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The riparian flora and plant communities of the Pilbara region of Western Australia

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Abstract – A survey of riparian flora and plant communities was undertaken at 98 wetlands and rivers in the Pilbara region of Western Australia. Sampling was quadrat-based, with floristics, surface soils and wetland attributes recorded. Selected sites captured the full range of Pilbara wetland types including springs, river pools, claypans, salt marshes and rock pools. A total of 455 taxa was recorded from the survey sites, representing ca. 25% of the known flora of the Pilbara bioregion. The flora is dominated by taxa with Eremaean and tropical affinities, with only six taxa endemic in the region. Of recorded taxa known from four or fewer bioregions, most are shared with the adjacent Carnarvon and Gascoyne bioregions rather than the adjoining internally draining deserts. Sixteen taxa of conservation significance were documented, with claypans, the Fortescue Marsh, and Millstream and Karijini National Park sites dominating occurrences of rare species. Eight major groups were defined by classifying wetlands in terms of species presence/absence data. Floristic patterning was strongly aligned with the major wetland types (geomorphic/hydrological) used in the primary sampling stratification. A combination of wetland morphology/hydrological setting, site edaphic attributes and distance to the coast were dominant variables related to riparian floristic composition. Primary compositional separation was observed between riverine and non-riverine sites, with lowland turbid riverine sites with fine-textured soils compositionally related to claypans and clay flats. Limited biogeographic patterning was evident except where individual IBRA subregions and drainage basins were dominated by few wetland types.

Keywords – Pilbara, wetland, riparian, floristic composition, botanical survey, vegetation, rivers

INTRODUCTION

The Pilbara IBRA region of Western Australia is a region of approximately 179,000 km^2 that corresponds broadly with the Pilbara Craton, a major geological block of Archaean origin (Geological Survey of Western Australia 1990). The region is recognised as biogeographically distinct under the scheme developed by Thackway and Creswell (1994), based on the original Fortescue Botanical District defined by Beard (1990). A detailed description of the soils, climate and landforms of the region is provided by McKenzie *et al.* (2011).

The region's climate is broadly arid, with highly seasonal, typically intense, summer rainfall that may include cyclonic systems (Leighton 2004). This, coupled with a rocky middle and upper landscape, produces river flows of high energy and volume and relatively short duration. Extensive aquifer systems discharge at the surface to form springs and contribute perennial flows to rivers and creeks. In lowlands, major rivers have broad channels with flood flows forming numerous side channels. Clay flats, claypans and lowland creeks with fine sediments are typically highly turbid.

Land use in the region is overwhelmingly dominated by mining and extensive pastoral use. These uses place pressures on Pilbara wetlands through hydrological changes associated with mine dewatering and discharges, and the impact of grazing cattle. In the Pilbara, stock watering at natural water points is uncontrolled, concentrating trampling and grazing in riparian zones, leading to

Plate 1 A highly turbid ephemeral claypan at Yarraloola (site PSW074A) in lowlands dominated by *Eriachne benthamii*. Trampling by cattle is evident (M.N. Lyons).

bank erosion and waterbody siltation. Aggregation of stock, particularly late in the dry season, leads to the eutrophication of waterbodies from accumulated faeces.

Protection of wetland biological values across the Pilbara is contingent on a greater understanding of their biogeographic patterning, for a number of their biotic components. The existing reserve network in the Pilbara consists of four reserves that, while capturing some major wetlands (e.g. Karijini National Park – gorges, Millstream National Park – springs), do not include the full diversity of Pilbara wetlands. The inclusion of wetland floristic data to inform formal conservation planning is a relatively recent feature of broad-scale biodiversity survey in Western Australia (Keighery *et al.* 2000; Lyons *et al.* 2004; Walshe *et al.* 2004). This paper aims to document the riparian flora of the wetlands and rivers of the Pilbara and examine how the major geographic and site environments correlate with floristic composition. The data sets and understanding developed in the current study, coupled with studies of aquatic invertebrates by Pinder *et al.* (2011), will provide the basis for spatially explicit modelling of the biotic composition of Pilbara wetlands and rivers.

STUDY AREA AND METHODS

The Pilbara region as defined in this study is bounded to the south by the Ashburton River and the east by the De Grey–Oakover River system. A small number of wetlands were also sampled in the Rudall River area to the east of the main study area (Figure 1). The study area includes the entire Pilbara IBRA region (Thackway and Cresswell 1994) and additional small areas of the adjoining Gascoyne and Little Sandy Desert regions, representing a total area of approximately 225,000 km^2.

Precipitation across the region is dominated by summer rainfall associated with tropical low-pressure systems producing thunderstorms and cyclones. Annual average rainfall is 290 mm.

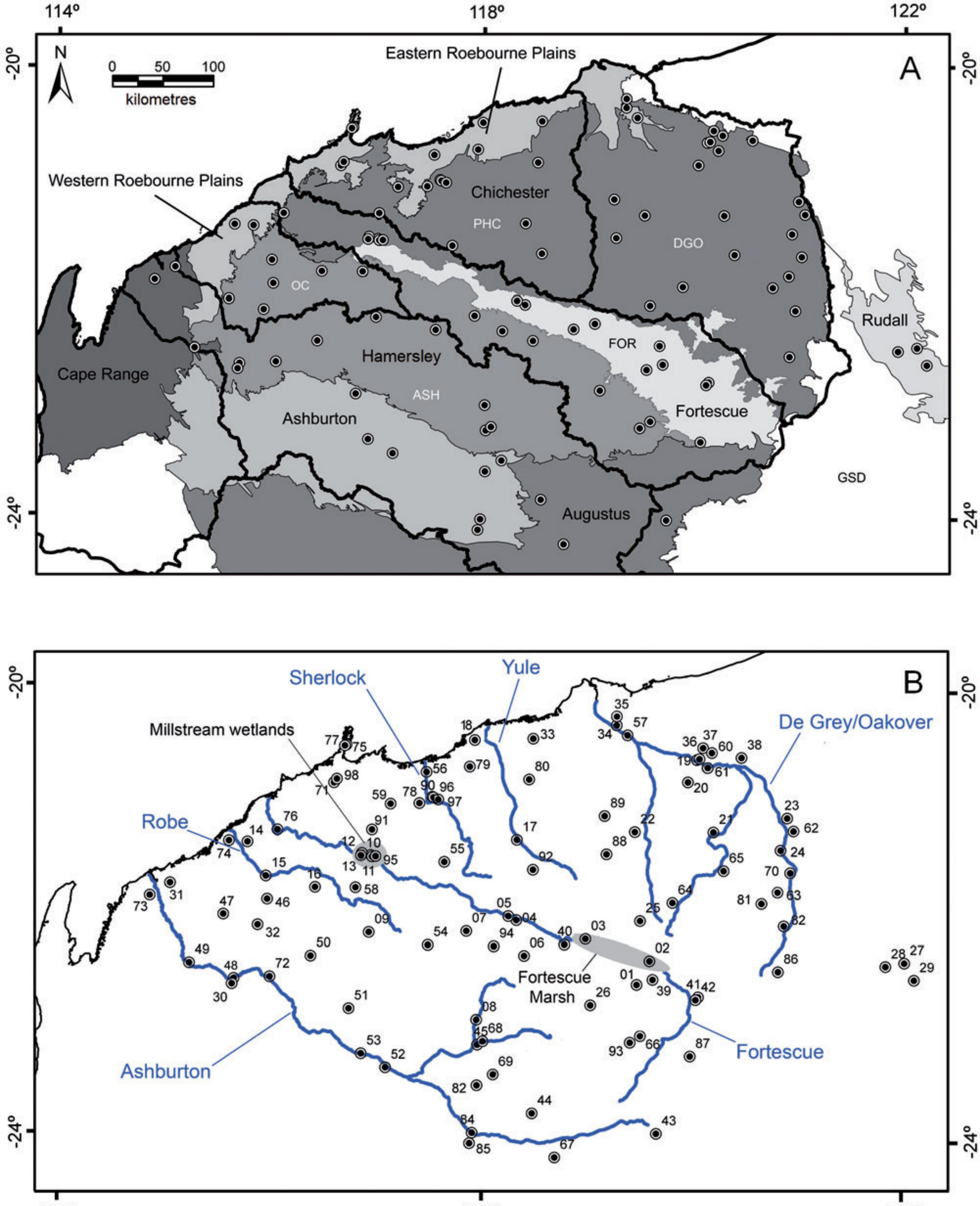

Figure 1 Maps of the Pilbara study area showing the 98 wetland sites sampled (note A and B sites at the same wetland are shown as a single point). Figure 1A shows IBRA6.1 subregions as shaded areas with full names; the Pilbara Bioregion comprises four subregions: Roebourne Plains (Eastern & Western), Chichester, Fortescue and Hamersley. Drainage basin boundaries are outlined in black and labelled with abbreviated names as follows: ASH, Ashburton; OC, Onslow Coast; FOR, Fortescue; PHC, Port Hedland Coast; DGO, De Grey-Oakover; GSD, Great Sandy Desert. Figure 1B shows the main rivers in blue and two major wetlands (shaded grey). The sampled wetland sites are numbered as per Table 1.

Inter-annually and spatially, rainfall variability is high, driven largely by the occurrence and path of cyclones. Winter rainfall from cold fronts originating in the south contributes significantly in the western coastal and central uplands of the region, and attenuates markedly towards the east. Two resulting bioclimatic zones were identified by Beard (1990), with the western coastal area characterised as semi-desert tropical, and the remainder as desert.

Site selection and sampling

Ninety-eight wetlands were selected to capture the diversity of wetland types present in each of the five major drainage basins within the Pilbara (Figure 1A, Table 1). The selected wetlands formed the basis of an integrated wetland survey of the Pilbara that covered a variety of biotic groups of the water column, including the riparian flora and vegetation reported here (see McKenzie *et al.* 2009, Pinder *et al.* 2010). Here, riparian is used to describe environments at the edge of waterbodies; i.e. under the hydrological influence of the wetland but not inundated at the time of sampling. This includes river banks, the waterlogged shallow soil aprons of rock pools, and the margins of claypans. Some riverine communities, such as *Melaleuca glomerata* on sandy islands, were rarely sampled since they were often not adjacent to waterbodies.

The primary stratification employed in the survey was the *a priori* designation of a number of wetland types based on hydrological and morphological attributes. These closely follow the scheme adopted for the region by Masini (1998): rock pools; springs and their outflow creeks; river pools; turbid linear pools; claypans and flooded clay flats; ephemeral creeks; salt marshes; and gorges. Wetlands were selected by examining topographic maps and consulting local experts, followed by aerial and ground-based reconnaissance. Within major river systems, sampling sites were distributed along the length of the main channel, and included the full range of stream orders from ephemeral headwater creeks to near-coastal river pools (Figure 1B).

Sampling was undertaken within a representative section within each selected wetland. At most wetlands (93), a single linear quadrat (200 m^2) was established parallel to the waterbody margin and positioned to capture the typical riparian setting of the wetland. Typically, quadrat configurations at each wetland were a single 4 m x 50 m or 5 m x 40 m rectangle, depending on riparian zone width. Within each quadrat, all vascular plants were scored within eight contiguous 25 m^2 subquadrats to evaluate the adequacy of quadrat size. Two 200 m^2 quadrats (designated A and B, see Table 1) were sampled at each of five large wetlands (PSW002, PSW003, PSW004, PSW035, and PSW080), to capture the major wetland zonation. At some small wetlands (typically small claypans and ephemeral streams), discontiguous subquadrats were surveyed in order to cumulatively sample 200 m^2 and to avoid upland vegetation. Quadrats were marked with steel pegs and their locations recorded using handheld GPS. For wetlands where the entire riparian zone was less than 200 m^2, such as very small claypans and rock pools with fringing shallow soil aprons, the whole wetland fringe was sampled (Table 1). These different quadrat configurations are herein referred to as sites. Sites were scored twice, in autumn and spring, between 2004 and 2006.

Plate 2 Munreemya Billabong, a seasonal/episodic wetland on Yarrie Station (wetland site PSW036A). The riparian zone dominated by *Eucalyptus camaldulensis* and *E. victrix* over *Eriachne benthamii* and *Dichanthium fecundum* sampled using a linear quadrat (M.N. Lyons).

