

# Flora and vegetation of the greenstone ranges of the Yilgarn Craton: Warriedar Fold Belt

RACHEL A MEISSNER AND REBECCA COPPEN

Science and Conservation Division, Department of Parks and Wildlife,  
Locked Bag 104, Bentley Delivery Centre, Western Australia, 6983.

Corresponding author email: rachel.meissner@dpaw.wa.gov.au

## ABSTRACT

The Warriedar Fold Belt is an Archaean greenstone belt composed of banded ironstone formations and basalts, located in the Yalgoo IBRA Bioregion of Western Australia. Previous systematic surveys on the banded ironstone formation highlighted an area rich in endemic flora and restricted communities. This paper discusses the flora and vegetation on the basalt hills. A total of 286 taxa, with 137 annuals, were recorded during the survey. Twenty-three priority flora were recorded, with a significant new population of *Allocasuarina tessellata* discovered, as well as several taxa that are restricted to the basalt hills. Six vegetation communities were described from the Warriedar Fold Belt, with a clear differentiation between communities on the Bullajungadeah Hills from communities on the Rothsay and Mulgine hills. The species turnover from the western to eastern hills is associated with a rainfall gradient.

**Keywords:** greenstone, floristics, ranges, vegetation communities, Yilgarn

## INTRODUCTION

The Warriedar Fold Belt is a series of low undulating hills of Archaean greenstone, composed of banded ironstone and basalts, in the Murchison Region of Western Australia. The belt occurs in an area rich in rare and endemic flora (Gibson et al. 2007; Markey & Dillon 2008). Previous surveys on the fold belt focussed upon the vegetation growing on the banded ironstone associated with the Blue Hills and Gnows Nest range (Markey & Dillon 2008), but there is little detailed knowledge of the vegetation occurring on the basalt hills to the south. This paper is part of a continuing series of surveys describing the flora and vegetation of the greenstone ranges within the Yilgarn Craton, which aim to provide a regional context and baseline information for future land management. The main aim of this study was to describe the flora and vegetation and associated environmental variables on the southern basalt hills within the Warriedar Greenstone Belt and to examine if similar levels of endemism occur on the basalt hills compared with the adjacent banded ironstone hills.

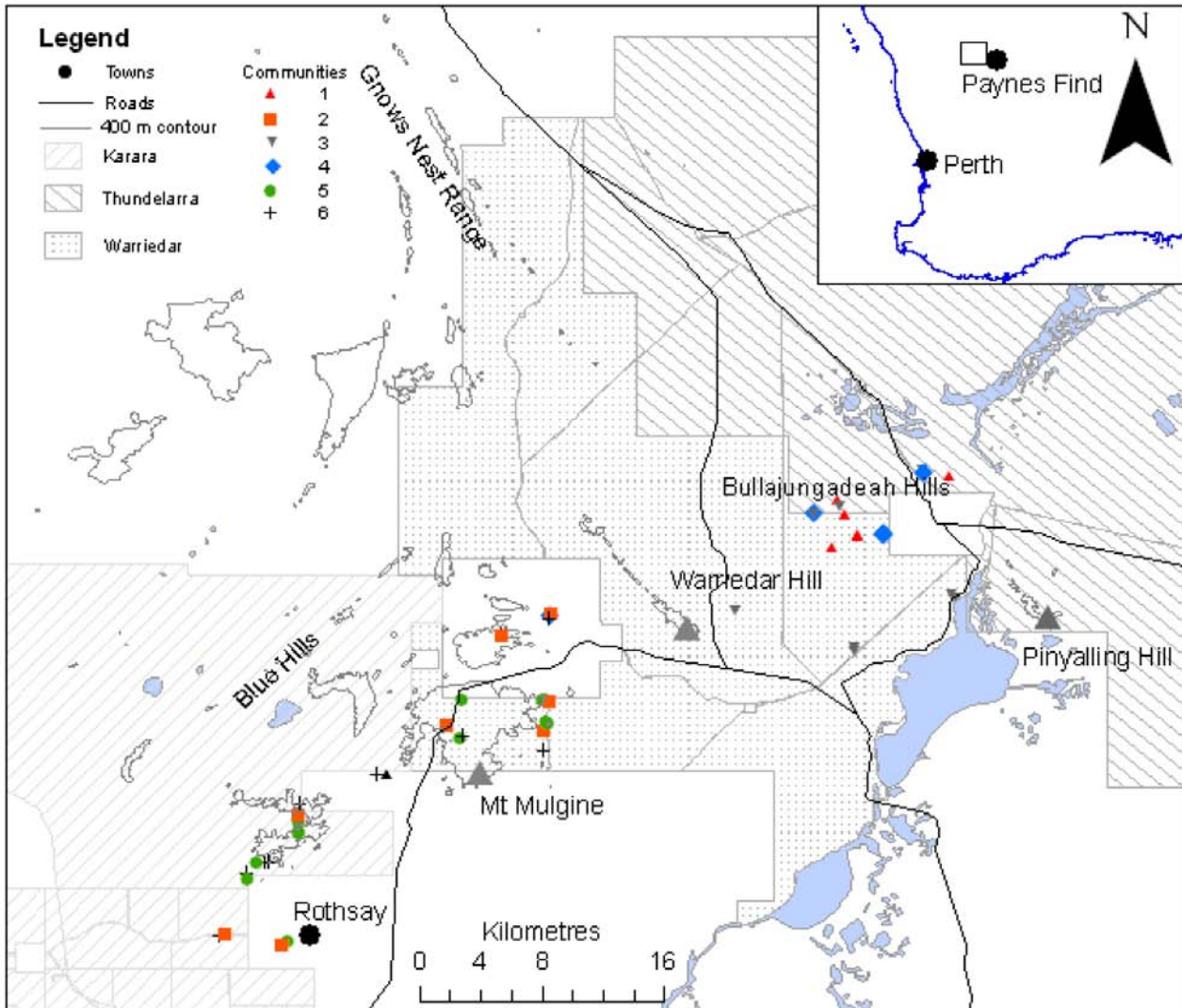
## Land use

Over 100 years of mining and pastoralism have occurred on and around the Warriedar Fold Belt; activities that can impact heavily on the environment. The study area occurs across three ex-pastoral leases: Karara, Warriedar and Thundellarra, which are now managed by the Department

