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Sand Mining Restoration on the Swan Coastal Plain using Topsoil: Learning from Monitoring of Previous Rehabilitation Attempts

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ABSTRACT

This paper reports on the results of several years of monitoring rehabilitation at a silica sand mine on the Swan Coastal Plain, south of Perth. Mining here occurs below the regional watertable and leaves a post-mine landscape of dredge pond voids (pit lakes) with surrounding battered slopes. The restoration we recommended was to develop the pit lakes as wetlands of regional analogue and value. Several different restoration techniques have been applied to revegetate pit lake slopes over many years which have enabled an evaluation of reasons for success/failure of different restoration approaches. Learnings acquired clearly showed the benefits of using fresh topsoil for restoration over topsoil that has been stockpiled for several years Most topsoil used in restoration was from seasonal wetlands and consequently restoration was most successful in the riparian zone from the edge of pit lakes to about 2 m vertically above the water table. Topsoil restored areas above this level remained poor in plant species and cover. Conversely, remedial seeding/planting proved largely unsuccessful. Permanently and seasonally flooded pit lake margins recolonised relatively quickly and successfully with native sedges and rushes. Development of rehabilitated upper slope plant communities over time was evident with loss of typical wetland species and greater growth and survivorship of upland and dampland plant species on mid to upper rehabilitated slopes. Plant communities of lower slopes showed a converse pattern of development, with a shift towards a more typical wetland composition. We believe matching topsoil to site and development of topographic profiles similar to natural wetlands of the region are the keys to optimising restoration success of sand mines with shallow water tables.

INTRODUCTION

Mining of sands containing heavy minerals and/or other mineral resources often leaves a legacy of dredge ponds – relatively shallow and small, permanent or near-permanent freshwater ponds (Lubke et al., 1996). This is because watertables may be relatively close to the surface in sand-dune and sandplain systems and dredging is usually the preferred method to remove ore-containing sands occurring below the watertable. Dredging of sand involves creating ponds followed by the removal of sand from bottom of ponds through suction or bucket. Following mining, overburden and sometimes residue can be used to fill ponds, but insufficient volumes of waste material usually mean some permanent ponds will be maintained. Waste material is typically used for reconstructing landforms and to batten-down the edges of the mined area. Dredge ponds are a type of pit lake – a more general term used to describe post-mining landscapes which fill with water to varying depths (Kumar et al., 2011).

The challenge for restoration of this post-mine landscape is to create a sustainable and productive aquatic ecosystem within the pit lakes and acceptable levels of vegetation cover and species diversity on the slopes (Lubke et al., 1996). Depending on the locality and local circumstances, it may be important for restoration to resemble or approach natural ecosystem(s) previously existing at or nearby the site, and/or to contribute to regional scale biodiversity conservation. An often ignored element of pit lake restoration is the transitional zone between permanent water and truly terrestrial environment – the fringing and riparian vegetation. Fringing vegetation here refers to plants growing at waters' edge, either emerging from permanent water or experiencing regular flooding; whereas riparian vegetation refers to plants growing above the fringing zone which can access lake water through tapping into shallow groundwater and/or irregular flooding episodes. There are many examples of pit lake margins where little or no vegetation cover has been re-established (McCullough et al., 2009), although there are exceptions (Wilcox & Whillans, 1999). The riparian/fringing vegetation has numerous potential value and benefits to pit lake ecology (such as habitat, organic matter and nutrient input, bank stability etc) and aesthetics (van Etten, 2011).

Harvesting and then spreading topsoil over reformed landforms ("topsoiling") has become a widely used and generally successful technique for restoring post-mining environments (van der Valk & Pederson 1989; Cooke & Johnson 2002). Some researchers report high proportions of plant species (of 'reference' or 'target' ecosystems) being restored via a returned topsoil seed bank following mining; for example: 1) Koch (2007) reports around 70% of species are returned via topsoil for jarrah forest in south-west Australia (following bauxite mining); 2) Holmes (2001) found 60% species returned for fynbos shrubland in South Africa (kaolin mine); 3) Parrotta & Knowles (2001) report 40% species of tropical rainforest species return in Amazonian Brazil (bauxite); and 4) Hall et al. (2010) found 60-70% species recovery for an oak-hickory forest in the Appalachian Mountains, USA (coal). Bellairs & Bell's (1993) study of rehabilitation at a sand mine on the Swan Coastal Plain north of Perth (Eneabba), where only terrestrial landforms (dunes) were re-created, concluded that applied topsoil was responsible for the majority (63-78%) of plant species emerging from rehabilitation. In contrast, Herath et al. (2009) found only between 29-48% of species in rehabilitation originated from topsoil in the same mining area. Both studies from Eneabba, demonstrated the importance of brushing and mulching to increase species diversity of rehabilitation given that relatively large numbers of species in the heathlands of this area maintain an aerial (plant) seed store as opposed to a soil seed store.In addition to contributing to post-mining rehabilitation, topsoil has been used to successfully restore degraded land, including denuded wetland margins (Nishihiro et al. 2006a,b).

Ongoing research and practice has ensured a continued refinement of the topsoiling approach to restoration. Although accepted best practice is still evolving, and it is likely that some key parameters and decisions will depend on ecosystem type, degree of modification and so forth, there is general agreement that restoration outcomes improve with: 1) minimal topsoil storage time with direct return recommended where feasible (Tacey and Glossop 1980; Ward et al. 1996; Rokich et al. 2000; Milton 2001); 2) relatively shallow depth of topsoil collection, storage and spread (Grant et al. 1996; Redente et al. 1997; Rokich et al. 2000); and 3) sieving and concentration of seed in topsoil before spreading (Koch 2007).

In this paper, we present and evaluate results of rehabilitation monitoring of pit lakes (dredge ponds) margins and slopes created following sand mining for silica and heavy minerals at a mine-site on the Swan Coastal Plan south of Perth, Australia. At this site, rehabilitation has been progressively implemented in stages over a number of years, with topsoil being used as the prime method to restore plant species cover and diversity. Distinct zones (or sectors) therefore occur with different age of topsoil application (varying from one to eight years post-rehab at time of monitoring) and different topsoil storage times (from topsoil stored for several years before application to direct return of topsoil). This has enabled some evaluation of the effects of topsoil storage and time since application on restoration success. It is clear from observations that restoration success has been highly variable both between and within rehabilitation sectors, with some areas having very poor recovery in terms of native plant cover and species diversity. Various remedial actions have been implemented over the years in these ‘poor’ areas (such as planting, ripping, fertilizing), the relative success of which will be assessed in this paper using monitoring data. Specifically we address the following questions: 1) what is the potential for restoration success using topsoil at this sand mine site; 2) what are the likely reasons for differences in success both within and between treatment sectors; 3) is rehabilitation becoming more or less similar to local native plant communities over time in terms of plant species composition and soil development; and 4) to what degree have remedial actions in poorly performing areas been successful?

METHODS

Study Area

The Kemerton Silica Sand Pty Ltd (KSS) project area occupies some 1 600 ha of land at the northern end of Kemerton Industrial Park, 20 km north of Bunbury (Figure 1). The KSS Project Area is located on the Swan Coastal Plain, primarily on gently undulating Bassendean Sands (dune system). Vegetation comprises *Eucalyptus-Banksia* woodland with diverse shrub understorey on uplands and various wetland communities from unvegetated basins, fringing sedge communities of permanently to seasonally inundated zones, and riparian zones of Melaleuca spp. with mostly sedge understorey where there is close exposure to surface and/or groundwater. These riparian areas also include large expanses of species-rich woodland and shrublands on seasonally waterlogged flats, commonly known as damplands (sensu Semeniuk 1987). Topsoil is typically sourced from these dampland/riparian zones as they are the most extensive vegetation types of the area and are where mining predominantly occurs.