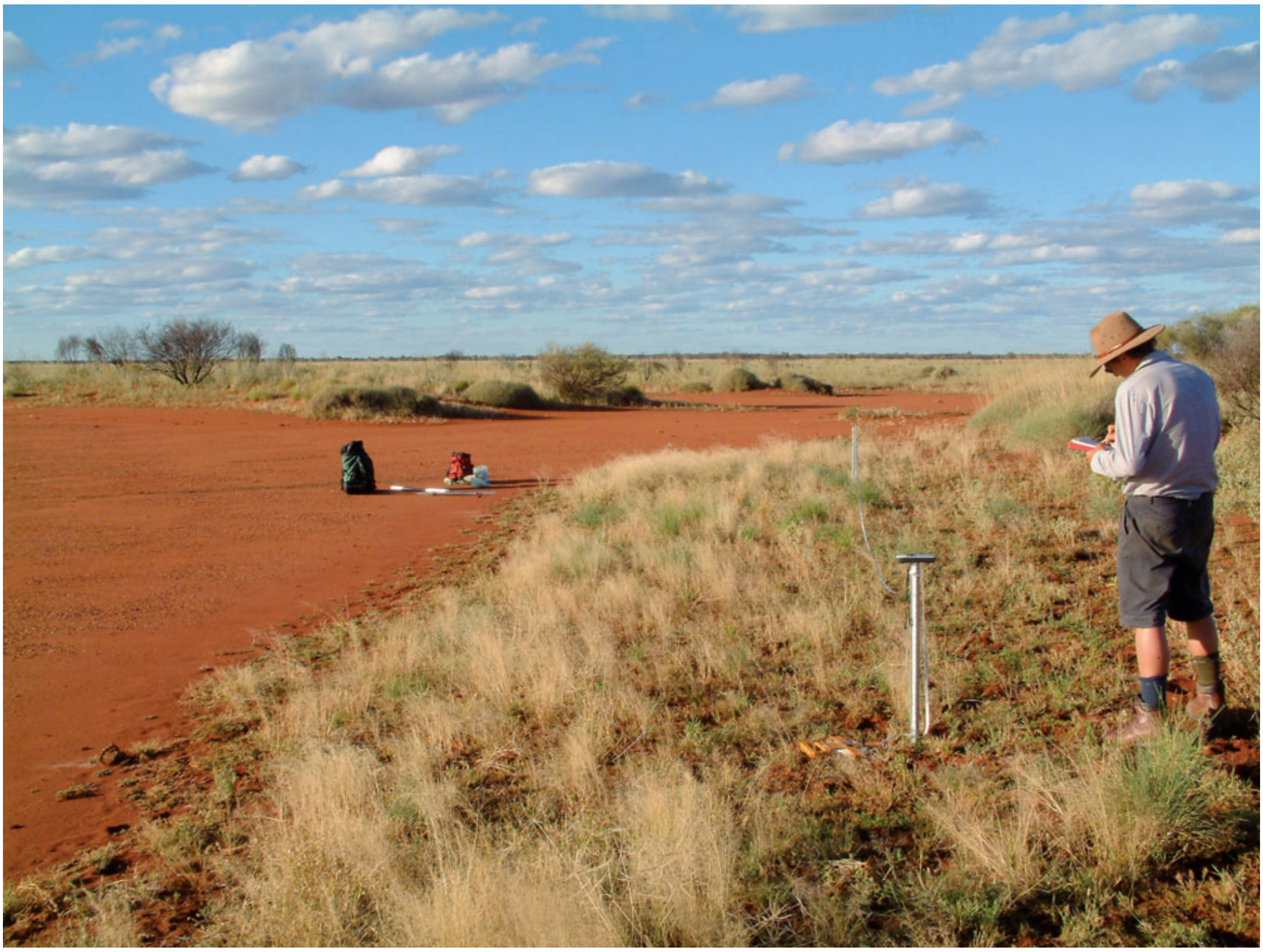

Plate 3 Ephemeral claypan on Roy Hill Station (site PSW039A). Sampling the grass- and herb-rich margin downslope of upland vegetation dominated by *Triodia* (D. Mickle).

Species accumulation curves were produced in *EstimateS* (using *Mao Tau*) for eight sites to examine the adequacy of the quadrat design (Colwell 2009). Input data were compiled as a presence/absence matrix of species at the eight subquadrats (25 m^2) within each 200 m^2 quadrat.

Within sites, surface soil samples (at 5–15 cm depth) were collected from 30 spaced points and bulked in the field to yield approximately 2.5 kg samples. Particle size and soil chemistry were analysed by the Chemistry Centre of Western Australia. Parameters analysed included pH, electrical conductivity, organic carbon, phosphorous, nitrogen, potassium, calcium, magnesium, sodium, and percent silt, clay and sand, and three gravel fractions (Table 2). A number of additional variables were derived for the sites by Pinder *et al.* (2011) and are used here. They include Strahler stream order (Strahler 1952), four inferred permanence/hydroperiod classes (1 = ephemeral, 2 = seasonal episodic, 3 = near permanent, 4 = permanent), straight line distance to coast, riverine versus non-riverine sites, and altitude (Table 3). A suite of climatic variables (Table 3) was derived from the BIOCLIM module of ANUCLIM (Houlder *et al.* 2000).

To provide a broader perspective on the riparian flora, the proportion it represents of the known Pilbara flora, based on records held at the Western Australian Herbarium (S. Dillon, unpublished data), was determined. Additionally, the broader biogeographic relationships of the riparian flora were explored by examining the IBRA regional occurrences of the taxa across Western Australia based on voucher specimen geocodes. Due to differences in taxonomic resolution across the data sets, some taxa were amalgamated at the specific level to yield a final dataset of 430 taxa across the State's IBRA regions. Data on the occurrence of Pilbara riparian taxa were also compiled for the botanical provinces (Northern, Eremaean and South-West) of Beard (1990), treating the Coolgardie IBRA region as Eremaean.

Table 1 Sites sampled for riparian flora.

Codes: Site code – unique sample site identifier (see Quadrat dimensions for sampling configuration) ; Site group – group derived from UPGMA classification; Perm class – Inferred permanence class (1 – ephemeral, 2 – seasonal/episodic, 3 – near permanent, 4 – permanent); Stream order – Strahler stream order (Strahler, 1952); Riverine/non-riverine (0 – non-riverine, 1 – riverine); DisCoast – straight line distance to coast (km); AnMeTemp – annual mean temperature (°C); MedDiuRa- mean temperature diurnal range (°C); MaxTeCoP – maximum temperature coldest period (°C); TempAnRa – temperature annual range (°C); MeTemWeQ – mean temperature wettest quarter (°C); AnnPrec – annual precipitation (mm); PrecSeas – precipitation seasonality; PrecColQ – precipitation coldest quarter (mm); Quadrat dimensions in metres (A – 5 x 40; B – 4 x 50 ; C – discontiguous 5 x 30 + 5 x 10; D – discontiguous 4 x 37.5 + 4 x 12.5; E – 10 x 20; F – discontiguous 5 x15 + 5 x 25; G – discontiguous 5 x 20 +5 x 20; H – sampled out.

Site code	Site name	Wetland type	Latitude (°S)	Longitude (°E)	Site group	Perm class	Stream order	Riverine	DisCoast	AnMeTemp	MedDiuRa	MaxTeCoP	TempAnRa	MeTemWeQ	AnnPreci	PrecSeas	PrecColQ	Quadrat dimensions
PSW001A	Coondiner Pool	turbid creek pool	22.7256	119.6566	1	3	4	1	286	24.7	15.3	40.1	32.1	31	275	87	44	A
PSW002A	Fortescue Marsh East	salt marsh	22.5091	119.7769	5.1	2	0	0	267	24.8	15.6	40.2	32.3	31	279	88	42	A
PSW002B	Fortescue Marsh East	salt marsh	22.5085	119.7796	5.1	2	0	0	267	24.8	15.6	40.2	32.3	31	279	88	42	A
PSW003A	Fort Marsh West (Moojari)	salt marsh	22.3162	119.1499	5.2	2	0	0	228	25.2	14.9	40.1	30.6	31.2	303	93	40	A
PSW003B	Fort Marsh West (Moojari)	salt marsh	22.3132	119.1530	5.2	2	0	0	228	25.2	14.9	40.1	30.6	31.2	303	93	40	A
PSW004A	Gnalka Gnoona Claypan	claypan	29.1530	118.4920	2	2	0	0	180	25.7	13.9	39.7	29.2	31.4	345	96	44	A
PSW004B	Gnalka Gnoona Claypan	claypan	29.1546	118.4751	2	2	0	0	180	25.7	13.9	39.7	29.2	31.4	345	96	44	A
PSW005A	Koondepindawarrina Pool	turbid creek pool	22.1203	118.3952	2	2	2	1	174	25.7	13.8	39.6	29.1	31.4	349	97	44	A
PSW006A	Fortescue Falls	Gorge creek (spring fed)	22.4774	118.5513	6.1	4	3	1	216	23.4	13.4	37.9	29.4	29.6	371	88	53	A
PSW007A	Hamersley Gorge	Gorge creek (spring fed)	22.2587	117.9859	6.1	4	4	1	177	24.6	13.5	38.7	29	30.7	357	96	48	A
PSW008A	Bobswim Pool	river pool	23.0585	118.0903	7	4	5	1	365	24.9	14.2	39.8	31.1	31	299	84	51	A
PSW009A	Palm Spring on Caves Creek	spring	22.2674	117.0383	6.1	4	1	1	169	24.8	14.3	39.3	29.7	30.8	350	88	59	A
PSW010A	Palm Pool at Millstream	river pool	21.5698	117.0553	6.1	4	5	1	95	25.6	14.1	38.7	27.9	31.1	352	100	48	A
PSW011A	Millstream Delta	spring	21.5839	117.0677	6.1	4	1	1	97	25.6	14.1	38.8	28	31.1	354	100	48	A
PSW012A	Gregory Gorge Pool	river pool	21.5519	116.9686	6.1	4	5	1	92	25.7	14.2	38.8	27.9	31.1	345	99	48	A
PSW013A	Palm Spring at Millstream	spring	21.5721	116.9615	6.1	4	1	1	95	25.6	14.2	38.8	27.9	31.1	346	98	48	B

Site code	Site name	Wetland type	Latitude (°S)	Longitude (°E)	Site group	Perm class	Stream order	Riverine	DisCoast	AnMeTemp	MedDiuRa	MaxTeCoP	TempAnRa	MeTemWeQ	AnnPreci	PrecSeas	PrecColQ	Quadrat dimensions
PSW014A	Myanore Creek Pool	turbid creek pool	21.4435	115.8625	3	2	2	1	21	25.9	14.2	37.9	26.3	30.9	291	91	54	A
PSW015A	Chalyarn Pool	river pool	21.7551	116.0365	6.1	4	4	1	62	26.2	14.8	39.5	28.1	31.5	307	91	57	A
PSW016A	Nyeetbury Spring	spring	21.8593	116.5147	6.1	4	3	1	99	25.9	14.8	39.8	29	31.6	351	92	58	A
PSW017A	Wodgina Pool	river pool	21.4255	118.4725	7	3	5	1	114	26	15.1	39.8	29.3	31.5	314	102	37	A
PSW018A	Munda Homestead Pool	river pool	20.5220	118.0618	6.1	4	5	1	8	25.9	13.1	36.4	24.5	30.6	304	101	41	A
PSW019A	De Grey at Yarrie Station	river pool	20.6800	120.2020	8	3	6	1	85	27.4	14.2	40.5	27.8	32.1	319	107	34	A
PSW020A	Coppin Gap Pool	river pool	20.8840	120.1180	6.1	4	2	1	104	26.9	14.6	40.5	28.8	31.8	329	104	37	A
PSW021A	Pelican Pool	river pool	21.3321	120.3744	7	4	5	1	161	26.3	15.6	40.7	30.7	31.8	302	99	37	A
PSW022A	Glen Herring Pool	river pool	21.3424	119.6136	6.1	4	3	1	141	25.9	15.5	40.4	30.6	31.4	330	99	42	C
PSW023A	Tarquin Rockhole	river pool	21.1906	121.0838	7	3	2	1	164	26.3	15.3	40.1	30	31.5	286	94	38	A
PSW024A	Carawine Gorge	river pool	21.4774	121.0279	8	4	6	1	192	26.1	15.6	40.4	30.9	31.7	272	93	36	A
PSW025A	Bamboo Spring	spring	22.1489	119.6793	6.1	4	3	1	226	24.8	15.7	40.2	32	31.1	301	91	39	A
PSW026A	Weeli Wolli Spring	spring	22.9156	119.2050	6.1	4	2	1	291	24	14.5	39.1	31.2	30.6	297	88	44	A
PSW027A	Queen Desert Spring	river pool	22.4674	122.2583	3	3	2	1	342	25.1	15.1	40	31.9	31.2	230	88	34	A
PSW028A	Watrara Creek Pool	river pool	22.5038	122.0768	3	3	3	1	337	24.9	15.1	39.9	31.9	31.1	231	87	35	A
PSW029A	Poonamerrala Creek Pool	river pool	22.6186	122.3586	7	2	2	1	362	25.1	15.2	40.1	32.1	31.3	224	88	33	B
PSW030A	Moreton Pool	claypan	22.6765	115.7161	3	1	2	1	128	25.7	15.4	40.8	30.6	31.8	277	87	65	A
PSW031A	Cane River Claypan	claypan	21.8057	115.1048	2	2	0	0	14	25.3	13.1	37.3	24.9	30.3	304	92	69	A
PSW032A	Creek Pool near Mt. Amy Well	river pool	22.1945	115.9556	6.2	3	2	1	90	25.9	15	40.1	29.3	31.5	321	94	61	A
PSW033A	Cooliarin Pool	turbid creek pool	20.5051	118.6219	3	2	2	1	18	25.7	13.2	36.2	24.8	30.3	308	104	39	A
PSW034A	Paradise Pool	claypan	20.3777	119.4204	3	3	0	0	38	26.6	13.8	38	25.9	31.2	309	103	35	A
PSW035A	DeGrey Claypan	claypan	20.2894	119.4310	1	2	0	0	24	26.5	13.6	37.7	25.5	31.1	305	103	35	A
PSW035B	DeGrey Claypan	claypan	20.2886	119.4334	1	2	0	0	24	26.5	13.6	37.7	25.5	31.1	305	103	35	A