of Parks and Wildlife (CALM 2004). These pastoral leases were originally established in the second half of the 19th century and were still being settled in the early 1900s as the gold mining boom began (Hennig 1998). The mines established in late 19th and early 20th century have since closed and the towns abandoned (Murray et al. 2011). Today, there are still several gold mines active on the Blue Hills, but most mining activity in the area now centres on open-cut iron ore mining in the banded iron formations in the Karara area.

## Geology

Greenstone belts are metamorphosed volcanic rocks, such as basalt, associated with sedimentary rocks, such as banded ironstone, that occur within Archaean and Proterozoic cratons, and are generally expressed at the surface as a series of ranges or hills. The name greenstone comes from the green hue of the mafic rocks, a type of volcanic rock, predominantly basalt or gabbro that is high in magnesium and iron. The Warriedar Fold Belt encompasses the larger area of the Blue Hills, Gnows Nest Range, Bullajungadeah Hills, Pinyalling Hill and the unnamed hills in the south-west surrounding Mount Mulgine and the abandoned town of Rothsay (Fig. 1). The belt consists of metamorphosed Archaean rocks in a defined sequence of more than 10 km thick (Lipple et al. 1983). The Blue Hills are composed predominantly of banded iron formations and are located north of the more predominantly mafic associations of the Bullajungadeah Hills and Rothsay and Mount Mulgine areas. The area of interest for this study was the southern base of the Blue Hills, which contains the oldest units of mafic rock.



*Figure 1. Location of the study area, approximately 100 km east of Morawa. Fifty quadrats were established on the Warriedar Fold Belt with six plant communities identified.*

The mafic hills can be separated into two main survey areas: the mafic hills in the Rothsay and Mt Mulgine area, which generally reach between 420–480 m above sea level, with the highest point the granite intrusion of Mt Mulgine (513 m); and the Bullajungadeah Hills, east of Warriedar Hill (546 m), which consists of more subdued hills up to 386 m. The surrounding plains occur approximately 280 m above sea level. The mafic formations at Rothsay and Mt Mulgine are over 8 km thick, consisting mainly of basalt flows with thin subvolcanic intrusions of dolerite and gabbro (coarse-grained, intrusive, mafic igneous rocks; Baxter & Lipple 1985). The Bullajungadeah Hills are composed of mafic volcanic rocks including metamorphosed gabbros and thin metamorphosed basaltic flows. Thin layers of banded ironstone separate some of these flows (Lipple et al. 1983).

## Climate

The climate of the Warriedar Fold Greenstone Belt is a semi-desert Mediterranean climate, with mild, wet winters and hot, dry summers (Beard 1990). Mean annual rainfall recorded at Paynes Find is 283.3 mm, and rainfall is highly variable in the region (181 mm 1st decile; 387.1 mm 9th decile; recorded 1919–2012; BOM 2012). Rain primarily falls in winter, although some summer rainfall does occur. The highest maximum temperatures occur during summer, with January as the hottest month (mean maximum temperature 37.4 °C and mean 8.5 days above 40 °C). Winters are mild, with the lowest mean maximum temperatures recorded for July of 18.4 °C. Temperatures occasionally fall below 0 °C in winter (a mean 2.9 days below 0 °C), with a mean minimum of 5.5 °C in July.

## Vegetation

The Warriedar Fold Belt occurs within the Yalgoo IBRA Bioregion, with 60% of the vegetation represented by *Acacia* woodlands and shrublands (Department of Sustainability, Environment, Water, Population and Communities 2012). The Yalgoo IBRA Bioregion lies in a transitional region between the Eremaean flora of the arid zone and the flora of south-western Western Australia (Beard 1976). The vegetation retains taxa characteristic of the Eremaean flora, and is dominated by *Acacia aneura* (mulga) but, with an increase in rainfall towards the south-west, mulga is gradually replaced by other species of *Acacia* and finally eucalypts (Beard 1976).

In addition to the targeted survey of the banded ironstone by Markey & Dillon (2008), several broad-scale surveys have been conducted within the Warriedar Fold Greenstone Belt. Payne et al. (1998) undertook a rangeland condition survey and described the country in terms of land systems that were primarily characterised by four different vegetation habitats: SIMS (stony ironstone mulga shrubland), SIAS (stony ironstone acacia shrubland), GHAS (greenstone hill acacia shrubland) and GHMW (greenstone hill mixed woodland or shrubland). The Bullajungadeah Hills are described by only one land system, the Gabanintha (greenstone ridges and hills), and are characterised by SIMS, SIAS and GHAS on the hillcrests, hillslopes and stony plains. Rothsay and Mulgine hills are described by three landsystems: Graves (basalt and greenstone rises and low hills) characterised by SIAS, GHAS and GHMW; Moriarty (low greenstone rises and stony plains) characterised by SIMS and GHMW; and Singleton (rugged greenstone ranges) characterised by SIAS, GHAS and GHMW.