Climate is Mediterranean with most of the average *c*.890 mm of annual rainfall falling in winter and spring. Summers are warm to hot and typically very dry (average February maximum temperature 28^{o}C and rainfall 13 mm), whilst winters are cool and wet (average July maximum 17^{o}C and rainfall 186 mm). The rehabilitation and monitoring period 2001–2008 was one of the driest on record with total rainfall each year below the long-term average, and most below the recent (1995–2008) average (Figure 2). In 2006, annual rainfall was very close to the lowest on record (510 mm).

Sands containing feldspathic silica and heavy minerals (mostly titanium oxide) are extracted from below the watertable using dredge ponds. The resource generally lies beneath <1 m of topsoil and 4 to 7 m of overburden (which generally contains a band of coffee rock at the inter-phase between high and low groundwater levels). The overburden is removed by earth moving equipment. The ore resource is then extracted from a 30 m deep superficial aquifer using a surface floating dredge to a maximum permitted depth of 15 m. Approximately 500,000 tonnes of silica sands are extracted annually at this mine. Once ore extraction is complete, the dredge pond is approximately 10 m deep. As the dredge pond is essentially an expression of the groundwater, the results are permanently inundated lakes. Fines, overburden and topsoil are available for sculpting and landscaping of the dredge ponds and surrounds.

This study has focused on the main rehabilitation area around the northern most dredge pond of the Kemerton active mining area, hereafter referred to as “North Lake” (Figure 3). This area was mined and the pond created in the late 1990’s. Rehabilitation of the surrounding slopes commenced in 2001 and progressively implemented until 2006 with different techniques used in different areas (called ‘sectors’ here). Full details of restoration and monitoring techniques applied to each sector are summarized in Table 1. Rehabilitation of dredge ponds immediately south of North Lake commenced in 2007 and these also have been monitored (once).

Monitoring Methods

Monitoring commenced in March 2004 for sectors rehabilitated in 2001–2003 and continued on a semi-regular basis thereafter (Table 1). Monitoring used permanent transects established up the slope from pit lake margin to the upper reaches of the rehabilitation. One or two transects, with random starting positions along the shore, were established in each sector. They varied in length from 80 to 200 m. Along each transect, cover and abundance of all plant species were recorded in 2 m x 2 m permanently marked quadrats set 5 m apart. Notes on plant health and size, including presence of any new seedlings were made.

Natural wetland and dampland communities within the active mine area were selected as suitable reference sites to compare to and evaluate rehabilitation. These have been studied by the authors prior to assessment of rehabilitation (van Etten et al., 2009). Native plant communities of the study area were surveyed by recording plant species and their cover within plots placed in visually distinct vegetation types along transects running up slopes from wetland basin to uplands and including riparian zones. Topographic profiles were constructed for rehabilitation and natural wetlands using a theodolite and staff to measure relative height along transects.

Soil profile measurements were completed to help establish reasons for lack of growth and cover across much of the rehabilitated sites. Different vegetation zones were identified along the permanent transects established in each rehabilitation sector. A sampling trench was then dug in each zone and depth to different soil horizons to 50 cm were measured. A soil samples was then collected from each horizon. Soil samples were dried, ground and analysed in the laboratory for the following parameters: Texture, Colour, Nitrate-N, (mg/kg), Ammonium, (mg/kg), Phosphate, (mg/kg), Potassium, (mg/kg), Sulphur, (mg/kg), Carbon, (%), Iron, (mg/kg), Conductivity, (dS/cm) and pH. Soil were also sampled and analysed in similar fashion along transects through natural wetland communities.

Data Analysis

Data analysis involved calculating the mean and standard error of quadrat cover, density (number of plants per quadrat) and richness (number of species per quadrat) for each transect. The mean values of these parameters were then compared between transects and between monitoring periods. Analysis was conducted on perennial species only to enable fair comparison between monitoring periods given previous monitoring has occurred over different seasons. Differences in species composition between transects and between quadrats were explored using ordinations. Ordination techniques attempt to arrange surveyed sites so that the degree of similarity in plant species composition is represented in the physical spacing of the sites when the data are plotted i.e., similar sites sit close to one another. Differences between sites were then tested using ANOSIM which can be considered to be similar to analysis of variance (ANOVA) for this type of analysis. Similarities were determined using the Bray-Curtis measure (based on square root transformed cover values of species). Ordination and ANOSIM were then performed using the Primer (v6) software (Clarke & Warwick 2001).

RESULTS

Plant Cover and Abundance

Rehabilitation sectors differed significantly from each other in terms of cover (both native species and weeds), native plant density, native species richness and species composition (Table 2; Figure 4). Cover was consistently higher in Sector 2 with total cover around 50% on average (Figure 4a). This sector, although receiving the same initial topsoil treatment as other older rehabilitation (Table 1), was characterised by being lower in the profile (closer to groundwater) and on gentler slopes (Figure 5). The two recently rehabilitated sectors (5 & 6) had markedly increased in cover over time, with Sector 5 (rehabilitated with stored topsoil) having average cover of ~42% which was greater than sector 6 (fresh topsoil; Figure 4a). Overall cover (across all sectors) increased over time although the significant interaction between sector and time indicates that such increases were inconsistent across sectors (Table 2), with older rehabilitated Sectors 1 and 3 maintaining very low cover (<20%) over the 5 years of monitoring (Figure 4a) despite receiving remedial treatments such as planting, seeding, fertilisation and weed control (Table 1).

Native plant density remained relatively stable over time but differed between sectors (Table 2). Sector 6, the most recently rehabilitated with fresh topsoil, had the greatest numbers of plants, whilst Sectors 1 & 3 had few plants persisting (Fig. 1b). Species richness followed a similar pattern with Sector 6 having far greater richness (average of 13 native plant species per quadrat) than other sectors (Table 2; Fig. 1c). There were improvements in species richness from 2008 to 2009 (Table 2), although Sectors 3 and 4 clearly lost species between 2005 and 2007 (Fig 1c).

Comparisons to Native Vegetation

Wetland vegetation was divided into fringing (ie flooded), riparian (waterlogged) and wetland-upland ecotone zones (Figure 6a). Plant species composition of rehabilitation (when collated for each sector) was dissimilar to riparian vegetation of natural wetlands (ANOSIM Global R=0.67; p=0.002) and other local vegetation types (p<0001; Figure 6a). The closest rehabilitation to the natural wetlands in terms of floristics was Sector 2 which mostly closely resembled the riparian vegetation of local wetlands, although the two most recent rehabilitation efforts (Sectors 5 & 6) showed the largest shift in species composition from 2007 to 2008, becoming more similar to riparian communities generally. The differences between the rehabilitation and natural wetlands were predominantly in tree species *Melaleuca viminalis and M. rhaphiophylla* (greater average abundance in natural wetlands), dominant sedges such as *Lepidosperma longitudinale* and *Meeboldina scariosa* (greater abundance in natural wetlands, although locally common in rehabilitation), leguminous shrubs such as *Viminaria juncea* and *Acacia pulchella* (greater abundance in rehabilitation), and shrubs from Myrtaceae family such as *Hypocalymma angustifolium* and *Kunzea* spp. (greater abundance in rehabilitation). Together such species account for 68% of the difference in composition between rehabilitation and natural wetland riparian zones (as determined by SIMPER; Table 3).

