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Comparison of post-mine rehabilitated and natural shrubland communities in southwestern Australia

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Abstract

Following mineral sand-mining near Eneabba, southwestern Australia, rehabilitation managers have the difficult task of restoring shrubland communities of exceptional plant species richness. Species diversity, composition, structure, and key functional attributes in four mined sites rehabilitated 8 (R8) to 24 (R24) years ago were compared with those of typical nearby natural areas classified on the basis of substrate type (Low and High sand Dunes, shallow sand Swales, sand over Laterite and sand over Limestone). The rehabilitated sites (except R8) had more species (~140) than natural sites (~100) in 40 · 40 m plots with 12–37 % species in common with natural sites. Rehabilitated sites were more similar in composition to each other than they were to the natural sites, with two strong colonizers, the fire-killed *Acacia blakelyi* and the fire-tolerant *Melaleuca leuropoma*, universally present. Dendrograms and ordinations based on composition and cover showed that rehabilitated sites grouped with each other before they did with the Dune and Swale sites (physically closest), and last with the Laterite and Limestone sites. Plant densities for R16 and R24 were about half those of the High Dune and Limestone, and about a quarter those of the Swale and Laterite. Fire-resprouters were under-represented in the rehabilitated sites. Growth form distribution in rehabilitated sites was most similar to those of the Dunes, with some woody shrubs up to 2.5 m tall present. Total iron and soil hardness (penetrability) were the only soil factors consistently different (higher) in the rehabilitated sites.

Key words: rehabilitation, shrubland, Eneabba, species richness, species diversity, composition, structure, function.

Introduction

Disturbance may be defined as an event that can change community structure and composition by altering the physical environment and/or resource availability (Drake et al. 1989). Mining is a form of exogenous disturbance, and mining of mineral sands in particular has produced substantial areas of disturbed vegetation in Australia (Clark 1975; Brewer & Whelan 2003; Ross et al. 2004). It negatively affects plant communities since it involves complete mechanical removal of the vegetation and disruption of ecological processes (Hobbs & Hopkins 1990).

Rehabilitation on previously mined land involves techniques such as pre-stripping (from areas ahead of a mining front) and returning propagule-containing topsoil, seeding, fertilizing, mulching, and infill planting of seedlings (Fox et al. 1996). Rehabilitation to a standard equivalent to the pre-mining natural diversity, structure, and function is usually the desired criterion. However, the time and effort required to rehabilitate the structure and function of Australian ecosystems can be considerable (Collins et al. 1985), especially in areas of outstanding species diversity such as the Eneabba sandplain in southwestern Australia (Bellairs & Bell 1993).

Rehabilitation success ideally requires determining if the ecosystem components are similar to, or are on a similar successional trajectory towards, the desired endpoint (Chambers et al. 1994). A common and realistic means of evaluation is through comparison with surrounding undisturbed reference areas that exhibit the desired ecosystem properties (Chambers et al. 1992; Aronson et al. 1995). The selected reference sites should occur in close geographical proximity to the rehabilitated sites since the composition, structure, and environmental circumstances, of vegetation in nearby areas are more likely to be similar to those of the rehabilitated sites prior to disturbance, than are more distant sites. Replication of reference sites is also essential to account for the variation that exists in surrounding natural areas (Ruiz-Jaen & Aide 2005).

Iluka Resources Ltd (and their precedessors) has been conducting mineral sand mining on the Eneabba sandplain since the 1970s. Approximately 2500 hectares have been mined to date, and best-practice rehabilitation is required in this biodiverse region (Lamont et al. 1984). Topsoil is double-stripped and returned in two layers with a 20 cm second cut applied first, followed by a 5 cm first cut (Jefferies et al. 1991). A seed mix is sourced from the surrounding natural vegetation usually from within the mine lease area and spread over restored topsoil. Shrubland vegetation is removed 30 cm above ground, mulched and spread over the restored topsoil as a further source of seeds (Bellairs & Bell 1993). Seedlings of selected species are grown in a nursery and infill planted into rehabilitated sites. There has been a lack of documentation (especially in the 1970s – late 1990s) on the origins of the topsoil, mulch, species in the seed mix, seedlings of species produced in the nursery, and the quantities in which they were applied to each rehabilitated block. However, better documentation and more efficient techniques have developed since Iluka Resources Ltd acquired the Eneabba operations in 1999.

Rehabilitation efforts at Eneabba aim to satisfy completion criteria that focus on rehabilitating species richness, plant density, and foliage cover (Jefferies et al. 1991; EMRC 1996). However, restoration of composition, structure and function are also desirable goals. The aim of the work reported here was to compare the species diversity, composition, structure, and functional attributes of post-mine rehabilitated sites with that of surrounding vegetation types near Eneabba, southwestern Australia. On the basis of these results, we make recommendations to further refine the mining company's rehabilitation efforts. Specifically, the objectives were to:

(1) Compare species diversity and composition between four selected rehabilitated and five nearby natural sites representing typical plant community-types;

(2) Compare structural characteristics (plant cover and density, and growth-form distribution) between rehabilitated and natural sites;

(3) Compare key functional attributes (soil nutrient levels and species regeneration modes) between rehabilitated and natural sites; and

(4) Provide recommendations for improving the rehabilitation of species diversity and composition, structure and function towards those of natural analogues.