## METHODS

The methods used in this survey follow the standard procedure used in previous vegetation surveys of other ironstone and greenstone ranges in Western Australia (Markey & Dillon 2008; Meissner & Caruso 2008). Fifty 20 × 20 m quadrats were established on the stony crests and slopes of the greenstone ranges of the Warriedar Fold Belt during September 2011 (Fig. 1). The greenstone traverses two areas, Bullajungadeah Hills and the Rothsay and Mulgine hills. The Bullajungadeah Hills occur on the eastern extent of the survey area on the ex-Warriedar and Thundelarra pastoral stations, east of Warriedar Hill. The Rothsay and Mulgine hills occur on the western extent of the survey area mainly on ex-Karara and ex-Warriedar pastoral stations (Fig. 1). Quadrats were established to cover the broader geographical and geomorphological variation found within the study area. The quadrats were strategically placed across the hills in a toposequence, from crests to foot slopes and plains. Each quadrat was permanently marked with four steel fence droppers and their positions determined using a GPS unit (Garmin GPS map 60CSx). All vascular plants within the quadrat were recorded and collected for later identification at the Western Australian Herbarium.

Data on topographical position, disturbance, abundance, size and shape of coarse fragments on the surface, the abundance of rock outcrops (defined as the cover of exposed bedrock), cover of leaf litter and bare ground were recorded following McDonald et al. (1990). Additionally, growth form, estimated height and cover were recorded for dominant taxa in each strata (tallest, mid and lower). The qualitative data were used to describe the plant communities following McDonald et al. (1990).

Twenty soil samples were collected from the upper 10 cm of the soil profile within each quadrat. The samples were bulked and the 2 mm fraction analysed for Al, B, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, S and Zn using an Inductively Coupled Plasma – Atomic Emission Spectrometer (ICP–AES). Electrical conductivity (EC), organic C, N and pH were determined using alternative methods, which are fully described in Meissner and Wright (2010).

Quadrats were classified on the basis of similarity in species composition, based upon presence-absence data on perennial species only and excluding species that only occurred in one quadrat. This was to remove any temporal variations in the numbers of annuals that may confound comparisons with other greenstone and banded ironstone ranges (Markey & Dillon 2008, Meissner & Caruso 2008). The quadrat and species classifications were undertaken using the Bray–Curtis coefficient followed by hierarchical clustering (using group-average linking). Quadrat classification was followed by similarity profile (SIMPROF) testing to determine the significance of internal group structures using permutation testing (Clarke & Gorley 2006). Community groups were determined based upon the SIMPROF results and detailed field knowledge. Indicator species for community groups were determined following De Cáceres et al. (2010) using the 'indicpecies' package in the R statistical language (De Cáceres & Legendre 2009), and determined for each community. Following the classification, the quadrat data was ordinated using non-metric multidimensional scaling (MDS), a nonparametric approach that is not based upon the assumptions of linearity, or presumption of any underlying model of species response gradients (Clarke & Gorley 2006).

To determine the environmental variables that best explained the community pattern, the BEST analysis using BIOENV algorithm in PRIMER v6 (Clarke & Gorley 2006) was undertaken on a Euclidean Distance resemblance matrix based on normalised environmental data. Prior to normalisation, EC, Na and Ni were transformed using  $\log(x + 1)$ . The BEST routine selects environmental variables that best explain the community pattern, by maximising a rank correlation between their respective resemblance matrices (Clarke & Warwick 2001). In the BIOENV algorithm, all permutations of the following environmental variables were tried and up to five of the best variables selected. In addition to BEST analysis, the environmental variables were fitted to the MDS ordination and Pearson correlation values were

calculated ( $r > 0.6$ ) to determine linear relationships between the variables and the vegetation communities.

Nomenclature generally follows Western Australian Herbarium (1998–).

## RESULTS

### Flora

A total of 286 taxa (species, subspecies, varieties and forms) represented by 36 families were recorded from the Warriedar Fold Belt. The most speciose families were Asteraceae (56 taxa), Fabaceae (36), Chenopodiaceae (19), Poaceae (17) and Myrtaceae (15). Of the 91 genera recorded, the dominant genera were *Acacia* (23 taxa), *Eremophila* (13), *Rhodanthe* (11), *Ptilotus* (8) and *Senna* (8). A total of 137 annuals and 14 introduced taxa were recorded.

Prior to the survey, there were good seasonal rains which resulted in an abundance of ephemeral species, mainly from the Asteraceae, Goodeniaceae and Amaranthaceae. The annual species that occurred in more than 40% of sites were *Calandrinia eremaea*, *Cephalopterum drummondii*, *Haloragis trigonocarpa*, *Stenopetalum filifolium*, *Pentameris airoides* subsp. *airoides*, *Podolepis canescens*, *Trachymene ornata*, *Velleia rosea*, *Goodenia berardiana*, *Ptilotus helipteroides*, *Cuscuta planiflora*, *Schoenus nanus*, *Crassula colorata* var. *acuminata*, *Erodium cygnorum*, *Schoenia cassiniana*, *Calocephalus multiflorus*, *Calotis hispidula*, *Plantago debilis*, *Waitzia acuminata* var. *acuminata*, *Phyllangium sulcatum* and *Lobelia rhytidosperma*.