Shifts in Species Composition

Sectors differed from each other in plant species composition measured at the quadrat level, and shifted in composition over time (Table 2; Figure 6b), with pair-wise tests using ANOSIM showing each sector differed to all others ($p<0.01$). Species composition also varied with position along transects from lake edge to upland; such gradual change is evident along transects placed through the two recently rehabilitated sectors just 1-2 years after topsoil treatment (Figure 6b). These two sectors showed significant differences in floristics between upper (upland), middle (riparian) and lower (fringing) zones of transects (Global $R=0.32$; $p<0.001$), as well as significant shifts between 2007 and 2008 (Global $R=0.19$; $p=0.003$). The temporal change in composition in the fringing zone was predominantly due to substantial increases in emergent sedges/rushes and decline of legumes (Table 4). In contrast, the major shifts in composition of uplands were increases in cover of Myrtaceae and leguminous shrubs and decreases in typical fringing sedge/rush species. Riparian (middle zone) floristic changes were mainly attributable to increases in shrub abundances. In terms of resemblance to native plant communities, lower parts of recent rehabilitation resembled the fringing vegetation of natural wetlands, and showed the greatest degree of change in composition over time (Figure 6b). In contrast, riparian parts of the recent rehabilitation had changed relatively little and were if anything shifting closer to dampland (site W4-3). Upper parts of rehabilitation showed relatively substantial changes in floristics but were not always becoming more similar to wetland-upland ecotones (Figure 6b), although they contained many understorey species of uplands (Table 4).

Topography

Topographic profiles (Figure 5) showed Sector 4 was generally the lowest in the landscape with the most gentle slopes and was most similar to natural wetlands studied. In contrast, Sectors 1 and 3 rose rapidly from the lake edge with the majority of transects 3 m or more above water level at time of measurement. The most recent rehabilitation (Sectors 5 and 6) were intermediate in topography with relatively gradual and consistent slopes (but steeper than profiles of local wetlands studied).

Soil

Chemical and physical characteristics of soil samples collected at each (visually) identifiable soil horizon within each rehabilitation sector are shown in Table 10. Rehabilitated soils were generally grey colored (Figure 7) and fine textured (1.5 mm grain size) with concentrations of organic carbon under 2%, unlike wetland soils with 3–6% carbon. Mean rehabilitated area soil pH was also under 5, whilst wetlands soils were above pH 6. Soil pH was mildly to strongly acidic in rehabilitation, but generally in line with variation seen in natural wetland substrates. With one or two exceptions, rehabilitation soils were very low in nutrients with levels of nitrate and phosphate levels likely to be below the limits of detection limits at most sites (i.e., below 1 ppm). In contrast, levels of macro-nutrients in natural wetland soils were at least several times higher, on average, than that of rehabilitation (Table 5). Conductivity, an indicator of soil salinity, was generally lower in rehabilitated (Table 5).

There were some distinct exceptions to these general trends. Topsoil (first 32 cm) of Sector 3 was quite high in nitrogen in the form of ammonium. This Sector also has high organic carbon. This is not surprising given the high plant density and surface leaf litter cover in this area. Organic carbon was also relatively high in the newly rehabilitated areas, although it was somewhat higher at Sector 6 (where fresh topsoil was used) compared to Sector 5 (old, stored topsoil). However both these sites are low in available macronutrients (Table 5).

An ordination (**Error! Reference source not found.** shown) illustrated overall differences in soil characteristics between sites and shows the rehabilitation is distinct and relatively uniform in soil when compared to the widespread variation found in natural wetlands. However no differences were detected between rehabilitated and natural wetland soils using ANOSIM tests, although this may reflect the huge variability in wetland soil characteristics. Topsoil of Sector 3 is most like wetland soils, and then only that of fringing *Melaleuca* species at EPP wetland 7 (Table 5). The main differences, as determined by SIMPER, between rehabilitated and wetland is in terms of organic carbon, sulphur, potassium, texture and conductivity (all greater than 10% contribution to overall difference in soils, and all greater in wetlands compared to rehabilitated areas).

DISCUSSION

Restoration Success

The key finding in this study was the marked variation in restoration success within and between rehabilitation sectors. The fact that some areas of rehabilitation are clearly successful, being diverse in plant species and life-forms, structurally complex and dense, and similar to local natural wetland communities in terms of species composition and soil, means that the use of topsoil as a restoration method has considerable potential to successfully restore margins and slopes of pit lakes formed following sand mining on the Swan Coastal Plain. These successfully restored areas were generally in the fringing zone and in some riparian areas, with uplands generally being unsuccessful in terms of restoration outcomes. The reasons for these differences across the post-mining landscape are explored below.

Fringing Zone

McCullough et al. (2009) reported that the margins of pit lakes were typically the most difficult post-mining landforms to restore and were often devoid of vegetation. Conversely, the most successful restoration sites in our study area were fringing zones where dense sedgeland of species such as *Lepidosperma longitudinale*, *Juncus* spp. (Juncaceae), *Isolepis* spp., *Baumea articulata* and *Meeboldina scariosa*

(Restionaceae) have developed (although characteristic woody vegetation is slow to develop), and this supports other studies demonstrating the utility of using topsoil in wetland environments (Brown & Bedford 1997; Wilcox & Whillans 1999). However, there are practical considerations which need to be heeded when using topsoil in the fringing zone. Firstly, topsoil can only be feasibly applied in the dry season or other times of low water levels. Rising water levels may cause chemical and other changes to the topsoil (Anderson et al. 2005) and even erosion, especially on slightly steeper slopes and or where wave action is prevalent (Wilcox & Whillans 1999). Stabilisation of wetland edges may be required by means of plant material (logs, brushing), sandbags, or matting (Wilcox & Whillans 1999; Nishihoro et al. 2006a).

Several studies have demonstrated the accumulation of plants and species via wind dispersed seed in this zone (eg van der Valk et al. 1999) and problems can occur when this zone becomes dominated by exotic and/or other ruderal species (Brown & Bedford 1997). There is evidence that species known to produce abundant wind dispersed seed have been colonising the fringing zone of the lake (eg *Juncus* spp., Bakker et al. 1996; *Meeboldina* spp., Meney & Pate 1999) although the dominant species in this zone (*L. longitudinale*) is likely to have arisen from topsoil given its widespread emergence soon after topsoil treatment and its ant-dispersed, dormant seed (Kodym et al. 2010; Lengyel et al. 2010). Lastly, consideration needs to be given to acute hydro-period gradients across the fringing zone with plant species composition known to be sensitive to any variations in microtopography (,Naiman et al 2005; Nishihoro et al. 2006b). Overall, we found restoration of wetland fringing zones considerably easier to achieve than the surrounding riparian slopes and uplands.

Riparian Zone

The riparian zone around the main rehabilitated pit lake generally lacked the *Melaleuca* trees and other woody species which characterise the riparian zone of local natural wetlands. However where slopes were relatively gentle, a healthy stand of *Melaleuca* and associated species did develop. Presumably success in these areas is linked to their topographic and hydrological similarity with natural wetlands of the area which also develop on subtle slopes (van Etten et al. 2009), as well as the extra expanse of this zone where slopes are subtle (Figure 8). This pattern was also found in the more recently rehabilitated area south of the main pit lake where subtle and undulating slopes were reformed after mining with large numbers of smaller and shallower ponds between; here a relatively large number of *Melaleuca* seedlings were found on the slightly raised ground above the ponds. Woody debris was scattered over this area, with some with some of the *Melaleuca* re-establishing via suckering (resprouting) from root systems persisting in or on the surface of the topsoil. The same had been noted around the margin of the main pit lake, albeit at lower density. Therefore, the incorporation of woody debris, particularly root systems, in the topsoil could well be an innovative approach to improve restoration outcomes in riparian zones, and further experimentation with the technique is recommended.

Terrestrial Zones

The older rehabilitated upland sites (those generally 2 m above the high lake water levels) were unsuccessful with low native species diversity, considerable weed cover and few to no woody plants. They were also markedly dissimilar to native plant communities in the vicinity, including eucalypt woodlands and forests which characterise the terrestrial vegetation of the study area. The more recent rehabilitated areas were considerable richer in native species, but there was evidence that upland areas (again those above 2 m) were declining in terms of diversity and may, over time, begin to resemble the older unsuccessful rehabilitated areas. Reasons for this decline and general shifts in species composition are discussed below.