Methods

Vegetation sampling

Shrubland vegetation at four rehabilitated and five nearby natural sites was examined near the town of Eneabba, approximately 280 km north of Perth (29° 49' S Latitude, 115° 16' E Longitude). The four sites rehabilitated by Iluka Resources Ltd (or their predecessors) were chosen to represent a variety of post-mined rehabilitated ages (R8 (8 y), R15 (15), R16 (16) and R24 (24): Table 1). Five natural sites were chosen to represent the main substrate types near the mined areas in order to allow a comparison between the rehabilitation sites and the variability expected in the surrounding natural areas (High dune = High, Low dune = Low Swale, Laterite = Lat, Limestone = Lim: see Table 1 for site details). At all sites, a 40 · 40 m plot was established, and divided into 5 × 5 m subplots. Within each subplot, all individuals (except annuals) were identified to species where possible using a field herbarium based on material in the Western Australian Herbarium, South Perth, Florabase (Western Australian Herbarium 1998–), and field knowledge of B. Lamont, B. Miller, N. Enright, D. Herath, A. Tinker and C. van den Bergh. Species abundance was recorded at all sites, except at Low, R8 and R15, where species cover was assessed instead using the Braun-Blanquet (BB) scale (Braun-Blanquet 1932; Braun-Blanquet 1964) since the human resources were not available to undertake the individual plant approach at all sites. This scale is based on visual assessment of plant cover at coded percentage intervals: 1 = <1 %; 2 = 1–5 %; 3 = >5–25 %; 4 = >25–50 %; 5 = >50–75 %; 6 = >75–100 %. The BB scores were assessed for each species in each subplot, then converted to their mid-point cover values for each subplot (e.g. 0.5 % for BB class 1, 15 % for BB class 3). The average of the 16 mid point-cover values (from 16 subplots) for each species gives an estimate of their % crown cover area within the whole plot. For all other sites, % crown cover area was calculated using equation 1 based on measured height and crown width (1: N to S and 2: E to W) for all plants and assuming their shape is ellipsoid*.

Equation 1:

% crown cover of spp = [{(average of width 1 × average of width 2) × no. of plants} × 0.7854*] / plot area] × 100

At Low, R8 and R15, up to 10 individuals per species were measured (selected randomly) for determining their mean heights, to allocate species into growth forms (described below).

Soil hardness and nutrients

An Australian standard sand penetrometer (AS 1289 6.3.3) with a 16 mm diameter flat-ended rod driven by a 9 kg mass dropping 600 mm was used to assess soil hardness. After one hammer blow, the distance the rod penetrated the ground was measured. 20 random measurements along the edges of each plot were recorded.

Soil samples (14 x 14 cm area, 0–5 cm depth) were collected from 90 random points within each plot to investigate nutrient levels. All litter was removed at each point. Individual soil samples were dried at 40°C for 48 h, mixed, and then a 20 mL subsample was extracted and analysed by CSBP Wesfarmers, Perth for total nitrate, ammonium, phosphate, potassium, sulphur, organic carbon, reactive iron, conductivity, pH (in $CaCl_2$ solution) and pH (in H_2O). The same procedures were used for examining nutrient levels at R8, R15 and low dune, except that samples from 30 random points were analyzed.

Data analyses

Three widely accepted indices were used as estimates of diversity:

(a) Shannon Weiner diversity (Shannon & Weaver 1949): $H' = -\sum[p_i \cdot \ln(p_i)]$

where p_i = the fraction of cover of a given species to the total cover of species in the community;

(b) Pielou's evenness index (Pielou 1966): $J' = H'/H_{\max}$ where H_{max} = species richness; and

(c) Simpson's index of diversity (Simpson 1949): $D' = 1 - \sum[n_i(n_i - 1)/N(N - 1)]$ where n_i = the cover of the ith species, and N = the total cover of all species.

Ordination and classification was used to compare species composition. Ordinations were performed on both presence-absence data (floristic composition), and semi-quantitative data (species % cover values) using SYN-TAX 2000 (Podani 2001). Principal Coordinate Analysis (PCoA) was selected as the ordination technique, a metric multidimensional scaling method that is flexible in its choice of dissimilarity index (Gower 1966). Classifications, using the group average linkage method, were run in SYN-TAX 2000 (Podani 2001) to identify the order of clustering of sites. Classification results were superimposed on the ordinations to offer a more complete picture of the relationships between sites. Each classification was truncated once 5 groups were formed, and the members of each grouping were identified on the ordination. Sorensens distance was selected as the dissimilarity measure for the composition dendrogram and ordination, and Bray curtis dissimilarity for the composition plus cover dendrogram and ordination (Podani 2001).

All species were classified into one of six growth forms: tall shrubs = woody plants 1–2.5 m on average, small shrubs = woody plants <1 m, herbs = non-woody plant <1 m, graminoid = grass or grasslike plants (including reeds and sedges), parasite = plants depending on a host plant for survival. Regeneration mode (resprouter or nonsprouter) was determined by examining if a lignotuber was present, or extent of recovery after fire, or from existing data sources (Enright et al. 2007). Resprouters recover from fire vegetatively and/or from seeds; nonsprouters are killed by fire and regenerate from seeds only.

Soil attributes were analyzed using Principal Components Analysis (PCA) in PcORD 5.0 (McCune & Mefford 1999). Vectors corresponding to specific nutrient variables were drawn on the ordination with their direction relative to their values at the sites and lengths proportionate to their overall correlation with other variables. One-way analysis of variance

(ANOVA) was used (SPSS 13.0, 2004) to determine if any variables were consistently and significantly different between rehabilitated and natural sites (excluding the Lim site which was an outlier in terms of its chemistry). For PCA analysis, the number of variables needs to be less than the number of sites, so soil attributes were screened to remove redundant variables (i.e. those highly inter-correlated). These included pH (in $CaCl_2$ solution), sulphur, and ammonium.

