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1 **Setting goals and choosing appropriate reference sites for restoring mine pit** 2 **lakes as aquatic ecosystems: a case study from south west Australia**

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8

9 **Abstract.** Pit lakes may form when open cut mining leaves a pit void behind that fills with ground and
10 surface water. Often replacing terrestrial ecosystems that existed prior to mining, the pit lake may offer
11 an alternative ecosystem with aquatic biodiversity values that can be realised through planned
12 restoration. Restoration theory and mine closure regulatory requirements guides us toward restoring
13 disturbed systems towards landscapes that are of regional value and relevance. But how do we identify
14 a restoration target for a novel aquatic habitat that did not exist prior to the new post-mining landscape?
15 This paper presents a process of first identifying and then surveying local analogue aquatic systems to
16 provide a direction for pit lake restoration efforts and achievement criteria for pit lake relinquishment.
17 We illustrate this process using a case study from a sand mining operation located amongst wetlands in
18 south-western Australia. The company mines silica sands following mechanical removal of topsoil and
19 then extraction of the ore from below the water table by dredging. Assessment of wetland and riparian
20 vegetation in the surrounding area was completed through the establishment and measurement of
21 temporary monitoring transects across five natural wetlands in the Kemerton area with several more
22 visited and observations made. Distinct zonation of vegetation was found across each wetland, although
23 typically wetland basins were unvegetated or filled with younger woody plants with patchy
24 distributions. Fringing riparian vegetation consisted of few species (commonly *Melaleuca*
25 *rhaphiophylla* and *Lepidosperma longitudinale*) but community composition and structure were
26 variable between wetlands. The pattern of vegetation seen across natural wetlands was best explained
27 by topography and soil chemistry with low lying areas more likely to experience regular flooding and
28 accumulate organic matter and nutrients. We consider that, with good planning, rehabilitation,
29 monitoring and management interventions to achieve a restoration trajectory, these new mining pit
30 lakes can positively contribute to regional ecological values.

31 **Key words:** Pit lake, restoration goals, wetland, riparian, vegetation, mine closure

32 **Introduction**

33 Increasingly frequent, and of growing scale, open-cut/cast mining has left a legacy of many thousands
34 of mining pit voids worldwide (Klapper and Geller, 2002). Restoration of habitats following mining has
35 become a well-researched and standard practice that borrows from both disciplines of ecology and
36 engineering and which often scales across entire landscapes and regions where mining is active
37 (McCullough and Van Etten, 2011). However, this restoration typically ceases at the edge of these pit
38 voids (Van Etten, 2011), unless the potential for backfill and/or landscaping can incorporate the pit into
39 the terrestrial system (Lund and McCullough, 2011b). Backfill of pits is often promoted as best practice
40 for managing pit voids at mine closure (Puhlovich and Coghill, 2011). Moreover, backfill is often not
41 an economic or feasible option, and if the pit extends into the water table then pit lakes with aquatic
42 ecosystems of varying value will form (Castro and Moore, 2000; McCullough et al., 2013).

43 Internationally, closure planning can best be described as a “land redevelopment” exercise (Jones,
44 2012). In most Australian states, the primary objective is to leave the site in a condition suitable for the
45 agreed final land use, along with other goals relating to making the site safe, stable, non-polluting and
46 maintenance free (Clark, 1999). Early consideration of the land redevelopment goals can provide clear
47 direction to both company and stakeholders on what risks and/or beneficial end uses are expected from
48 the post-mining landscape following closure (McCullough et al., 2009). Typically, closure outcomes
49 (objectives) and how they will be measured (criteria) are required at least in a preliminary stage early
50 on in a mining project development (Laurence, 2006). Leading international mine-closure guidance and
51 practice both internationally, e.g. ICMM (2008), and domestically ,e.g. DMP/EPA (2011), is therefore
52 to identify clear closure objectives and criteria. Mine closure planning for pit lakes specifically is no
53 different in this sense (Jones and McCullough, 2011).

54 A first step in the development of a pit lake ecosystem of environmental value is to recognize an
55 ‘Identifiable Desired State’ (*c.f.* Grant, 2006) as a restoration goal (McCullough and Van Etten, 2011).
56 Importantly, for the pit lake and its catchment to contribute value to the environment, this should
57 proceed by establishing restoration targets for aquatic through to terrestrial ecosystems that are
58 considered of ecological value and that are regionally representative (Jones and McCullough, 2011).

59 Setting appropriate goals and objectives is the most important stage of planning restoration projects and
60 critical to the success of restoration. Objectives should be focussed, achievable and measureable,
61 whereas goals should specify the desired outcomes over both the short and long term (SERI, 2004).
62 Restoration goals typically address multiple attributes including biodiversity, aesthetics, safety,
63 production, sustainability and social benefits, and should incorporate the concerns and expectations of
64 stakeholders and the wider community. It is common practice in ecological restoration to select
65 reference ecosystem(s) to use as restoration targets and to help gauge the success (or otherwise) of
66 restoration efforts (SERI, 2004). Reference ecosystems may represent a historical or pre-disturbance
67 state, a nearby ecosystem or a synthesis of attributes deemed desirable (Brewer and Menzel, 2009).

68 However selection of appropriate reference systems is fraught with difficulties and complexities, much
69 of which stems from inherent variability of natural ecosystems over a range of temporal and spatial
70 scales (White and Walker, 1997; Hobbs, 2007).

71 Even though, in a pit lake context, an aquatic ecosystem may not have been present before disturbance,
72 development of wetland environments in the face of global (Kundzewicz et al., 2008), national (Hobday
73 and Lough, 2011) and regional (Horwitz et al., 2008) aquatic habitat loss may be justified as preferred
74 restoration targets, especially where there are regionally rare aquatic species or ecosystems present
75 (Brewer and Menzel, 2009). However, restoration of a representative and functional amphibious
76 ecotonal ecosystem is often most challenging for shallow pit lakes that may ecologically resemble
77 wetlands, and for the riparian margins of lakes proper. The absence of riparian vegetation around new
78 pit lakes above certain thresholds may often be unrelated to water quality (Fyson, 2000) and may more
79 likely be a consequence of initial bank instability and/or unsuitable soils for seedling establishment
80 (Van Etten, 2011). Further, profound variation in topography, hydrology and soil across aquatic-
81 terrestrial ecotones needs to be taken into account (Naiman et al., 2005). Indeed, wetland margins
82 typically experience pronounced zonation in response to a seasonal flooding regime, which is further
83 complicated by inter-annual and longer-term variability in water levels. These ecotones of riparian
84 zones, are therefore, noted for their acute spatial heterogeneity which results in high levels of species
85 turnover across their perimeters (Naiman et al., 2005; Ward et al., 2002).