### Priority flora

Twenty-two taxa of conservation significance were recorded during the survey, including one significant new population of the Priority 1 taxa, *Allocasuarina tessellata*, previously known only from a single population (Table 1). These taxa are listed as priority flora according to Department of Parks and Wildlife conservation codes for Western Australia (Smith 2012). No taxa are listed under the *Environment Protection and Biodiversity Act 1999*. There were 12 taxa that were endemic to the area, with three taxa, *Acacia diallaga*, *A. sulcaticaulis* and *Chamelaucium* sp. Warriedar (AP Brown & S Patrick APB 1100), endemic to the Mulgine and Rothsay hills, and one taxon, *Eremophila grandiflora*, restricted to the Bullajungadeah Hills (Table 1). Endemics are defined as taxa restricted to an area within 100 km and near-endemics defined as having most populations located within an 100 km radius with one to two outlying disjunct populations (Markey & Dillon 2008).

*Acacia diallaga* (Priority 2) is restricted to a small area surrounding the Mulgine hills. When under drought stress, this species exhibits diallaga, a change in foliage cover from glaucous to a purple-red, and reverts back to glaucous when conditions improve (Maslin & Buscumb 2008a).

*Acacia karina* (Priority 2) is more commonly found on banded ironstone but in this survey was collected on basalts and other mafic rocks within the Warriedar Fold Belt. *A. karina* is a straggly perennial shrub to 1.5 m, characterised by long, terete phyllodes and long, cylindrical inflorescences with flowers loosely arranged (Maslin & Buscumb 2007).

**Table 1**

The 23 priority taxa recorded from the survey, their conservation status within Western Australia (Western Australian Herbarium 1998–) and their endemism to the Warriedar Fold Belt (including the banded ironstone ranges).

Family	Species	Conservation Code	Endemic
Aizoaceae	<i>Gunniopsis rubra</i>	P3	N
Araliaceae	<i>Hydrocotyle</i> sp. Warriedar (PG Wilson 12267)	P1	Y (basalt)
Asteraceae	<i>Millotia dimorpha</i>	P1	Y
Asteraceae	<i>Rhodanthe collina</i>	P1	N
Casuarinaceae	<i>Allocasuarina tessellata</i>	P1	Near endemic
Cyperaceae	<i>Lepidosperma</i> sp. Blue Hills (A Markey & S Dillon 3468)	P1	Y
Fabaceae	<i>Acacia diallaga</i>	P2	Y (basalt only)
Fabaceae	<i>Acacia karina</i>	P2	Y
Fabaceae	<i>Acacia subsessilis</i>	P3	N
Fabaceae	<i>Acacia sulcaticaulis</i>	P1	Y (granite/basalt)
Hemerocallidaceae	<i>Tricoryne</i> sp. Morawa (GJ Keighery & N Gibson 6759)	P3	N
Myrtaceae	<i>Chamelaucium</i> sp. Warriedar (AP Brown & S Patrick APB 1100)	P1	Y (basalt only)
Myrtaceae	<i>Micromyrtus acuta</i>	P3	N
Myrtaceae	<i>Micromyrtus trudgenii</i>	P3	Y
Orchidaceae	<i>Cyanicula fragrans</i>	P3	N
Poaceae	<i>Austrostipa blackii</i>	P3	N
Portulacaceae	<i>Calandrinia</i> sp. Warriedar (F Obbens 04/09)	P2	Y
Proteaceae	<i>Grevillea scabrida</i>	P3	Y
Proteaceae	<i>Grevillea subtiliflora</i>	P3	Y
Proteaceae	<i>Persoonia pentasticha</i>	P3	N
Rhamnaceae	<i>Stenanthemum poicilum</i>	P3	N
Sapindaceae	<i>Dodonaea amplisemina</i>	P4	N
Scrophulariaceae	<i>Eremophila grandiflora</i>	P3	Y

*Acacia subsessilis* (Priority 3) is shrub to 2 m high with short pungent phyllodes. This species was only collected on Bullajungadeah Hills. It is closely related to *Acacia diallaga* but differs in that it has thinner, narrowly linear to linear-triangular phyllodes and also exhibits diallaga.

*Acacia sulcatacaulis* (Priority 1) is a multi-stemmed, obconic shrub to 4 m with longitudinally smooth, fluted stems (Maslin & Buscumb 2008b). This species occurs within the *Acacia coolgardiensis* group and is highly restricted and found only on the slopes of Mulgine Hill on dolerite or quartz. This was an opportunistic collection.

*Allocasuarina tessellata* (Priority 1) is a shrub to 4 m with distinctive female cones, and is closely related to *Allocasuarina campestris*. During the survey, the species was collected from Mulgine and Rothsay basalts. This is a significant new population as the taxon was previously known only from Mount Singleton, approximately 50 km to the south-east. Single collections have been made from the Die Hardy Ranges (ca. 250 km south-east) and a granite outcrop between Mullewa and Morawa, and it is unknown whether there are significant populations at either location.

*Austrostipa blackii* (Priority 3) is a perennial tufted grass found mainly in the eastern states of Australia. It was collected from the Rothsay and Mulgine greenstone hills.

*Calandrinia* sp. Warriedar (F Obbens 04/09; Priority 2) is a small, succulent annual herb known from only five collections, mainly from Warriedar Station where the Bullajungadeah Hills are situated. A single collection was made during the survey from Bullajungadeah Hills.

*Chamelaucium* sp. Warriedar (AP Brown & S Patrick APB 1100; Priority 1) is a shrub to 0.6 m with small, nondescript white flowers. It is highly restricted and known only from the basalts found on Mulgine and Rothsay.

*Cyanicula fragrans* (Priority 3) is an orchid with light blue flowers. This species is found within the Yalgoo IBRA Bioregion, mostly on granite substrates. In this survey, we found it at two locations in the Mulgine hills.