Results

Species diversity and composition

In all, 348 species were recorded in the study and all sites generally displayed high species richness, diversity and evenness (Table 2). Rehabilitated sites (except R8) had greater species richness (128-146 spp) than adjacent natural sites (78-113 spp). Shannon Weiner (*H'*) and Simpson's diversity indices (*D'*) both showed little difference between rehabilitated and natural sites, except that R8 had lower diversity than all other sites. Pielou's Evenness index (*J'*) showed that the rehabilitated sites, especially R8 and R16, had lower evenness than natural sites.

The natural sites supported 266 species in 107 genera and 39 families. The most common families were Proteaceae (49 spp), Myrtaceae (45), Cyperaceae (19), Papilionaceae (20), and Epacridaceae (16). The rehabilitated sites supported 237 species in 93 genera and 31 families. Common families were Proteaceae (51 spp), Myrtaceae (39), Cyperaceae (17), Papilionaceae (16), and Epacridaceae (14). The most common genera in natural and rehabilitated sites are listed in Table 3, and show that *Stylidium* and *Leucopogon* were better represented in the natural areas and *Acacia* in the rehabilitated areas.

The five most dominant (based on % cover) species in each site are given in Table 4. In all rehabilitated sites, *Acacia blakelyi* and *Melaleuca leuropoma* were among the top three dominant species, whereas in the natural sites, *A.blakelyi* was infrequent or absent, and *M.leuropoma* was abundant only at Lim and Low. The identity of dominant species varied more in natural sites than that of rehabilitated sites. The most abundant species in the rehabilitated sites had higher cover values than the most abundant species in the natural sites. Most dominant species in rehabilitated sites were nonsprouters, while resprouters were more dominant in natural sites.

Species composition of rehabilitated sites (excluding R8) were most similar to the Low (32–37 % spp in common), Swale (25–37) and High (26–31), and least similar to the Lat (16–24) and Lim (12–16). Within natural sites, the Lat (12–28 % similarity) and Lim (10–15) were least similar to the other sites and also had the highest percentage of unique species (Table 2). Within the rehabilitated sites, R8 (24–36 % similarity) was least similar to the other sites (39–49 with each other). Natural sites had a broader range of unique species (8–43 %) than rehabilitated sites (8–13). R8 had the lowest percentage of soil seed bank (SSB) species (52 %) compared with 69–81 % for all other sites.

Vegetation density and cover

The Swale and Lat sites had nearly four times the plant density of the rehabilitated sites (R16, R24), and the High and Lim sites were nearly twice as dense (Table 2). Total cover of all rehabilitated sites was around 105 % and most similar to the High and Lim.

Ordination and classification

PCoA based on Sorensen's distance (Figure 1a) for species presence-absence data show Lat and Lim as outliers. The Dune and Swale sites group early as do R15, R16 and R24, while R8, Lat and Lim are unlinked at the 5 group level in the classification. At the 4 group level, the Dune and Swale sites group with R15, R16 and R24, with R8 joining next (3 groups), followed by Lat (2 groups). Although Lim appears relatively close to the Dune samples in the PCoA using Bray-Curtis similarity/cover data (Figure 1b), the classification keeps it separate at all linkage levels. All rehabilitated sites group early at 5 groups, as do the Dunes, and the rest remain unlinked. The Dunes link with the rehabilitated sites at 3 groups, with the Swale and Lat joining next at 2 groups.

Growth forms

At all sites, small shrubs and graminoids accounted for most species and greatest density (Figure 2a, 2b). Tall shrubs were lacking in the Swale and Lat sites. The R8 site lacked a herb layer and had more tall shrubs compared with other sites. Growth form distributions in the rehabilitated sites (apart from R8) were most similar to the Dune. Small shrubs accounted for most cover at all sites (Figure 2c) except R8 and R16 which had greater shrub cover.

Regeneration modes

Regeneration-mode composition was more variable in natural sites than rehabilitated sites (Table 2). The percentage of resprouting species in rehabilitated sites (71–74 %) were within the range of the natural sites (67–88 %) sites. All natural sites had more resprouter (67–98 %) than nonsprouter individuals, especially in the Swale (84 %) and Lat (98 %), whereas rehabilitated sites R16 (39 %) and R24 (49 %) had fewer resprouter individuals. Cover of resprouters and nonsprouters varied greatly among sites but that of resprouters tended to be lower in rehabilitated (<69 %) than most natural (>60 %) sites.

Soil hardness and nutrients

PCA analysis of soil properties separated the rehabilitated sites from the natural sites (Figure 3). Only reactive iron and soil hardness was significantly different ($P < 0.05$, 1-way ANOVA) between treatments (excluding Lim site). Total reactive iron levels were nearly double in the rehabilitated sites and soil hardness was about twice as hard. Lim was an outlier due to its high pH and nutrient levels.

Discussion

The rehabilitated sites (except R8) had more species than natural sites. The high species richness reflects a concerted effort to satisfy the stipulation by the Government conservation authority that the pre-mining species richness should be restored (Jefferies et al. 1991; EMRC 1996). Species arose from seeding, mulching, topsoil replacement, and infill planting. Bellairs & Bell (1993) showed for a rehabilitated block at the same mine that topsoil (3 %) and mulch (96 %) contributed 99 % of the total germinable perennial seeds. However, seeding and interplanting of nursery stock seedlings were also important in supplementing species (~46 % of spp.) that were poorly or not represented in topsoil and mulch (recalcitrant species). Other studies have also highlighted the value of seed broadcasting in restoring south Australian Eucalypt forests (Roche et al. 1997), South African fynbos shrublands (Holmes 2001) and North American prairie grasslands (Wali 1999). Seeds are generally collected within the mine lease area (Pamela Grout 2007, Iluka Resources Ltd, personal communication) that covers all substrate-types included here, plus some winter-wet depressions not included in our study. It is evident from our results and the literature (Lamont et al. 1977; Hnatiuk & Hopkins 1981; Griffin et al. 1983) that some species not represented in the pre-mined vegetation (which was dune and swales) were also obtained from limestone and laterite areas, as well as winter-wet locations, possibly to ensure that the species richness target was achieved and uncertainty about which species would succeed.

