age, although understorey density and cover did not. Classification and ordination of a matrix of species composition and structural data, revealed that the 33 rehabilitated sites formed six distinct groups (3.3.3). The remaining nine woodland sites were closely related to each other and formed the reference group, State Sx.

Chapter 4 utilised ordination techniques to reveal the relationships between the vegetation composition and structure of rehabilitation and woodland sites, and a range of environment and management variables. Six variables varied significantly between rehabilitation and woodland, including site age, litter depth, topsoil utilisation, seed mix, litter cover, and fertiliser (Section 4.3.2). Positive and negative relationships between vegetation measures and particular species were identified, contributing to understanding of the inter- and intra-species facilitation and competition mechanisms operating in the rehabilitation. For example, there was a negative correlation between grasses and eucalypt cover, canopy cover, overstorey acacia density, overstorey basal areas, litter cover and litter depth, highlighting the capacity of grasses to capture and dominate sites to the competitive exclusion of woody species.

A range of potential management interventions and a field trial was described in Chapter 5 with the aim of identifying options to control or affect the successional development of rehabilitation. The field trial focussed on the differences between fresh topsoil, subsoil, a topsoil/subsoil mix and a 'sandtails' waste product, to produce the best substrate conditions for early rehabilitation germination and establishment. Topsoil introduced many species in addition to those supplied as seed; however, topsoil-containing treatments showed less early establishment of the keystone eucalypts and higher grass cover than other treatments (Section 5.3.4). These findings, in addition to the good tree growth observed without fertiliser, challenge the traditional rehabilitation practices at GEMCO.

Chapter 6 combined a vital attributes (VA) model of the response of key species to time and disturbance by fire, with a state-and-transition (S&T) approach to develop a state-and-transition model for rehabilitation at Groote Eylandt incorporating the rehabilitation groups identified in Chapter 3. Rehabilitation sites with vegetation sharing the same set of vital attributes were considered to constitute a 'state' and were either transient or stable. Desirable rehabilitation states progress along a trajectory of states towards the target end-point ecosystem (Sx). States not positioned along this trajectory were regarded as undesirable and required further disturbance or management to effect their transition back to the desired trajectory. The Groote Eylandt S&T model includes a catalogue of states (Section 6.3.2) and a set of diagrammatic representations of the observed and hypothetical transitions between states. A set of interventions were developed that managers can adaptively apply to redirect deviated sites.

7.3 Management Recommendations for GEMCO

7.3.1 A Preliminary S&T Assessment Tool

The information and models presented in earlier chapters were used to produce a key to classify sites into successional groups or states. The classificatory key was based on the rehabilitation sites sampled during field research (Figure 7-1). Unfortunately, one limitation of the research was the inclusion of only one site in the very early developmental stage. This precluded detailed modelling of rehabilitation in this category, and the classificatory key is thereby limited to dealing with rehabilitation of an intermediate or greater stage of development. This is highlighted by the exclusion of any sites dominated by plants with an average height less than 2 m. Such sites are referred to an alternate key ('< 2m key'), which is yet to be developed.

The classificatory key should enable classification of new rehabilitation into one of the identified states (Figure 7-2). As sites are identified to a particular state, appropriate management interventions can be selected from the model (Table 7-1). The key will also be useful for auditing the existing rehabilitation so that the operation can determine the proportions of rehabilitation sites that are in a desirable condition or are substandard and potentially require management intervention to redirect them toward the desired end point. In addition to assessing the condition of more mature rehabilitation, an annual monitoring program would want to focus on early developmental stages but the current data do not permit this adequately.

The full suite of states also included states based on VA modelling and observations, which have yet to be quantified at Groote Eylandt. For states predicted in the modelling but yet to be observed, monitoring will have to target specific ages or developmental states to detect them. As more monitoring of rehabilitation is conducted at GEMCO, it is anticipated that more of the rarer rehabilitation states predicted from the VAST model will be identified and quantified. These can then be added to the simplified model, and the detailed model confirmed or corrected accordingly.

The sites most requiring further attention are those that occur early in the successional trajectory, when management efforts are likely to be most effective at ensuring desirable development. Repeated monitoring of the germination and establishment of sown seed will indicate where the most important stages of potential risk and opportunity exist. For example, low eucalypt densities observed after 1 year would be caused by either poor germination (requiring revision of the rehabilitation establishment technique, including timing, seed mix composition and quantities, seed handling and pre-treatments) or mortality in the first dry season (requiring assessment of other factors such as soil moisture holding capacity or competition from other species like grasses). Understanding these factors will enable management to respond to maximise success at these early developmental stages and improve the model in the area dealing with rehabilitation establishment and management options.

It is easier to make changes to rehabilitation processes or techniques at the start (substrate handling and vegetation establishment) than to attempt to deal with older failed rehabilitation, with problems like high grass loads, woody competition and so on. Resources available to progressive rehabilitation of newly mined-out areas may be affected by the need to redirect efforts to treating failed mature rehabilitation.

The general classificatory key has been developed for rehabilitation over 2 m in height, based on the quantitative data summarised in the catalogue of states (Section 6.3.2). Utilising seven vegetation variables than enable differentiation between the eight measured states, the dichotomous key proceeds through a series of first structural and then compositional assessments (Figure 7-1). These variables are:

- the presence or absence of vegetation;
- average dominant height;
- canopy cover;
- overstorey eucalypt density;
- overstorey density of non-eucalypt trees and tall shrubs;
- understorey cover of non-eucalypt trees and shrubs; and
- understorey weed cover.

General Classificatory Key for Rehabilitation at Groote Eylandt

1.	Bare ground	State 0
	Vegetation present	2
2.	Average dominant height ≤ 2 m	Use <2m key
	Average dominant height > 2 m	3
3.	Canopy cover ≤ 10 %	State D7
	Canopy cover > 10%	4
4.	Average dominant height < 5 m	State D10
	Average dominant height > 5 m	5
5.	Overstorey eucalypt density < 180 stems/hectare	State D9
	Overstorey eucalypt density > 180 stems/hectare	6
6.	Overstorey other tree density usually > 100 stems/hectare	7
	Overstorey other tree density usually < 100 stems/hectare	8
7.	Understorey other tree cover usually > 4 %	State S4
	Understorey other tree cover < 4 %	State S5
8.	Understorey weed cover usually > 2%	State S6
	Understorey weed cover usually < 2%	State Sx