*Dodonaea amplisemina* (Priority 4) is a shrub to 1 m high with distinctive three-horned fruit and large seeds. This species occurs on a variety of geology, including banded ironstone and basalts (Shepherd et al. 2007). In the survey, this species was found on the Bullajungadeah Hills only.

*Eremophila grandiflora* (Priority 3) is a perennial shrub to 3 m high with large, light purple flowers. It is the most southerly member of the *Eremophila fraseri* complex (Brown & Buirchell 2007). This species is known only from the Bullajungadeah Hills from five collections. Further populations were discovered during the survey at other locations within these hills.

*Grevillea scabrada*, *Grevillea subtiliflora* and *Persoonia pentasticha* are all proteaceous shrubs listed as Priority 3. *G. scabrada* is an intricate shrub with short, scabrid leaves, while *G. subtiliflora* is a shrub to 5 m high with dissected leaves. *Persoonia pentasticha* is a small shrub to 2 m with small yellow flowers and grows on both banded ironstone and basalt geologies. This species has a much wider

distribution than the *Grevillea* spp., which are restricted to the Warriedar Fold Belt and Mount Singleton. *G. scabrada* and *G. subtiliflora* were well represented on the Mulgine and Rothsay hills, while only three collections were made of *P. pentasticha* on these hills.

*Micromyrtus acuta* and *M. trudgenii* (both Priority 3) are shrubs restricted to the Warriedar Fold Belt. *M. trudgenii* was more widely collected in the survey from the Mulgine hills area, while only a single collection was made of *M. acuta* on an ironstone substrate. The former species is more commonly found growing on ironstone but in this survey it found growing on basalt on the crests on the hills.

*Hydrocotyle* sp. Warriedar (PG Wilson 12267; Priority 1) is an annual herb known only from six collections from the Warriedar Fold Belt and surrounding pastoral stations. The species was found on the crests and slopes in the Mulgine hills area.

*Lepidosperma* sp. Blue Hills (A Markey & S Dillon 3468; Priority 1) is a sedge related to *L. costale* (Markey & Dillon 2008) This species is known from only six collections and is found growing on a variety of soils but restricted in distribution to the Warriedar Fold Belt and ca. 50 km south on Charles Darwin Reserve. This species was an opportunistic collection along a creekline within the Mulgine hills area.

*Millotia dimorpha* (Priority 1) is a small, yellow-flowered daisy characteristically with two rows of glandular involucre bracts. This species has been collected from the area previously. In this survey, it was found at only one location on Rothsay.

*Rhodanthe collina* (Priority 1) is an annual daisy with small, delicate flowers. It is known mainly from the pastoral stations near Paynes Find on flats and water-gaining sites. It was found in several locations across the whole study area.

*Stenanthemum poicilum* (Priority 3) is a small shrub to 0.5 m previously collected from the region from rocky hills and slopes. In the survey it was found in the Mulgine hills growing on the lower slope of a basalt hill.

*Tricoryne* sp. Morawa (GJ Keighery & N Gibson 6759; Priority 3) is a tuberous herb with small, delicate, yellow flowers. It is known from the Yalgoo IBRA Bioregion and is commonly found in a variety of habitats. In the survey it was found at a single site on the lower slope of a basalt hill in the Mulgine area.

## Plant communities

Six communities were determined from the classification (Fig. 2; Table 2). An outlier was removed from the analysis as it consisted of an isolated, single quadrat that contained a high proportion of banded ironstone bedrock. This quadrat was dominated by BIF taxa found in the surrounding BIF hills (Markey & Dillon 2008). The first two divisions in the dendrogram separated community 1, occurring on the slopes of Bullajungadeah Hills on laterised ironstone and greenstone, from the remaining five communities, and community 2, the woodland communities on the lower slopes in Rothsay and Mulgine,

Table 2

Summary of the six communities found on the Warriedar Fold Belt by locality, topography and geology.

Community	Vegetation	Locality	Topography	Geology
1	<i>Acacia ramulosa</i> and mulga shrublands	Bullajungadeah Hills	Crests and slopes	Laterised ironstone and basalt
2	<i>Eucalyptus</i> woodlands	Rothsay and Mullgine hills	Lower slopes	Basalt
3	<i>Acacia</i> shrublands	Bullajungadeah Hills	Crests and slopes	Basalt
4	<i>Acacia umbraculiformis</i> and <i>Acacia burkittii</i> shrublands	Bullajungadeah Hills and one quadrat on Mullgine hills	Crests and slopes	Gabbro or basalt
5	<i>Allocasuarina dielsiana</i> , <i>Acacia burkittii</i> or <i>Melaleuca hamata</i> woodlands	Rothsay and Mullgine hills	Crests and midslopes	Basalt
6	<i>Acacia</i> spp. and <i>Allocasuarina dielsiana</i> shrublands	Rothsay and Mullgine hills	Crests and slopes	Basalt

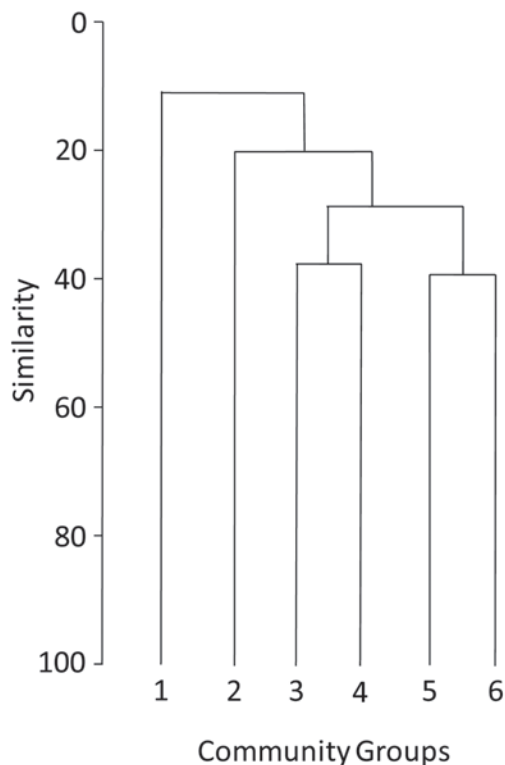


Figure 2. Dendrogram of the six-group-level classification of 49 quadrats established on the Warriedar Fold Belt.

from the remaining four communities. The subsequent divisions separated communities 3 and 4 found on Bullajungadeah Hills, from communities 5 and 6, found on Rothsay and Mullgine.