Site code	Site name	Wetland type	Latitude (°S)	Longitude (°E)	Site group	Perm class	Stream order	Riverine	DisCoast	AnMeTemp	MedDiuRa	MaxTeCoP	TempAnRa	MeTemWeQ	AnnPreci	PrecSeas	PrecColQ	Quadrat dimensions
PSW036A	Munreemya Billabong	claypan	20.6696	120.2269	3	2	4	1	84	27.2	14.2	40.4	27.8	31.9	323	106	35	A
PSW037A	Coppin Pool	claypan	20.5729	120.2604	3	2	0	0	73	26.9	13.9	39.9	27.3	31.5	333	105	38	B
PSW038A	Sweet Well Claypan	claypan	20.6521	120.6327	4	1	0	0	92	26.8	14.6	39.9	28.1	31.5	321	103	35	B
PSW039A	Roy Hill Claypan	claypan	22.6750	119.8111	4	1	0	0	285	24.7	15.5	40.1	32.3	31	272	86	43	D
PSW040A	Mulga Downs Outcamp Claypan	claypan	22.3619	118.9763	3	2	0	0	225	25.4	14.5	40	30.3	31.3	309	94	40	A
PSW041A	Ethel Creek Claypan	claypan	22.8234	120.2587	1	1	0	0	312	24.4	15.6	39.7	32.6	30.8	257	86	36	A
PSW042A	Jackson Bore Claypan	claypan	22.8502	120.2356	4	1	0	0	317	24.4	15.5	39.7	32.6	30.8	257	85	37	A
PSW043A	Weelarrana Salt Lake	salt marsh	24.0661	119.8781	5.2	2	0	0	436	22.8	14.9	38.6	33.2	29.6	223	73	37	E
PSW043B	Weelarrana Salt Lake	salt marsh	24.0706	119.8734	5.2	2	0	0	436	22.8	14.9	38.6	33.2	29.6	223	73	37	E
PSW044A	Yandibiddy Pool	river pool	23.9022	118.7123	7	4	5	1	369	23.8	14.8	39.6	32.8	30.6	236	70	45	A
PSW045A	Fork Spring	spring	23.2836	118.1020	6.2	3	1	1	289	24.8	14.4	40.1	31.6	31.2	269	78	49	A
PSW046A	Red Hill Creek Pool	river pool	21.9623	116.0477	7	3	4	1	74	26	14.9	39.8	28.7	31.5	330	92	61	A
PSW047A	House Pool on Cane River	river pool	22.0960	115.6209	8	3	5	1	65	25.8	14.6	39.4	28.2	31.3	318	98	63	A
PSW048A	Henry River Pool	river pool	22.7273	115.6993	8	4	5	1	132	25.7	15.4	40.9	30.8	31.8	274	87	64	A
PSW049A	Whiskey Pool on Ashburton R.	river pool	22.5296	115.2832	8	4	7	1	95	25.5	15	40.1	29.4	31.4	288	88	70	A
PSW050A	Wallarook Pool on Duck Creek	river pool	22.4791	116.4684	7	4	5	1	148	25.7	15	40.6	30.5	31.8	332	85	61	A
PSW051A	Cheela Spring	spring	22.9573	116.8403	6.2	4	1	1	215	25.8	15.1	41.2	31.6	32	275	82	52	A
PSW052A	Berringarra Claypan	claypan	23.4922	117.1981	2	2	0	0	288	25.7	15.1	41.4	32.5	32.2	224	78	47	A
PSW053A	Catfish Pool on Ashburton R.	river pool	23.3667	116.9596	8	3	7	1	257	25.8	15.2	41.5	32.4	32.2	234	81	47	A
PSW054A	Wackilina Creek Pool	turbid creek pool	22.3828	117.6140	3	2	2	1	185	24.5	13.8	38.8	29.5	30.5	341	88	51	A
PSW055A	Errawallana Spring	spring	21.6265	117.7752	7	4	2	1	105	25.1	13.9	38.3	28.1	30.6	372	105	48	A
PSW056A	Pool Spring on Sherlock River	river pool	20.8124	117.5969	7	4	5	1	12	26.2	13.4	37.4	25.4	31	304	103	41	A
PSW057A	Carleecarleethong Pool	river pool	20.4655	119.5295	8	4	6	1	43	26.7	13.9	38.6	26.4	31.5	319	103	37	A

Site code	Site name	Wetland type	Latitude (°S)	Longitude (°E)	Site group	Perm class	Stream order	Riverine	DisCoast	AnMeTemp	MedDiuRa	MaxTeCoP	TempAnRa	MeTemWeQ	AnnPreci	PrecSeas	PrecColQ	Quadrat dimensions
PSW058A	Kumina Creek	river pool	21.8626	116.9090	3	3	3	1	125	25.1	14.2	38.9	28.7	30.8	366	95	57	A
PSW059A	The Springs on Jones River	spring	21.1039	117.2483	6.1	4	2	1	53	25.9	13.7	37.8	26.3	31	323	111	40	A
PSW060A	Chinaman Spring	spring	20.6105	120.3448	6.1	3	1	1	77	27.1	14.2	40.2	27.6	31.8	324	105	35	A
PSW061A	Miningarra Creek	ephemeral creek	20.7492	120.3067	7	2	4	1	94	27.3	14.4	40.5	28.2	32	318	106	34	A
PSW062A	Gregory Range Creek	ephemeral creek	21.2538	121.0783	6.1	1	2	1	178	26	15.3	40	30.3	31.3	285	91	39	A
PSW063A	Skull Springs	spring	21.8635	121.0078	6.1	4	1	1	230	25.4	15.7	40.2	31.7	31.3	265	89	37	A
PSW064A	Bonnie Pool	river pool	21.9778	119.9912	7	4	3	1	217	24.3	16.1	39.8	32.6	30.6	319	89	42	A
PSW065A	Cookes Creek Pool	river pool	21.6806	120.4813	3	3	3	1	193	25.2	15.9	40.2	31.9	31.1	301	91	41	A
PSW066A	Kalgan Pool on Kalgan Creek	river pool	23.1871	119.6976	7	3	4	1	336	23.4	14.6	38.4	31.7	30	291	79	45	A
PSW067A	Wannagunna Spring	river pool	24.3006	118.8731	8	4	4	1	418	23.3	15.1	39.6	33.6	30.4	226	68	43	A
PSW068A	Flatrocks Spring	spring	23.2533	118.1514	7	4	1	1	288	24.8	14.4	40	31.5	31.1	275	79	49	A
PSW069A	Horrigans Pool	river pool	23.5552	118.2586	6.2	4	5	1	320	24.7	14.7	40.2	32.2	31.3	245	74	47	A
PSW070A	Running Waters	spring	21.6858	121.1253	6.1	4	1	1	218	25.9	15.6	40.3	31.3	31.5	263	91	36	A
PSW071A	Karratha Granite Rock	rock pools	20.9100	116.7353	4	1	0	0	22	26	13.3	37.2	25.1	30.9	269	93	49	H
PSW072A	Curara Claypan	claypan	22.6647	116.0702	8	2	1	1	142	26	15.4	41.1	30.9	32	280	87	60	A
PSW073A	Mindaroo Claypan	claypan	21.9146	114.9090	4	1	0	0	20	25.1	13.1	37.2	24.9	30.1	300	90	72	B
PSW074A	Yarraloola Claypan	claypan	21.4285	115.6847	3	1	0	0	11	25.8	13.6	37.3	25.2	30.7	292	92	57	B
PSW075A	Burrup Peninsula Creek	ephemeral creek	20.5656	116.8247	7	2	1	1	0.9	25.9	12.5	36.3	23.7	30.6	274	94	43	F
PSW076A	Pool on Lower Fortescue River	river pool	21.3324	116.1547	6.1	4	5	1	35	26.1	14.6	38.3	26.9	31.1	303	90	61	A
PSW077A	Burrup Peninsula Rockhole	ephemeral creek	20.5736	116.8075	7	3	1	1	1	25.9	12.5	36.4	23.7	30.6	272	94	43	H
PSW078A	Croyden Claypan	claypan	21.0383	117.6534	4	1	1	1	38	26.1	13.7	37.9	26.4	31	319	107	41	G
PSW079A	West Peawah Creek Pool	turbid creek pool	20.7641	118.0150	3	2	4	1	24	26.1	13.5	37.2	25.6	30.9	307	102	41	A
PSW080A	Redrock on Indee Station	rock pool	20.8755	118.5885	4	2	0	0	62	25.8	14.3	37.9	27.1	30.7	309	102	39	H

Site code	Site name	Wetland type	Latitude (°S)	Longitude (°E)	Site group	Perm class	Stream order	Riverine	DisCoast	AnMeTemp	MedDiuRa	MaxTeCoP	TempAnRa	MeTemWeQ	AnnPreci	PrecSeas	PrecColQ	Quadrat dimensions
PSW080B	Redrock on Indee Station	rock pool	20.8746	118.5895	4	1	0	0	62	25.8	14.3	37.9	27.1	30.7	309	102	39	H
PSW081A	Billan Ballan Creek Pool	river pool	21.9690	120.8556	7	3	2	1	238	25.2	15.8	40.2	32	31.2	265	89	37	A
PSW082A	Tongololo Creek Pool	river pool	22.1653	121.0803	3	3	5	0	266	25.1	15.6	40	32.1	31.1	247	88	34	A
PSW083A	Turee Creek Claypan	claypan	23.6525	118.0988	3	1	0	1	337	25.1	14.8	40.7	32.5	31.6	230	72	47	D
PSW084A	Gorge Junction Pool	river pool	25.0842	118.0548	6.1	2	6	1	378	24.6	15	40.7	33.1	31.5	221	68	50	A
PSW085A	Glen Ross Creek	ephemeral creek	24.1790	118.0298	3	2	3	1	386	24.4	14.9	40.5	33.2	30.9	223	67	52	B
PSW086A	Carrowina Pool	river pool	22.5784	121.0343	3	4	3	1	308	24.6	15.6	39.7	32.4	30.9	230	87	32	A
PSW087A	Innawally Pool	river pool	23.3621	120.1904	3	3	4	1	370	23.6	15	38.8	32.5	30.3	255	81	39	B
PSW088A	Rocky Island Pool	river pool	21.5481	119.3435	7	3	5	1	150	25.8	16	40.8	31.2	31.5	319	99	38	A
PSW089A	Panorama Spring	spring	21.2018	119.3205	6.1	4	1	1	115	26.1	15.7	40.3	30.2	31.5	336	103	42	A
PSW090A	Kangan Pool on Sherlock River	river pool	21.0977	117.6271	7	4	5	1	41	25.7	13.6	37.7	26.4	30.9	329	108	43	A
PSW091A	Harding River Pool	river pool	21.3377	117.0697	7	4	2	1	70	25.3	13.8	37.8	27	30.6	344	105	47	A
PSW092A	Cangan Pool on Cockerega Ck.	river pool	21.6953	118.6296	6.1	3	4	1	147	25.9	15.2	40.3	30	31.5	313	100	37	A
PSW093A	Homestead Creek	ephemeral creek	23.2485	119.5992	7	2	2	1	335	23.1	14.5	38.1	31.6	29.7	296	79	46	A
PSW094A	Joffre Creek	ephemeral creek	22.3918	118.2583	3	2	4	1	201	24.2	13.3	38.4	29.1	30.3	375	91	51	B
PSW095A	Un-named Creek in Millstream N.P.	ephemeral creek	21.5799	117.1029	3	2	2	1	98	25.5	14.1	38.7	27.9	31	356	102	48	A
PSW096A	Benmore Well Claypan	claypan	21.0444	117.6636	1	2	1	1	40	26.1	13.7	37.9	26.4	31	319	107	41	A
PSW097A	Croydon Crabhole Flat	clay flat	21.0638	117.7091	3	1	1	1	43	26.2	13.9	38.1	26.5	31.2	316	107	41	A
PSW098A	Karratha Crabhole Flat	clay flat	20.8759	116.7298	3	1	0	0	24	26	13.2	37.1	24.9	30.8	269	93	49	A

Table 2 Soil variables for each riparian site sampled. For detail on soils analyses see Meissner *et al*. (2009).

Codes: EC (1:5) mS/m – electrical conductivity; pH (H20) – pH in distilled water; OrgC (W/B) % – percent organic carbon (Walkely Black); P (total) mg/kg – total Phosphorus; P (HCO3) mg/kg – extractable Phosphorus; Ca (exch) me% – exchangeable Calcium milliequivalent percent; Mg (exch) me% – exchangeable Magnesium milliequivalent percent; Na (exch) me% – exchangeable Sodium milliequivalent percent; K (exch) me% – exchangeable Potassium milliequivalent percent.