Figure 7-1 General classificatory key for rehabilitation at Groote Eylandt

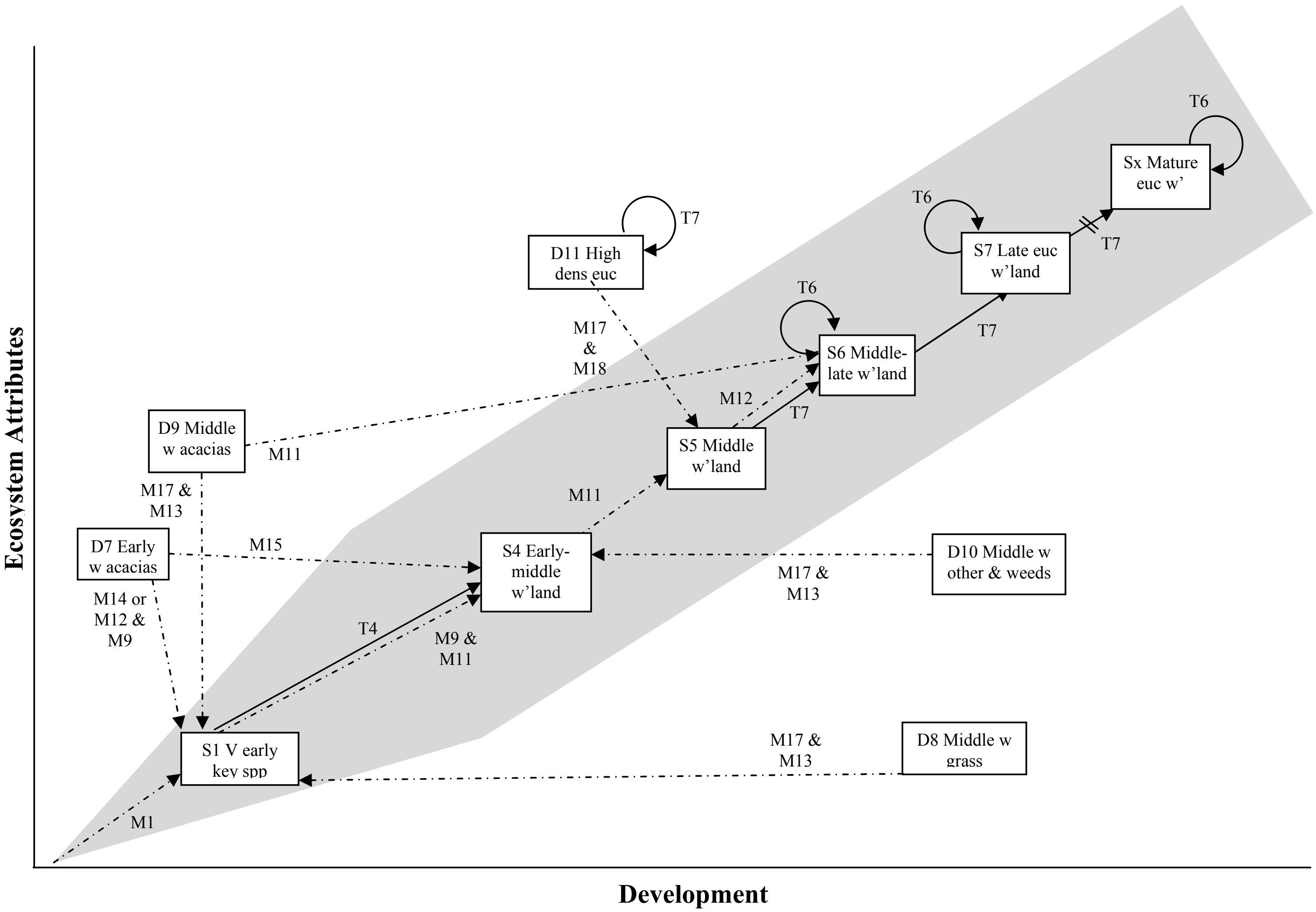


Figure 7-2 Simplified S&T model of observed states in GEMCO rehabilitation. Passive transitions (solid arrows) and management interventions (dashed arrows) facilitate development of desired states and redirect undesirable states. The shaded area represents the desired successional trajectory. Full descriptions of each state-and-transition are provided in Table 7-1

Table 7-1 Observed desirable and deviated states, and passive transitions and management interventions, in GEMCO rehabilitation

Identified desired states (approximate age in parentheses)	
S1 (< 1)	Very early-stage development eucalypt woodland (all seeded—keystone species present)
S4 (3 – 5)	Early–middle-stage development eucalypt woodland
S5 (5 – 10)	Middle-stage development eucalypt woodland
S6 (10 – 20)	Middle–late-stage development eucalypt woodland
S7 (> 20)	Late-stage development eucalypt woodland
S*x*	Mature eucalypt woodland
Identifiable deviated states	
D7	Early-stage development of eucalypt woodland dominated by acacias
D8	Middle-stage development of eucalypt woodland with high proportion of grasses
D9	Middle-stage development of eucalypt woodland dominated by acacias
D10	Middle-stage rehabilitation, dominated by non-eucalypt woody species and weeds
D11	Eucalypt–acacia woodlands with high stand density
Passive transitions	
T4	Time, natural recruitment
T6	Fire (natural regime, i.e. once every 2–3 years)
T7	Time (with no fire)
Management interventions	
M1	Fresh topsoil, good cultivation, native seed applied, weeds and grasses controlled
M9	Supply extra seed
M11	Protect from fire
M12	Prescribed (controlled) burn
M13	Cultivation/herbicide to remove grasses; supply extra seed/plants
M14	Cultivation to remove acacias; supply extra seed/plants
M15	Plant seedlings; protect from weeds and fire until mature
M17	Clear/thin dominant woody shrubs or trees
M18	Apply topsoil (e.g. sieved soil) seed store, and/or seed mix, as islands or strips

An additional classificatory key is required for rehabilitation with vegetation predominantly below 2 m in height, which could include young, desirable states (e.g. States S1 and S2) or deviated states with stunted growth or dominance by mid-storey or understorey species such as grasses (e.g. State D15 and D4; respectively). Development of such a classificatory key was beyond the scope of this research as the range of sites sampled did not extend to the early rehabilitation. Research to achieve this is proposed in Section 7.5.

7.3.2 Assessment Criteria and Rehabilitation Monitoring

The quantified characteristics of the desirable rehabilitation states could be considered preliminary interim assessment criteria for the different stages of rehabilitation. Diagrams summarising this information is presented for each state in the Catalogue of States (Section 6.3.2). The classificatory key is also based on these data, and represents a simplified method of application of the criteria for rehabilitation assessment. The key enables sites to be readily classified into one of the recognised eight successional states.

The classificatory key will be useful for general auditing of existing rehabilitation so that the operation can get a handle on the proportion of rehabilitation site wide that is of a desirable condition or is substandard and potentially requiring management intervention to progress it toward the desired end point.

These criteria are best applied within the context of regular rehabilitation monitoring. An annual monitoring program should focus on rehabilitation sites of ages where vegetation life stages is expected to meet the criteria of one of the recognised desired successional states. However, this annual program should include a clear focus on early developmental stages and it is apparent that this current set of data does not support this adequately. As more monitoring of rehabilitation is conducted at GEMCO, it is anticipated that more of these younger, predicted or rarer rehabilitation states will be able to be measured and quantified descriptive data obtained. These can then be added to this simplified model, and the overall model refined and updated accordingly. Further research is recommended below to further develop this area of the successional trajectory.

7.3.3 A Management Intervention Strategy

Existing mining operations undertaking progressive rehabilitation, such as GEMCO at Groote Eylandt, are likely to have existing rehabilitation containing a range of successional states, including failed and successful, and young and older sites. The overall aim of managing this rehabilitation is to influence the development of all failed sites so that they result in successful, older rehabilitation. Successful, younger rehabilitation may require some management to enable it to continue to develop toward the desired mature state.

A reasonable strategy for prioritising the limited resources and time available to manage existing rehabilitation would include:

- Protect young successful sites from fire and weeds so that their development toward a successful state is likely;
- Undertake obvious remedial activities (such as supplementary planting, weed control, fire exclusion) in failed younger rehabilitation sites as this is where the most 'return' for effort will be gained;
- Consider some obvious remedial activities in failed older rehabilitation, however these systems may require more significant, complicated efforts that should be fully researched and understood prior to expending significant effort;
- Conduct research and development into the best remedial activities available to correct identified characteristics of failed rehabilitation of all ages; and
- Consider high intensity remedial activities for failed sites with no potential to respond to simple, obvious remediation measures. As an extreme example, this could include clearing the site, treating for any weed presence, and re-seeding from scratch.

A range of remedial activities, or management interventions, is proposed in this thesis with the potential to effect desired transitions, either facilitating rehabilitation along the desired trajectory, or redirecting deviant sites back toward it. It is important to apply the most effective intervention with due regard to resourcing constraints such as labour, machinery, costs and timing. It is therefore advisable that the operation assess each recommended management intervention for its practicality, and take the opportunity to identify innovative or modified methods for effecting desired transitions within existing operating constraints. A series of small scale trials is proposed, which would be best carried out utilising the range of substandard rehabilitation already present, to assess the practical implications of the management interventions as well as assess the response of the vegetation to treatment. The information from such trials would ideally build on the model proposed here.

The success of ecosystem rehabilitation in mining is heavily influenced by activities that may occur well before the first clod of earth is turned. Issues relating to soil handling, substrate selection, seed collection and dispersal, use of fertilisers and so on all have a significant bearing on the final outcome of rehabilitation (Table 7.1). Another major factor in the success of rehabilitation is its development through time, so management options involving protection from fire or competition from weeds and desirable species in undesirable densities are important (Table 7.2). As research into the rehabilitation processes utilised on Groote Eylandt is still at an early stage, initial trials must remain simple due to the number of unknown factors. It is recommended that a number of trials be conducted to continue to refine current techniques and identify the management interventions that are most promising for facilitating desirable rehabilitation at Groote Eylandt.

These trials require the use of heavy machinery to create fire-breaks to restrict fires to appropriate treatment areas. Replicated sets of measuring plots per treatment would be required for each trial (e.g. Figure 7-3). The success of remedial plantings could also be assessed by including this as a factor in the trial (Figure 7-4). It would be necessary to have rehabilitation areas of varying ages of the same state (e.g. acacia overabundance) for each trial. However, it has been argued in Section 6.4, that state is more important for correcting deviated states than age. The experiments utilising deviated sites of varying age would test the hypothesis that age is not important to remediating a particular state and that remediation can focus on state, regardless of age.