Community 1 was characterised by open shrublands (10–30% cover) to shrublands (30–70% cover) of *Acacia ramulosa* var. *ramulosa* and *Acacia* spp. (*A. incurvaneura*, *A. sibina*, *A. caesaneura*), over open shrublands of *Aluta aspera* subsp. *hesperia*, *Eremophila latrobei*, *E. forrestii* and *Philotheca* spp. (*P. brucei* and *P. sericea*), over various ephemeral species (*Waitzia acuminata*, *Goodenia*

*occidentalis*, *Calocephalus multiflorus*). Quadrats characterised in this group (n = 6) occurred on the slopes and crests of laterised ironstone and greenstone at Bullajungadeah Hills. Indicator species (Table 2) were *Monachather paradoxus*, *Aluta aspera* subsp. *hesperia*, *Philotheca brucei* subsp. *brucei*, *P. sericea*, *Sida* sp. Golden calyces glabrous (HN Foote 32), *Acacia assimilis* subsp. *assimilis*, *Acacia incurvaneura*, *Mirbelia bursarioides*, *Cheiranthra simplicifolia*, *Eremophila latrobei*, *E. glutinosa*, *Hemigenia benthamii* and *H. sp.* Yalgoo (AM Ashby 2624). Mean species richness was 13.8 ( $\pm 2.2$  SE) perennial taxa per plot.

Community 2 was characterised by open woodlands (<10% cover) to open forests (30–70% cover) of *Eucalyptus loxophleba* subsp. *supralaevis* or *Eucalyptus clelandii*, over sparse shrublands (<10%) of *Eremophila* spp. (*E. oppositifolia* subsp. *angustifolia* or *E. pantonii*), *A. tetragonophylla*, *A. andrewsii*, *Senna artemisioides* subsp. *filifolia* and *Exocarpos aphyllus*, over low shrublands (30–70% cover) of *Ptilotus obovatus*, *Maireana trichoptera*, *M. georgei*, *Acacia erinacea* and various ephemeral species. Quadrats characterised in this group (n = 8) occurred in *Eucalyptus* woodland communities on the lower slopes of the Rothsay and Mullgine basalt hills. Indicator species are *Exocarpos aphyllus*, *Eucalyptus loxophleba* subsp. *supralaevis*, *Acacia erinacea*, *Maireana georgei*, *M. marginata*, *Austrostipa elegantissima*, *Eremophila pantonii*, *Sclerolaena fusiformis*, *S. diacantha* and *S. patentiuspis* (Table 2). Mean species richness was 19.9 ( $\pm 1.6$  SE) perennial taxa per plot.

Community 3 was characterised by sparse tall shrublands (<10% cover) to open tall shrublands (10–30% cover) of *Acacia umbraculiformis* and other *Acacia* spp. (*A. subsessilis*, *A. ramulosa* subsp. *ramulosa* or *A. burkittii*), over sparse shrublands (<10% cover) of *Thryptomene costata* and *Eremophila grandiflora*, over sparse low shrublands (30–70% cover) of *Ptilotus obovatus*, *Austrostipa nitida*, *Aristida contorta* and various ephemerals. Quadrats characterised in this group (n = 8)

were found on the Bullajungadeah Hills, mostly on the crests and slopes of the basalt hills. Indicator species were *Thryptomene costata* and *Eremophila grandiflora* (Table 2). Mean species richness was 13.8 ( $\pm 0.9$  SE) perennial taxa per plot.

Community 4 was characterised as open tall shrublands (10–30% cover) to tall shrublands (30–70% cover) of *Acacia umbraculiformis* and *A. burkittii*, over shrublands (30–70% cover) of *Senna* spp. (*S. artemisioides* subsp. *filifolia* and *S.* sp. Austin [A Strid 20210]), *Eremophila pantonii* and *Acacia acuaria*, over low shrublands (30–70% cover) of *Ptilotus obovatus* and *Austrostipa nitida* (Table 2). Quadrats characterised in this group ( $n = 5$ ) were primarily found on the crest and slopes of gabbro or basalt hills within Bullajungadeah Hills, with one site found within the Mulgine Hills area. Indicator species were *Acacia acuaria*, *Ptilotus schwartzii* and *Senna* sp. Austin (A Strid 20210). Mean species richness was 19.2 ( $\pm 2.2$  SE) perennial taxa per plot.