Site code	EC (1:5) mS/m	pH (H2O)	OrgC (W/B) %	P (total) mg/kg	Sand %	Silt %	Clay %	Gravel >16mm %	Gravel 8–16mm %	Gravel 4.8–8mm %	Gravel 2–4.8mm %	P (HCO3) mg/kg	Ca (exch) me%	Mg (exch) me%	Na (exch) me%	K (exch) me%
PSW001A	8	6.4	1.55	640	56.5	12	31.5	0	0	0	0	50	6.3	2.75	0.33	1.18
PSW002A	140	7.4	0.37	450	34	32	34	0	0	0	0	34	7.11	3.13	3.41	3.56
PSW002B	150	7.9	0.52	370	63	15.5	21.5	0	0	0	0	24	5.48	2.12	2.27	2.34
PSW003A	290	7.9	0.49	350	49	32.5	18.5	0	0	0	0	19	15.02	3.02	1.64	4.12
PSW003B	770	8.2	0.78	240	49.5	31	19.5	0	0	0	0	8	9.32	6.54	3.32	5
PSW004A	8	6.5	0.9	480	44	19.5	36.5	3.9	9.8	13.3	18.1	23	10.76	4.64	0.46	2.02
PSW004B	8	6.5	0.9	480	44	19.5	36.5	3.9	9.8	13.3	18.1	23	10.76	4.64	0.46	2.02
PSW005A	11	6.3	1	520	36	22	42	0	0	0	0	54	10.18	4.42	0.63	2.03
PSW006A	70	8.3	2.02	480	83.5	10.5	6	15.7	15.4	17.1	19.2	6	4.12	6.9	1.5	0.69
PSW007A	19	8.4	0.76	270	83.5	8	8.5	19.6	10.2	12.9	28.9	3	5.59	4.14	0.41	0.55
PSW008A	12	8.6	0.66	190	90.5	5.5	4	4.3	8.3	5.3	33	5	4.47	1.32	0.22	0.17
PSW009A	200	8.4	0.86	220	74.5	11.5	14	11.1	15.9	30.1	16.5	3	5.46	14.23	2.99	1.2
PSW010A	83	8.8	0.41	170	77	8	15	24.1	19.5	15.5	16.4	2	4.83	7.16	2.07	0.89
PSW011A	410	8.3	3.7	290	55.5	29.5	15	0	0	0	0	9	12.1	15.58	11.89	5
PSW012A	85	8.3	1.28	270	74.5	11.5	14	9	24	40.5	14.4	4	7.24	5.14	1.78	0.9
PSW013A	420	8.3	1.02	110	75	17	8	0	0	0	0	3	11.57	9.7	7.62	1.6
PSW014A	5	6.3	1.24	380	24	29	47	0	0	0	0	9	15.54	5.73	0.18	1.16

Site code	EC (1:5) mS/m	pH (H2O)	OrgC (W/B) %	P (total) mg/kg	Sand %	Silt %	Clay %	Gravel >16mm %	Gravel 8–16mm %	Gravel 4.8–8mm %	Gravel 2–4.8mm %	P (HCO3) mg/kg	Ca (exch) me%	Mg (exch) me%	Na (exch) me%	K (exch) me%
PSW015A	67	9	0.92	330	77.5	14	8.5	0	0	0	0	9	4.35	6.86	3.11	1.8
PSW016A	50	8.4	1	280	88	8	4	15.7	16.6	7.8	16.7	3	6.52	6.8	1	0.44
PSW017A	30	9	0.5	190	87.5	5.5	7	26.1	13.6	6.8	16.5	4	6.34	1.91	1.67	0.26
PSW018A	38	8.4	0.56	150	81	7	12	9	11.7	16.9	11.2	12	8.37	2.02	0.84	0.48
PSW019A	23	8	0.54	190	88	5	7	0	0	0	0	10	6.1	1.86	0.36	0.38
PSW020A	48	9.7	0.38	100	91.5	5	3.5	12	10.7	7.9	25	2	1.72	3.52	3.18	0.26
PSW021A	33	9.4	0.4	150	93	4.5	2.5	0	0	0	0	5	1.88	1.48	1.66	0.13
PSW022A	110	9.6	0.74	200	89	6	5	8.1	14.3	25.1	19	4	2.96	4.54	4.75	0.19
PSW023A	39	9	1.56	260	81.5	12	6.5	0	0	0	0	16	6.25	4.91	2.72	0.41
PSW024A	100	8	2.41	310	74.5	14	11.5	0	0	0	0	17	12.19	5.63	1.74	0.45
PSW025A	48	8.4	1.22	380	81.5	8.5	10	6.4	12.3	19.1	30.5	9	10.06	6.33	1.06	0.28
PSW026A	40	8.5	0.89	300	88	7	5	6	6.4	12.1	27.4	3	4.58	4.63	0.83	0.53
PSW027A	53	7.1	1.02	87	93.5	3.5	3	0	0	0	0	4	1.19	1.93	1.01	0.35
PSW028A	84	8	0.67	200	90	5.5	4.5	0	0	0	0	9	2.22	2.48	1.38	0.22
PSW029A	230	7.9	0.38	110	93.5	2.5	4	0.9	3.6	5.3	12.2	5	2.31	2.11	1.18	0.18
PSW030A	17	6.6	1.68	380	27	34	39	0	0	0	0	38	9.22	5.09	0.64	2.61
PSW031A	10	7.4	0.28	190	73.5	10	16.5	0	0	0	0	15	2.21	1.27	0.85	0.5
PSW032A	350	8.9	1.17	250	57.5	29.5	13	0	0	0	0	13	1.73	16.03	4.2	1.49
PSW033A	4	7.4	0.17	93	94	2	4	0	0	0	0	5	0.98	0.27	0.14	0.18
PSW034A	5	6.9	0.81	240	86	7	7	0	0	0	0	28	4.56	1.87	0.25	0.42
PSW035A	7	7.3	0.14	130	52	9	39	0	0	0	0	5	4.24	5.5	1.67	0.86
PSW035B	4	6.1	0.18	140	73	8	19	0	0	0	0	7	1.32	2.34	0.35	0.39

Site code	EC (1:5) mS/m	pH (H2O)	OrgC (W/B) %	P (total) mg/kg	Sand %	Silt %	Clay %	Gravel >16mm %	Gravel 8–16mm %	Gravel 4.8–8mm %	Gravel 2–4.8mm %	P (HCO3) mg/kg	Ca (exch) me%	Mg (exch) me%	Na (exch) me%	K (exch) me%
PSW036A	6	6.6	0.86	280	56.5	17	26.5	0	0	0	0	14	9.61	5.22	0.27	0.64
PSW037A	2	6.5	0.16	83	97.5	0.5	2	0	0	0	0	6	0.66	0.25	0.08	0.1
PSW038A	9	7.7	0.08	78	93	1	6	0	0	0	0	5	0.76	0.41	0.55	0.29
PSW039A	5	7.8	0.16	93	95	1	4	0	0	0	0	4	0.73	0.45	0.49	0.46
PSW040A	39	7.3	0.21	460	58.5	13	28.5	0	0	0	0	12	5.43	2.41	1.42	2.7
PSW041A	8	7.4	0.27	840	53.5	15.5	31	0	0	0	0	19	5.52	1.74	0.81	2.57
PSW042A	17	7.7	0.11	220	55	9	36	0	0	0	0	13	6.66	3.79	1.69	0.77
PSW043A	300	8	0.18	280	86	6	8	0	0	0	0	7	9.84	1.06	0.66	1.11
PSW043B	530	8.2	0.14	200	94	2	4	0	0	0	0	12	8.01	1.25	1.42	1.2
PSW044A	32	8.7	0.71	180	84.5	6	9.5	0	0	0	0	3	4.78	2.16	0.9	0.31
PSW045A	130	8.5	2.93	240	88	7.5	4.5	4.5	10.3	9.9	26.4	12	6.63	9.5	3.22	2.54
PSW046A	48	8.4	0.59	390	88.5	5.5	6	26.5	19.5	11.1	10	9	4.02	2.13	0.97	0.36
PSW047A	50	7.7	0.57	200	79	11	10	0	0	0	0	4	4.98	2.5	0.33	0.34
PSW048A	21	8.5	0.44	160	91	4.5	4.5	2.9	3.8	3.1	4.8	9	2.7	1.5	0.25	0.22
PSW049A	20	8.3	0.42	230	80.5	9	10.5	0	0	0	0	11	6.58	1.77	0.23	0.36
PSW050A	54	8.4	0.46	280	81	7.5	11.5	0	0	0	0	5	5.74	3.84	1	0.5
PSW051A	280	9.1	0.45	92	52	30	18	0	0	0	0	4	2.94	3.45	7.28	0.87
PSW052A	25	7.5	0.36	260	83	8	9	3.1	11.1	14	22.4	14	3.02	1.36	0.38	0.49
PSW053A	71	8	0.44	210	82	9	9	0	0	0	0	12	5.72	2.2	1.02	0.43
PSW054A	8	6	0.96	360	43	16	41	0	0	0	0	15	9.61	5.21	0.37	1.2
PSW055A	49	8.6	1.72	240	82.5	8	9.5	0	0	0	0	10	6.4	6.48	1.82	0.33
PSW056A	56	8.9	0.29	120	93	2	5	0	0	0	0	4	3.6	2.29	1.39	0.29

Site code	EC (1:5) mS/m	pH (H2O)	OrgC (W/B) %	P (total) mg/kg	Sand %	Silt %	Clay %	Gravel >16mm %	Gravel 8–16mm %	Gravel 4.8–8mm %	Gravel 2–4.8mm %	P (HCO3) mg/kg	Ca (exch) me%	Mg (exch) me%	Na (exch) me%	K (exch) me%
PSW057A	6	8.3	0.07	110	97	0.5	2.5	0	0	0	0	5	2.85	0.91	0.32	0.11
PSW058A	20	7.4	0.38	440	93.5	3	3.5	16.4	22.9	18.8	19.1	5	2.47	1.58	0.52	1.17
PSW059A	38	8.5	1.27	140	84	8	8	0	0	0	0	2	8.01	12.76	0.89	0.17
PSW060A	100	6.8	4.22	320	86.5	8	5.5	0	0	0	0	15	9.21	7.64	1.27	0.85
PSW061A	31	9.2	0.37	190	96	1.5	2.5	8.1	5.4	6	35	4	3.06	1.32	1.34	0.11
PSW062A	32	8.8	1.44	210	84	9.5	6.5	0	0	0	0	6	5.63	5.56	1.38	0.7
PSW063A	150	8.4	0.45	350	95	2	3	0	0	0	0	6	2.14	2.4	1.39	0.15
PSW064A	190	8.9	1.37	480	69	13.5	17.5	0	0	0	0	32	7.77	3.82	10.03	0.46
PSW065A	11	7	0.38	110	90.5	5.5	4	0	0	0	0	2	1.5	1.11	0.37	0.12
PSW066A	24	8.4	0.62	330	92.5	3.5	4	20.6	22.1	12.5	19.1	4	3.37	2.75	0.73	0.33
PSW067A	36	8.6	0.45	180	88.5	5.5	6	5.4	9.9	12.7	21	3	5.26	3.32	0.94	0.49
PSW068A	140	8.5	1.1	200	91.5	5	3.5	0	0	0	0	7	4.43	4.02	2.72	1.02
PSW069A	24	8.4	0.3	78	95.5	2	2.5	0	0	0	0	1	1.51	0.7	0.3	0.15
PSW070A	37	8.3	0.21	270	95	1	4	3.1	7.9	9.9	24.2	2	2.01	1.07	0.42	0.25
PSW071A	15	6.2	0.78	300	71.5	14	14.5	0	0	0	0	22	4.17	3.03	0.5	0.39
PSW072A	9	5.2	1.15	410	31.5	23.5	45	0	0	0	0	25	6.5	5.5	0.31	0.89
PSW073A	6	9.2	0.06	78	93	0.5	6.5	0	0	0	0	2	1.05	0.66	1.2	0.22
PSW074A	12	7.4	0.28	290	57.5	12	30.5	0	0	0	0	10	5.12	2.59	0.71	1.18
PSW075A	190	8.2	1.68	240	82.5	10.5	7	0	0	0	0	8	7.81	3.62	2.42	0.41
PSW076A	290	8.2	0.84	280	85	6	9	23.4	18.4	12.8	10.6	11	7.34	6.35	1.78	0.55
PSW077A	7	5.9	0.76	270	63	8	29	0	0	0	0	22	4.19	2.39	0.25	0.81
PSW078A	23	7.6	0.16	110	82.5	4	13.5	0	0	0	0	4	1.12	0.2	0.85	0.31