The rehabilitated sites had lower evenness than natural sites mostly because of two dominant species, *Acacia blakelyi* and *Melaleuca leuropoma.* Following topsoil replacement, *Acacia blakelyi* was historically mixed with cover crop seeds to provide stabilization of tailings and to produce a quick scattered cover of native shrubs to tide over the period between cover crop decay and full native regeneration (Black 1979). However, due to its prolific reproductive capacity and ability to dominate disturbed sites (personal observation), it survives, reproduces and remains dominant in older rehabilitated stands. Similarly, the highly fecund *Melaleuca leuropoma*, which usually possesses an order of magnitude more viable seeds per unit area in all substrate types than other serotinous species (Enright et al. 2007), dominates rehabilitated sites after the mulching process.

In view of the above, why the youngest stand (R8) had less species and lower H', D' and J' than other rehabilitated sites requires an explanation. R8 received topsoil that had been stockpiled for 10 years, creating an ideal environment for *Acacia blakelyi* to flourish and contribute to the soil seedbank before spreading (Bob Muir 2007, Iluka Resources Ltd, personal communication). As a result, *Acacia blakelyi* covered 36 % of the site post-rehabilitation (more than other rehabilitated sites) and may have competitively displaced other species (Lamont et al. 1989). In addition, it is the only site on a slope and may have meant it dried out faster than other sites and led to differential survival, as soil moisture is critical for establishment here (Enright & Lamont 1992). A lower ratio of soil to canopy-stored species was also observed at R8 compared with other sites likely due to its topsoil being stockpiled for such a long period which may have affected the seed viability of soil-stored species. Several studies have shown areas that receive fresh topsoil yield more species and/or individuals than areas receiving stockpiled topsoil (Ward et al. 1996), and the longer the stockpile is stored, the lower the species diversity (Bellairs & Bell 1993).

Vegetation densities were lower in rehabilitated sites possibly due to seeds and/or seedlings being added at lower (than required) densities, or the seeds and/or seedlings experiencing greater mortality levels associated with the adverse substrate-type (lack of sand over poorly penetrable silt-sand). After simulating mining conditions, Holmes (2001) reported lower densities and survival of fynbos shrublands (Cape floristic kingdom, South Africa) in subsoil *versus* topsoiled plots. Griffins & Hopkins (1985) suggested that the principal influence on species distribution on the Eneabba sandplain was related to the depth of sand over clay having a consequential effect on water relations and root penetration. Shallow or no sand over clay may prevent taproots from accessing groundwater (Enright & Lamont 1992), intensifying the effect of drought, and over winter, occasionally creating waterlogged soils.

Rehablitated sites were most similar to each other (averaging 45 %; except R8) due to similar selections of species being restored at most sites. Among the natural sites, the Swale and the Dunes (High and Low) were most similar to the rehabilitated sites (~30 % similarity) possibly due to their close proximity as a source of seeds. The distinctly different substrate type and distance away of the Lim, and to a lesser extent the Lat site, contributed to their reduced similarity with other sites. This also reflects rehabilitation efforts primarily aimed in restoring the original swale and dunal communities of the local sandplain. However, some species that are usually restricted to limestone (e.g. *Labichea cassioides*) or laterite (e.g. *Hakea stenocarpa, Conostylis androstemma*) were also present in some rehabilitated sites indicating that collections may have occurred over broader areas than the adjacent swales and dunes. Rehabilitated sites were also more similar to each other in the composition plus cover ordination probably again due to the outcome of similar rehabilitation efforts. Of all natural sites, the Dunes were most similar to the rehabilitated sites, both having some species with taller and broader growth forms (e.g. *Adenanthos cygnorum*, *Banksia attenuata*).

The rehabilitated sites had growth form distributions most similar to those of the Dunes with some tall shrubs. The reduced competition associated with low plant densities may have allowed many species to grow large in rehabilitated sites. The addition of unknown quantities of fertilizers into rehabilitated sites may have also contributed to larger plant size (Phil Scott 2007, Iluka Resources Ltd., personal communication). Percentage growth form cover varied in the rehabilitated sites due to variable cover values of a few species in the shrub layers, such as *Acacia blakelyi, Banksia leptophylla* and *Adenanthos cygnorom.*

All sites had more resprouter (~70 % average) than nonsprouter species. It is important to restore similar regeneration mode proportions to maximise the vegetation's resilience to future disturbances such as fire, drought, and herbivory (Bellairs & Bell 1993). However, the relative richness, density and cover of resprouters were lower in rehabilitated sites than nearby natural sites. The most common species were also mostly nonsprouters in rehabilitated sites and resprouters in natural sites. Similarly, Grant and Loneragan (1999) recorded lower densities of resprouters in rehabilitated versus natural sites in eucalypt forests of SW Australia. This poorer representation of resprouters in post-mined lands reflects the difficulty in restoring resprouters. They generally produce fewer seeds than nonsprouter species (Lamont & Wiens 2003) so their seed densities are lower in the added seed mix, mulch and topsoil.

Only a few resprouter species were well represented in rehabilitated sites (e.g. *Melaleuca leuropoma, Jacksonia floribunda*) and these produce moderate numbers of seeds in natural areas (Enright et al. 2007). In rehabilitated sites, they show even faster growth and higher seed set and storage than do the same species in natural areas (personal observation). The longer-term consequences of these growth responses (e.g. type of recruitment after fire returns to rehabilitation sites) is worthy of investigation.