86 This study sought to determine what regional wetland ecosystems might constitute reference systems
87 and restoration targets for a sand mining operation that was causing direct loss to natural wetland
88 habitat, but that had potential to restore some type of wetland habitat through targeted restoration
89 efforts. It addresses the important question of what are appropriate and realistic targets where there have
90 been major biological and physical perturbations, an inherent part of mining. Post-mining environments
91 are unlikely to ever completely resemble pre-mining conditions, even over the long-term, and therefore
92 are classic novel ecosystems, *sensu* Hobbs et al. (2009). So what, under these circumstances, should we
93 aim for and what is realistically achievable? White and Walker (1997) argue that we need to understand
94 ecological patterns and processes in natural ecosystems across both time and space to select appropriate
95 reference systems and that such understanding can improve restoration decision-making and practice.
96 This study also sought to understand what environmental drivers were most important for developing
97 representative wetland vegetation community structure and dynamics, and to assess the value of such
98 information to help guide restoration.

99

100 **Methods**

101 **Study Area**

102 The study was conducted at the Kemerton Silica Sand (KSS) mine located within the Kemerton
103 wetlands (33°08'S, 115°47'E), 30 km north of Bunbury and 150 km south of Perth (Van Etten et al.
104 2012) on the Swan Coastal Plain, Western Australia. The project area consists of an extensive aeolian
105 sand-dune system forming a distinct Australian bioregion. Approximately 500,000 t of feldspathic silica
106 sands are extracted annually at this mine from below the water table using dredging, both from wetland
107 and woodland ecosystems. Once ore extraction is complete, pit lakes are formed and progressively
108 rehabilitated. As the pit lake is essentially an expression of the groundwater, the final post-mining
109 landforms are permanently inundated lakes. Overburden and topsoil are available for sculpting and
110 landscaping of the pit lakes and surrounding slopes. Around 10 lakes are expected at eventual mine
111 closure of between 10–15 ha surface area and approximately 10 m deep (MBS Environmental, 2009).

112 Study area climate is distinctly Mediterranean with most of the average *c.*890 mm of annual rainfall
113 falling in winter and spring. Summers are warm to hot and typically very dry (average February
114 maximum temperature is 28°C and rainfall is 13 mm), whilst winters are cool and wet (average July
115 maximum is 17°C and rainfall is 186 mm). The project operates on privately-owned land comprising
116 and mostly surrounded by intact and relatively healthy examples of the natural ecosystems of the Swan
117 Coastal Plain (*Eucalyptus-Banksia* woodland on uplands and various wetland systems of high
118 conservation value). Shallow depth to groundwater in the inter-dunal depressions results in numerous
119 wetland areas of palusplain, damplands, sumplands and lakes (as per the definitions of Semeniuk (1987)
120 within the project area. The climate and shallow nature of wetlands in the Kemerton area ensure that all
121 natural wetlands are seasonal and these wetlands become inundated from rainfall or the rising
122 groundwater table, typically from July to November (Galeotti et al., 2010). The south west of Western
123 Australia is regarded as a biodiversity hotspot for fauna and flora, with high levels of endemism and
124 high numbers of threatened species (Myers et al., 2000). For example, at least eight of the ten native
125 freshwater fish found in the south-west are endemic (Morgan et al., 1998).

126 Currently dredge ponds ecologically differ significantly from regional aquatic habitat analogues such as
127 nearby Environmental Protection Policies (EPP) wetlands (Lund and McCullough, 2011a; van Etten et
128 al., 2012). Specific closure restoration requirements of the KSS project therefore include the need to
129 develop a closure plan with criteria to measure rehabilitation outcomes relevant to the post-mining
130 landscape where approximately 50% of cleared land will be dredge ponds (EPA, 2012).

131 **Riparian Vegetation Assessment**

132 Riparian transects were used to characterise the biotic patterns of natural wetlands and to identify likely
133 processes driving community structure. This was achieved through comparing: 1) structural attributes;
134 2) plant composition (using multivariate techniques such as ordination); 3) dominance and diversity
135 patterns (Grant and Loneragan, 2003); and 4) soil and topographic features across and between
136 transects.

137 Transects were placed across several natural wetlands in the Kemerton mining area (KMA) and nearby
138 Kemerton Nature Reserve (KNR) during winter 2007. At time of survey all wetlands in the study Area
139 were dry and three (EP4, EP5 and EP7) were surveyed in detail. Two other small wetlands (PD, PS)
140 adjacent to EP7 were also surveyed. In addition, observations were also made at three other wetlands:
141 EP1, EP3 and EP9. (Note: the prefix 'EP' was used because these wetlands were mapped as part of
142 Environmental Protection (Swan Coastal Plain Lakes) Policy 1992). Each transect commenced at
143 wetland base (lowest point in profile), traversed the fringing wetland and then finishing at the upland
144 vegetation (if present). Each transect therefore captured the typical zonation and variation in vegetation,
145 soil and landform of the wetland system and its fringing vegetation. To capture the variation in
146 vegetation along transects in the most efficient manner, the relevé sampling approach was used, where a
147 study site (or relevé) was established within each distinct vegetation type along the transect. Each relevé
148 was positioned in vegetation representative of the wetland riparian and the cover of each plant species
149 was then estimated within a circular area of 20 m radius. Height and cover of each vegetation strata was
150 also recorded.

151 **Soil and Topographic Profiling**

152 A theodolite, GPS and tape measure were used to determine the changes in elevation and slope along
153 the riparian transect. A sampling trench was dug in each of the different vegetation zones identified
154 along transects and different soil horizons were identified to a maximum depth of 0.5 m. A soil sample
155 was then collected each horizon from three different sites in each vegetation zone and then pooled for
156 each horizon and zone. The pooled soil sample was then dried, ground and analysed for: texture, colour,
157 nitrate-N, ammonium, phosphate, potassium, sulfur, iron, carbon, conductivity, (dS/cm) and pH (pH
158 1:5, CaCl₂ and H₂O).