Community 5 was characterised by open woodlands (<10% cover) of *Allocasuarina dielsiana*, *Acacia burkittii* or *Melaleuca hamata*, over shrublands (30–70% cover) of *Allocasuarina tessellata*, over forbland (30–70% cover) of *Borya sphaerocephala* and *Chamelaucium* sp. Warriedar (AP Brown & S Patrick APB 1100) and other ephemerals. Quadrats characterised in this group ( $n = 12$ ) were located within the Rothsay and Mulgine areas, mainly on the crests and mid-slopes of basalt hills. Indicator species were *Allocasuarina tessellata*, *Chamelaucium* sp. Warriedar (AP Brown & S Patrick APB 1100), *Micromyrtus trudgenii*

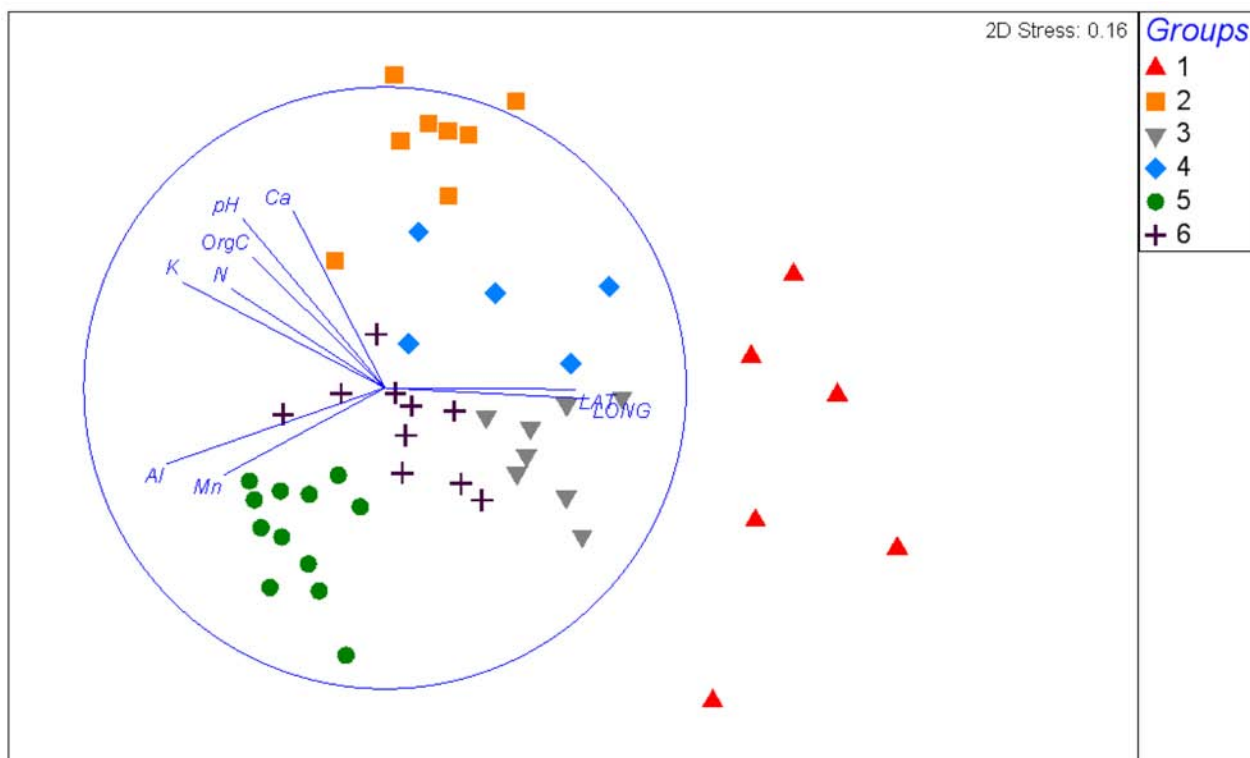
and *Melaleuca hamata* (Table 2). Mean species richness was 12.4 ( $\pm 0.6$  SE) perennial taxa per plot.

Community 6 was characterised by open tall shrublands (10–30% cover) of *Acacia umbraculiformis*, *A. burkittii*, *A. tetragonophylla* and *Allocasuarina dielsiana*, over shrublands (30–70% cover) of *Grevillea scabrida*, *Ptilotus obovatus* over various ephemerals. Quadrats characterised in this group ( $n = 10$ ) were located on the basalt crests and slopes in the Rothsay and Mulgine areas. Indicator species were *Austrostipa trichophylla* and *Acacia kochii* (Table 2). Mean species richness was 17.2 ( $\pm 0.6$  SE) perennial taxa per plot.

## Environmental correlates

Nonparametric analysis of variance found that 18 of the 20 soil parameters were significantly different (Table 4), while seven of the 12 site attributes were significantly different between the six communities (Table 5). The main differences were between community 1, the laterite community found on Bullajungadeah Hills, and community 2, the *Eucalyptus* woodland community found on the lower slopes of Rothsay and Mulgine. Communities 3 and 4, on Bullajungadeah Hills, and communities 5 and 6, on Rothsay and Mulgine, showed similar soil chemistry apart from higher Al concentrations in the soil from communities 5 and 6. Community 5 also had higher organic C content while communities 5 and 6 also had significantly lower P than community 2.

Community 1 was found on laterite landforms, on



**Figure 3.** Two dimensional ordination of the 49 quadrats established on Warriedar Fold Belt. The six communities are shown and lines represent the strength and direction of the nine environmental variables correlated with the MDS using Pearson rank correlation ( $r > 0.6$ ).

**Table 3**

Sorted two-way table of the quadrats established on the Warriedar Fold Belt showing species by community type. Taxa shaded black within a community are indicator species determined by 'indicspecies' (De Cáceres & Legendre 2009) at the six-group level ( $p < 0.05$ ).