Although the ordination revealed a strong separation of rehabilitated sites from natural sites, the only variables that were significant in separating them were total iron and soil hardness.

This results from mining the finer iron-bearing particles of the B horizon and bringing them to the surface during the soil replacement process. This has no doubt contributed to some differences in species composition and structure between rehabilitated and natural areas (Enright & Lamont 1992). Subsequent erosion of topsoil appeared partly responsible for the lack of sand over the fines in rehabilitated sites, thus increasing soil hardness at just 5 cm depth.

Conclusions and recommendations

Although the flora of rehabilitated blocks was more similar to each other than to any nearby natural plant communities, there were some compositional, structural and functional affinities with the nearest Swale and Dune substrate sites. Growth form structure was most similar to High. Most soil nutrients were low and similar to those of the Swale and Dunes while extractable iron and soil hardness were much higher in restored sites. Species composition was most similar to that of Swale and Dunes, albeit only in the order of 30 % species in common. Other studies in the region have also shown low similarity among samples between shrubland communities, even for similar substrate types (Griffin et al. 1983; Hnatiuk & Hopkins 1981; Lamont 1977), highlighting the floristic complexity of the region. Similar restoration difficulties appear in species-rich fynbos shrublands in South Africa (Holmes & Richardson 1999; Holmes 2001).

To further improve similarity to swale or dune shrublands, recent protocols (since Iluka Resources Ltd acquired the Eneabba operations in 1999) have formulated swale, dune, laterite and wetland seed species mixes that are not combined during the rehabilitation process. This should produce species richness levels closer to those of the natural community types. Topsoil needs to be stockpiled for as short a period as possible to minimize the loss of viability of soil-stored species. The practice of growing *Acacia blakelyi* to stabilize tailings has ceased but it is still a major component of newly rehabilitated pits and remains a problem. It may be possible to manually clip or chainsaw the main stems of weedy species (e.g., *Acacia blakelyi*) at early stages of rehabilitation before the onset of seed production (2 to 3 years, personal observation). However, sufficient native vegetation cover is necessary to buffer against topsoil erosion.

To increase restored vegetation densities, seeds and seedlings may need to be added at higher densities (including subsequent years post rehabilitation) and/or greater efforts need to be made to mimic the deeper sands of the natural substrates (Enright & Lamont 1992). Topsoil should always be stripped in natural areas ahead of mining fronts, and spread over the rehabilitated subsoil. If no topsoil is available, subsoil should be ripped to reduce compaction and improve root and water penetration (Holmes 2001).

The low density of resprouters is of particular concern as fire is inevitable in the long term, and may kill individuals with inadequate rootstock development (personal observation). The paucity of seeds of some resprouter species makes their adequate collection via soil or mulch difficult, so that targeting seed collection and infill planting is required. Given the fast growth and high seed set of some resprouter species within rehabilitation blocks (personal observation), it may also be possible to harvest seeds from plants of these species within the rehabilitation area in order to increase their abundance in seed mixes used elsewhere on site. It would have assisted interpretation of our data if initial site preparation treatments and composition of seeding mixtures and nursery stock were better documented, so that good data storage and management procedures are also important to the long-term success of rehabilitation programs.

Implications for practice

- Tailings should be returned in such a way as to mimic the range of substrates (in this case dune and swale) present pre-mining and to create a variety of habitat-types.
- Collections/mixes of topsoil, mulch and seeds for minesite rehabilitation should be restricted to the pre-mined substrate type, to achieve similar composition and abundance to that present prior to mining.
- Highly fecund species that dominate disturbed lands (e.g. *Acacia blakelyi, Melaleuca leuropoma*) should be identified and managed to prevent competitive exclusion of other native species. This involves minimizing their presence in seed applications and avoiding mulching in thickets containing these species.

- Increased densities, especially of the poorly represented resprouters, may be achieved by supplementary sowing seeds and/or interplanting nursery stock in subsequent years until resprouters are adequately represented. The seeds could be harvested from plants within rehabilitated areas, which are more fecund than those in surrounding natural areas.
- Completion criteria in rehabilitation projects should consider including a degree of compositional and regeneration mode similarity to that of the desired 'local community', in addition to species richness and vegetation density goals.

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Table 1: Location, selected attributes, and sampling methods employed at study sites in natural and rehabilitated shrublands near Eneabba, southwestern Australia. Lat = Laterite, High = High dune, Lim = Limestone, Low = Low dune.

Sites	*Location*	*Substrate type*	*Age (years)*	*Plot size (m^2)*	*Subplot size (m^2)*	*Data collected*	*Size measurements*
High	S29°52'23.6" E115°15'02.4'	6–10 m of sand over silt and clay	19 since fire	40 · 40	5 · 5	Species*, no. of individuals, LH*	All, H · W1 · W2*
Low	S29°42'41.4" E115°13'28.1"	2–3 m of sand over silt and clay	8 since fire	40 · 40	5 · 5	Species*, BB score*, LH*	H*
Swale	S29°51'54.8" E115°15'12.5"	10–50 cm of sand over silt and clay	24 since fire	40 · 40	5 · 5	Species*, no. of individuals, LH*	All, H · W1 · W2*
Lat	S29°35'45.7" E115°15'22.4"	50 cm of sand over Lat and clay	15 since fire	40 · 40	5 · 5	Species*, no. of individuals, LH*	All, H · W1 · W2*
Lim	S29°52'15.3" E115°05'27.8"	0-50 cm sand over Lim, some	19 since fire	40 · 40	5 · 5	Species*, no. of individuals, LH*	All, H · W1 · W2*

		outcropping Lim					
R8	S29°55'48.6" E115°17'15.6"	0–30 cm sand over silt and clay	8 since mined	40 · 40	5 · 5	Species*, BB score*, LH*	H*
R15	S29°53'44.6" E115°17'02.9"	0–10 cm sand over silt and clay	15 since mined	40 · 40	5 · 5	Species*, BB score*, LH*	H*
R16	S29°54'08.1" E115°16'56.4"	0–10 cm sand over silt and clay	16 since mined	40 · 40	5 · 5	Species*, no. of individuals, LH*	All, H · W1 · W2*
R24	S29°55'58.9" E115°16'27.8"	0–20 cm sand over silt and clay	24 since mined	40 · 40	5 · 5	Species*, no. of individuals, LH*	All, H · W1 · W2*