Best Practice for using Topsoil as a Restoration Tool

This study supports generally-accepted ‘best’ practice for restoration of disturbed land using topsoil. Specifically, we demonstrated the advantages of using direct return of topsoil with superior restoration of native species and plant density in areas treated with fresh topsoil compared to where applied topsoil had been stored for several years. Superior plant establishment using fresh topsoil has been shown elsewhere (Tacey and Glossop 1980; Dickie et al. 1988; Bellairs and Bell 1993; Milton 2001; Parrotta and Knowles 2001). Rokich et al. (2000) reported that mean seedling numbers and species richness emerging from three year old topsoil was only 34% and 61%, respectively, of that recorded in areas where fresh topsoil was applied for a rehabilitated *Banksia* woodland following sand mining near Perth; this is broadly the same geomorphic unit as our study (albeit their study was restricted to uplands). The decline in seedling emergence from topsoil following storage is generally attributed to loss of seed viability over time, although others point to the role of seed damage when placed in large piles, early germination when piles are kept moist, or to dilution effects when surface layers containing most seeds are mixed with deeper layers (van der Valk and Pederson 1989; Rokich et al. 2000; Scoles-Sciulla & DeFalco 2009). Van der Valk et al. (1999) showed seed of several *Carex* spp. did not germinate when older than 6 months and recommended fresh topsoil for fringing wetland restoration.

When assessing benefits of topsoil application, Burke (2008) highlighted the difficulty in knowing whether seedling recruitment is from stored seed or seed dispersed into the soil after topsoil application via wind, animal or water. In this study, the original rehabilitation sites were not monitored until three years after topsoil treatment and therefore the relative roles of soil seed bank versus seed dispersal cannot be clearly differentiated in these areas. However, the most recent rehabilitation was first monitored one year post-treatment, and here the clear advantages of fresh over stored topsoil could be confidently attributed to differences in soil seed store given the spatial distributions and patterns of seedling emergence (relative even spread of plants and most species confined to topsoiled areas) and the relatively large seed size for many species (eg legumes; Bell et al. 1993). We also recorded reasonable germination in the second year after topsoil treatment; again this is mostly attributable to soil seed bank as it mainly involved species with pronounced innate seed dormancy (Bell et al. 1993). Much of the older rehabilitation areas had high weed cover (mostly grasses and other ruderals) and seed of these species may have accumulated in the topsoil before or after stockpiling as has been reported elsewhere (Dickie et al. 1988; Rokich et al. 2000). However, given weed cover was increasing and dominated rehabilitation where native plant cover was low, it is likely much of the weed problem can be attributed to wind-blown seed arriving after topsoil application.

Effectiveness of Remedial Treatments

Large areas of rehabilitation are in ‘poor’ condition and have not improved for several years with persistent low cover (mostly < 15%) and low diversity of native plants despite a number of corrective restoration treatments being applied during this time (including planting of seedlings, ripping, fertilising, herbicide and direct seeding). We conclude that such remedial actions have been largely forlorn and, in the case of ripping the surface soil, may have even had a negative impact on plant cover and species diversity. This highlights the importance of getting the site treatments and revegetation prescriptions right, as best as possible, in the intitial phase (eg just after landforming in a post-mine context) as follow-up treatments become more difficult and expensive with time, especially where there is some recovery of plant cover (Koch, 2007).

Matching of Topsoil Source and Receiving Sites

Poor and seemingly intractable rehabilitation areas were in stark contrast to the most successful rehabilitation (Sector 2) which was also treated with topsoil at the same time as these 'poor' sites. Sector 2 had developed structure and species composition similar to that of riparian zones of many local wetlands. Its main distinction from poor rehabilitation was its lower position in the landscape being within 2m (vertically) of the mean water level of the pit lakes and consequently more likely to remain moist to waterlogged throughout the year. Poor sectors were mostly greater than 2m above pit lake water levels and have mostly dry sandy soils. The fringing vegetation of these sectors was generally performing better with dense sedgeland, except on the east side where wave action actively eroded the littoral edge creating small highwalls. We therefore conclude that site factors, specifically height above groundwater levels, also play a critical role in restoration success. Further, we argue that a major reason for lack of restoration success within our study area can be attributed to inappropriate matching of topsoil source to receiving sites given topsoil has been routinely collected from natural wetlands, particularly damplands. These topsoils have failed to develop adequate plant cover and diversity when applied to higher parts of the landscape which, in terms of the physical environment, are more similar to uplands of the region. We have not found similar results in the literature regarding lack of success of 'wetland' soils when applied to uplands, although Brown and Bedford (1997) reported superior long-term development of wetland vegetation occurred where wetland topsoil was applied compared to where topsoil was sourced from uplands. Nishihiro et al. (2006a,b) also demonstrated that topsoil origin significantly affected species composition of re-established vegetation in a degraded Japanese wetland.

Based on these findings, we advocate that topsoil be separated based on topographical position in landscape from where it is collected (specifically, for our study area, uplands, riparian and fringing zones) and then applied to similar areas in reformed landscapes as much as practicable (Figure 8). For the restored pit lakes of our study, we recommend that around 2 m above mean water level be used to broadly demarcate upland and riparian zones (based on our findings and observations), although more generally this boundary will be influenced by such factors as hydro-period, degree of hydraulic conductivity and groundwater connectedness, as well as long-term trends in groundwater levels (Bedford 1996). We also recommend that more gradual slopes be constructed where possible to: 1) maximise the extent of land suited to the development of riparian wetland vegetation (Figure 8) given this is the predominant vegetation being mined and for which topsoil is therefore available; 2) prevent erosion of fringing zones; and 3) more closely mimic the gentle topography of natural wetlands of the district.

We have demonstrated shifting plant species composition within rehabilitation, albeit over a relatively short time period. Given topsoil was sourced from a relatively homogeneous area and applied uniformly over slopes, some preferential establishment is likely to have occurred given gradients in species composition were evident after one year within the most recently rehabilitated sectors. Other authors have reported differential establishment of species from applied topsoil in response to variations in the physical environment, particularly topography (Cobbaert et al. 2004; Nishihoro et al. 2006a; Burke 2008). We found these gradients developed further over the second year post-rehabilitation, due predominantly to loss of wetland species and increased cover of typical upland species on upper parts of the topographic profile; the reverse trend was found in the seasonally-flooded fringing zone. Therefore, there is evidence that species are sorting into preferred habitats to some degree and this would be expected to develop further over time. However as temporal shifts seem to be mainly driven by changes in species dominance, rather than species migration, broad separation and application of topsoil is advocated to improve restoration success.

CONCLUSIONS

Although not set up as a controlled field experiment, our study has shown that repeated monitoring of rehabilitation can reveal valuable insights into the factors likely to contribute to successful restoration of post-mining landscapes. This is particularly so where rehabilitation is compared to appropriately chosen reference or analogue sites (White & Walker, 1997). From our study we recommend the following prescriptions for pit lake margins and slopes of the study area, and as potential general approaches to improve restoration success elsewhere:

1) use topsoil as main method for restoration;

2) direct return or apply fresh topsoil where possible;

3) broadly segregated topsoils based on physical characteristics of collection locality applied to similar areas around lakes; and

4) create gentle slopes and shallow wetlands which more closely resemble that of natural wetlands of the region

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FIGURE CAPTIONS

FIG 1 - Location of Kemerton study area in south-western Australia

FIG 2 - Annual rainfall for Bunbury (20 km S of study area) for the period 1998-2008 compared to average annual rainfall for 1880-1995 (long-term; green broken line) and 1995-2006 (recent; blue broken line).

FIG 3 - Aerial photograph from 2006 showing Sectors around North Lake. Topsoil has been recently applied to Sector 5 in the photo. Position of monitoring transects are shown by red lines.