Site code	EC (1:5) mS/m	pH (H2O)	OrgC (W/B) %	P (total) mg/kg	Sand %	Silt %	Clay %	Gravel >16mm %	Gravel 8–16mm %	Gravel 4.8–8mm %	Gravel 2–4.8mm %	P (HCO3) mg/kg	Ca (exch) me%	Mg (exch) me%	Na (exch) me%	K (exch) me%
PSW079A	6	6.4	1.02	130	85.5	6	8.5	0	0	0	0	18	4.34	1.34	0.15	0.41
PSW080A	4	6	0.48	120	81.5	10.5	8	2.4	3.2	7.1	19.4	3	1.44	0.94	0.17	0.18
PSW080B	20	5.3	0.42	480	86	7	7	22.1	14	10.4	17.3	96	1.17	0.73	0.52	0.28
PSW081A	110	9.3	1.95	390	77	13	10	0	0	0	0	29	4.62	2.32	7.91	1.02
PSW082A	14	7.3	1.06	280	77.5	9.5	13	5.8	10.1	6.9	8.6	11	8.11	2.14	0.39	0.57
PSW083A	17	6.7	0.24	190	78.5	5	16.5	0	0	0	0	13	2.58	2.75	0.77	0.58
PSW084A	64	7.6	1.09	260	71	13	16	26.5	8.1	7.7	16.6	7	9.46	3.04	0.57	0.81
PSW085A	160	7.5	0.5	390	84	7	9	6.2	9.6	0	24.7	11	4.93	4.18	2.46	0.36
PSW086A	35	7.7	1.13	290	80	7.5	12.5	0	0	0	0	10	6.71	1.22	0.38	1.06
PSW087A	14	7.6	0.45	120	89.5	4	6.5	0	0	0	0	3	3.19	1.22	0.66	0.19
PSW088A	53	9.4	0.54	180	91.5	4	4.5	24.8	20.2	20.1	19.8	7	2.69	0.9	2.77	0.26
PSW089A	190	8.2	1.94	220	87	8	5	0	0	0	0	8	4.42	8.37	3.17	0.24
PSW090A	19	8.6	0.64	140	92	3.5	4.5	7.6	3.2	4	14.7	6	5.05	2.16	0.66	0.24
PSW091A	94	8.8	1.72	390	77.5	12	10.5	15.8	10.5	5.9	15	6	5.53	10.52	4.58	0.31
PSW092A	41	9.6	0.71	250	92.5	3	4.5	7.4	14.6	12.3	30.2	5	3.81	1.95	3.29	0.28
PSW093A	8	8.5	0.37	240	92.5	3.5	4	11.8	26.5	16.5	21.6	6	5.53	1.98	0.2	0.27
PSW094A	5	6.4	1.6	400	80.5	10.5	9	3.6	17.1	11.8	23.9	4	4.51	2.12	0.14	0.33
PSW095A	11	8	1.01	270	60	19.5	20.5	0	0	0	0	4	11.48	3.23	0.27	0.79
PSW096A	2	6.6	0.21	190	79.5	6.5	14	0	0	0	0	8	1.59	0.93	0.09	0.28
PSW097A	9	8	0.38	180	46	16.5	37.5	0	0	0	0	8	19.53	2.82	0.39	0.7
PSW098A	12	8.6	0.42	120	53.5	14	32.5	0	0	0	0	5	16.12	4.99	0.89	0.65

Table 3 Mean values ± standard error (SE) for species richness and environmental variables for the site groups defined from sampling Pilbara riparian vegetation.

Codes: Species richness – number of taxa per site; Perm class – Inferred permanence class (1 – ephemeral, 2 – seasonal/episodic, 3 – near permanent, 4 – permanent); Stream order – Strahler stream order (Strahler, 1952); Riverine/non-riverine (0 – non-riverine, 1 – riverine); DisCoast – straight line distance to coast (km); AnMeTemp – annual mean temperature (°C); MedDiuRa – mean temperature diurnal range (°C); MaxTeCoP – maximum temperature coldest period (°C); TempAnRa – temperature annual range (°C); MeTemWeQ – mean temperature wettest quarter (°C); AnnPrec – annual precipitation (mm); PrecSeas – precipitation seasonality; PrecColQ – precipitation coldest quarter (mm); EC (1:5) mS/m – electrical conductivity; pH (H20) – pH in distilled water; OrgC (W/B) % – percent organic carbon (Walkely Black); P (total) mg/kg – total Phosphorus; P (HCO3) mg/kg – extractable Phosphorus; Ca (exch) me% – exchangeable Calcium milliequivalent percent; Mg (exch) me% – exchangeable Magnesium milliequivalent percent; Na (exch) me% – exchangeable Sodium milliequivalent percent; K (exch) me% – exchangeable Potassium milliequivalent percent.

Site Group	1		2		3		4		5.1		5.2		6.1		6.2		7		8	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Species richness	13.8	2.2	22.0	4.6	41.8	3.0	39.4	3.6	23.5	7.5	10.0	0.9	18.4	1.0	9.8	2.6	26.9	1.6	19.9	2.7
Perm class	2.0	0.2	2.0	0.0	2.2	0.2	1.1	0.1	2.0	0.0	2.0	0.0	3.7	0.2	3.5	0.3	3.2	0.2	3.4	0.2
Stream order	1.0	0.8	0.4	0.4	2.1	0.3	0.1	0.1	0.0	0.0	0.0	0.0	2.8	0.3	2.3	0.9	3.3	0.3	5.2	0.6
Riverine/lacustrine	0.4	0.2	0.2	0.2	0.7	0.1	0.1	0.1	0.0	0.0	0.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0
DisCoast	137.2	66.2	167.2	43.9	166.8	27.3	119.4	47.9	267.0	0.0	332.0	60.0	143.6	18.2	228.5	51.1	173.6	27.7	158.8	39.2
Climatic variables																				
AnMeTemp	25.6	0.4	25.6	0.1	25.4	0.2	25.6	0.2	24.8	0.0	24.0	0.6	25.6	0.1	25.3	0.3	25.3	0.2	25.8	0.3
MedDiuRa	14.4	0.4	14.0	0.3	14.4	0.2	14.3	0.4	15.6	0.0	14.9	0.0	14.6	0.2	14.8	0.1	14.6	0.2	14.9	0.2
MaxTeCoP	38.6	0.5	39.5	0.7	39.0	0.3	38.6	0.4	40.2	0.0	39.4	0.4	39.3	0.2	40.4	0.3	39.2	0.3	40.2	0.3
TempAnRa	28.4	1.4	29.0	1.2	29.1	0.6	28.1	1.2	32.3	0.0	31.9	0.7	29.2	0.4	31.2	0.2	29.4	0.6	30.0	0.7
MeTemWeQ	31.0	0.0	31.3	0.3	31.0	0.1	30.9	0.1	31.0	0.0	30.4	0.4	31.2	0.1	31.5	0.2	31.0	0.1	31.6	0.2
AnnPreci	292.2	10.2	313.4	22.5	292.1	9.7	292.4	8.7	279.0	0.0	263.0	20.0	318.6	7.1	277.5	7.4	300.0	8.0	281.1	10.6
PrecSeas	97.2	4.0	91.8	3.4	92.2	2.1	95.1	3.1	88.0	0.0	83.0	5.0	94.9	1.8	82.0	1.9	92.5	2.4	90.2	3.3
PrecColQ	38.2	1.6	49.6	4.7	44.1	1.8	45.1	4.5	42.0	0.0	38.5	0.8	45.5	1.6	52.3	1.3	43.8	1.7	50.4	4.2
Soil variables																				
Gravel >16mm (%)	0.0	0.0	2.2	0.8	1.4	0.8	0.3	0.3	0.0	0.0	0.0	0.0	8.6	1.8	1.1	1.1	7.0	2.3	0.9	0.6
Gravel 8–16mm (%)	0.0	0.0	6.1	2.4	2.6	1.3	0.5	0.5	0.0	0.0	0.0	0.0	9.0	1.6	2.6	2.4	6.3	2.0	1.5	1.1

Site Group	1		2		3		4		5.1		5.2		6.1		6.2		7		8	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Gravel 4.8–8mm (%)	0.0	0.0	8.1	3.1	1.6	1.0	1.0	1.0	0.0	0.0	0.0	0.0	10.8	2.2	2.5	2.3	4.5	1.4	1.8	1.4
Gravel 2–4.8mm (%)	0.0	0.0	11.7	4.6	3.3	1.6	2.8	2.7	0.0	0.0	0.0	0.0	13.3	2.3	6.6	6.2	9.4	2.3	2.9	2.3
Sand %	62.9	5.0	56.1	8.8	71.6	4.1	81.6	5.1	48.5	7.3	69.6	10.3	82.6	1.9	73.3	9.6	85.7	2.0	79.1	6.3
Silt %	10.2	1.4	15.8	2.7	10.8	1.5	5.7	1.9	23.8	4.1	17.9	7.0	9.1	1.2	17.3	6.1	6.5	0.9	9.1	2.2
Clay %	26.9	4.1	28.1	6.1	17.7	2.7	12.6	4.0	27.8	3.1	12.5	3.3	8.3	0.9	9.5	3.5	7.7	1.4	11.8	4.2
EC (1:5) mS/m	5.8	1.1	12.4	3.0	23.9	7.3	11.3	2.7	145.0	2.5	472.5	98.4	114.3	23.9	196.0	54.1	69.0	14.7	37.3	10.2
pH (H2O)	6.8	0.2	6.8	0.2	7.2	0.1	7.5	0.4	7.7	0.1	8.1	0.1	8.5	0.1	8.7	0.2	8.6	0.2	7.8	0.3
OrgC (W/B) %	0.5	0.2	0.7	0.1	0.7	0.1	0.3	0.1	0.4	0.0	0.4	0.1	1.2	0.2	1.2	0.6	0.9	0.1	0.7	0.2
P (total) mg/kg	388.0	131.9	386.0	63.0	251.0	24.9	142.7	30.2	410.0	20.0	267.5	27.7	254.3	15.5	165.0	37.3	245.7	22.8	222.2	29.3
P (HCO3) mg/kg	17.8	7.5	25.8	7.3	10.6	1.7	7.6	2.7	29.0	2.5	11.5	2.4	5.8	0.8	7.5	2.4	9.4	1.9	10.7	2.3
Ca (exch) me%	3.8	0.9	7.4	1.8	6.5	1.0	2.3	0.8	6.3	0.4	10.5	1.3	6.2	0.6	3.2	1.1	4.8	0.4	5.9	0.9
Mg (exch) me%	2.7	0.7	3.3	0.7	2.7	0.3	1.4	0.5	2.6	0.3	3.0	1.1	6.4	0.8	7.4	2.0	3.1	0.5	2.8	0.6
Na (exch) me%	0.7	0.3	0.6	0.1	0.6	0.1	0.8	0.2	2.8	0.3	1.8	0.5	2.5	0.5	3.8	1.4	2.2	0.6	0.6	0.2
K (exch) me%	1.1	0.4	1.4	0.3	0.8	0.1	0.4	0.1	3.0	0.3	2.9	0.9	0.8	0.2	1.3	0.5	0.4	0.1	0.4	0.1

Data analysis

Species presence/absence data were compiled for sites by combining seasonal samples. Site resemblance matrices were generated using the Bray-Curtis similarity measure in Primer (Primer-E Ltd 2008). The influence of singleton species (species with a single site occurrence) was assessed by comparing resemblance matrices, including and excluding singletons, using Primer's RELATE routine (999 permutations). Analysis of similarity (anosim) routines (Clarke and Green, 1998) were used to examine the significance of relationships between the floristic composition of sites with *a priori* wetland types, IBRA sub-region, permanence, riverine versus lacustrine waterbodies, and catchment basin occurrence. For interpretation, categorical variables were overlain on non-metric multidimensional scaling ordinations of sites (nMDS, 50 starts; Primer-E Ltd. 2008). Two-dimensional ordinations were used as they showed similar stress to 3D outputs.

The BEST/BIOENV procedure in PRIMER was used to explore the relationship between site compositional similarity and environmental attributes. This module uses Spearman's rank–order correlation to match distances in a site association matrix to Euclidean distances among each of its environmental attributes. Continuous variables used in the analysis included chemical and textural attributes of the soil, BIOCLIM climatic variables, distance to coast and altitude. Categorical variables included ordinal permanence class, Strahler stream order and the two-state categorical variable riverine/non riverine. For pairs of variables that were highly intercorrelated ($P > 0.9$), a single variable was retained. In the final data set, distance to coast was retained in preference to annual range of temperature, and percentage clay was retained in preference to percentage sand. Highly skewed variables were log-transformed and the resulting variable matrix normalised.

Some sites were excluded from the analysis of environmental correlates. Soil data were not available for PSW004B, and PSW003A was an extreme compositional outlier. Six saline sites sampling the Fortescue Marsh and Weelarana Salt Lake were also excluded from the BEST/BIOENV procedure since they were compositionally and environmentally very distinct from the remainder of the data set.

Site and species classification

The data matrix of species presence/absence at sites (excluding singletons) was re-ordered to produce a two-way table for interpretation (Appendix 1) (Belbin 1995) by using the program PATN (v3.12) to classify sites according to similarities in their species composition (Bray-Curtis measure of dissimilarity), and species according to their co-occurrence at sites (the two-step algorithm, Belbin 1980). Both classifications used the flexible UPGMA (unweighted pair-group mean average) sorting strategy with the beta value set to -0.1 (Belbin 1995; Sneath and Sokal 1973). Indicator species showing high fidelity and/or specificity to site groups were identified using the 'Indicspecies package' in the R statistical computing language (De Caceres and Legendre 2009, R development core team 2009). Monte Carlo randomisation was used to test the significance of taxa indicative of both individual and multiple groups of sites ($P < 0.05$).