Species* = All species identified except annuals

BB score* = Braun-Blanquet cover score (see text) recorded

LH* = Life history characteristics (such as regeneration mode and seed storage) noted

H · W1 · W2* = Plant dimensions (height (H), crown width from north to south (W1), crown width from east to west (W2) recorded

H* = Average height of all spp. recorded (up to 10 random individuals measured per spp.)

Table 2: Species diversity, plant density, total plant cover, and plant functional attributes in natural and rehabilitated shrubland near Eneabba, southwestern Australia. CSB = Canopy seed bank, SSB = Soil seed bank, RS = Resprouter, ind. = individuals.

	Natural					*Rehabilitated*			
Measure	*High*	*Low*	*Swale*	*Lat*	*Lim*	*R8*	*R15*	*R16*	*R24*
Spp richness	113	101	109	93	78	83	128	146	144
% Unique spp	18	8	15	26	43	10	12	8	13
H'	1.53	1.6	1.66	1.47	1.41	1.08	1.51	1.4	1.51
D'	0.96	0.96	0.98	0.95	0.95	0.84	0.94	0.93	0.95
J'	0.74	0.81	0.82	0.75	0.75	0.57	0.72	0.65	0.7
Density (m^{-2})	6.6	-	14.3	15.2	6.7	-	-	4.0	3.9
% Total cover	125	171	79	68	115	143	102	90	120
% CSB spp	26	25	28	24	19	48	31	30	29
% SSB spp	74	75	72	76	81	52	69	70	71
% RS spp	69	79	81	88	67	72	71	74	71
% RS ind.	67	-	84	98	71	-	-	39	49
% RS cover	68	72	87	97	61	49	59	37	68

Table 3: Five most speciose genera in natural and rehabilitated shrubland near Eneabba, southwestern Australia.

Speciose genera (# spp in brackets)	
Natural sites	*Rehabilitated sites*
1. *Hakea* (11)	1. *Hakea* (14)
2. *Leucopogon* (10)	2. *Dryandra* (9)
3. *Dryandra* (10)	3. *Lepidosperma* (9)
4. *Stylidium* (10)	4. *Acacia* (8)
5. *Lepidosperma* (10)	5. *Conostylis* (7)
Acacia (4)	*Leucopogon* (6)
Conostylis (6)	*Stylidium* (4)

Table 4: The five most dominant (by % cover) species (regeneration mode in parentheses) at each natural and rehabilitated shrubland site near Eneabba, southwestern Australia. r = resprouter, n = nonsprouter.

	Natural					*Rehabilitated*			
Species	*High*	*Low*	*Swale*	*Lat*	*Lim*	*R8*	*R15*	*R16*	*R24*
Acacia blakelyi n	0	0.3	0	0	0	**36.4**	**6.7**	**12.2**	**10.2**
Acacia pulchella n	0	0	0	0	0	0.3	1.3	0.2	**5.6**
Acacia spathulifolia n	0	0	0	0	**10.5**	0	0	0	0
Adenanthos cygnorum n	**9**	0	0	0	0	4.81	2.8	**11**	0
Allocasuarina microstachya r	0	0	0	**3.9**	0	0	0.1	0.1	0.4
Banksia attenuata r	**13.2**	**15.7**	0	0	0	1	0	0	1.4
Banksia hookeriana n	**15**	0	0	0	0	0	0	**3.9**	1.4
Banksia lanata n	0.2	0	0	0	0	**6.8**	0	0	0
Banksia leptophylla n	0	0	0	0	**8.8**	6.3	**16.5**	**14**	0
Beaufortia elegans n	4.1	28	**4.5**	0	0	0.44	1.3	1.38	2.77
Cassytha pubescens n	0	**8.2**	0	0	0	3.7	**8.5**	0.4	**7.8**
Desmocladus semiplanus r	1.7	**10.4**	0.7	0	4.9	0.15	0.1	0.12	0.28
Dryandra falcata r	0	0	0	0	0	**9.2**	0	0	0
Dryandra shuttleworthiana r	0.14	0	**3.3**	1.6	0	2	3.3	1	0.3
Ecdeiocolea monostachya r	0	0	**5.9**	**11.3**	0	0	0.3	0.2	**18.1**
Eremaea beaufortioides r	0	4	0.7	0.8	0	0.1	**2.8**	1.4	3.5
Georgeantha hexandra r	0	0	0	**5.7**	0	0	0	0	0
Hakea polyanthema n	0.4	**10.8**	0.6	0	0	0	0	0	0.2
Hibbertia hypericoides r	**10.1**	1.8	2.9	**3.5**	**14.7**	0.44	0.98	0.33	2.25