159 **Data analysis**

160 The mean and standard error of relevé cover, density (number of plants per relevé) and richness
161 (number of species per relevé) was calculated for each transect. Differences between transects, depth
162 and position along transect were tested using univariate analyses of soil variables such as one- and two-
163 way ANOVA in SPSS (2007) with a Type I error of 0.05. Prior to analysis data were $\log_{10}(x+1)$
164 transformed to improve normality where required and were also checked for parametric assumptions
165 (McGuinness, 2002).

166 Multivariate data analyses were performed using PRIMER v6 software (Clarke, 1993; Clarke and
167 Gorley, 2006) following a process of data transformation, graphical exploration and then statistical
168 hypothesis testing. Two-dimensional nMDS ordinations of multivariate data were constructed for taxa
169 frequency data using 100 iterations and based on the Bray-Curtis dissimilarity matrix. Principal
170 Components Analysis (PCA) was used to produce ordinations of soil (environmental) data. Differences
171 between *a priori* treatment groups were tested using the ANOSIM permutation routine with 9999
172 iterations (all other variables default) (Clarke and Gorley, 2006). Environmental variables and taxa

173 most contributing to differences between wetlands were determined using the SIMilarity-PERcentages
174 (SIMPER) routine (cut-off at 95% cumulative similarity) (Clarke, 1999). The BIO-ENV procedure was
175 then used to determine the combination of environmental variables best rank correlating with riparian
176 vegetation communities (Clarke and Ainsworth, 1993). Bubble Plots showing values of the
177 environmental variables (selected using BIO-ENV) were then projected onto site positions within the
178 ordination. Environmental – vegetation relationships were also explored using Redundancy Analysis
179 (RDA) within CANOCO for WINDOWS version 4 (ter Braak, 1998).

180 **Results**

181 **Topographic Profiles**

182 Topographic profiles of the wetlands (Fig. 1) showed that wetland basins were generally flat with
183 slopes of <0.1% and ended in relatively abrupt change of slope where dense fringing vegetation
184 developed on slightly higher ground some 0.2 to 1 m above than the wetland basin. EP4 was slightly
185 different as the lake basin was generally smaller in area and had a more concave profile with slopes
186 between 0.2 to 0.4% (Fig. 1).

187 **Soil Characteristics**

188 The first or A-horizon of wetland riparian soil was generally sand with the highest content of organic
189 matter ($6.2\pm 0.9\%$ organic C) and was consequently grey to black in colour. At some sites, the A-
190 horizon was further visually split into two layers (A1 and A2) and the A2 horizon generally had
191 intermediate chemical characteristics compared to A1 and B horizons. The second or B-horizon was
192 generally deep sand with low organic matter content ($3.0\pm 0.7\%$ organic C) and generally white or
193 yellow in colour. The A-horizon was generally thicker in the wetland basin (0.06–0.30 m) compared to
194 fringing vegetation and uplands (Table 1; Fig. 1).

195 EP7 and the adjoining two small wetlands (PD and PS) had thick, dense organic matter accumulation at
196 the surface (i.e. peat) to 0.3 m depth. Organic carbon and soil nutrients, including nitrogen and
197 phosphorus, were substantially higher in these wetland soils compared to others (Table 1). An exception
198 to this trend is zone 3 of EP5 which had high levels of organic matter content, organic carbon,
199 ammonium nitrogen, potassium and phosphorus in surface- and sub-soils. This site was in a slight
200 depression adjacent to fringing vegetation where it would be expected to inundate for greater periods
201 than the surrounding wetland basin.

202 Soil nutrient concentrations (phosphorus, ammonia & nitrate) were normally higher in the A1 horizon
203 than in the other soil horizons. Soil phosphorus levels were generally higher in soils of wetland basins
204 compared to fringing vegetation, whereas ammonia was generally highest in fringing paperbark
205 vegetation. Nitrogen, especially as nitrates, was particularly low in wetland basin soils, often at or
206 below levels of detection ($\leq 1 \text{ mg kg}^{-1}$). Soil phosphorus levels were very low (A1 horizon: 20.3 ± 8.0 ;
207 range 2–114 mg kg^{-1}) compared to those recorded for Perth wetlands by Davis *et al.* (1993) at a mean of

208 1,100±580 mg kg⁻¹ (range 20–40,000 mg kg⁻¹). Phosphorus concentrations were highest in EP7 and
209 lowest in EP4 (Table 1).

210

Table 1. Chemical parameters of soils collected at multiple horizons and zones across wetlands of the Kemerton Silica Sands Project area and Kemerton Nature Reserve. All units mg/kg unless otherwise stated.

Wetland Zone		EP4		EP5				EP7				PD		PD-PS	PS
		1	2	1	2	3	4	1	2	3	4	1	2	1	1
Soil Horizons (cm)	A1	0-6	0-5	0-8	0-8	0-8	0-5	0-20	0-5	0-5	0-5	0-30	0-3	0-3	0-10
	A2	6-19	-	8-25	8-15	-	5-27	-	-	-	-	-	-	-	-
	B	19-50	5-50	25-50	15-50	8-50	27-50	20-50	5-50	5-50	5-50	30-50	3-50	3-50	10-50
Nitrate-N	A1	1	1	1	1	3	3	4	2	1	1	1	7	1	5
	A2	1	-	1	1	-	3	-	-	-	-	-	-	-	-
	B	1	1	1	1	1	2	4	1	1	1	1	1	1	2
Ammonium-N	A1	1	2	1	3	19	5	1	15	7	6	2	33	5	18
	A2	1	-	1	3	-	2	-	-	-	-	-	-	-	-
	B	1	1	1	1	2	1	3	3	2	1	2	1	1	9
Phosphorus	A1	10	2	2	2	24	6	114	41	39	6	3	18	6	11
	A2	2	-	2	2	-	4	-	-	-	-	-	-	-	-
	B	2	2	2	5	5	21	17	5	2	2	5	4	4	4
Potassium	A1	364	325	121	295	790	402	436	495	374	113	57	303	110	439
	A2	73	-	66	25	-	134	-	-	-	-	-	-	-	-
	B	109	58	91	160	417	136	382	33	25	28	138	40	107	151
Sulfur	A1	240	185	22	5	32	15	202	24	17	3	52	65	7	115
	A2	112	-	66	2	-	12	-	-	-	-	-	-	-	-
	B	151	84	74	9	12	21	92	40	9	4	108	4	3	269
Organic Carbon (%)	A1	2.1	6.6	1.2	3.0	10.0	6.1	10.0	4.7	10.0	4.2	3.9	10.0	6.0	9.3
	A2	0.2	-	0.4	0.2	-	3.4	-	-	-	-	-	-	-	-
	B	0.2	0.4	0.5	0.6	3.4	1.4	4.2	3.5	2.3	2.6	6.8	3.5	2.9	9.8
Iron (g/kg)	A1	0.98	0.80	0.13	0.66	0.30	0.48	1.49	1.88	0.39	0.17	0.36	1.06	0.33	1.06
	A2	0.19	-	0.16	0.11	-	0.36	-	-	-	-	-	-	-	-
	B	0.12	0.14	0.32	0.20	0.62	0.29	0.93	0.44	0.23	0.15	0.93	0.39	0.34	0.34
Conductivity (mS/cm)	A1	1.42	2.46	0.49	0.07	0.28	0.33	2.24	3.24	0.18	0.09	0.61	0.65	0.10	2.54
	A2	1.35	-	0.88	0.05	-	0.30	-	-	-	-	-	-	-	-
	B	2.62	1.25	1.02	0.19	0.36	0.33	2.14	0.84	0.21	0.07	1.24	0.12	0.06	4.63
pH (CaCl ₂) (no units)	A1	5.2	4.7	5.9	5.3	5.1	7.3	5.5	4.9	4.4	3.8	4.9	3.9	4.0	4.8
	A2	6.6	-	6.5	6.7	-	7.5	-	-	-	-	-	-	-	-
	B	6.6	6.4	6.8	7.7	7	7.3	5.1	5.1	4.1	3.1	5.3	4.1	3.9	5.0