FIG 4 - Trends in mean values (with ±standard error bars) over time of: a) native plant cover; b) native plant density; and c) native plant species richness per quadrat for the six rehabilitation sectors.

FIG 5 **-** Topographic profiles showing height above lake water level (winter 2007) for selected monitoring transects placed perpendicular to contour. For natural wetland profiles, 0 m height was taken at the lowest point of lake bed.

FIG 6 **-** Ordinations of floristic data using multi-dimensional scaling (MDS) for: a) monitoring transects in rehabilitation (R1 to R6; with number indicating sector) at two monitoring dates (2007 & 2008*), and wetland sites (W*x*-*y*; where *x* indicates wetland and y refers to point along transect across wetland from lake basin (lowest number) to wetland-upland ecotone (highest number); and b) monitoring quadrats for most recent rehabilitation (R5 & R6 with second number referring to position of quadrat along transect with lowest number being the highest point) over two monitoring dates with reference sites located in nearby natural wetlands (wetland numbering as per a) above). Arrows show trajectory of floristic change between monitoring dates. Floristic data used to generate similarity measures were square-root transformed cover of perennial plant species.

FIG 7 **-** Typical natural wetland topsoil profile a). and Rehabilitated Area topsoil profile b).

FIG 8 **-** Recommended rehabilitation zoning for restoration of wetlands (particularly pit lakes) which are linked to groundwater systems. ($Note_1$: vertical heights are largely dependent on relative lake and groundwater depth and degree of fluctuation, with figures here applicable to the pit lake studied at Kemerton; $Note_2$: horizontal distances depend largely on slope of reformed land; $Note_3$: vertical height exaggerated relative to horizontal distance).

TABLE CAPTIONS

TABLE 1. Summary of rehabilitation history and monitoring of slopes around North Lake.

TABLE 2. Statistical test results comparing means between different rehabilitation sectors and year of establishment (as well as interaction between these two factors where possible). Significant results (P<0.05) are in bold. T.S.=test statistic.

TABLE 3. Differences between rehabilitation and natural wetland transects in species composition as determined using SIMPER analysis of dissimilarity in PRIMER (Clarke and Warwick 2001). Abundance refers to mean squared-root transformed cover. Dissimilarity refers to average contribution of species to average Bray-Curtis dissimilarity between rehab and wetlands.

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FIGURES

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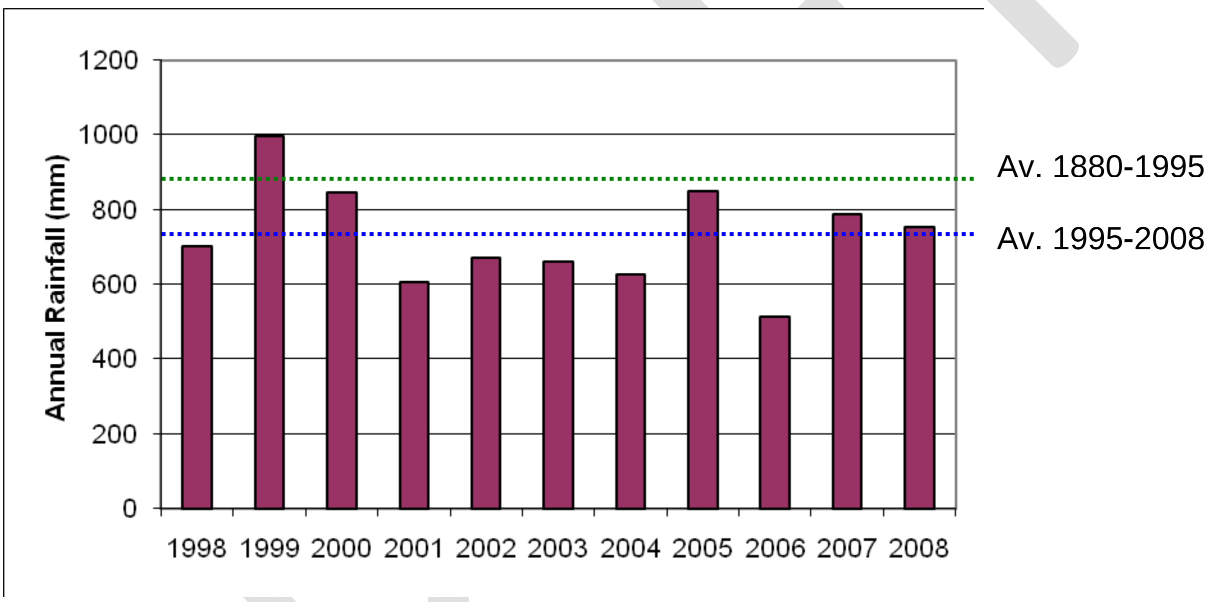

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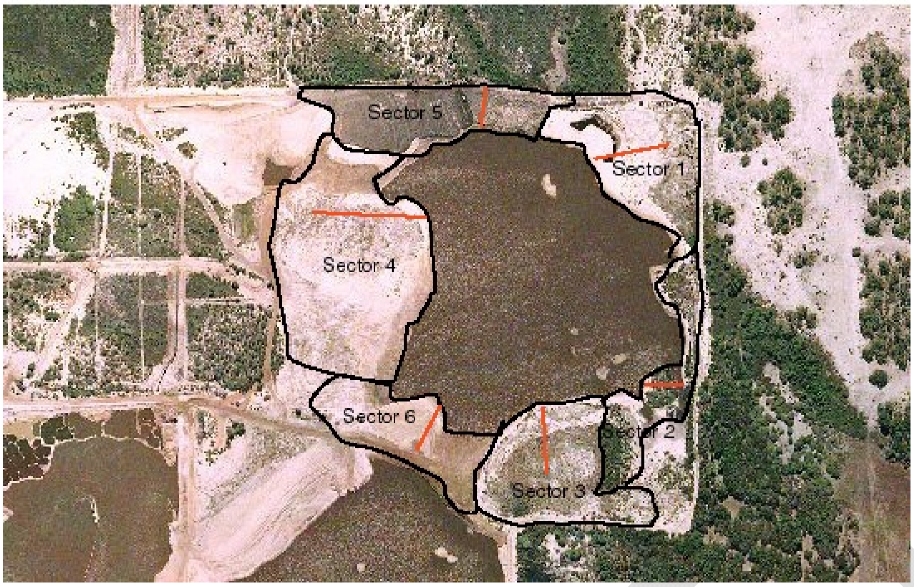