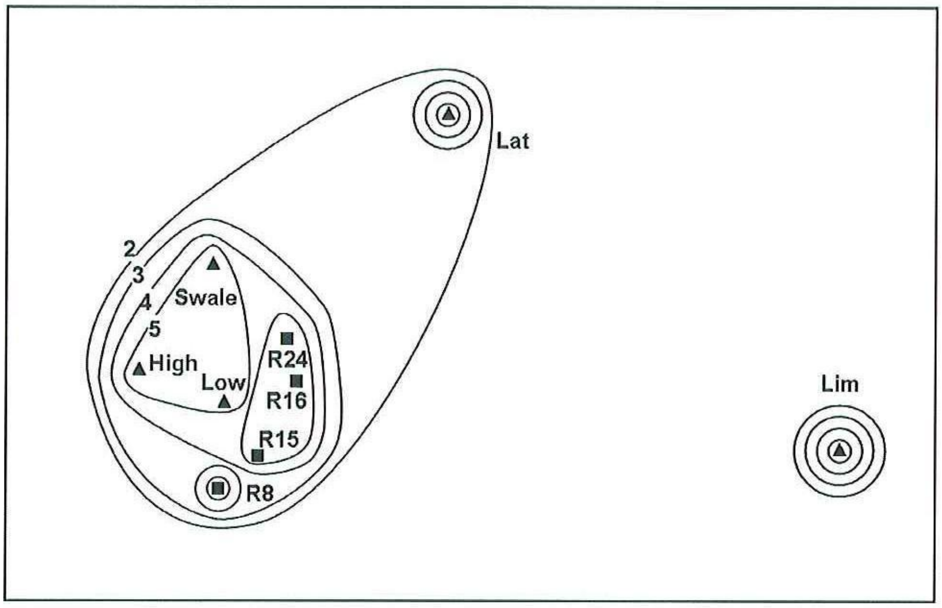
School of Environmental Science, Murdoch University, Murdoch, WA 6150 AUSTRALIA

Labichea cassioides r	0	0	0	0	**8.7**	0	0.06	0	0
Lepidobolus preissianus r	0	0	**5.9**	0	0	0.1	0	0.1	0
Melaleuca leuropoma r	4.7	**15.5**	4.1	2.1	**9.4**	**30**	**24.4**	**8.9**	**12.5**
Melaleuca scabra r	0	0	0	**3.3**	0	0	0.1	0	0.1
Mesomelaena stygia r	0.4	0	**4.9**	0	0	0	0.25	0.01	0.21
Petrophile drummondii n	4.4	3.0	0.1	0	0	**7.8**	3.53	1.62	0.4
Xylomelum angustifolium r	**6**	0	0	0	0	0	0	0	0

Figure 1: PCoA on: a) presence–absence data using Sorensen's distance (horizontal axis = 20.8 % of total variance (tv), vertical axis = 17.4 % tv), and b) composition plus cover data per species using Bray–Curtis dissimilarity (horizontal axis = 26.3 % tv, vertical axis = 19.4 % tv). Lines represent dendrogram groupings (numbers indicate the # of groups formed).

Figure 2: Growth form percentage: a) species composition; b) density; and c) crown cover in natural and rehabilitated shrubland sites near Eneabba, southwestern Australia.

Figure 3: Principal components analysis of natural shrubland and sand-mine rehabilitation sites near Eneabba, southwestern Australia based on soil properties. Axis 1 = 57.3 % tv, axis 2 = 25.7 % tv, * $P < 0.05$ one way ANOVA, Fe = iron, NO_3 = nitrate, e.c. = electrical conductivity, K = potassium and C = organic carbon.



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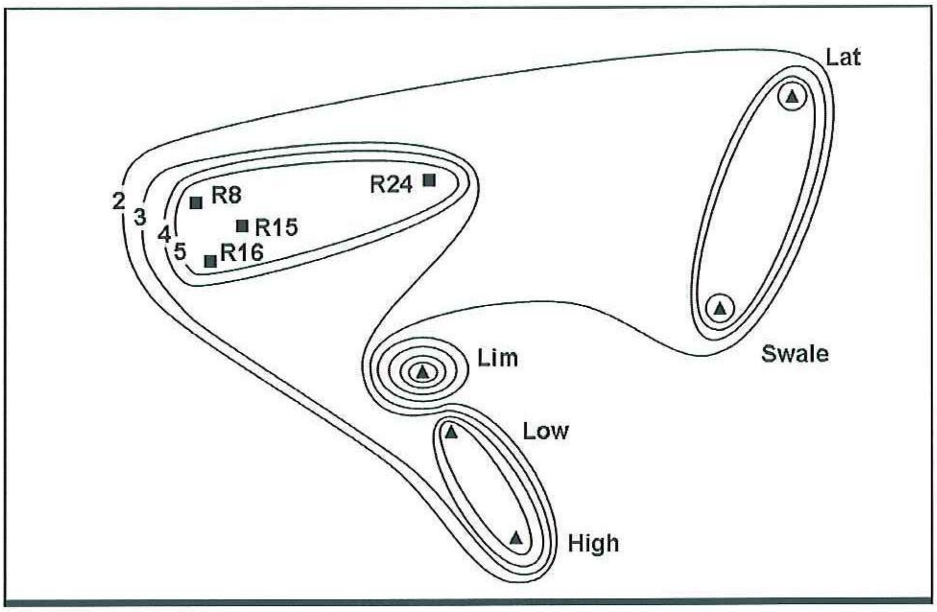