Table 7-2 A list of the various experimental trials and treatments suitable for management interventions available at rehabilitation establishment

Management Intervention	Treatments to Trial
Topsoil application method	• Double stripped and direct return • Double stripped and stockpiled • Single stripped and direct return • Single stripped and stockpiled *(current procedure)* • [Nil (sandtails or overburden)]
Cultivation methods	• Ripping only • Ripping and scarifying • Ripping and double scarifying *(current procedure)*
Cultivation timing	• Ripping early • Ripping and scarifying early • Ripping early and scarifying later (nearer seeding) • Ripping late dry and scarifying later (*current procedure*)
Seeding timing (consider with cultivation methods/timing)	• Early dry season • Late dry season
Seeding details	• Composition of seed mix • Use of germination cues, e.g. smoked water (Norman *et al*. 2006b)
Fertiliser type	• SuperP (*current procedure*) • DAP (*current procedure*) • More-reduced N content
Fertiliser timing	• Just prior to seeding (*current procedure*) • 6 Weeks after seeding or x months after seeding
Fertiliser application rates	• 200-300 kg/ha SuperP (*current procedure*) • 200-300 kg/ha DAP (*current procedure*) • 500 kg/ha Lime (*current procedure*)

Table 7-3 A list of the various experimental treatments available involving management interventions to correct deviated rehabilitation

Factor	Treatments
Chemical weed management	• Pre-establishment herbicide spraying • Post-establishment herbicide spraying
Physical weed management	• Late scarifying to remove emergent weeds followed by re-application of broadcast seed mix • Application of sandtails over weed-infested areas (incl. around existing seedlings) (followed by fertiliser and/or re-seeding) • Other mulching methods • Use of overburden versus topsoil (depth of application, sown and/or planted) • Use of sandtails versus topsoil (depth of application, sown and/or planted) • Thinning or clearing of acacias to alleviate suppression of other woody species
Fire management	• Prescribed burning (timing, age of rehabilitation, acacia-dominated) • Use of fire-retardant mulch

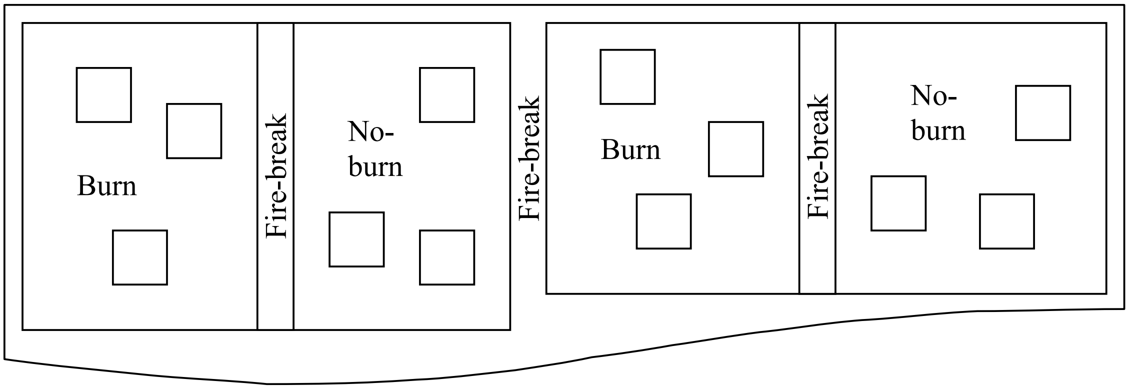


Figure 7-3 Diagrammatic representation of the proposed fire management trial for grasses and acacias.

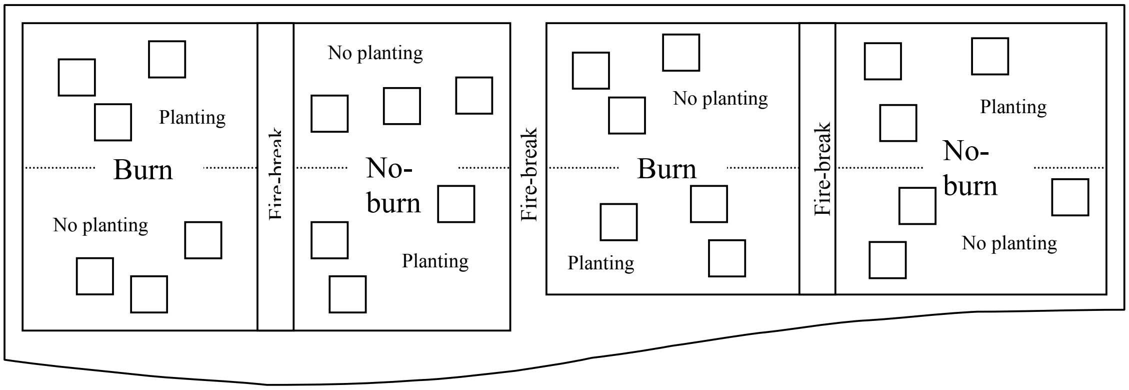


Figure 7-4 Diagrammatic representation of the proposed fire management trial for grasses and acacias incorporating remedial planting of seedlings versus none

7.4 Broader Implications of the Research for Theory and Practice

The approach to defining successional development and assessment criteria in the rehabilitation of a natural ecosystem presented in this thesis has considerable potential to be applied to other restoration scenarios in Australia and around the world. This approach is applicable in a wide variety of ecosystems and land uses (e.g. mining, forestry and agriculture) (Bestelmeyer *et al*. 2003; Ruiz-Jaen and Aide 2005; Grant 2006). It is a practical land management approach that can provide value even in a relatively simple form. It can also be continually refined and updated through repeated use and testing.

The particular S&T model developed by the research should be valuable model to GEMCO land managers as it not only describes all existing and suspected vegetation states, but identifies the factors effecting transitions between these states and the intervention strategies that can be used to bring unsuccessful rehabilitation attempts back to the desired trajectory. The contribution of the vital attributes is that they focus attention on the critical life stages of the keystone rehabilitation species so that managers are able to concentrate their efforts on facilitating positive transitions and avoiding negative changes at each stage. For example, the risk of fire in young eucalypt communities which have yet to develop fire-resistant characteristics cannot be stressed too highly. Control of weeds and grasses during this period will reduce the risk of fire in this vegetation, as will adopting fire prevention strategies such as fire breaks and prescribed burning in surrounding vegetation.

This research shows that application of successional theory to practice is not simple, especially in a rehabilitation scenario where the origin of the developmental trajectory is unlike any normally encountered in the natural environment. Observations of transitions in response to disturbance, in particular fire, would generate information that could greatly improve the model.

The combination of VAs and S&T in a VAS&T (VAST) approach to understanding rehabilitation succession permitted development of a classificatory key for practical rehabilitation assessment and identification of management intervention opportunities at Groote Eylandt. The VAST approach has potential for post-mining rehabilitation elsewhere and will be an invaluable tool for simply and clearly communicating rehabilitation targets and development with government regulators, which has otherwise been a difficult task (Morrison *et al*. 2005).

The overall objective of minesite rehabilitation is to successfully reach the stated target endpoint, to the satisfaction of all relevant stakeholders, and achieve relinquishment of land to the appropriate regulator. While the application of expert effort and resources to rehabilitation at the operational level is of critical importance, the objective relies equally on the ability of the government regulator to understand the predicted succession of the rehabilitation so that they can have the high level of confidence required before relinquishment (reduction in ongoing liability) is approved (Qld EPA 2004). This understanding of complex ecological theories and analyses is often lacking at the regulator level (and often at the operator level also). Simple tools, based on sound ecological science, that can be developed to clearly and directly explain the current and predicted condition and dynamics of rehabilitation would significantly improve the level of regulator-operator communication and confidence regarding rehabilitation efforts. The VAST approach provides such as simple tool whilst ensuring a foundation of sufficient scientific rigour.

7.5 Recommendations for Further Research

While the VAST approach has proven useful, the criteria developed as part of this research are insufficient to provide quantitative criteria for the younger or more deviant rehabilitation states. An additional classificatory key is required for rehabilitation where vegetation is predominantly below 2 m in height, including young desirable states (e.g. states S1 and S2) or deviated states with stunted growth or dominance by mid-storey or understorey species such as grasses (e.g. states D15 and D4, respectively). Such a key would focus less on the structural characteristics of the community and more on the composition and densities of desirable keystone species and undesirable plants (such as weeds and exotic grasses). These assessments would require less specialised training and botanical expertise, and be primarily concerned with the presence of minimum densities of desired species and an absence, or maximum density or cover, of undesirable species such as grasses, weeds and acacias.