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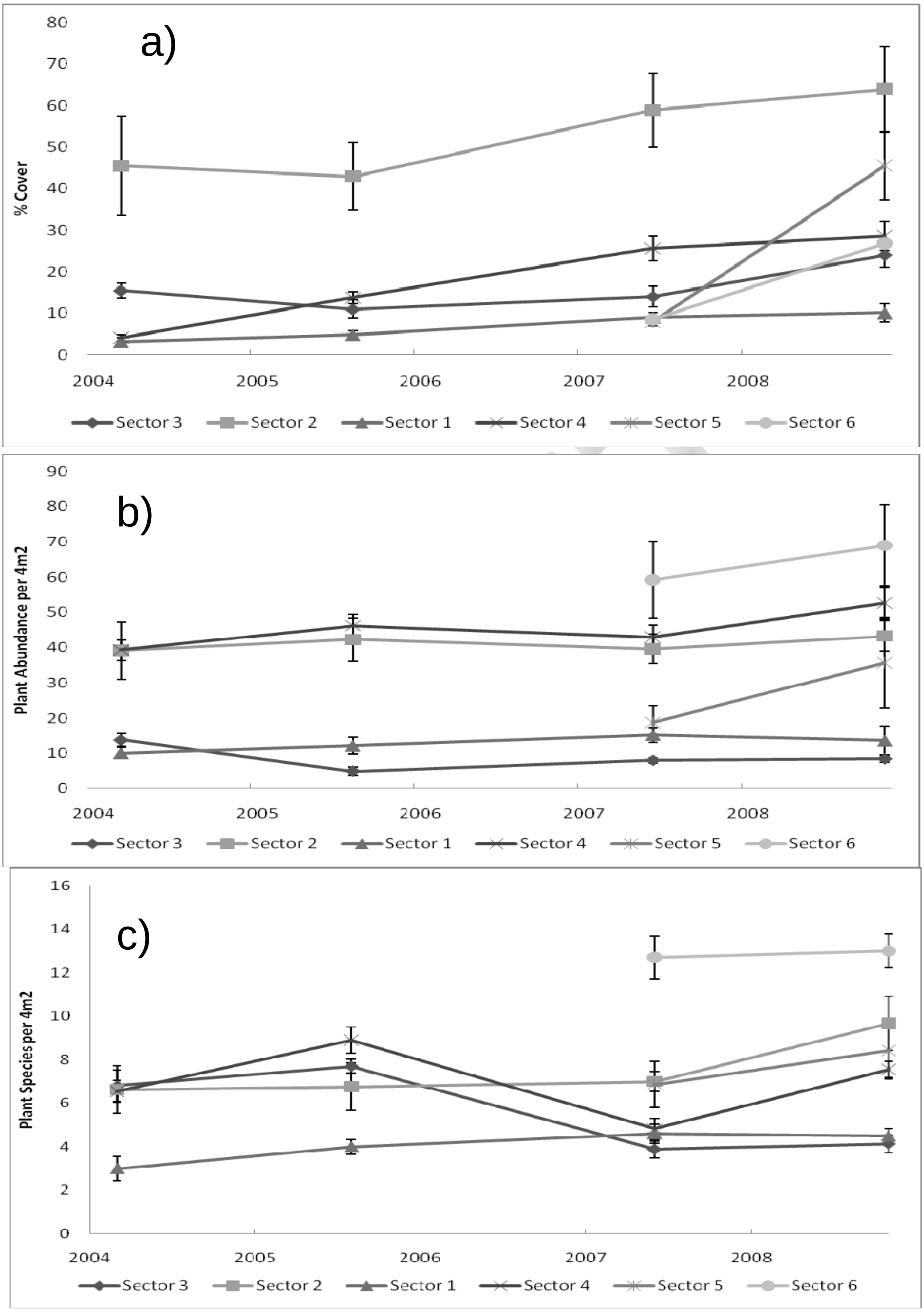

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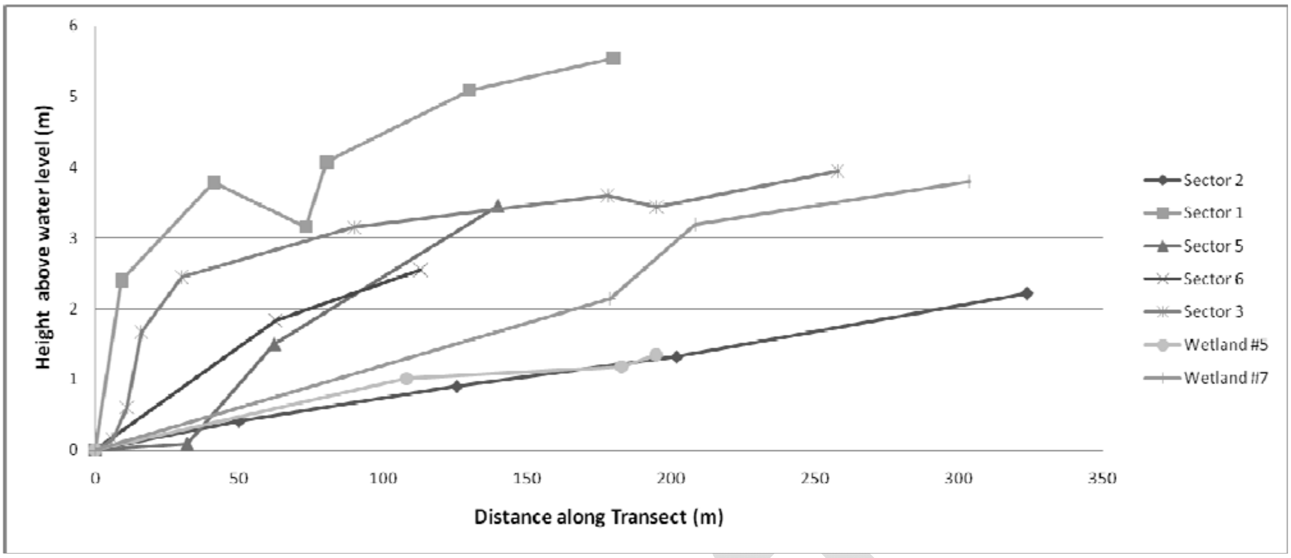

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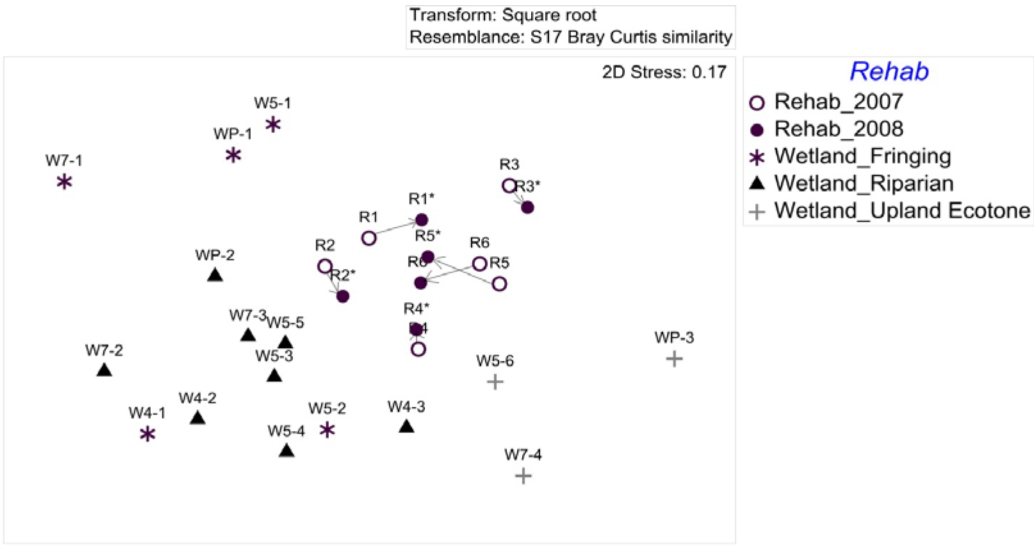
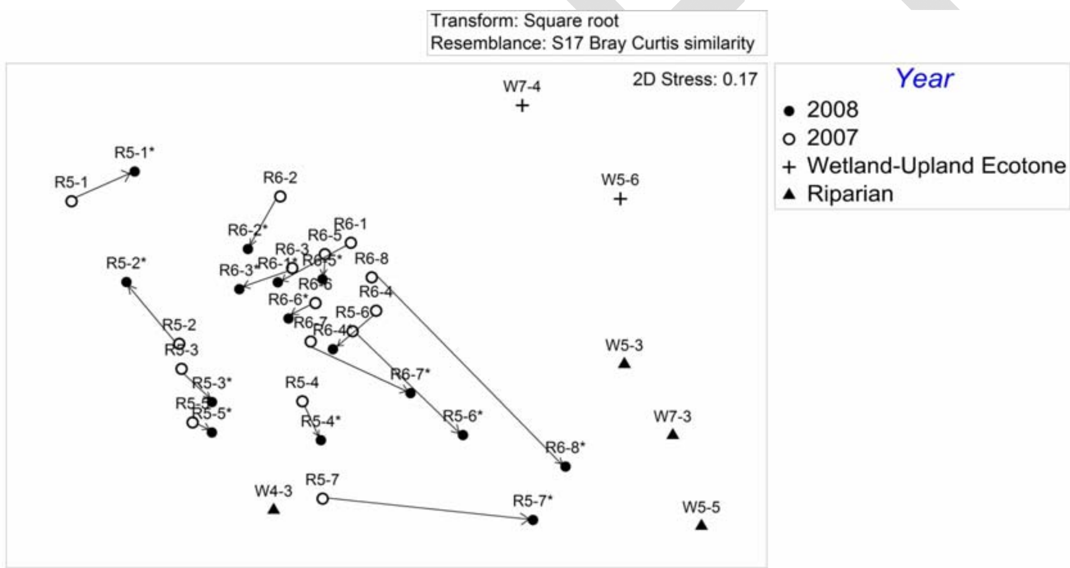


b)