1 Other soil parameters, such as electrical conductivity, total sulphur and iron concentrations,
2 were generally higher in the wetland basins than in fringing zones (Table 1). Topsoil pH
3 (CaCl₂) at EP7 was 5.5 in the wetland basin but declined to 3.8 in zone 4 of EP4. EP5 had the
4 highest pH from 5.9–7.3 in zones 1 and 4 respectively. EP5 had significantly more alkaline
5 topsoils and subsoils than other wetlands (F=4.1, p=0.038 for A1; F=23.9, p<0.001 for B). pH
6 was generally higher in horizon B than A (Table 1).

7 **Riparian and Wetland Vegetation Structure & Floristics**

8 Within the KSS project area, the basins of larger wetland systems which experience regular
9 winter-spring inundation, and which are relatively deeper, such as EP7, were largely devoid
10 of perennial vegetation. Instead these basins mostly comprised annual herbland which grew
11 following subsidence of the water in late spring/early summer. Smaller wetlands which do not
12 flood to the same depth or extent, had some tree cover in wetland basin (e.g., EP4 & 5), but
13 this vegetation was patchy. EP4 was recently colonised by *Melaleuca* trees following flooding
14 some 5 years earlier, with counts of growth rings of cut stems confirming the age of these
15 trees. Other observed wetlands (eg EP8, EP9) were completely in-filled with larger and
16 presumably older *Melaleuca* trees.

17 Fringing the wetlands was very dense vegetation with total cover sometimes exceeding 100%
18 (Table 2). Vegetation was most dense at the edge with little to no understorey. Further out
19 from the wetland basin and at slightly higher elevations, the *Melaleuca* woodland was more
20 open with an understorey of sedges and/or rushes. At slightly higher elevations, woodland
21 dominated by eucalypts with relatively diverse understorey of shrubs, bracken, sedges and/or
22 rushes occurs. Clear zonation of vegetation types was evident in most areas of wetlands,
23 particular within the fringing vegetation (Table 2). Areas which are seasonally waterlogged
24 typically had more open woodland structure with dense, diverse understorey dominated by
25 shrubs and sedges (e.g., site EP4-3).

26

27 **Table 2.** Summary of vegetation at sample sites in natural wetlands areas showing cover of
 28 natives, weeds and trees, and the number of native species per site.

Wetland	Site	Description	Cover Native (%)	Cover Weeds (%)	Tree Cover (%)	Native Species Richness
EP7	1	Wetland basin with annuals	40	0	1	2
	2	Fringing <i>M. raphiophylla</i>	60	2	60	3
	3	Fringing <i>M. raphiophylla</i> with sedge	100	10	45	5
	4	Fringing Eucalypt woodland	100	1	45	13
PD	1	Wetland basin	60	0	30	4
	2	Fringing <i>M. raphiophylla</i> with sedge	60	0	40	4
PD-PS	1	Fringing Eucalypt woodland	40	0	25	6
PS	1	Fringing <i>M. raphiophylla</i>	80	0	80	2
EP5	1	Wetland basin	40	0	10	5
	2	<i>Melaleuca</i> thicket with sedge and rush	70	0	40	8
	3	Fringing <i>M. raphiophylla</i> with sedge	100+	0	60	10
	4	Fringing <i>Melaleuca</i> – Eucalypt Transition	100+	0	60	8
	5	Fringing mixed <i>Melaleuca</i>	80	0	60	10
	6	Fringing Eucalypt woodland	100+	0	30	13
EP4	1	Wetland basin with young <i>M. viminea</i>	45	0	45	3
	2	Fringing mixed <i>Melaleuca</i>	55	0	55	4
	3	Dampland Community – <i>Melaleuca</i> over heath	65	0	13	13

29
 30 Dominant species in fringing vegetation were paperbarks such as *Melaleuca raphiophylla*,
 31 *M. priessii* and *M. viminea*. Understorey below *Melaleuca* thickets and woodland, where
 32 present, consists mainly of sedges and rushes, with *Lepidosperma longitudinale* the dominant
 33 species, and *Juncus pallidus*, *Baumea articulata* and *Meeboldina scariosa* common in places.
 34 *Astartea scoparia* and *Kunzea glaucescens* are also common understorey shrubs, particularly
 35 on outer edges of the fringing *Melaleuca* communities.

36 The fringing eucalypt woodland which surrounded fringing *Melaleuca* was dominated by
 37 *Eucalyptus rudis* (Flooded Gum), although *Corymbia calophylla* (Marri) and *E. marginata*
 38 (Jarrah) occurred on higher ground. Understorey was varied; common species included
 39 *Pteridium esculentum*, *Astartea scoparia*, *Hypocalymma angustifolium*, *Lepidosperma*
 40 *longitudinale*, *Pericalymma ellipticum* and *Dasypogon bromeliifolius*.