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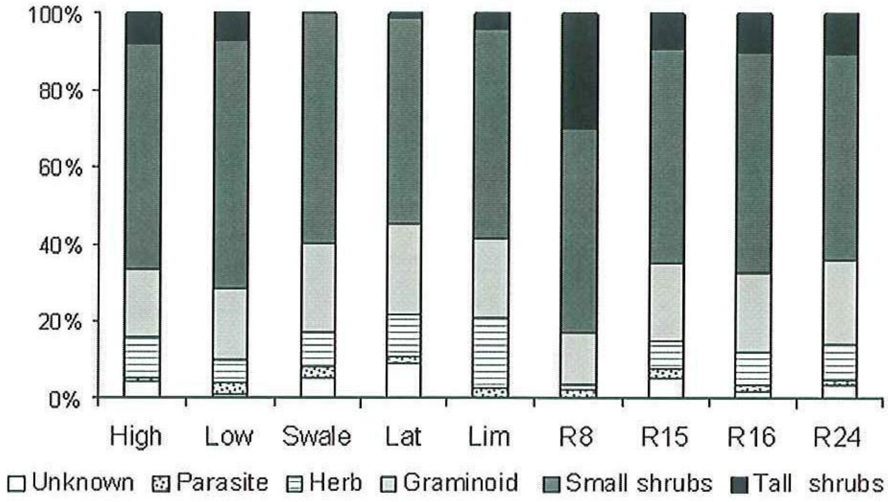

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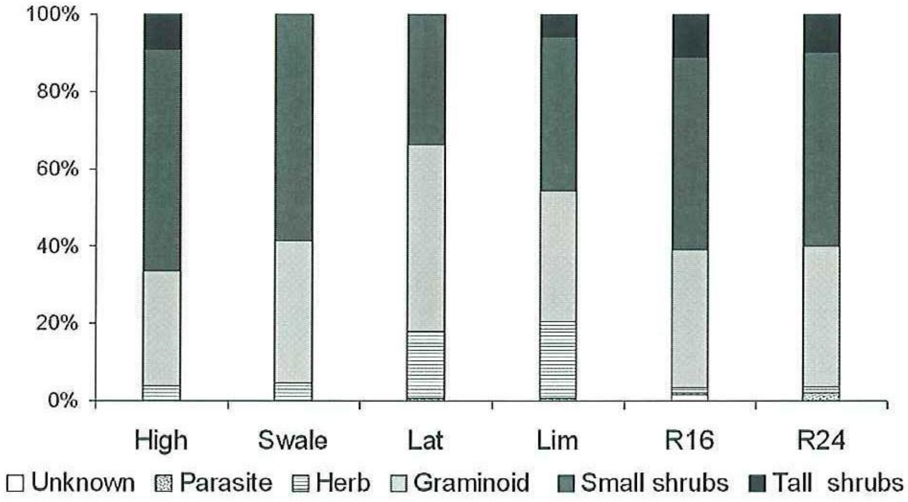

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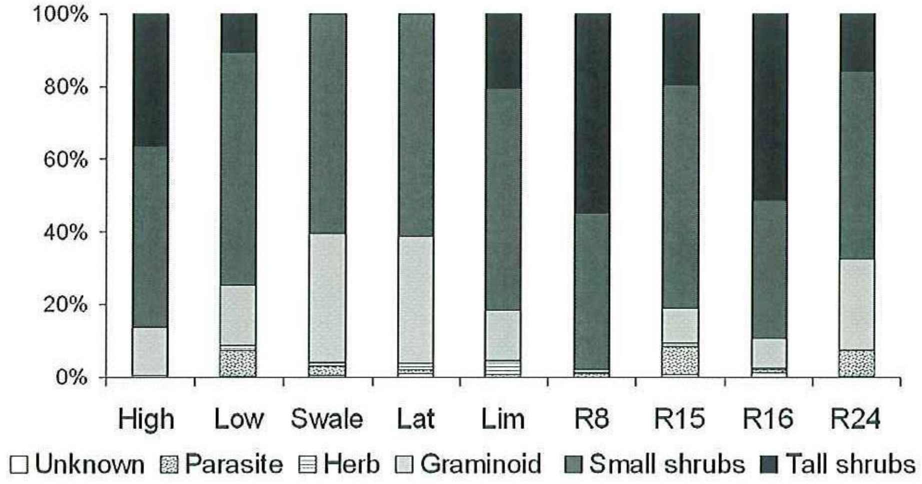

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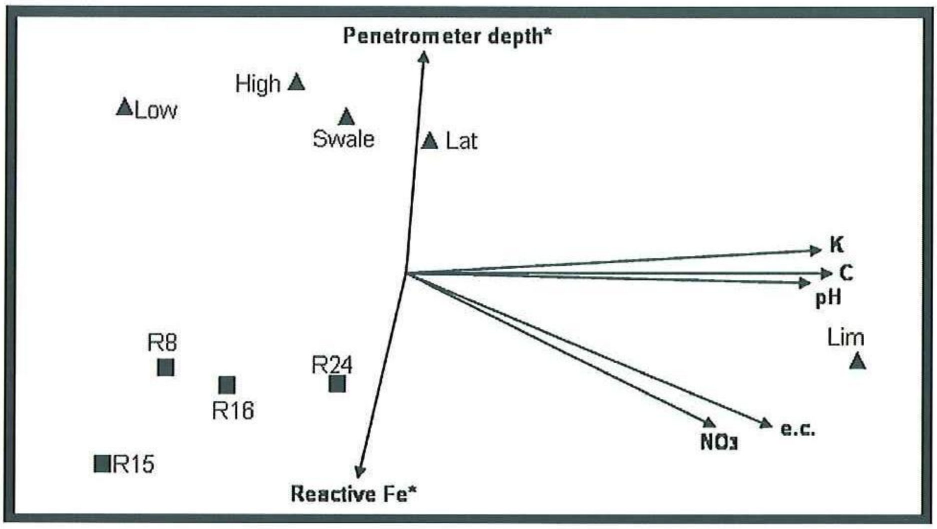

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