RESULTS

Sampling adequacy

Sites included a range of species richness scores (12–52 taxa) and wetland types. Comparison of the observed richness for each site and estimators of total richness (Figure 2 – four examples shown) revealed that the quadrat design employed had captured, on average, 89% (79%–100%) of the total richness in the sites (ICE estimator, see Colwell, 2009).

Riparian plant diversity

A total of 455 taxa was identified from the 98 wetlands and rivers sampled during the survey (Table 1, Appendix 2). These taxa were distributed among 62 families and 202 genera. Dominant plant families were Poaceae (18.5% of taxa), Fabaceae (11.4%), Asteraceae (10.8%), and Cyperaceae (8.1%). Dominant genera included *Acacia* (4.4%), *Eragrostis* (2.9%), *Cyperus* (2.9%), *Ptilotus* (2.0%), *Eriachne* (2.0%) and *Fimbristylis* (2.0%).

The taxa represent approximately 25% of the known flora of the Pilbara bioregion (S. Dillon unpublished data), and are dominated by species that occur elsewhere in the Eremaean (398 taxa) and Northern (295 taxa) Botanical Provinces (after Beard 1990). Pilbara populations of twenty taxa (e.g. *Atalaya hemiglauca*, *Lobelia arnhemiaca* and *Terminalia canescens*) occur in the Pilbara as populations disjunct from the Kimberley. A group of 143 taxa extend into the South-West Botanical Province. Of these, the majority occur at the periphery of this province, i.e. within the Avon-Wheatbelt (105 taxa) and Geraldton Sandplains (also 105 taxa) bioregions.

Of those taxa with more restricted distributions (known from six or fewer IBRA regions – 88 taxa), only the cosmopolitan *Pteris vittata* occurs in the

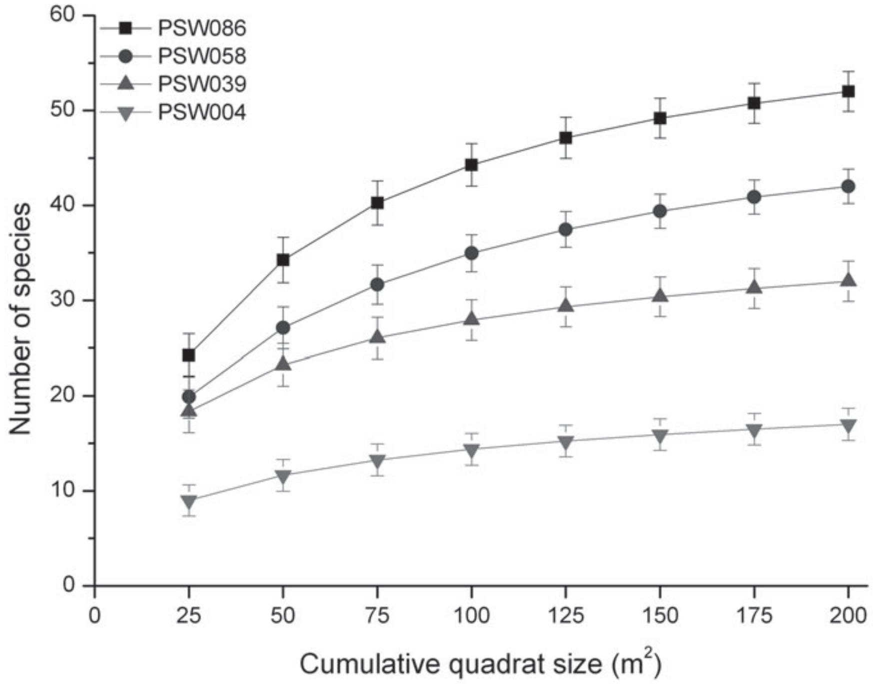

Figure 2 Expected species richness accumulation curves based on the *Mao Tau* function for four sites with a range of total observed richness. Error bars equal one standard deviation.

temperate south-west of Western Australia. Taxa known from four or fewer bioregions (64 taxa) largely extend into adjacent bioregions. Of these, the Carnarvon (29 taxa) and Gascoyne (29 taxa) share a greater number of taxa with the Pilbara than Dampierland (10 taxa) and the Murchison (nine taxa), with a small component occurring in the adjacent Great Sandy Desert (seven taxa) and Little Sandy Desert (nine taxa) bioregions.

Naturalised taxa represented 6.6 % of the flora, noting that the weed status of some species (e.g. *Flaveria trimera*) remains contentious (see Keighery 2010). The most frequently recorded weeds included *Cenchrus ciliaris* (46% of sites), *Cynodon dactylon* (22%), and *Cenchrus setiger* (17%). Notable weed records included *Conyza parva* collected from Chinaman Spring (PSW060), on the northern edge of the study area, a major range extension from near-coastal areas of south-west Western Australia. Previously known anecdotally (Keighery 2010), *Gnaphalium polycaulon* is confirmed as occurring in the Pilbara, with a record from Coondiner Pool (PSW001).

Sixteen taxa on the Department of Parks and Wildlife's Priority Flora List (Smith 2013) were recorded (see Appendix 2). A number are associated with wetlands within and bordering the Fortescue Marsh Land System as defined by Van Vreeswyk *et al*. (2004). Both *Helichrysum oligochaetum* and *Rhodanthe ascendens* were recorded from Koondepindawarrina Pool (PSW005). *Tecticornia medusa* and *T. globulifera*, formerly known only from the Fortescue Marsh, were also recorded from Weelaranna Salt Lake (PSW043). *Eleocharis papillosa*, previously known from scattered localities across central Australia and near Onslow at the edge of the Pilbara, was recorded from two sites on the Fortescue Marsh (PSW002, PSW003). The new record of *Myriocephalus scalpellus* from near Onslow (PSW073) represents the only known population other than the type locality at Coondiner Pool (PSW001). *Eremophila spongiocarpa*, endemic in the Pilbara and restricted to the Fortescue Marsh, was recorded within its known range (PSW003). Other notable priority taxa include *Cladium procerum* which occurs in the Pilbara as a major outlier from populations in eastern Australia. Known from both Millstream and Karijini National Park, it was recorded at a known locality (at PSW006). Also recorded from a known population at Fortescue Falls, *Adiantum capillus-veneris* has a scattering of localised populations across much of Australia. *Eragrostis surreyana* is endemic in the Pilbara IBRA region, and was recorded from a known population on the Burrup Peninsula. Although not listed as priority taxa, the Pilbara endemics *Bergia perennis* subsp. *perennis*, *Eriachne tenuiculmis*, *Sida arsiniata* and *Stemodia kingii* were also recorded during the survey.

Major range extensions

The grasses *Imperata cylindrica* and *Pseudoraphis spinescens* have distributions that extend from the Kimberley region across northern Australia and down the eastern Australian coast to South Australia, with numerous inland occurrences. Not previously known from the Pilbara, *Imperata cylindrica* occurred at three sites: Fortescue Falls (PSW006), Palm Spring on Cave Creek (PSW009) and Millstream Delta (PSW011). Prior to the current survey, the only Pilbara record of *Pseudoraphis spinescens* was a collection by A. Forrest on the Fortescue River in 1878 (Mueller 1881a, 1881b). During the survey it was collected at four sites: Moreton Pool (PSW030), Munreemya Billabong (PSW036), Curara Claypan (PSW072), and West Peawah Creek Pool (PSW079). *Nymphoides indica*, recorded at De Grey claypan (PSW035), is the first collection for the Pilbara bioregion. Its known distribution includes much of the world's tropics and extends from the Kimberley across the north and down the east coast of Australia.

Species frequency and richness

Of the 450 taxa analysed, two-thirds (66.4%) occurred at fewer than five sites (see Appendix 1), and one-third (33.2%) occurred at a single site (Appendix 3). Three taxa, *Cyperus vaginatus* (perennial sedge), *Eragrostis tenellula* (annual grass) and *Centipeda minima* (annual herb), occurred at more than half the sites. Species richness ranged from three (PSW032) to 87 taxa per site (PSW085) and averaged 26.3 ± 1.4. Richness showed significant differences between wetland types (Kruskal-Wallace 1-way ANOVA, $P < 0.005$), with gorge creeks (20.0 ± 2), springs (18.3 ± 1.4) and salt marshes (14.5 ± 3.5), showing the lowest richness. Gorge creeks were characterised by massive rock and provided limited habitats for annual taxa, instead being dominated by dense perennial sedges and shrubs in soil pockets that are perennially moist. Springs were commonly dominated by dense patches of perennial sedges (typically *Cyperus vaginatus*), often interspersed with bare areas of calcrete. Salt marsh sites had a limited suite of halophytic taxa.

Rock pools (42.5 ± 2.5), clay flats (41.0 ± 6), clay pans (29.7 ± 3.2) and ephemeral creeks (28.7 ± 4.4) had the highest mean richness with rich assemblages of herbs and annual and perennial grasses.

Richness also showed significant differences between inferred permanence classes (Kruskal-Wallace 1-way ANOVA, $P < 0.005$). Ephemeral sites had the highest mean species richness (39.2 ± 3.6) and permanent sites the lowest (20.8 ± 2.4). This is related largely to the relative proportion of different wetland types within each class. Ephemeral sites included a number of rock pools (PSW071A, PSW080A) with herb-rich aprons, and claypans and clay flats with rich assemblages of annual taxa. Permanent sites included river pools (15 sites), gorge creeks and the majority of species-poor springs (13 of 15). Seasonal and near-permanent sites showed little difference in richness and were dominated by river pools. Little difference in richness was evident for riverine sites in relation to Strahler stream order; with only order-one versus order-three showing significant pairwise differences ($P < 0.05$).

Richness of rare taxa, including singletons and species occurring at fewer than six sites, was examined for geographic patterns (Figure 3). Concentration of rare taxa was evident within the Fortescue Marsh and on the periphery of the study area at a small number of sites which included Weelarrana Salt Marsh (PSW043B), claypans, granite rocks and a single seasonal creek (PSW085) at the southern edge of the region. Some concentration of rare taxa along the northern edge of the Hamersley IBRA subregion is associated with rarely recorded taxa from the gorges and upland ephemeral creeks of the Hamersley Range. Notably, few singleton and rare taxa were observed in the Chichester IBRA subregion (Figure 3). High numbers of rare taxa were associated with both wetland-type and water permanence. Overall, ephemeral and seasonal wetland types such as salt marshes, rock pools and claypans showed highest numbers of rare taxa, and their non-uniform distribution across the study area explains much of the observed geographical patterning.

Site classification

Comparison of the full and reduced (singletons excluded) species presence/absence matrices revealed that the two were highly correlated (Rho = 0.99, $p < 0.001$). In preference, the reduced matrix was used.

The primary division in the classification largely separated non-turbid riverine sites from predominantly non-riverine wetlands and turbid riverine sites with fine-textured soils. Within the last major group, the small number of saline sites formed a distinct group at the next division in the classification. The site classification was ultimately examined at the 8-group level (Figure 4). The ten-group classification and *a priori* wetland types overlain on 2D nMDS ordinations (Figure 5 A and B), revealed a strong correspondence between floristic groupings and wetland type.

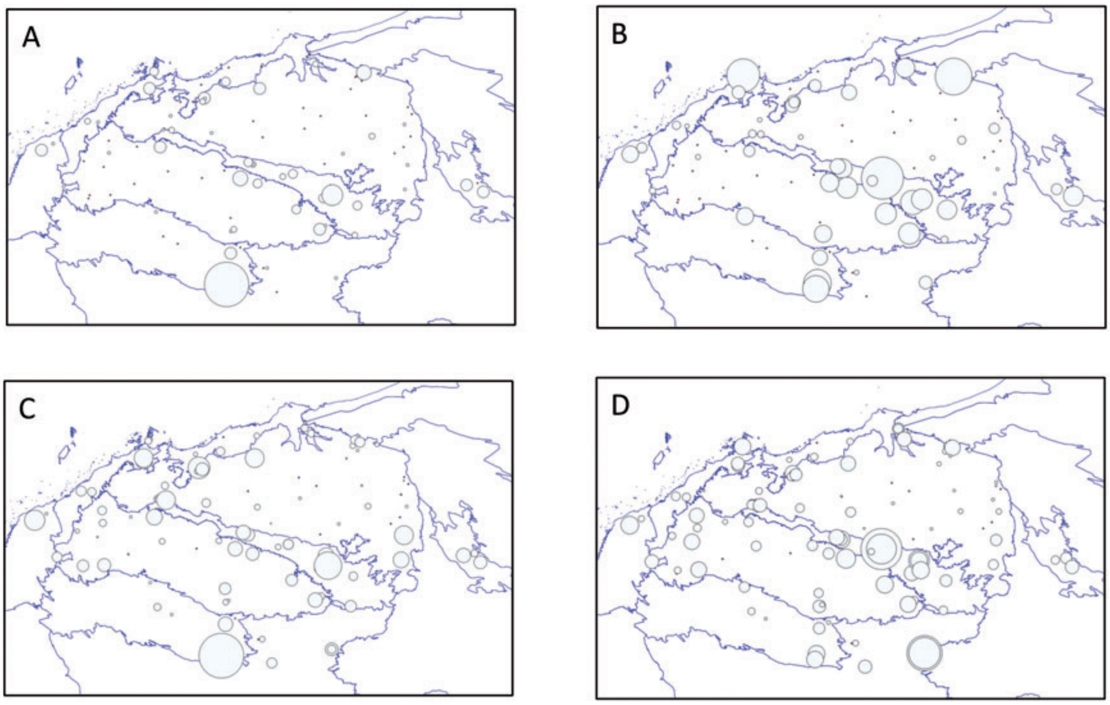

Figure 3 Number of rare taxa (single site record) or uncommon taxa (≤ 5 site records) recorded per site, with symbol-size proportional to richness. (A) Richness within sites containing rare taxa (maximum 15 taxa). (B) Richness within sites containing rare taxa as a proportion of total site richness (maximum 0.27). (C) Richness within sites containing uncommon taxa (maximum 31). (D) Richness within sites containing uncommon taxa as a proportion of total site richness (0.87). Sites with no rare taxa are solid dots.