41 The ordination of wetland vegetation (Fig. 2) showed a general trend in plant species
 42 composition from wetland basin (e.g., 7-1, 4-1) to upland vegetation (e.g., 7-4, 5-6 and PD-
 43 PS) from right to left. There was also a separation of different fringing *Melaleuca* vegetation

44 from top to bottom in the ordination, with *M. raphiophylla* dominated sites towards the top
 45 (mostly EP7), and other *Melaleuca* spp. dominants at the base (e.g., *M. viminea*, *M.*
 46 *teretifolia*, etc.). *M. preissiana* dominated woodlands are in the middle. Testing significant
 47 differences between wetland riparian community structure with ANOSIM show no significant
 48 difference in species composition between wetlands (Global R = 0.021; p=0.41). Indeed,
 49 changes in species composition along transects of a single wetland far exceeded overall
 50 differences between wetlands.

51 **Environment – Vegetation Relationships**

52 Pair-wise correlations between plant species composition and environmental variables,
 53 analysed using the BIO-ENV module, were mostly modest to weak.. Highest correlations
 54 were with depth of horizon A (A1+A2), elevation above wetland basin, horizon A potassium
 55 concentrations and horizon B pH (Table 3). Slope and iron concentration were modestly
 56 correlated to variation in plant species composition.

57 **Table 3.** Six highest Spearman rank correlations between floristic similarity and
 58 environmental variables as determined using BIO-ENV module of PRIMER.

Variable	Correlation
Depth of horizon A	0.30
Elevation above wetland base (m)	0.25
K (horizon A)	0.21
pH (horizon B)	0.21
Slope	0.15
Fe (horizon B)	0.14
Fe (horizon A)	0.12

59
 60 The first two axes of the Redundancy Analysis (RDA), where the ordination was constrained
 61 by environmental variables, explained 50.6% of the variance in species composition. The
 62 RDA biplot (Fig. 3) showed the relationship between main floristic gradients (the axes), sites
 63 and environmental variables (the arrows). Specifically this biplot revealed two different
 64 complexes of environmental variables linked to differences in plant species composition
 65 across sites. The first of these environmental complexes was generally correlated with the first
 66 (horizontal) axis and revealed changes in species composition along the toposequence from
 67 wetland lowest point (left side) to upland (right side). This complex included soil fertility (N,
 68 P, etc.), conductivity, gravel content and organic carbon which all increased with height
 69 above wetland basin. Only depth of horizon A generally declined with distance along this

70 toposequence (Fig. 3). The second complex of environmental variables was related to pH,
 71 iron concentration and texture and separated the wetland EP5 (the most alkaline) from and
 72 EP7 (the most acidic).

73 Many of the variables in the RDA biplot were poorly correlated to floristic gradients (shown
 74 by short arrows) and were highly correlated to other environmental variables (Fig. 3). The
 75 forward selection procedure showed that only three variables could explain a significant and
 76 unique proportion of the variance in species composition: potassium (horizon A), pH (horizon
 77 B) and gravel content (horizon B) (Table 4). These three variables explain 46% of the
 78 variance in the species-environment relationship.

79

80 **Table 4.** Results of forward selection (in order of selection) of environmental variables in
 81 redundancy analysis (RDA) with significance determined following Monte-Carlo
 82 testing against a random model. *Variance explained is proportion of variance in
 83 species-environment relationship.

Order	Variable	Variance Explained (%) [*]	P-value
1	Topsoil potassium-a	18	0.008
2	Subsoil pH (H ₂ O)	14	0.022
3	Subsoil gravel	14	0.024
4	Subsoil phosphorus	9	0.108
5	Subsoil iron	7	0.238
6	Slope	6	0.304

84

85 The species richness of wetlands of the KSS project area and KNR was not high relative to
 86 adjacent uplands. In fact, wetland basin and fringing vegetation were often depauperate in
 87 species with as few as 1–3 species in the dense fringing vegetation (Table 2). Fringing
 88 eucalypt woodland and winter-wet depressions were found to have the highest number of
 89 species (each had 13). As survey work occurred in early winter, these figures do not include
 90 most of the annual plant and geophytic species.

91 **Discussion & Conclusions**

92 **Spatial Patterns of Wetland Vegetation**

93 As is characteristic of wetlands in general, substantial differences were found in vegetation
 94 structure, species richness and species composition within wetlands with distinct zonation of
 95 vegetation occurring across the wetland profile (Naiman et al., 2005). Wetland basins were
 96 generally flat and varied from bare in terms of perennial plants through to having a variable
 97 but patchy cover of paperbark trees and shrubs. These areas were seasonally inundated for
 98 some months each year. On raised ground around the edge of the basin, where some minor

99 flooding would be expected, dense paperbark thickets were typical on slightly raised ground.
100 At higher elevations, flooded gum woodland and then, higher still, jarrah-marri-banksia
101 uplands were found. This substantial change in vegetation characteristics *across* wetlands
102 tends to mask any differences in species composition *between* wetlands. Although the major
103 paperbark trees (*M. raphiophylla* and *M. preissiana*) and the understorey sedges and rush
104 species were common to all fringing vegetation wetlands, other species of tree and shrubs
105 varied. In addition to seasonally-flooded wetland complexes, the KSS Project Area had large
106 expanses of seasonally waterlogged vegetation consisting of sparse *Melaleuca preissiana* and
107 *Banksia littoralis* tree canopy over a diverse shrub and sedge/rush understorey. Only one site
108 was located in such vegetation (site 4–3). Much of the proposed mining expansion area will
109 occur on this vegetation type.

110 Wetlands of the Swan Coastal Plain (SCP) are renowned for their complexity with
111 geomorphic, edaphic and hydrological characteristics influencing vegetation composition and
112 structure (Balla, 1994). Wetlands of the SCP have been classified in numerous ways, based on
113 attributes such as geomorphology, hydrology, vegetation, aquatic biota, as well as
114 combinations of these. Wetland vegetation of the SCP has been commonly categorised at two
115 levels: the uppermost level or ‘complex’ refers to vegetation units linked by dominant plant
116 species and structural attributes, and the secondary level for classification, the ‘community’,
117 based on common or typical species within the overall complex (Cresswell and Bridgewater,
118 1985; Pen, 1997; Semeniuk et al., 1990). The fringing vegetation around wetlands of the KSS
119 project area resembles fringing vegetation elsewhere on the SCP in terms of structure and
120 dominant species.