Potential states identified by the VAST approach but that have not yet been identified in the field should be located and quantitatively defined, as part of refining the GEMCO rehabilitation model, increasing the number of the field sample sites (and therefore model rigour), and improving the underlying data set and information base. Improving the succession model of rehabilitation at Groote Eylandt will also require continued monitoring (Section 7.3.2), plus onsite field trials (Section 7.3.3). A monitoring program should be instituted to develop the S&T

model, utilise the assessment criteria developed as part of this research, and effect the required transitions, through management intervention, to improve rehabilitation outcomes.

The research presented in this thesis focussed on vegetation composition and structure. This should represent the first phase of a larger program to improve rehabilitation outcomes at Groote Eylandt. Later phases of the program should investigate rehabilitation in terms of functional aspects such as nutrient cycling, invertebrate and vertebrate recolonisation, seed set and presence of pollinators.

Germination of sown seed in the field trial (Section 5.3) was remarkably low, with some species failing to germinate and establish at all, regardless of substrate. Failure to germinate when supplied as seed, or from freshly-returned topsoil, suggests that further research is required into the species which failed to emerge to ensure correct seed management and identify recalcitrant traits which need special techniques, for example pre-seeding treatments such as scarification.

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Appendices

Appendix A Plant species list of 195 species recorded in monitoring plots

Family	Species Name	Abbreviation	Life form
Adiantaceae	*Cheilanthes contigua* Baker	Che con	Fern
Amaranthaceae	*Alternanthera denticulata* R.Br.	Alt den	Herb
	Ptilotus distans (R.Br.) F.Muell.	Pti dis	Herb
Amaryllidaceae	*Crinum uniflorum* F.Muell.	Cri uni	Sedge/Lily
Anacardiaceae	*Buchanania obovata* Engl.	Buc obo	Tree, other
Apocynaceae	*Alyxia spicata* R.Br.	Aly spi	Shrub
	Carissa lanceolata R.Br.	Car lan	Shrub
	Wrightia saligna (R.Br.) F.Muell. ex Benth.	Wri sal	Tree, other
Aristolochiaceae	*Aristolochia pubera* R.Br.	Ari tho	Vine
Asclepiadaceae	*Marsdenia viridiflora* R.Br.	Mar vir	Vine
Asteraceae	*Blumea saxatilis* Zoll & Moritzi	Blu sax	Herb
	Cyanthillium cinereum (L.) H.Rob. (syn *Vernonia cinerum* (L.) Less.)	Cya cin	Herb
	Emilia sonchifolia (L.) DC	Emi son	Non-native
	Pterocaulon serrulatum (Montouz.) Guillaumin	Pte ser	Herb
	Tridax procumbens L.	Trx pro	Herb
Bixaceae	*Cochlospermum gillevayii* Benth.	Coc gil	Tree, other
Boranginaceae	*Heliotropium ventricosum* R. Br.	Hel ven	Herb
Burseraceae	*Canarium australianum* (F.M. Bailey) Leeh.	Can aus	Tree, other
Caesalpinaceae	*Chamaecrista absus* (L.) Irwin & Barneby (syn *Cassia absus* L.)	Cha abs	Herb
	Chamaecrista mimosoides (L.) Greene (syn *Cassia mimosoides* L.)	Cha mim	Herb
	Erythrophleum chlorostachys (F.Muell.) Baill.	Ery chl	Tree, other
Centrolepidaceae	*Centrolepis exserta* (R.Br.) Roem. & Schult.	Cen exs	Sedge/Lily
Combretaceae	*Terminalia carpentariae* C.T.White	Ter car	Tree, other
	Terminalia hadleyana subsp. *carpentariae* (C.T.White) Pedley	Ter had	Tree, other
	Terminalia sp. 2	Ter sp2	Tree, other
Commelinaceae	*Cartonema spicatum* R.Br.	Car spi	Herb
	Commelina ensifolia R.Br.	Com ens	Herb
	Murdannia graminea (R.Br.) A.Bruckn.	Mur gra	Herb
Convolvulaceae	*Bonamia media* (R.Br.) Hallier f.	Bon med	Vine
	Evolvulus alsinoides var. *decumbens* (R.Br.) Ooststr.	Evo als	Vine
	Ipomoea diversifolia R.Br.	Ipo div	Vine
	Ipomoea eriocarpa R.Br.	Ipo eri	Vine
	Ipomoea pes-caprae (L.) R.Br.	Ipo pes	Vine
	Ipomoea polymorpha Roem. & Schult.	Ipo pol	Vine
	Ipomoea sp. aff. *gracilis*	Ipo gra	Vine
	Merremia quinata (R.Br.) Ooststr	Mer qui	Vine
	Polymeria ambigua R.Br.	Ply amb	Vine
Cupressaceae	*Callitris intratropica* R.T.Baker H.G.Sm.	Cal int	Tree, other
Curcurbitaceae	*Mukia maderaspatana* (L.) M.Roem.	Muk mad	Vine
Cycadaceae	*Cycas arnhemica* subsp. *Muninga* K.D.Hill	Cyc arn	Tree, other
Cyperaceae	*Cyperus compressus* (L.)	Cyp com	Non-native
	Fimbristylis cinnamometorum (Vahl) Kunth	Fim cin	Sedge/Lily
	Fimbristylis densa S.T.Blake	Fim den	Sedge/Lily
	Fimbristylis dichostema	Fim dic	Sedge/Lily
	Fimbristylis macrantha Boeck.	Fim mac	Sedge/Lily
	Fimbristylis squarrulosa F.Muell.	Fim squ	Sedge/Lily
	Fuirena cilliaris (L.) Roxb.	Fui cil	Sedge/Lily
	Rhynchospora heterochaeta S.T.Blake	Rhy het	Sedge/Lily
	Schoenus sparteus R.Br.	Sch spa	Sedge/Lily
	Scleria sp.	Scl sp1	Sedge/Lily
Dilleniaceae	*Hibbertia lepidota* R. Br.	Hib lep	Herb
	Hibbertia oblongata R.Br. ex DC.	Hib obl	Shrub