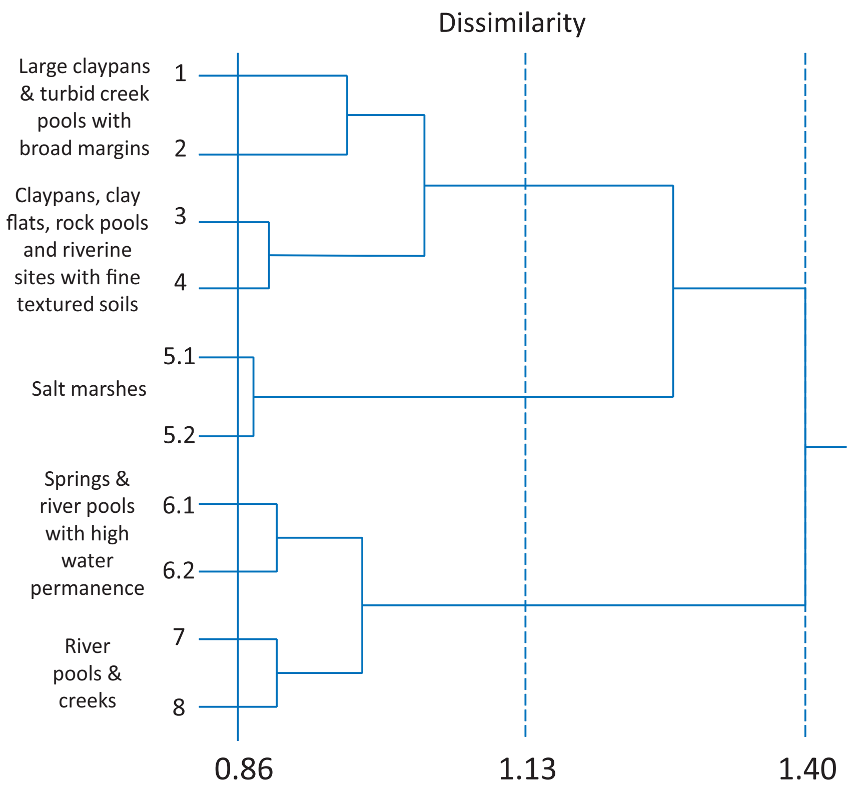

Figure 4 Classification of 103 survey sites (UPGMA) based on species presence/absence. Classification is shown at the eight group level with descriptions summarising divisions in the classification.

Plate 4 Large seasonal/episodic claypan on Mulga Downs Station (site PSW040A). Stands of *Acacia stenophylla* occur across the inundated bed and within the riparian zone.

Large claypans and turbid linear pools with broad margins

Group 1. A group of five claypan sites at four wetlands including large claypans and a single linear turbid claypan (Coondiner Pool), all typified by very broad, low-gradient margins. Structural dominants within the group included scattered *Eucalyptus victrix* over *Eriachne benthamii* with *Marsilea* spp. forming dense swards. Significant indicator species included *Schoenoplectus laevis*, *Elytrophorus spicatus*, *Eriocaulon cinereum*, *Nymphoides indica*, *Glossostigma diandrum* and *Rotala diandra*. Sites sampled showed a high percentage of clay content (26.9 ± 4.1) and the lowest EC (5.8 ± 1.1) and pH (6.8 ± 1.1) of all site groups. These sites, with fine-textured soils, also had high total phosphorus (388.0 ± 131.9 mg/kg). The few wetlands in the group were scattered from the north-west coastal margin to the inland eastern edge of the study area and had the lowest species richness of groups 1–4 (13.8 taxa per site).

Group 2. A group of five sites at four wetlands including three claypans and the margin of a linear, turbid pool. This group also featured *Eucalyptus victrix* as a structural dominant over a relatively species-rich herb layer. Significant indicator species included *Sporobolus mitchellii*, *Bergia trimera*, *B. perennis*, *Myriocephalus oldfieldii*, *M. rudallii* and *Muehlenbeckia florulenta*. The sites showed similar soil chemistry attributes to group 1 (Table 2).

Claypans, clay flats, rock pools, and riverine sites with fine-textured soils

Group 3. A large group of 23 sites with the highest species richness of all site groups (41.8 taxa per site). Sites sampled the riparian zones of linear turbid creeks, river pools, ephemeral creeks, claypans and clay flats (Table 1). Although including a number of wetland morphologies, sites within the group shared fine-textured soils in both riverine and non-riverine settings (mean silt 10.8 ± 1.5 % and clay 17.7± 2.7%). Seventeen sites included *Eucalyptus victrix* or *E. camaldulensis* subsp. *refulgens* as overstorey trees within the riparian zone. Analysis revealed a single taxon, *Fimbristylis littoralis*, as the significant indicator species for the group. The group shared a number of taxa with group 4 (see below) with *Fimbristylis microcarya*, *Wahlenbergia tumidifructa*, *Lipocarpha microcephala*, *Oldenlandia galioides* and *Drosera indica* being significant indicator species for both site groups taken together.

Group 4. A group of seven sites on the margins of claypans and the aprons of rock pools. As a group, the sites were close to the coast relative to all other groups (119.4 ± 47.7 km). Claypans in the group were small, highly ephemeral, and occurred within *Triodia*-dominated flats and dune systems. The edges of pans were low sandy rises with a narrow band of annual taxa recruiting after rainfall and wetland-filling. The group showed similarly high species richness to group 3 (39.4 taxa per site). Sixteen herbs and annual grasses were significant indicator species for the group with *Synaptantha tillaeacea* var. *tillaeacea*, *Eriachne aristidea*, *Bulbostylis barbata*, *Calandrinia ptychosperma*, *Cyperus pulchellus* and *Gomphrena leptoclada* subsp. *leptoclada* significant at $P < 0.05$.

Salt marshes

Group 5.1. A subgroup of two sites within the upper fringe of the Fortescue Marsh, characterised by a group of salt-tolerant indicator species including *Cressa australis*, *Muellerolimon salicorniaceum*, *Cyperus bulbosus* and *Eleocharis papillosa*. The sites showed high EC (145 ± 2.5) and phosphorus (total P, 410 ± 20) and high clay content (27.8 ± 3.1). The current survey, however, did not attempt to capture the full floristic variation evident within and bordering the Fortescue Marsh. These two sites sample an extensive zone within the Fortescue Marsh that is dominated structurally by *Muellerolimon salicorniaceum*.

Group 5.2. A subgroup comprising four sites at two wetlands, sampling the edges of the main basins of the Fortescue Marsh and Weelarrana Salt Lake. They were characterised by low shrublands dominated by *Tecticornia* spp. Significant indicator species for the subgroup included *Tecticornia halocnemoides* sens. lat., *T. indica*, *T. medusa*, *T. globulifera* and *Triglochin hexagona*. The sites showed the highest soil EC (472.5 ± 98.4) of all groups, and high total P (267.5 ±27.7 mg/kg). Species richness was low with 10 taxa per site. The sites are likely to experience significant periods of inundation during major flooding events.

Springs and river pools with high water permanence

Group 6.1. A subgroup of 23 sites from river pools and 11 of the 15 springs sampled. Sites had a mean species richness of 18.4 taxa, the significant indicator species being *Schoenoplectus subulatus* and *Fimbristylis sieberiana*. Structural dominants included *Melaleuca argentea*, *Eucalyptus camaldulensis* subsp. *refulgens*, *Acacia ampliceps*, *Typha domingensis* and *Cyperus vaginatus*. The group also included all the sampled springs and gorges within Karijini and Millstream National Parks. The group had the highest mean permanence score (3.7) of all site groups. This was coupled with the highest mean annual rainfall (318.6 mm/yr). The soils of the sites contained the highest percentage gravel (all fractions) and were otherwise typically sandy. Exchangeable calcium was the highest of all groups (6.2 me%) and is likely to reflect the contribution of calcium-rich groundwater to the riparian zone substrate.

Plate 5 Areas of bedrock and calcrete dominate the margins of Palm Spring (site PSW013A). *Melaleuca glomerata*, juvenile *Livistona alfredii* (Millstream fan-palm) and sedges occur in the shallow soil pockets along the spring-fed creek (M.N. Lyons).

Group 6.2. A subgroup of four species-poor sites (9.8 taxa per site) comprising two river pools and two small springs. Structural dominants included *Acacia ampliceps* and *Cyperus vaginatus*. Sites showed significant cattle disturbance or flood damage, which probably accounted for their low species richness scores. *Stylobasium spathulatum* and the naturalised taxon *Bidens bipinnata* were significant indicator species for the group.

River pools and creeks

Group 7. A group of 21 riverine sites including 15 clear river pools, four ephemeral creeks and two springs. The group shows compositional similarities to subgroup 6.1 yet showed higher mean species richness (26.9 cf. 18.4 taxa per site). The group had a mean permanence score of 3.1 (cf. 3.7 for group 6.1), reflecting the small number of springs and inclusion of ephemeral creeks within the group. Indicator species analysis did not reveal any taxon to be individually significant for the group. *Eucalyptus camaldulensis* subsp. *refulgens* and *Cyperus vaginatus* are structural dominants. The separation of groups 6.1 and 7 is due largely to the very low frequency of taxa dependent on high/permanent moisture, such as *Melaleuca argentea*, *Schoenoplectus subulatus* and *Typha domingensis* within group 7, and the presence of a group of widespread annual taxa including *Eragrostis tenellula*, *Wahlenbergia tumidifructa*, and *Centipeda minima* that are largely absent from group 6.1. Soil texture attributes of groups 6.1 and 7 were very similar (Table 2).

Group 8. A group of nine sites on permanent and near-permanent higher-order river pools structurally dominated by *Melaleuca argentea*, *Eucalyptus camaldulensis* subsp. *refulgens*, *Cyperus vaginatus* and *Cynodon dactylon*. Average species richness was lower than the other group dominated by river pools (19.9 taxa per site, cf. 26.9 in group 7). Soils within the group were more finely textured than groups 6.1 and 7, with lower gravel fractions (Table 2).

Plate 6 Pool in ephemeral creek (site PSW062A) at the base of the Gregory Range. The riparian zone is dominated by *Eucalyptus victrix* and *Cyperus vaginatus*, with *Schoenoplectus subulatus* in the waterbody (N. Gibson).

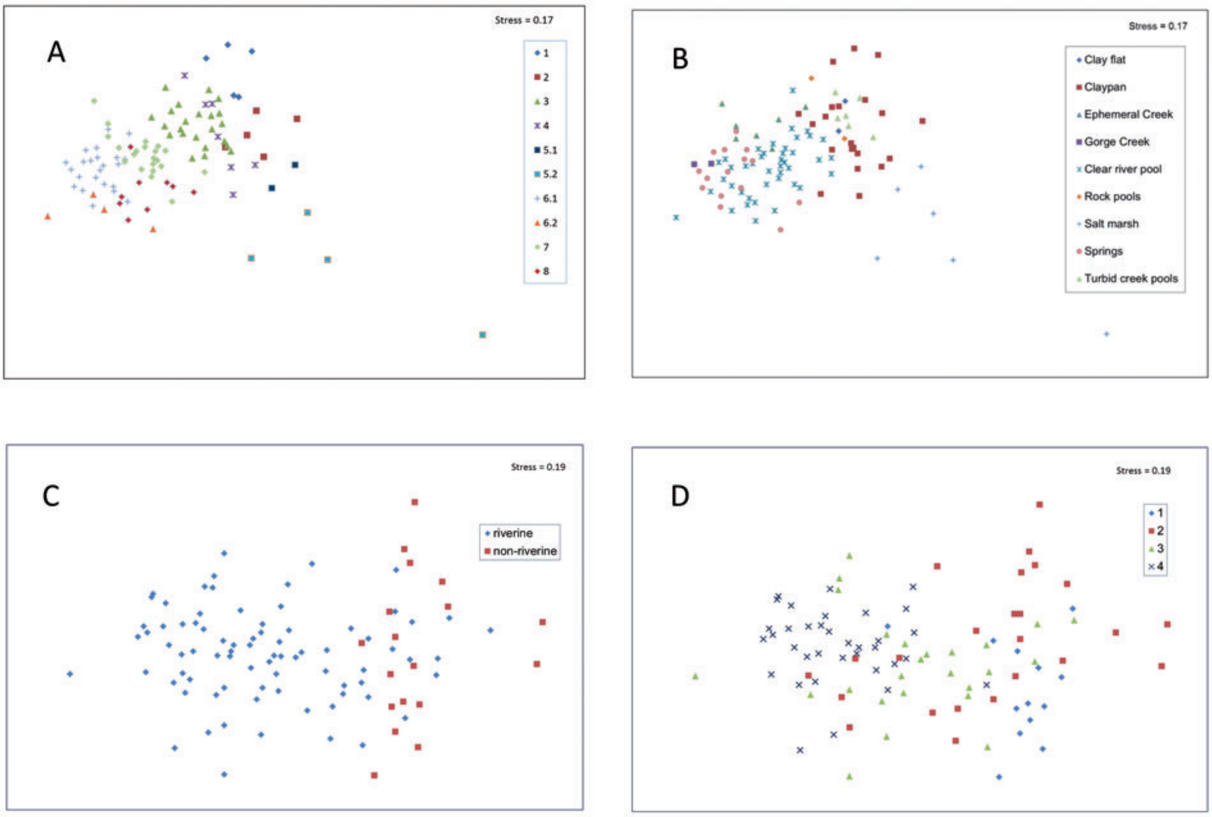

Figure 5 Two dimensional. non-metric multi-dimensional scaling ordination (2D nMDS) of 103 sites based on presence / absence of plant species overlain with (A) floristic groups and (B) a *priori* wetland types. Also, 2D nMDS ordination excluding salt marshes (floristic subgroups 5.1 and 5.2) with sites coded (C) as riverine/non-riverine and (D) according to permanence class (1, ephemeral; 2, seasonal episodic; 3, near permanent; 4, permanent).