121 Whereas the majority of wetlands on the SCP are expressions of underlying aquifers (i.e.,
122 they are discharge areas; Balla, 1994), there is evidence that many wetlands of the Kemerton
123 area are perched wetlands which are separated from aquifers by thick clay and other
124 impermeable layers (e.g., ‘coffee rock’). Consequently inundation in these perched wetlands
125 is a function of rainfall directly onto the wetland basins plus run-off from surrounding slopes.
126 EP4 appears to be a perched wetland, primarily receiving water inflows from the surrounding
127 wetlands which effectively act as a catchment to this wetland. It is therefore important that
128 this catchment area is actively managed to avoid adverse impacts on inflow water quantity
129 and quality.

130 **Environmental Drivers of Spatial Patterns in Vegetation**

131 Restoration of mined lands frequently uses natural ecosystem as a restoration goal (Bell,
132 2001). However, the environmental variables driving vegetation patterns remain unclear. This
133 study found few strong correlates between plant species composition and environmental
134 variables. In particular, we found that elevation (AHD) was not a good predictor of vegetation

135 composition, although relative height above the wetland basins and slope was a reasonably
136 reliable predictor of the main floristic differences found across wetlands. Soil variables such
137 as thickness of horizon A (humus layer or peat), organic carbon, nutrient levels and potassium
138 were also linked to this main floristic gradient. This general topographic-soil-vegetation
139 relationship is also likely to be linked to hydrological regime. The higher an area is elevated
140 above the wetland basins, the lower the duration and depth of flooding it will experience and,
141 consequently, the lower the accumulation of organic matter (peat and so on). Both the indirect
142 effects of inundation and soil changes which flooding promotes are likely to influence
143 vegetation composition and structure. A clearer picture of environmental causes of vegetation
144 patterns should emerge through more detailed studies of the hydrology of these wetland
145 systems, with variables such as distance to groundwater and their fluctuations (for
146 groundwater-dependent wetlands) and area of catchment (for perched wetlands), suspected to
147 be strongly correlated to vegetation patterns.

148 A second floristic gradient was found to be linked to soil pH and appear to separate EP5 from
149 the others. This is likely to be due to its proximity of EP5 to limestone formations and may
150 explain floristic differences in vegetation between wetland systems on the south-east side of
151 Kemerton compared to those of the north and west.

152 **Dynamics of Wetland Vegetation**

153 The measurements of the three wetlands and observations made at other wetlands in the KSS
154 project area and KNR enabled a clearer picture of wetland dynamics at the KSS Project Area
155 to emerge. Such vegetation change was most clearly demonstrated at EP4 where basin
156 vegetation of EP4 had two zones of distinct tree age (or cohorts). The inner basin consists of
157 *ca.* 5 years old saplings (as judged by growth rings counted on cut stems) of more-or-less the
158 same height (1.5 m) and stem diameter (25–40 mm). This was surrounded by a ring of
159 fringing vegetation which was 7–10 m tall and likely to be much older **Error! Reference**
160 **source not found.** The hypothesis is that a reduced incidence of flooding (through
161 combination of groundwater and/or rainfall decline) has allowed colonisation of *M. viminea*
162 and some *M. raphiophylla* in the basin of this wetland following the last major flooding
163 event in 2001-2. Previously the wetland basin was devoid of vegetation. We anticipate that
164 seedlings may successfully establish during drier times, but may be eliminated if and when
165 prolonged inundation returns. It is likely that tolerance to inundation will increase with age
166 and size of tree, so seedlings/saplings are most vulnerable to flooding in first few years. The
167 role of wetland infill with sediment may also play a role in encouraging seedling
168 establishment as this would decrease the depth, extent and duration of inundation. Such infill
169 can be the response of gradual ‘natural’ accumulation, or can be enhanced through some level
170 of vegetation/soil disturbance in surrounding area.

171 These hypothesised flooding and drying events at EP4 concords with rainfall records of the
172 region. Good rains over 1998–2001 are likely to have resulted in flooding of this wetland and
173 subsequent abundant seed crops, either in soil seed stores or in fruits retained in the canopy.
174 This flooding may also have promoted seedling establishment on moist lake basin as the
175 flooding subsided. Rainfall from 2001 onwards has been well below long and short term
176 averages. Only 2005 rainfall was above the short-term average, but this year was followed by
177 very close to the driest year on record in 2006.

178 This and other studies have demonstrated that wetland basin and flats in the Kemerton area
179 can experience relatively rapid change in structure and composition. Regular and persistent
180 flooding of these areas, where inundation occurs for a least several months each year, inhibits
181 tree colonisation of wetland basins and persistence, and promotes accumulation of peat
182 deposits. Alternatively, drier periods result in lower and shorter flooding events which, in
183 turn, enable seedling establishment of *Melaleuca* and other species on the wetland floor. This
184 woody vegetation would be expected to become denser and more resistant to flooding the
185 longer this dry period persisted. It seems such a dry period has encouraged colonisation of
186 EP4 by *Melaleuca* spp. between 2001–2003 with a 5 year-old cohort of such trees dominant
187 in the centre of the wetland basins at the time of study. EP4 may well be a perched wetland,
188 so that elements of its hydrology such as hydroperiod is more sensitive to rainfall fluctuations
189 and changes in surface drainage compared to the more common scenario of groundwater-fed
190 wetlands on the SCP. With a drying climate in SW Australia, drying of wetlands and
191 colonisation of wetland basins would be expected to become more common (Malcolm et al.,
192 2006).

193 Although the fringing paperbark vegetation appears to be relatively stable over recent years at
194 Kemerton, it too is likely vulnerable to changes in flooding regime with changes in species
195 composition and structure expected with changes in inundation frequency and duration. Fire
196 can also dramatically affect both fringing and basin vegetation, commonly killing trees and
197 shrubs outright, especially when burning through peat and other layers rich in organic matter
198 (Horwitz and Smith, 2005).

199 **Implications for Post-mining Restoration and Choosing Reference Sites**

200 Fringing wetland vegetation of natural wetlands was found to be floristically simple and
201 structurally complex. Such structurally complex wetlands therefore represent a mixed
202 challenge for rehabilitation; only relatively few species need to be restored, however they
203 need to be encouraged to develop into relatively dense vegetation formations, with distinct
204 bands of zonation. Vegetation of fringing zones are relatively species rich (some 10–30
205 species per 10 m²), but are probably not as diverse as many upland areas of Kemerton
206 dominated by jarrah, marri and banksia. The focus on these areas should be on quick return of

207 topsoil matched to site conditions so that high diversity will be encouraged (Van Etten et al.
208 2012).