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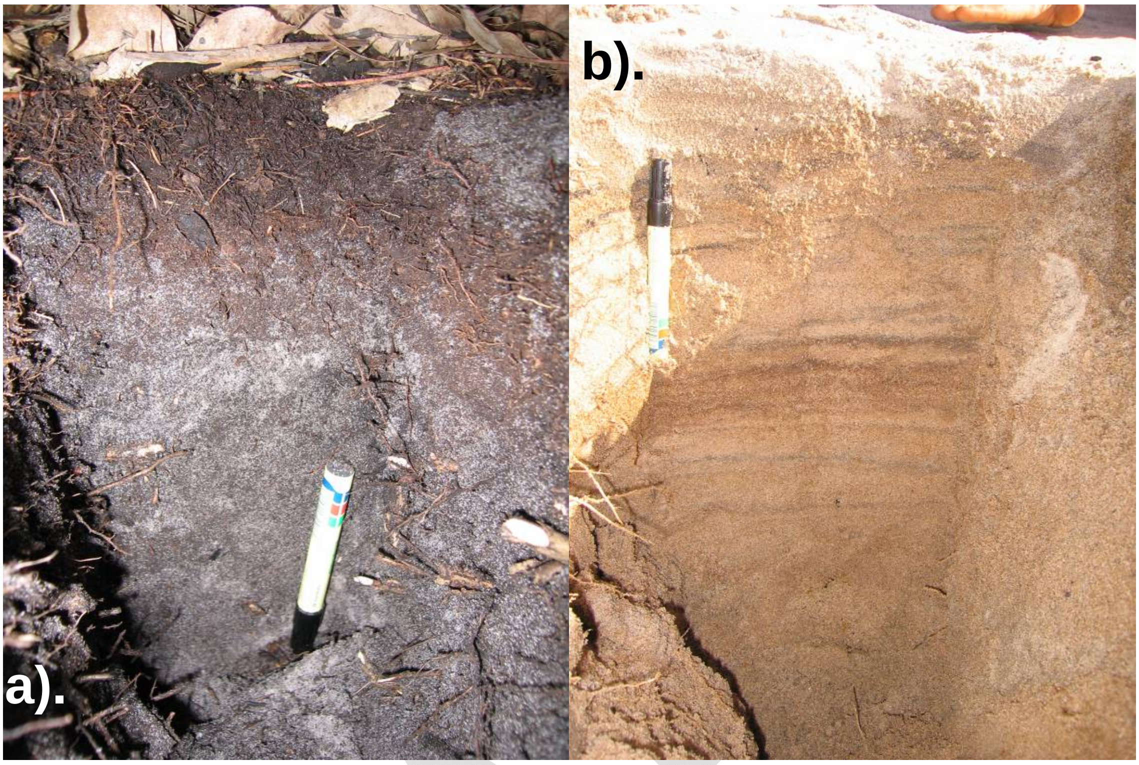

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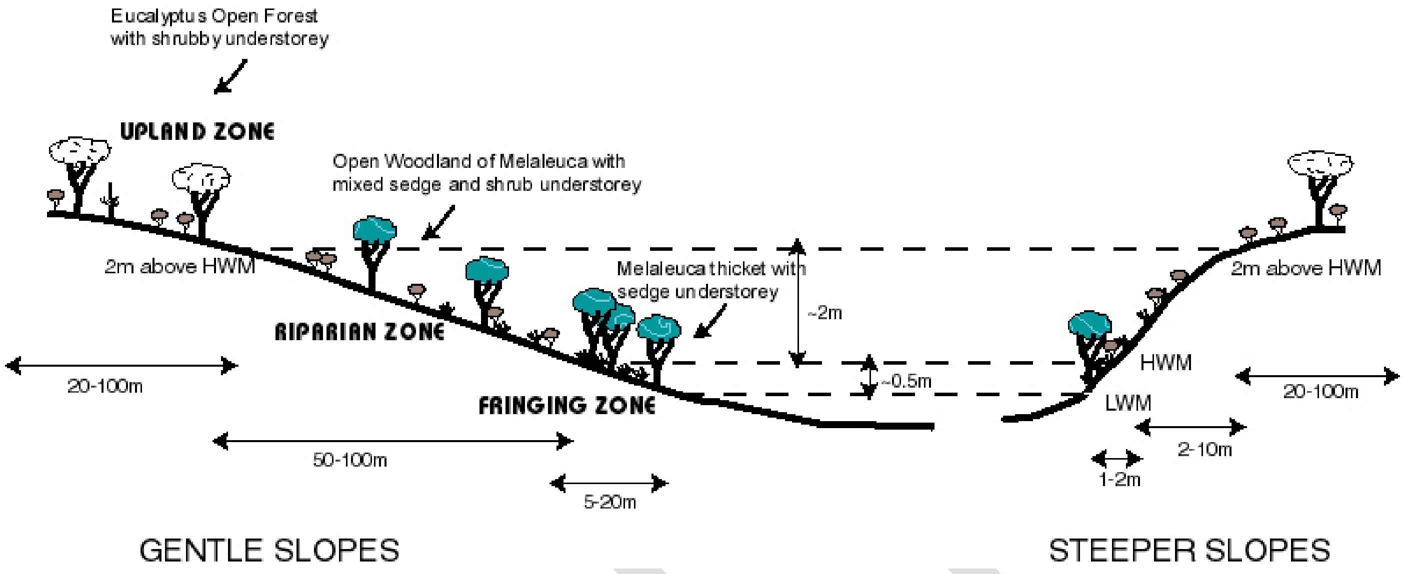

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TABLES

TABLE 2:

Summary of rehabilitation history and monitoring of slopes around North Lake.

Sector	Approx. Area (ha)	Treatment(s)	Monitoring History
1 (north-east)	2	February 2001: contoured and spread with topsoil (and understorey debris) Autumn/winter 2002: ripped on contour, herbicide treatment and planting of seedlings; fertilised and covered with tree bags Autumn 2006: ripped to 0.3 m, hand-seeded, brushed, herbicide and fertilised/limed	March 2004 August 2005 June 2007 November 2008
2 (east)	2	February 2001: contoured and spread with topsoil (and understorey debris) Autumn/winter 2002: minor ripping on contour, herbicide treatment and planting of seedlings (in gaps only); fertilised and covered with tree bags	March 2004 August 2005 June 2007 November 2008
3 (south-east)	1	February 2001: contoured and spread with topsoil (and understorey debris) Autumn/winter 2002: major ripping on contour, herbicide treatment, planting of seedlings' fertilised and covered with tree bags Autumn 2006: herbicide treated, hand-seeded and fertilised/limed	March 2004 August 2005 June 2007 November 2008
4 (west)	4	April 2003: contoured and spread with 0.2 m topsoil (and understorey debris)	March 2004 August 2005 June 2007 November 2008
5 (north)	2	Autumn 2006: contoured and spread with 10 year old, stored topsoil (with some understorey debris)	June 2007 November 2008
6 (south)	2	Autumn 2006: contoured and spread with fresh (direct) topsoil return (with understorey debris).	June 2007 November 2008

TABLE 2.