Environmental variables and floristic composition

Significant compositional differences were observed for riverine versus non-riverine sites (Figure 5C) (Rho = 0.525), and permanence class (Figure 5D) (Rho = 0.383). Within riverine sites, excluding the very small number of ephemeral sites, permanent sites were compositionally different from seasonal and near-permanent sites (Rho = 0.25), although there was no significant difference between stream orders (Rho = 0.022). Geographic patterns were examined by testing compositional differences against IBRA subregions and major drainage basins. IBRA sub-regions showed only moderate compositional differences (Rho = 0.241), with pairwise differences between both the Fortescue and Roebourne Plain against all other sub-regions accounting for the bulk of the patterning. Little support for compositional differences between drainage basins was observed (Rho = 0.073).

The BEST procedure revealed that a combination of five variables [riverine/non-riverine, DisCoast, clay%, EC (1:5), pH] provided the highest rank correlation with the site dissimilarity matrix (Spearman's rho = 0.53, $P < 0.01$). The inclusion of the categorical variable riverine/non-riverine confirms the major compositional separation of these two major wetland classes. The soil variables relate to a number of compositional gradients. High clay content corresponds to the separation of clear riverine sites with relatively coarse sediments, from claypans and turbid riverine sites typified by finely textured soils. The latter were compositionally distinct with relatively rich assemblages of annual taxa. The inclusion of soil electrical conductivity and pH also correlates with the compositional separation of riverine and non-riverine sites. The inclusion of DisCoast reflects the greater occurrence of a number of compositionally distinct groups along the subdued landscapes of the coastal plains of the study area, including claypans and turbid creek pools.

DISCUSSION

Flora and diversity

Prior to the current study, the only regional survey of the Pilbara riparian flora was undertaken by Masini (1998) and Masini and Walker (1989) as two separate studies sampling subsections of the region. Although interrupted by cyclonic activity and subsequent sampling late in the dry season, the authors recorded *ca.* 300 taxa. Many localised surveys assessing impacts of proposed mining developments have also been completed (e.g. Biota Environmental Sciences, 2012). Other studies have been undertaken to assess the impacts on Pilbara wetlands of water abstraction and mine dewatering and its disposal (e.g. Johnson and Wright, 2001; Braimbridge *et al.* 2010). The only other regional-scale wetland floristic survey undertaken in Western Australia's arid zone was completed by Gibson *et al.* (2000), in the southern half of the Carnarvon Basin bioregion to the south of the Pilbara. They recorded 263 taxa from 57 wetlands (albeit with smaller quadrat size) representing ca.12% of the region's flora (Keighery *et al.* 2000).

Gibson *et al.* (2000) observed that the wetland flora of the southern Carnarvon Basin, while dominated by taxa of the arid zone (Eremaean), had affinities with both temperate and tropical floras. In part, this is true of the Pilbara, although the temperate component of the flora is smaller and largely composed of very widespread taxa rather than those with temperate distributions for which the Pilbara is their northern range limit. The Pilbara riparian flora also includes a larger component of the tropical flora, from both the rocky landscapes of the northern Kimberley and the more topographically subdued central Kimberley, Ord–Victoria Plain and Victoria–Bonaparte bioregions. A subset of these does not occur elsewhere in the Eremaean areas of Western Australia (e.g. *Atalaya hemiglauca*). Notable elements of the tropical riparian flora are also near their southern limit in the Pilbara (e.g. *Melaleuca argentea* and *Sesbania formosa*).

While sharing broadly similar climates (Leighton, 2004; Wyrwoll *et al.* 2000), the strong affinities of the Pilbara flora with the adjoining Carnarvon and Gascoyne bioregions are also attributable to the regions possessing a similar suite of wetland types. All share a combination of riverine and non-riverine water bodies that represent similar hydrological settings. Indeed some of the major structural dominants in riverine riparian zones are common to the three regions (e.g. *Eucalyptus camaldulensis* subsp. *refulgens* and *Acacia coriacea* subsp. *pendens*). In contrast, the sandy deserts to the east and north-east of the Pilbara are characterised by internal drainage with few major riverine habitats. Where these occur they are commonly broad, sometimes saline, drainage lines flowing into basins, or highly ephemeral creek systems arising in isolated ranges. The saline coastal areas of the Pilbara and the Fortescue Marsh share taxa with these desert systems (e.g. *Tecticornia auriculata*). The deserts, like the Pilbara, contain a suite of claypans and clay flats that are episodically inundated and elements of their flora are shared.

The proportion of uncommon taxa recorded for the Pilbara – singletons (33.2%) and those from fewer than five sites (66.4%) – is of similar magnitude to other similar studies. Gibson *et al.* (2000) recorded that 55% of taxa occurred at a single site (singletons) in the southern Carnarvon Basin. A more comprehensive survey of temperate zone wetlands in Western Australia showed very similar proportions (31% and 59.3% respectively) to the current study (Lyons *et al.* 2004). The occurrence of this uncommon component of the flora (at similar levels) is also a consistent feature of quadrat-based floristic surveys carried out across the wider Western Australian landscape (Gibson *et al.* 2004; Keighery *et al.* 2000; Lyons *et al.* 2014), and poses problems for designing reserve systems that aim to capture major floristic communities.

Species richness of sites was related to both the *a priori* wetland types and the site groups derived from the classification based on floristic composition. Maximum richness occurred in less permanent wetlands, with concomitant higher richness in non-riverine sites. A similar pattern was observed for the proportion of uncommon taxa across the range of wetland types. Coarsely textured soils that limit moisture retention, as well as major disturbance associated with the high energy/volume flows following flood events, are likely to limit the suite of taxa that can persist along many riverine riparian zones in the Pilbara. The plant communities of these larger riverine sites are often simple, with groundwater-dependent overstorey trees (*Melaleuca argentea*, *Eucalyptus camaldulensis* subsp. *refulgens*) (O'Grady 2006) and simple understoreys of shrubs, rhizomatous grasses and sedges that are more resistant to flood waters (e.g. *Melaleuca linophylla*, *Cyperus vaginatus*). In contrast, more ephemeral sites, those with lower flow-energy (e.g. turbid linear creeks), as well as claypans, clay flats and rock pools, experience much-reduced flood disturbance and their soils are more finely textured. In many of these shallow wetlands, the wet/dry ecotone is broad, providing habitats for a larger range of taxa with differing responses to wetting and drying (Brock and Casanova 1997). The development of species-rich seed banks that persist for long periods between fill events has also been shown to contribute to the richness of these sites (Brock *et al.* 2006).

The extensive aquifer systems of the Pilbara (Waters and Rivers Commission 1996) discharge groundwater to form permanently flowing creeks, typically in rocky sites, or contribute flows to permanent pools within river channels. Springs form a group that is relatively poor in species (18.3 taxa per site) in the Pilbara, and are characterised by taxa requiring permanently damp or wet soil that physically dominated sites, e.g. *Cyperus vaginatus*, *Melaleuca argentea*, *Typha domingensis*. Studies of springs elsewhere in Australia confirm that springs of the Pilbara are floristically distinct from the remainder of the continent. In the Kimberley and tropical Northern Territory, rainforest floristic elements are a major component of spring floras (Kenneally *et al.* 1991; Russell-Smith 1991). Detailed studies of the springs of the Great Artesian Basin (Fensham and Fairfax 2003; Fensham and Price 2004), while very different floristically from the Pilbara, highlight the importance of springs in the conservation of endemic and relictual taxa. In the Pilbara, springs and spring-fed river pools and associated gorge habitats provide important mesic refugia for taxa such as *Livistona alfredii*, *Stylidium weeliwolli* and *Fimbristylis sieberiana*, including major distributional outliers such as *Cladium procerum*, *Phragmites karka, Imperata cylindrica* and *Adiantum capillus-veneris.* In arid Central Australia, permanent water bodies, including springs and seepages, have also been shown to be important refugia for relict and endemic species (White et al. 2000; Brim Box *et al*. 2008).

Floristic composition

Patterns in the floristic composition of Pilbara wetlands and rivers correspond to major hydrological and substrate attributes of the sites. These environmental differences are largely embodied by the initial *a priori* site groups that influenced the sampling design and are reflected in the site groups I derived.

The vegetation of the Fortescue Marsh is compositionally distinct from the remainder of the site groups, even though sampling of the Marsh was limited relative to its complexity and size. While I did not sample tidal environments along the Pilbara coast that are likely to share some taxa with the Marsh (e.g. *Tecticornia indica*) it contains a floristically unique element of the Pilbara wetland flora.

Among the remaining rivers and wetlands a major compositional separation is seen between riverine and non-riverine (wetland) sites. Turbid creek pools, while riverine, show clear floristic similarities to claypans. Turbid sites are a feature of creeks and smaller rivers in Pilbara lowlands. Like claypans, they have fine soils, have generally short hydroperiods and are not subject to major flood flows. This is reflected in the analysis with soil texture emerging as a significant term in the BEST analysis. Masini (1988) also highlighted the importance of sediment texture and water permanence in structuring Pilbara wetland plant communities, finding strong correspondence between morphological/hydrological (subjective) and floristic (objective) classification of sites. Importantly, both the current study and that of Masini (1988) are very site-specific. Dryland rivers show considerable heterogeneity in terms of channel morphology and sediment attributes along their length, particularly where over-bank flows fill secondary channels (Thoms *et al.* 2006). As a consequence, even a small stretch of river (< 5 km) may capture a number of floristic elements.

Biogeographic patterns in the riparian flora across the Pilbara are explained by gross differences in the distribution of major wetland types across its four IBRA subregions. This is not surprising, given that, relative to the broader landscape, riparian zones are somewhat buffered from the dominant climatic gradient that occurs from west to east in the region, particularly in terms of moisture availability (Leighton, 2004). In particular, at the regional scale, spring sites are largely decoupled from the prevailing climate. The topographically subdued, largely depositional landscapes of the Fortescue and Roebourne Plains IBRA sub-regions show significant differences from the remaining sub-regions.

Conclusions

The Pilbara riparian flora represents 25% of the Pilbara flora, and is dominated by Eremaean and tropical taxa, with strongest affinities to adjoining externally draining bioregions.

Biogeographic patterning is limited, with sub-regional differences being related to the relative proportion of wetland types within each subregion. Riverine sites, in particular, show limited compositional difference across the region. The Fortescue valley, coastal plains and other lowland areas make important contributions to the diversity of non-riverine wetlands. Claypans and clay flats capture a large component of the Pilbara wetland flora, and their scattered occurrence across the lowlands of the region poses difficulties in capturing their diversity in the reserve system. Within the region, the Fortescue Marsh, along with spring sites in Karijini and Millstream National Parks, support unique elements of the Pilbara riparian flora.

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APPENDIX 1 [ELECTRONIC]

Site by species data matrix, reordered according to their site and species classifications. The floristic groups are indicated. Taxa recorded from one site are excluded (see Electronic Appendix 3).

APPENDIX 2 [ELECTRONIC]

List of taxa recorded from 103 sites sampled during the survey (superscript [1] denotes pairs of infraspecific taxa analysed at specific rank, superscript [2] denotes closely related taxa that could not be reliably discriminated and were amalgamated for analysis). Numbers following taxa are Department of Parks and Wildlife priority flora codes (see Smith 2013).

APPENDIX 3 [ELECTRONIC]

Site by singletons species data matrix.

See CD inside the back cover or visit

http://www.museum.wa.gov.au/research/records-supplements/