209 Given high variability between floral communities of wetlands in the KSS project area and
210 KNR, it is difficult to establish a single reference or analogue wetland to compare with
211 rehabilitated mine ponds and slopes. The relationships found here between fringing flora, soil
212 characteristics, topography and hydrology however should help improve revegetation
213 practices and overall rehabilitation success. Specifically this information informs that
214 rehabilitation slopes should be subtle, with varying depth to groundwater and that organic
215 matter levels in new topsoils should be enhanced in rehabilitation attempts.

216 Flat or gently sloping wetland basins would be difficult to recreate in most post-mining
217 settings and probably undesirable given their general bareness. Also, post-mining wetlands
218 created at Kemerton will essentially be expressions of underlying groundwater with previous
219 impervious layers such as coffee-rock removed. However, there is scope for more subtle
220 slopes to be created near the wetland and more dramatic slope changes to be located higher in
221 the profile (opposite to current practice in some areas where the steepest slopes are closest to
222 the water). Also such gradual slopes would result in a greater area of fringing vegetation
223 around mine lakes and areas which are heavily waterlogged or partly inundated by
224 groundwater. Studies of the rehabilitation areas suggest that dense paperbark-sedge fringing
225 vegetation is only likely to establish in the seasonally flooded zone between high and low lake
226 water levels (van Etten et al., 2012). Areas up to 2 m above this lake level appear to be
227 influenced by groundwater (i.e., waterlogged soil) and appear to favour dampland or
228 seasonally-waterlogged areas in terms of vegetation. Restoration of post-mining areas is more
229 likely to resemble such damplands (i.e., seasonally-waterlogged wetlands) given topographic
230 profile and hydrological regime of post-mining landscapes.

231 The process of wetland dynamics described here for EP4 and elsewhere observed in the
232 Kemerton area (i.e., younger, even-aged stands of *Melaleuca* spp. in the wetland basin with
233 older *Melaleuca* spp. towards the edge) is conceptual and requires further investigation.
234 However, the challenge for a mine in an operational phase is to retain a view to how the
235 environment surrounding the project area changes and how closure objectives and criteria
236 may require readdressing to meets these changes.

237 Development of artificial wetlands from mining of either disturbed wetlands or even disturbed
238 uplands may not only offer opportunities to replace lost aquatic biodiversity but also to
239 contribute greater environmental values than previous land uses (McCullough and Van Etten,
240 2011). Any proposed use of such disturbed lands as environmental offsets must be able to
241 demonstrate that the regional biodiversity and the offset biodiversity are both understood and
242 accounted for (McKenney and Kiesecker, 2010). Significant monitoring and demonstration of

243 ecological values may still be required in order to validate this development as environmental
244 offsets (McCullough and Van Etten, 2011).

245 This study has demonstrated that, although pit lakes may be able to be restored to regionally
246 relevant wetlands, the highly altered nature of these systems prior to mining and the
247 variability and complexity of reference systems, both spatially and temporally, means that
248 clear restoration goals developed from robust assessment of regional wetlands are required for
249 development of pit lakes as regional analogue aquatic ecosystems.