Family	Species Name	Abbreviation	Life form
Dilleniaceae	*Pachynema sphrenandrom* F.Muell. & Tate	Pac sph	Herb
Dioscoreaceae	*Dioscorea bulbifera* L.	Dio bul	Vine
Droseraceae	*Drosera petiolaris* R.Br. Ex DC	Dro pet	Herb
Erythroxylaceae	*Erythroxylum ellipticum* R. Br. ex Benth	Ery ell	Tree, other
Euphorbiaceae	*Breynia cernua* (Poir.) Mull.Arg.	Bre cer	Tree, other
	Bridelia tomentosa Blume	Bri tom	Tree, other
	Drypetes deplanchei (Brongn. & Griseb.) Merr.	Dry dep	Shrub
	Euphorbia heterophylla L.	Eup het	Non-native
	Euphorbia schultzii Benth.	Eup shu	Herb
	Euphorbia vachellii Hook. & Arn.	Eup vac	Herb
	Flueggea virosa (Roxb. ex Willd.) Voigt	Flu vir	Tree, other
	Petalostigma banksii Britten & S.Moore	Pet ban	Tree, other
	Petalostigma quadriloculare F.Muell.	Pet qua	Tree, other
	Phyllanthus hebecarpus Benth.	Phy heb	Herb
	Phyllanthus minutiflorus F.Muell. ex Mull.Arg.	Phy min	Herb
	Phyllanthus trachygyne Benth.	Phy tra	Herb
	Phyllanthus virgatus G.Forst.	Phy vir	Herb
	Sauropus stenocladus (Muell. Arg.) subsp. *pinifolius* J.T Hunter & J.J. Bruhl	Sau ste	Herb
	Sebastiania chamaelea (L.) Mull.Arg.	Seb cha	Herb
Fabaceae	*Alysicarpus vaginalis* (L.) DC.	Aly vag	Non-native
	Cajanus marmoratus (R.Br. ex Benth.) F.Muell.	Caj mar	Vine
	Cajanus scaraboides	Caj sca	Vine
	Crotalaria calycina Schrank	Cro cal	Herb
	Crotalaria montana Roth	Cro mon	Herb
	Desmodium trichostachyum Benth.	Des tri	Herb
	Flemingia parviflora Benth. (syn *F. schultzii* (F.Muell.))	Fle par	Vine
	Gompholobium subulatum Benth.	Gom sub	Herb
	Macroptilium atropurpureum (DC.) Urb.	Mac atr	Non-native
	Pycnospora lutescens (Poir.) Schindl.	Pyc lut	Herb
	Stylosanthes scabra Vogel	Sty sca	Non-native
	Tephrosia leptoclada Benth.	Tep lep	Herb
	Tephrosia polyzyga R.Br. ex Benth.	Tep pol	Herb
	Uraria lagopodioides (L.) Desv. ex DC.	Ura lag	Vine
	Vigna lanceolata var. *filiformis* Benth.	Vig lan	Vine
	Vigna vexillata (L.) A.Rich	Vig vex	Vine
Goodeniaceae	*Goodenia pilosa* (R.Br.) Carolin	Goo pil	Herb
Haemodoraceae	*Haemodorum coccineum* R.Br.	Hae coc	Sedge/Lily
Haloragaceae	*Gonocarpus leptothecus* (F.Muell.)Orchard	Gon lep	Herb
Lamiaceae	*Hyptis suaveolens* (L.) Poit.	Hyp sua	Non-native
Lauraceae	*Cassytha filiformis* L.	Cas fil	Herb
Lecythidaceae	*Planchonia careya* (F.Muell.) Kunth	Pla car	Tree, other
Lilliaceae	*Chlorophytum laxum* R.Br.	Chl lax	Sedge/Lily
	Dianella longifolia R.Br.	Dia lon	Sedge/Lily
	Iphigenia indica (L.) Kunth	Iph ind	Sedge/Lily
	Thysanotus chinensis Benth.	Thy chi	Sedge/Lily
Loganiaceae	*Mitrasacme connata* R.Br. (syn *M.constricta* F.Muell.)	Mit con	Herb
	Mitrasacme exserta F.Muell.	Mit exs	Sedge/Lily
Lomandraceae	*Lomandra tropica* A.T.Lee	Lom tro	Sedge/Lily
Malvaceae	*Hibiscus meraukensis* Hochr	Hib mer	Herb
	Sida cordifolia L.	Sid cor	Non-native
Melastomataceae	*Melastoma affine* D.Don	Mla aff	Shrub
Mimosaceae	*Acacia auriculiformis* A.Cunn. ex Benth.	Aca aur	Acacia
	Acacia difficilis Maiden	Aca dif	Acacia
	Acacia holosericea A.Cunn. ex G.Don	Aca hol	Acacia
	Acacia lamprocarpa O.Schwarz (syn *A. aulacocarpa* A.Cunn. ex Benth.)	Aca aul	Acacia

Family	Species Name	Abbreviation	Life form
Mimosaceae	*Acacia latescens* Benth.	Aca lat	Acacia
	Acacia multisiliqua (Benth) Maconochie	Aca mul	Acacia
	Acacia oncinocarpa Benth.	Aca onc	Acacia
	Acacia sp.	Aca sp1	Acacia
	Acacia torulosa Benth.	Aca tor	Acacia
	Acacia yirrakallensis Specht	Aca yir	Acacia
Myrtaceae	*Asteromyrtus magnifica* (Specht) Craven	Ast mag	Tree, other
	Asteromyrtus symphyocarpa (F.Muell.) Craven	Ast sym	Tree, other
	Corymbia ferruginea ssp. *ferruginea*	Euc fer	Eucalypt
	Corymbia polycarpa (F.Muell.) K.D.Hill & L.A.S.Johnson	Euc pol	Eucalypt
	Eucalyptus bigalerita F.Muell.	Euc big	Eucalypt
	Eucalyptus camaldulensis Dehnh.	Euc cam	Eucalypt
	Eucalyptus miniata A.Cunn. ex Schauer	Euc min	Eucalypt
	Eucalyptus tetrodonta F.Muell.	Euc tet	Eucalypt
	Lithomyrtus retusa (Endl.)N.Snow & Guymer	Lit ret	Shrub
	Melaleuca leucodendra (L.) L.	Mel leu	Tree, other
	Melaleuca viridiflora Sol. Ex Gaertn.	Mel vir	Tree, other
Oleaceae	*Jasminum molle* R.Br.	Jas mol	Vine
Orchidaceae	*Habenaria ochroleuca* R.Br. (syn *H.eurystoma* Schltr)	Hab och	Orchid
Pandanaceae	*Pandanus spiralis* R.Br.	Pnd spi	Tree, other
Passifloraceae	*Passiflora foetida* L.	Pas foe	Vine
Poaceae	*Aristida holathera* var. *holathera*	Ari hol	Grass
	Aristida hygrometrica R.Br.	Ari hyg	Grass
	Arundinella nepalensis Trin.	Aru nep	Grass
	Brachiaria sp.	Bra sp1	Grass
	Chloris barbata (L.) Sw.	Chl bar	Non-native
	Cynodon dactylon (L.) Pers.	Cyn dac	Non-native
	Dactyloctenium radulans (R.Br.) P.Beauv.	Dac rad	Grass
	Dicanthium sp.	Dic sp1	Grass
	Digitaria decumbens Stent	Dig dec	Grass
	Echinochloa sp.	Ech sp1	Grass
	Ectrosia leporina R.Br.	Ect lep	Grass
	Eragrostis cumingii Steud	Era cum	Grass
	Eriachne avenaceae R.Br.	Eri ave	Grass
	Eriachne ciliata R.Br.	Eri cil	Grass
	Heteropogon contortus (L.) P.Beauv. ex Roem. & Schult.	Het con	Grass
	Heteropogon triticeus (R.Br.) Stapf	Het tri	Grass
	Melinis repens (Wild) Zizka	Mln rep	Non-native
	Mnesithea sp.	Mne sp1	Grass
	Panicum maximum Jacq. A.	Pan max	Non-native
	Paspalidium rarum (R.Br.) Hughes	Psp rar	Grass
	Paspalum sp.	Psp sp1	Grass
	Phragmites vallatoria (Pluk ex L.) Veldkamp (syn *P.karka* (Retz.) Trin. ex Steud.)	Phr kar	Grass
	Schizachyrium fragile	Sch fra	Grass
	Setaria apiculata (Scribn. & Merr.) K.Schum.	Set api	Grass
	Sorghum stipoideum (Ewart & Jean White) C.A.Gardner & C.E.Hubb	Sor sti	Grass
	Thaumastochloa pubescens (Benth.) C.E.Hubb	Tha pub	Grass
	Themeda quadrivalis (L.) Kuntze	The qua	Non-native
	Triodia sp.	Tri sp1	Non-native
	Yakirra muelleri (Hughes) Lazarides & R.D.Webster	Yak mue	Grass
Polygalaceae	*Polygala eriocephala* F.Muell. ex Benth.	Pol eri	Herb
	Polygala orbicularis Benth.	Pol orb	Herb
	Polygala pycnophylla Domin	Pol pyc	Herb
	Polygala stenoclada Benth.	Pol ste	Herb

Family	Species Name	Abbreviation	Life form
Proteaceae	*Grevillea heliosperma* R.Br.	Grv hel	Tree, other
	Grevillea pteridifolia Knight	Grv pte	Tree, other
	Grevillea pungens R.Br.	Grv pun	Tree, other
	Hakea arborescens R.Br.	Hak arb	Tree, other
	Persoonia falcata R.Br.	Per fal	Tree, other
Rhamnaceae	*Alphitonia excelsa* (A.Cunn. Ex Fenzl) Reissek ex Benth.	Alp exc	Tree, other
Rubiaceae	*Borreria leptidota*	Bor lep	Herb
	Kailarsenia suffruticosa (R.Br. ex Benth.) Puttock	Kai suf	Herb
	Oldenlandia mitrasacmoides (F.Muell.) F.Muell.	Old mit	Herb
	Spermacoce breviflora F.Muell. ex Benth.	Spe bre	Herb
	Spermacoce gilliesiae (Specht) J.R.Clarkson	Spe gil	Herb
Santalaceae	*Exocarpos latifolius* R.Br.	Exo lat	Shrub
Sapindaceae	*Distichostemon hispidulus* (Endl.) Baill.	Dis his	Shrub
Scrophulariaceae	*Striga curviflora* (R.Br.) Benth.	Str cur	Herb
Smilacaceae	*Smilax australis* R.Br.	Smi aus	Vine
Stackhousiaceae	*Stackhousia intermedia* F.M.Bailey	Sta int	Herb
Sterculiaceae	*Brachychiton diversifolius* R.Br.	Bra div	Tree, other
	Brachychiton paradoxus Schott & Endl.	Bra par	Tree, other
	Helicteres cana (Schott & Endl.) Benth.	Hel can	Herb
	Keraudrenia corollata (Steetz) Domin	Ker cor	Shrub
	Waltheria indica L.	Wal ind	Herb
Taccaceae	*Tacca leontopetaloides* (L.) Kuntze	Tac leo	Herb
Thymelaeaceae	*Thecanthes punicea* (R.Br.) Wikstr.	Thc pun	Herb
	Arnhemia cryptantha Airy Shaw	Arn cry	Vine
Tiliaceae	*Grewia retusifolia* Kurz.	Gre ret	Shrub
Ulmaceae	*Trema tomentosa* (Roxb.) H.Hara	Tre tom	Tree, other
Verbenaceae	*Clerodendrum floribundum* R.Br.	Cle flo	Tree, other
	Stachytarpheta jamaicens (L.) Vahl	Sta jam	Non-native
Violaceae	*Hybanthus enneaspermus* (L.) F.Muell.	Hyb enn	Herb
Vitaceae	*Ampelocissus acetosa* (F.Muell.) Planch.	Amp ace	Vine
Unknown	Unknown herb sp. 1	Hrb sp1	Herb
	Unknown sp. 1	Unk sp1	Tree, other
	Unknown sp. 2	Unk sp2	Shrub
	Unknown sp. 3	Unk sp3	Acacia
	Unknown sp. 6	Unk sp6	Shrub