Statistical test results comparing means between different rehabilitation sectors and year of establishment (as well as interaction between these two factors where possible). Significant results (*P*<0.05) are in bold. T.S.=test statistic.

Variable	Test Statistic	Sector		Year		Sector X Year	
		T.S.	*P*	T.S.	*P*	T.S.	*P*
Native Plant Cover %	F	**21.3**	**<0.001**	**31.3**	**<0.001**	**5.8**	**<0.001**
Native Plant Density	Wald Chi^2	**53.4**	**<0.001**	0.70	0.40	1.19	0.95
Native Species Richness	Wald Chi^2	**169.6**	**<0.001**	**7.3**	**0.007**	7.7	0.17
Weed Cover	Chi^2	**69.6**	**<0.001**	1.7	0.19	n.a.	
Species Composition	Global R	**0.093**	**0.004**	**0.74**	**<0.001**	n.a.	

TABLE 3

Differences between rehabilitation and natural wetland transects in species composition as determined using SIMPER analysis of dissimilarity in PRIMER (Clarke and Warwick 2001). Abundance refers to mean squared-root transformed cover. Dissimilarity refers to average contribution of species to average Bray-Curtis dissimilarity between rehab and wetlands.

Species	Rehab Abundance	Wetland Abundance	Average Dissimilarity	% Contribution to Overall Dissimilarity	Cumulative % Contribution to Overall Dissimilarity
Melaleuca rhaphiophylla	0.79	2.76	6.72	7.80	7.80
Lepidosperma longitudinale	1.94	2.08	5.31	6.16	13.96
Astartea scoparia	1.21	1.41	4.30	4.99	18.96
Melaleuca viminaria	0	1.78	4.15	4.82	23.77
Viminaria juncea	1.77	0	3.99	4.64	28.41
Juncus pallidus	1.26	1.18	3.93	4.56	32.96
Hypocalymma angustifolium	1.60	0.33	3.49	4.05	37.01
Kunzea recurva	1.30	0.15	3.18	3.69	40.71
Kunzea glaucescens	1.44	0.12	3.10	3.60	44.30
Meeboldina scariosa	0.74	1.00	2.76	3.21	27.51
Acacia pulchella	1.12	0.09	2.50	2.90	50.41
Melaleuca lateriflora	1.04	0.14	2.21	2.56	52.98
Melaleuca preissiana	0.82	0.49	2.14	2.48	55.48

0

TABLE 4 - Comparison of 2007 and 2008 species composition of recent rehabilitation (Sectors 5 & 6) and contribution of species to overall dissimilarity between years using SIMPER analysis of dissimilarity in PRIMER (Clarke and Warwick 2001). Abundance refers to mean squared-root transformed cover. Dissimilarity refers to average contribution of species to average Bray-Curtis dissimilarity between years.

Zone	Species	Life Form/ Family	Abundance 2007	Abundance 2008	Dissimil-arity	Contribution to Overall Dissimilarity (%)	□Contribution to Overall Dissimilarity (%)
Upland	*Kunzea glaucescens*	Sh / MY	1.0	2.6	10.2	16.1	16.1
	Acacia pulchella	Sh / FA	1.1	2.7	8.8	19.9	30.4
	Hypocalymma angustifolium	Sh / My	0.49	0.74	4.0	6.3	36.3
	Pericalymma ellipticum	Sh /MY	0.49	0.66	3.1	4.9	41.2
	Calytrix fraseri	Sh / MY	0.00	0.57	3.1	4.9	46.1
	Daviesia physodes	Sh / FA	0.00	0.54	2.8	4.4	50.5
	Empodisma gracillimum	Rh / RE	0.40	0.32	2.7	4.2	54.7
	Melaleuca preissiana	Tr / MY	0.27	0.37	2.6	4.1	58.8
	Aotus gracillima	Sh / FA	0.24	0.35	2.6	4.1	62.9
	Astartea scoparia	Sh / MY	0.38	0.00	2.2	3.5	66.4
	Lepidosperma longitudinale	Rh /CY	0.30	0.26	2.0	3.2	69.6
Riparian	*Acacia pulchella*	Sh / FA	1.2	3.2	8.4	14.0	14.0
	Calothamnus lateralis	Sh / MY	0.48	1.7	6.4	10.8	24.8
	Aotus gracillima	Sh / FA	0.84	1.9	6.3	10.6	35.4
	Lepidosperma longitudinale	Rh /CY	0.80	1.4	4.3	7.3	42.7
	Hypocalymma angustifolium	Sh / MY	1.1	2.3	4.3	7.2	50.0
	Kunzea glaucescens	Sh /MY	0.41	1.0	3.1	5.2	55.2
	Pericalymma ellipticum	Sh /MY	0.59	1.3	3.0	5.1	60.3
Fringing	*Lepidosperma longitudinale*	Rh / CY	0.97	4.7	14.1	20.3	20.3
	Juncus pallidus	Rh / JU	0.11	2.3	8.3	11.9	32.2
	Hypocalymma angustifolium	Sh / MY	1.4	1.8	6.8	9.9	42.1
	Baumea articulata	Rh / CY	0.00	1.6	6.0	8.6	50.7
	Calothamnus lateralis	Sh / MY	0.81	2.2	5.8	8.4	59.1
	Acacia pulchella	Sh / FA	1.4	0.22	4.7	6.8	65.9
	Astartea scoparia	Sh / MY	0.36	1.04	2.8	4.0	69.9

Life form codes: Tr=tree; Sh=shrub; Rh=rhizomatous plant.

Plant Family codes: MY=Myrtaceae; FA=Fabaceae; RE=Restionaceae; CY=Cyperaceae; JU=Juncaceae

TABLE 5 - Characteristics of distinguishable soil horizons of rehabilitation areas and averages for natural wetland surface and sub-surface horizons.

Depth (cm)	Rehab Sector	Texture	Colour	Nitrate-N (mg/kg)	Ammonium (mg/kg)	Phosphate (mg/kg)	Potassium (mg/kg)	Sulphur (mg/kg)	Carbon (%)	Iron (mg/kg)	Conductivity (dS/cm)	pH
0-30	4	1.5	GR	1	6	2	39	10.5	1.29	289	0.079	5.6
30-50	4	1.5	GRBR	1	1	2	19	9.5	0.27	290	0.048	5.4
0-7	6	1.5	GR	1	3	2	47	7.3	2.3	453	0.038	5.5
7-29	6	1.5	GRBR	1	1	2	17	7.1	0.35	367	0.025	5.5
29-50	6	1.5	GRBR	1	1	2	15	5.9	0.28	78	0.02	5.4
0-50	1	1.5	GR	1	1	2	30	2.5	0.11	55	0.017	5.7
0-50	1	1.5	GRYW	1	1	2	15	1.9	0.11	221	0.02	6.3
0-10	1	1.5	DKGR	1	1	3	20	3.7	0.79	261	0.034	6.7
10-50	1	1.5	GR	1	1	2	16	2.8	0.16	171	0.018	6.2
0-10	5	1.5	DKGR	1	1	2	41	10.7	1.37	641	0.047	4.9
10-50	5	1.5	DKGR	1	1	2	27	9.7	1.17	243	0.053	4.9
0-50	2	1.5	DKGR	1	1	2	136	6	1.59	397	0.07	5.6
0-32	3	1.5	DKGR	1	13	2	27	6.7	2.35	179	0.066	5.3
32-50	3	1.5	GR	1	1	2	19	7.8	0.2	57	0.031	6.3
Wetland	Topsoil	2.3	–	2.3	7.9	20.3	319.1	66.9	5.9	692	1.0	6.0
Wetland	Subsoil	2.2	–	1.4	2.1	4.1	199.8	61.8	2.6	351	1.0	6.5