250

251

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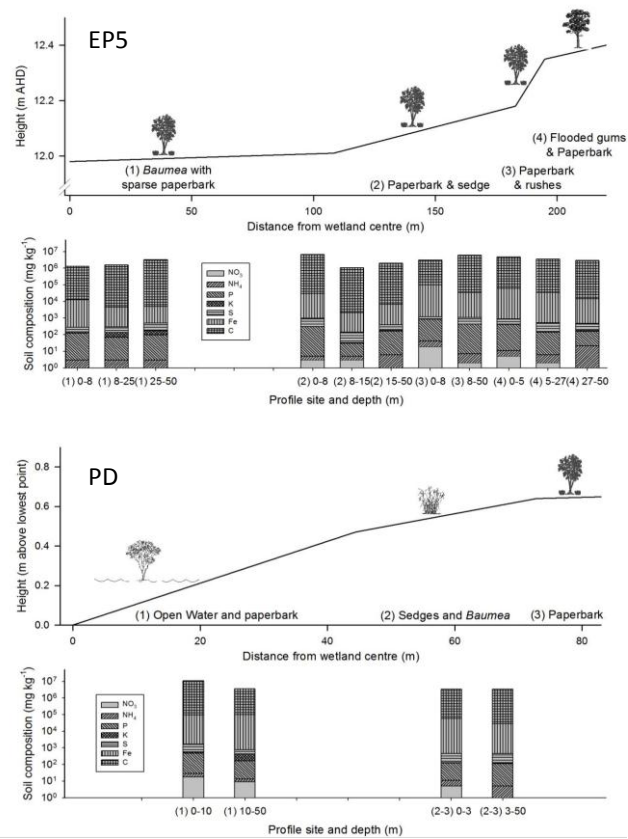
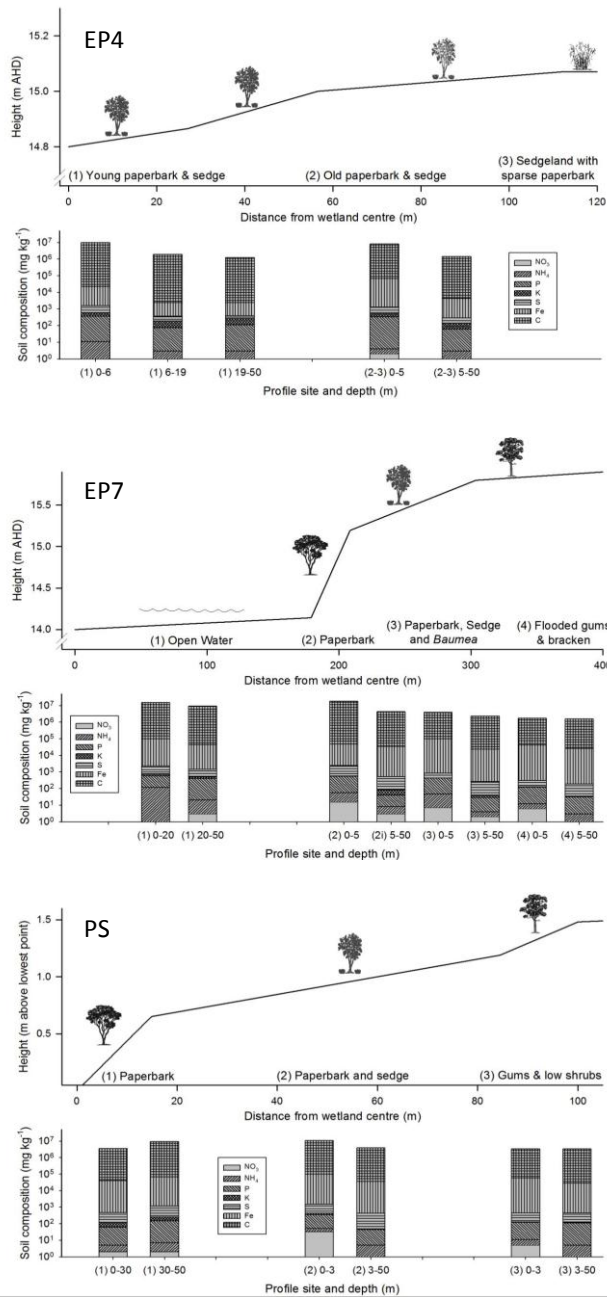
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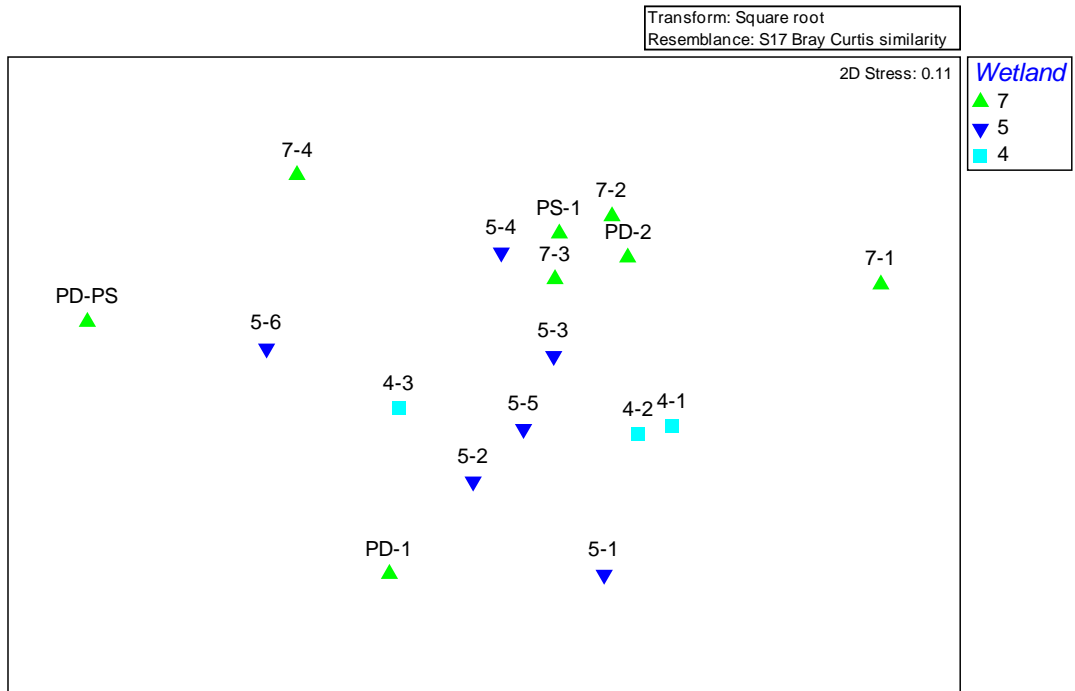
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388 **Figure 1.** Wetland topographic profiles with corresponding vegetation structure and
 389 chemistry.

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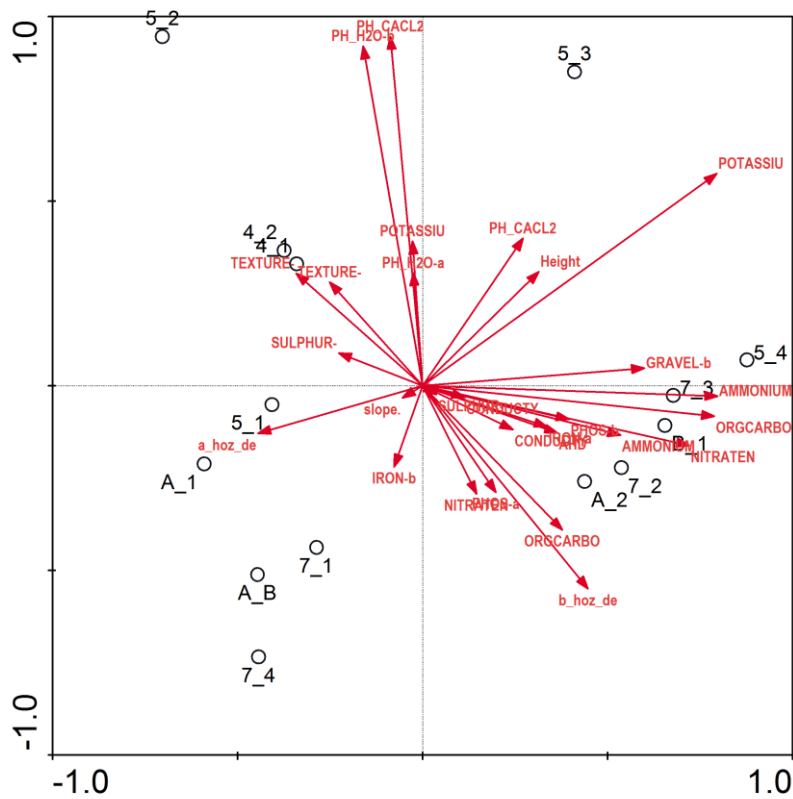
393 **Figure 2.** Non-metric multidimensional scaling of wetland sites at Kemerton based on plant

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395 indicates first vegetation sampling site along transect through EP4).

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401 **Figure 3.** RDA biplot of sites using all species and all environmental variables for sites
402 where soil was collected (14 sites). Length of arrow is proportional to strength of correlation
403 between environmental variables and axes (major floristic gradients). Note: Site A_1 is PD_1,
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409 FIGURE TITLES

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