Appendix B–a Select floristic characteristics of rehabilitation ages and forest sites (2000 dry season and 2001 wet season data)

Age of Rehab.	N (sites)	Canopy Cover (%)		Species Richness		Shannon–Wiener Diversity Index	
		Avg. (SE)	Range	Avg. (SE)	Range	Avg .(SE)	Range
0.5	1	0	0	50	na	3.0	na
2	3	8 (8)	0.1-23	45 (2.2)	42-49	2.4 (0.2)	2.1-2.7
3	4	30 (12)	10-63	42 (3.8)	31-48	2.6 (0.1)	2.4-2.7
4	6	39 (10)	14-68	39 (3.2)	31-49	2.6 (0.2)	2.0-3.1
6	1	61	na	45	na	2.5	na
7	4	67 (12)	32-85	41 (2.6)	34-46	2.9 (0)	2.8-3.0
8	1	40	na	35	na	2.3	na
11	3	46 (10)	28-61	41 (2.3)	39-46	2.5 (0.2)	2.0-3.1
12	1	60	na	47	na	2.7	na
13	2	61 (11)	50-72	30 (7)	23-37	2.1 (0.1)	2.0-2.2
14	1	45	na	32	na	2.1	na
15	3	61 (13)	38-83	34 (2.7)	30-39	2.3 (0.3)	1.7-2.7
17	2	38 (15)	23-54	40 (0.6)	39-40	2.3 (0.2)	2.2-3.2
19	1	37	na	50	na	3.2	na
Rehab. Average	33	43 (4)	0-85	41 (1.4)	23-50	2.5 (0.1)	1.7-3.2
Woodland	9	59 (4)	45-78	51 (2.7)	38-63	2.9 (0.1)	2.5-3.2
Analysis of Variance[1]		(sqrt) F = 10.95, P = 0.0057		(np) KWstat = 18.1033, P = 0.2021		(np) KWstat = 24.0793, P = 0.0448	
Significance[2]							

[1] Analysis of variance was conducted on transformed data (sqrt) or by the Kruskal-Wallis method where data were found to be non-parametric (np).

[2] Bonferroni correction for 16 tests: *** 0.001 P = 0.000063, ** 0.01 P = 0.00063, * 0.05 P = 0.0031

Appendix B–b Select overstorey vegetation characteristics of rehabilitation ages and woodland sites (2000 dry season data)

Age of Rehab.	N (sites)	Overstorey Eucalypts (stems/ha)		Overstorey Acacias (stems/ha)		Overstorey 'Other' (stems/ha)	
		Avg. (SE)	Range	Avg. (SE)	Range	Avg. (SE)	Range
0.5	1	0	na	0	na	0	na
2	3	11 (11)	0-33	33 (33)	0-100	22 (22)	0-67
3	4	133 (133)	0-533	258 (66)	100-367	8.3 (8.3)	0-33
4	6	106 (38)	33-267	606 (144)	100-1000	78 (65)	0-400
6	1	100	na	500	na	133	na
7	4	1200 (274)	500-1933	725 (203)	367-1300	442 (76)	267-600
8	1	333	na	467	na	67	na
11	3	511 (78)	367-633	233 (233)	0-700	167 (107)	0-367
12	1	900	na	0	na	33	na
13	2	1283 (217)	1066-1500	83 (50)	33-133	17 (17)	0-33
14	1	900	na	0	na	0	na
15	3	756 (230)	300-1033	167 (96)	167-333	56 (40)	0-133
17	2	317 (250)	67-567	133 (100)	33-233	67 (67)	0-133
19	1	67	na	200	na	67	na
Rehab. Average	33	450 (88)	0-1933	308 (58)	0-1300	73 (28)	0-400
Woodland	9	489 (76)	167-900	44 (36)	0-333	48 (27)	0-200
Analysis of Variance		F = 6.50, P = 0.0000		F = 3.16, P = 0.0046		F = 3.64, P = 0.0017	
Significance[1]		***				*	

[1] Bonferroni correction for 16 tests: *** 0.001 P = 0.000063, ** 0.01 P = 0.00063, * 0.05 P = 0.0031

Appendix B–c Select overstorey vegetation characteristics of rehabilitation ages and woodland sites (dbhob = diameter at breast height (1.3 m) over bark; 2000 dry season data)

Age of Rehab.	N (sites)	Average Overstorey Height[1] (m)		Average Dominant (Top 2) Height (m)		Average Overstorey dbhob[1] (cm)	
		Avg. (SE)	Range	Avg. (SE)	Range	Avg. (SE)	Range
0.5	1	-	na	2.1	na	-	na
2	3	4.5	na	3.8 (0.4)	3.2-4.4	5.7	na
3	4	4.6 (0.3)	4.0-5.5	5.3 (0.7)	4.1-6.8	6.0 (0.9)	4.3-8.7
4	6	5.6 (0.2)	4.8-6.3	5.7 (0.6)	3.1-7.3	6.4 (0.5)	5.1-7.6
6	1	5.5	na	5.9	na	6.3	na
7	4	6.8 (0.4)	5.8-7.6	10 (1.1)	7.3-13	6.7 (0.5)	5.8-8.1
8	1	6.9	na	8.3	na	7.7	na
11	3	6.3 (0.4)	5.3-7.1	7.2 (1.8)	3.5-12	8.0 (1.7)	5.9-11
12	1	7.9	na	9.5	Na	7.2	na
13	2	8.2 (0.8)	7.4-9.0	11 (1.0)	10.3-12	7.2 (0.9)	6.3-8.2
14	1	7.3	na	9.8	na	9.4	na
15	3	8.8 (1.0)	7.5-11	12 (1.6)	9.8-15	10 (0.9)	8.2-11
17	2	7.6 (0.5)	7.1-8.2	9.4 (0.2)	9.2-9.7	12 (2.9)	9.4-15
19	1	7.4	na	8.1	na	8.6	na
Rehab. Average	33	6.5 (0.3)	4.0-11	7.6 (0.6)	2.1-15.2	7.6 (0.4)	4.3-15
Woodland	9	13 (1.3)	7.5-21	15 (1.4)	8.3-23	16 (2.3)	5.9-30
Analysis of Variance[2]		(n) F = 4.38, P = 0.0008		(np) KWstat = 33.6602, P = 0.0023		(n) F = 2.25, P = 0.0410	
Significance[3]		*		*			

[1] n=30 for rehabilitation with trees over 4 m. [2] Analysis of variance was conducted on untransformed data where possible (n) or by the Kruskal-Wallis method where data were found to be non-parametric (np). [3] Bonferroni correction for 16 tests: *** 0.001 P = 0.000063, ** 0.01 P = 0.00063, * 0.05 P = 0.0031

Appendix B–d Select midstorey vegetation characteristics of rehabilitation ages and woodland sites (2000/01 wet season data)

Age of Rehab.	N (sites)	Midstorey Acacias (stems/ha)		Midstorey Eucalypts (stems/ha)		Midstorey Other Trees (stems/ha)	
		Avg. (SE)	Range	Avg. (SE)	Range	Avg. (SE)	Range
0.5	1	0	na	0	na	0	na
2	3	67 (67)	0-200	33 (33)	0-100	67 (67)	0-200
3	4	300 (41)	200-400	142 (142)	0-567	25 (25)	0-100
4	6	536 (147)	0-1017	167 (56)	0-400	17 (17)	0-100
6	1	350	na	300	na	100	na
7	4	608 (87)	450-783	725 (162)	467-1167	158 (58)	100-333
8	1	100	na	467	na	100	na
11	3	138 (138)	0-550	392 (142)	0-667	150 (120)	0-500
12	1	0	na	900	na	100	na
13	2	150 (50)	100-200	1058 (58)	1000-1117	50 (50)	0-100
14	1	0	na	733	na	0	na
15	3	233 (233)	0-700	678 (170)	367-950	167 (120)	0-400
17	2	133 (33)	100-167	500 (400)	100-900	100 (100)	0-200
19	1	500	na	200	na	100	na
Rehab. Average	33	297 (50)	0-1017	479 (355)	0-1167	98 (126)	0-500
Woodland	9	44 (24)	0-200	409 (67)	167-750	70 (38)	0-300
Analysis of Variance		F = 2.69, P = 0.0125		F = 3.62, P = 0.0018		F = 0.52, P = 0.9022	
Significance[1]				*			

[1] Bonferroni correction for 16 tests: *** 0.001 P = 0.000063, ** 0.01 P = 0.00063, * 0.05 P = 0.0031

Appendix B–e Select understorey vegetation characteristics of rehabilitation ages and woodland sites (2000/01 wet season data)

Age of Rehab.	N (sites)	Understorey Density (plants / m^2)		Juvenile Eucalypt Cover (%)		Juvenile 'Other' tree cover (%)		Weed cover (%)	
		Avg. (SE)	Range	Avg. (SE)	Range	Avg. (SE)	Range	Avg. (SD)	Range
0.5	1	12	na	0	na	0.5	na	0.3	na
2	3	18 (1.7)	15-21	0.9 (0.5)	0.1-1.9	5.2 (3.6)	0.5-12	11 (8.2)	0-27
3	4	18 (3.2)	12-25	2.1 (0.67)	0.8-3.7	0.8 (0.32)	0-1.5	16 (5.5)	0.2-26
4	6	16 (2.3)	7.7-23	1.9 (1.3)	0-8.3	3.8 (1.5)	0.1-9.4	3.9 (2.3)	0-15
6	1	15	na	0.8	na	3.3	na	0	na
7	4	10 (3.8)	2.4-21	4.3 (0.63)	2.7-5.8	2.1 (0.50)	0.8-3.3	0.4 (0.32)	0-1.3
8	1	15	na	0.7	na	10	na	8.5	na
11	3	10 (1.9)	4.4-13	2.1 (0.81)	0.7-4.0	1.4 (1.0)	0.1-3.9	0.2 (0.17)	0-0.7
12	1	9.6	na	0.3	na	1.1	na	0	na
13	2	10 (0.4)	10-11	4.1 (0.94)	3.2-5.0	2.4 (2.4)	0-4.9	0.7 (0.19)	0.5-0.9
14	1	20	na	14.3	na	0.8	na	0	na
15	3	9.2 (3.6)	5.0-16	1.6 (1.6)	0-3.1	1.6 (0.85)	0.8-2.5	0	0
17	2	16 (2.3)	14-19	0.8 (0.11)	0.7-0.9	1.3 (0.91)	0.4-2.2	2.6 (2.6)	0-5.2
19	1	68	na	1.7	na	7.6	na	1.1	na
Rehab. Average	33	15 (1.9)	2.4-68	2.3 (0.50)	0-14	2.7 (0.54)	0.0-12	4.1 (1.3)	0-27
Woodland	9	18 (1.5)	12-26	7.3 (3.3)	0.1-29	25 (3.2)	8.9-40	0.2 (0.14)	0-1.3
Analysis of Variance		F = 8.62, P = 0.0000		F = 0.81, P = 0.6509		F = 7.94, P = 0.0000		F = 2.37, P = 0.0253	
Significance[1]		***				***			

[1] Bonferroni correction for 16 tests: *** 0.001 P = 0.000063, ** 0.01 P = 0.00063, * 0.05 P = 0.0031

Appendix C–a Select floristic characteristics of 2000/01 site groupings (2000 dry season OS data and 2001 wet season MS and US data)

Rehab. Grouping	N (sites)	Canopy Cover (%)		Species Richness		Shannon–Wiener Diversity Index	
		Avg. (SE)	Range	Avg. (SE)	Range	Avg. (SE)	Range
B	6	66 (8)	32-83	39 (3.4)	23-46	2.6 (0.2)	2.0-3.0
C	5	58 (8)	38-85	37 (2.7)	30-46	2.4 (0.2)	1.7-2.9
D	4	57 (4)	45-63	39 (4.1))	32-47	2.6 (0.1)	2.1-2.7
E	8	38 (7)	14-68	38 (2.6)	31-50	2.6 (0.2)	2.0-3.2
F	3	21 (1)	20-23	47 (1.7)	44-49	2.6 (0.1)	2.5-2.7
G	3	3.3 (3.2)	0.1-10	44 (1.9)	42-48	2.3 (0.2)	2.1-2.6
rehab. A	1	28	na	39	na	2.4	na
Woodland	9	59 (4)	45-78	51 (2.7)	38-63	2.9 (0.1)	2.5-3.2
H	1	49	na	39	na	2.0	na
I	1	40	na	35	na	2.3	na
J	1	0	na	50	na	3.0	na
Analysis of Variance[1]		(sqrt) F = 12.1, P = 0.0000		(np) KWstat = 14.9150, P = 0.1864		(np) KWstat = 16.4731, P = 0.1245	
Significance[2]		***					

[1] Analysis of variance was conducted on transformed data (sqrt) or by the Kruskal-Wallis method where data were found to be non-parametric (np).

[2] Bonferroni correction for 16 tests: *** 0.001 P = 0.000063, ** 0.01 P = 0.00063, * 0.05 P = 0.0031

Appendix C–b Select overstorey vegetation characteristics of 2000/01 site groupings (dbhob = diameter at breast height (1.3 m) over bark; 2000 dry season data)

Rehab. Grouping	N (sites)	Average Overstorey Height[1] (m)		Average Dominant Height (m)		Average Overstorey dbhob[1] (cm)	
		Avg. (SE)	Range	Avg. (SE)	Range	Avg. (SE)	Range
B	6	7.2 (0.5)	5.5-9.0	10 (1.2)	5.9-12	7.8 (0.8)	6.0-11
C	5	7.0 (0.2)	6.4-7.5	9.1 (0.6)	6.7-10	7.3 (0.7)	5.8-9
D	4	7.9 (1.1)	5.5-11	10 (1.8)	6.8-15	8.2 (1.1)	5.6-11
E	8	6.0 (0.5)	4.2-8.2	6.9 (0.5)	5.3-9.2	8.1 (1.1)	5.1-15
F	3[1]	3.8 (0.8)	3.0-4.5	3.9 (0.4)	3.1-4.4	5.6 (0.1)	5.6-5.7
G	3[1]	2.8	na	3.7 (0.3)	3.2-4.2	4.3	na
rehab. A	1	7.1	na	8.3	na	11.3	na
Woodland	9	13 (1.3)	7.5-21	15 (1.4)	8.3-23	16 (2.3)	5.9-30
H	1	5.3	na	6.2	na	5.9	na
I	1	6.9	na	8.3	na	7.7	na
J	1	na	na	2.1	na	na	na
Analysis of Variance[2]		(n) F = 6.02, P = 0.0001		(np) KWstat = 31.5571, P = 0.0005		(n) F = 3.04, P = 0.0116	
Significance[3]		***		**			

[1] n=2 for group F, and n=1 for group G for average overstorey height and average overstorey dbhob. [2] Analysis of variance was conducted on untransformed data where possible (n) or by the Kruskal-Wallis method where data were found to be non-parametric (np). [3] Bonferroni correction for 16 tests: *** 0.001 P = 0.000063, ** 0.01 P = 0.00063, * 0.05 P = 0.0031

Appendix C–c Select overstorey vegetation characteristics of 2000/01 site groupings (2000 dry season data)

Rehab. Grouping	N (sites)	Overstorey Eucalypt Density (stems/ha)		Overstorey Acacia Density (stems/ha)		Overstorey 'Other' Tree Density (stems/ha)	
		Avg. (SE)	Range	Avg. (SE)	Range	Avg. (SE)	Range
B	6	744 (197)	100-1333	556 (168)	133-1300	278 (98)	0-600
C	5	1133 (260)	567-1933	160 (103)	0-533	187 (76)	33-367
D	4	817 (95)	533-933	67 (41)	0-167	42 (42)	0-167
E	8	63 (17)	0-167	517 (123)	33-1000	21 (9)	0-67
F	3	100 (84)	0-267	133 (33)	100-200	156 (124)	0-400
G	3	0 (0)	0	122 (122)	0-367	0 (0)	0
rehab. A	1	367	na	0	na	0	na
Woodland	9	489 (76)	167-900	44 (36)	0-333	48 (27)	0-200
H	1	533	na	700	na	133	na
I	1	333	na	467	na	67	na
J	1	na	na	na	na	na	na
Analysis of Variance		F = 6.19, P = 0.0001		F = 3.38, P = 0.0053		F = 2.21, P = 0.0490	
Significance[1]		**					

[1] Bonferroni correction for 16 tests: *** 0.001 P = 0.000063, ** 0.01 P = 0.00063, * 0.05 P = 0.0031

Appendix C–d Select midstorey vegetation characteristics of 2000/01 site groupings (2001 wet season data)

Rehab. Grouping	N (sites)	Midstorey Acacias (stems/ha)		Midstorey Eucalypts (stems/ha)		Midstorey Other Trees (stems/ha)	
		Avg. (SE)	Range	Avg. (SE)	Range	Avg. (SE)	Range
B	6	483 (83)	200-733	567 (109)	300-1000	172 (64)	0-400
C	5	210 (147)	0-783	960 (89)	667-1167	200 (78)	100-500
D	4	50 (50)	0-200	729 (68)	567-900	25 (25)	0-100
E	8	515 (104)	100-1017	163 (42)	0-400	38 (18)	0-100
F	3	167 (88)	0-300	33 (33)	0-100	67 (67)	0-200
G	3	133 (133)	0-400	0 (0)	0	0 (0)	0
rehab. A	1	0	na	400	na	0	na
Woodland	9	44 (24)	0-200	409 (67)	167-750	70 (38)	0-300
H	1	550	na	500	na	100	na
I	1	100	na	467	na	100	na
J	1	0	na	0	na	0	na
Analysis of Variance		F = 3.65, P = 0.0026		F = 11.4, P = 0.0000		F = 1.42, P = 0.2158	
Significance[1]		*		***			

[1] Bonferroni correction for 16 tests: *** 0.001 P = 0.000063, ** 0.01 P = 0.00063, * 0.05 P = 0.0031

Appendix C–e Select understorey vegetation characteristics of 2000/01 site groupings (2001 wet season data)

Rehab. Grouping	N (sites)	Understorey Density (plants / m^2)		Juvenile Eucalypt Cover (%)		Juvenile 'Other' tree cover (%)		Weed cover (%)	
		Avg. (SE)	Range	Avg. (SE)	Range	Avg. (SE)	Range	Avg. (SD)	Range
B	6	12 (2.2)	6.3-21	2.9 (0.9)	0-5.4	8.5 (3.6)	1.4-26	0.2 (0.1)	0-0.9
C	5	11 (2.4)	2.4-16	3.0 (0.8)	1.4-6.1	1.3 (0.6)	0.2-3.6	0.5 (0.2)	0-1.3
D	4	12 (3.2)	5-20	4.0 (1.7)	1-8.7	1.2 (0.2)	0.7-1.8	6.4 (6.4)	0-26
E	8	22 (6.8)	7.7-68	1.1 (0.5)	0.1-3.7	2.6 (1.1)	0-8.9	6.3 (2.7)	0-21
F	3	20 (0.9)	19-22	1.3 (0.4)	0.7-2.2	4.2 (0.9)	2.5-5.5	9.2 (9.0)	0.2-27
G	3	20 (3.0)	15-25	1.5 (1.0)	0.2-3.6	1.6 (0.8)	0.7-3.2	8.1 (5.1)	0-18
rehab. A	1	13	na	1.0	na	1.0	na	0	na
Woodland	9	18 (1.5)	12-26	7.3 (3.3)	0.1-29	25 (3.2)	8.9-40	0.2 (0.1)	0-1.3
H	1	11	na	1.6	na	2.6	na	0	na
I	1	15	na	0	na	7.7	na	8.5	na
J	1	12	na	0.3	na	2.0	na	0.3	na
Analysis of Variance		F = 0.76, P = 0.6679		F = 1.27, P = 0.2878		F = 10.1, P = 0.0000		F = 1.07, P = 0.4158	
Significance[1]						***			

[1] Bonferroni correction for 16 tests: *** 0.001 P = 0.000063, ** 0.01 P = 0.00063, * 0.05 P = 0.0031

Appendix D–a Select floristic characteristics of 2001/02 site groupings (2001 dry season OS data and 2002 wet season MS data)

Rehab. Grouping	N (sites)	Canopy Cover (%)		Average Dominant Height (m)		Overstorey Eucalypt Density (stems/ha)	
		Avg. (SE)	Range	Avg. (SE)	Range	Avg. (SE)	Range
B	6	37 (6.8)	16-57	9.7 (0.9)	6.2-13	528 (158)	67-1000
C	5	32 (6.5)	18-56	9.0 (0.5)	7.2-11	920 (255)	333-1733
D	4	37 (7.3)	22-57	11 (2.1)	6.6-17	775 (136)	433-1100
E	8	14 (2.3)	2.5-26	6.6 (0.7)	4.2-10	63 (15)	0-133
F	3	19 (8.5)	3.8-33	7.2 (0.5)	6.2-7.8	11 (11)	0-33
G	3	1.9 (0.7)	0.5-3	3.8 (0.8)	2.5-5.3	0 (0)	0
rehab. A	1	15	na	15.7	Na	267	na
Woodland	9	34 (2.4)	23-43	14 (1.0)	10-19	396 (75)	167-933
H	1	49	na	8.5	na	200	na
I	1	15	na	7.8	na	233	na
J	1	0.1	na	3.4	na	na	na
Analysis of Variance[1]		(sqrt) F = 7.93, P = 0.0000		(np) KWstat = 30.1054, P = 0.0008		(n) F = 5.04, P = 0.0003	
Significance[2]		***		**		**	
Repeated Measures		F = 12.88, P = 0.0049		F = 2.47, P = 0.1468		F = 8.63, P = 0.0165	
AOV – Signif. [2]		*					

[1] Analysis of variance was conducted on untransformed data where possible (n), transformed data (sqrt) where data were not normal or by the Kruskal-Wallis method where data were found to be non-parametric (np). [2] Bonferroni correction for 6 tests: *** 0.001 P = 0.00017, ** 0.01 P = 0.0017, * 0.05 P = 0.0083

Appendix E–b Select floristic characteristics of 2001/02 site groupings (2002 wet season MS and US data)

Rehab. Grouping	N (sites)	Midstorey Eucalypt Density (stems/ha)		Midstorey Acacia Density (stems/ha)		Juvenile ‘Other’ tree cover (%)	
		Avg. (SE)	Range	Avg. (SE)	Range	Avg. (SE)	Range
B	6	622 (152)	200-1167	397 (107)	100-800	3.5 (0.8)	0.8-5.9
C	5	1050 (213)	617-1800	257 (166)	0-883	2.3 (1.6)	0.3-8.7
D	4	810 (98)	567-1033	100 (100)	0-400	1.1 (0.2)	0.6-1.6
E	8	175 (45)	0-400	442 (93)	100-883	2.4 (1.0)	0-7.3
F	3	33 (33)	0-100	517 (73)	400-650	6.1 (1.0)	4.3-7.7
G	3	0 (0)	0	67 (33)	0-100	2.3 (1.1)	1.1-4.5
rehab. A	1	400	na	0	na	1.5	na
Woodland	9	465 (125)	150-1400	44 (24)	0-200	18 (1.7)	8.8-26
H	1	967	na	900	na	4.0	na
I	1	450	na	100	na	6.6	na
J	1	0	na	0	na	1.5	na
Analysis of Variance		F = 4.89, P = 0.0003		F = 3.50, P = 0.0035		F = 15.2, P = 0.0000	
Significance[1]		**		*		***	
Repeated Measures		F = 4.54, P = 0.0590		F = 0.98, P = 0.3462		F = 0.30, P = 0.5931	
AOV – Signif. [1]							

[1] Bonferroni correction for 6 tests: *** 0.001 P = 0.00017, ** 0.01 P = 0.0017, * 0.05 P = 0.0083