Species	1	2	3	4	5	6
<b>Group a</b>						
<i>Eremophila ericalyx</i>						
<i>Eremophila granitica</i>						
<i>Astroloma serratifolium</i>						
<i>Cyanicula fragrans</i>						
<i>Austrostipa scabra</i>						
<b>Group c</b>						
<i>Thysanotus pyramidalis</i>						
<i>Cheilanthes sieberi</i> subsp. <i>sieberi</i>						
<i>Dodonaea rigida</i>						
<i>Ptilotus schwartzii</i>						
<i>Cheiranthra simplicifolia</i>						
<i>Hemigenia</i> sp. <i>Yaigoo</i> (A.M. Ashby 2624)						
<i>Hemigenia benthamii</i>						
<i>Mirbelia bursarioides</i>						
<i>Philotheca brucei</i> subsp. <i>brucei</i>						
<i>Philotheca sericea</i>						
<i>Eremophila latrobei</i>						
<i>Monachather paradoxus</i>						
<i>Sida</i> sp. Golden calyces glabrous (H.N. Foote 32)						
<i>Acacia assimilis</i> subsp. <i>assimilis</i>						
<i>Aluta aspera</i> subsp. <i>hesperia</i>						
<i>Acacia incurvaneura</i>						
<i>Eremophila glutinosa</i>						
<i>Acacia ramulosa</i> var. <i>ramulosa</i>						
<i>Thysanotus manglesianus</i>						
<b>Group d</b>						
<i>Sclerolaena gardneri</i>						
<i>Eucalyptus clelandii</i>						
<i>Acacia andrewsii</i>						
<i>Maireana marginata</i>						
<i>Hemigenia</i> sp. <i>Yuna</i> (A.C. Burns 95)						
<i>Santalum spicatum</i>						
<i>Dodonaea inaequifolia</i>						
<i>Eremophila oldfieldii</i> subsp. <i>oldfieldii</i>						
<i>Solanum nummularium</i>						
<i>Eriochiton sclerolaenoides</i>						
<i>Sclerolaena fusiformis</i>						
<i>Acacia acanthoclada</i> subsp. <i>glaucescens</i>						
<i>Austrostipa elegantissima</i>						
<i>Maireana georgei</i>						
<i>Rhagodia drummondii</i>						
<i>Eucalyptus loxophleba</i> subsp. <i>supralaevis</i>						
<i>Euocarpos ophyllus</i>						
<i>Eremophila oppositifolia</i> subsp. <i>angustifolia</i>						
<i>Acacia erinacea</i>						
<i>Eremophila pantonii</i>						
<i>Sclerolaena patenticuspis</i>						
<i>Senna stowardii</i>						
<i>Maireana trichoptera</i>						
<i>Sclerolaena diacantha</i>						
<b>Group e</b>						
<i>Persoonia pentasticha</i>						
<i>Comesperma integerrimum</i>						
<i>Enchylaena lanata</i>						
<i>Dianella revoluta</i> var. <i>divaricata</i>						
<i>Maireana thesioides</i>						
<i>Acacia acuarua</i>						
<i>Senna</i> sp. <i>Austin</i> (A. Strid 20210)						
<b>Group f</b>						
<i>Senna artemisioides</i> subsp. <i>helmsii</i>						
<b>Group g</b>						
<i>Eremophila grandiflora</i>						
<i>Eremophila forrestii</i> subsp. <i>forrestii</i>						
<i>Thryptomene costata</i>						
<i>Acacia subsessilis</i>						
<i>Sclerolaena densiflora</i>						
<i>Dodonaea ampilsemima</i>						
<i>Maireana carnosia</i>						
<i>Abutilon oxycarpum</i> subsp. <i>prostratum</i>						
<i>Solanum ellipticum</i>						
<b>Group h</b>						
<i>Scaevola spinescens</i>						
<i>Eremophila clarkei</i>						
<i>Acacia kochii</i>						
<i>Mirbelia microphylla</i>						
<i>Rytidosperma caespitosum</i>						
<i>Wurmbea</i> sp. <i>Paynes Find</i> (C.J. French 1237)						
<b>Group i</b>						
<i>Cryptandra micrantha</i>						
<i>Eremophila georgei</i>						
<b>Group j</b>						
<i>Austrostipa eremophila</i>						
<i>Austrostipa trichophylla</i>						
<i>Grevillea scabrida</i>						
<i>Borya sphaerocephala</i>						
<i>Acacia burkittii</i>						
<i>Allocasuarina dielsiana</i>						
<i>Arthropodium dyeri</i>						
<i>Cheilanthes adiantoides</i>						
<i>Austrostipa nitida</i>						
<i>Ptilotus obovatus</i>						
<i>Acacia umbraculiformis</i>						
<i>Solanum lasiophyllum</i>						
<i>Acacia tetragonophylla</i>						
<i>Sida</i> sp. dark green fruits (S. van Leeuwen 2260)						
<i>Austrostipa blackii</i>						
<i>Grevillea subtiliflora</i>						
<i>Melaleuca hamata</i>						
<i>Acacia karina</i>						
<i>Melaleuca radula</i>						
<i>Caesia</i> sp. <i>Wongan</i> (K.F. Kenneally 8820)						
<i>Allocasuarina tessellata</i>						
<i>Chamelaucium</i> sp. <i>Warriedar</i> (A.P. Brown & S. Patrick APB 1100)						
<i>Acacia diallaga</i>						
<i>Micromyrtus trudgenii</i>						

skeletal soils with the lowest fertility (significantly lower N and P), pH and EC, but the highest S content (Table 3; Table 4). In contrast, community 2, the eucalypt woodlands, was the most fertile community, with the least acidic soils with the highest EC (Table 4). This community also had significantly lower coarse fragment abundance

and size and significantly greater soil depth and leaf litter cover (Table 5).

The two dimensional MDS (stress = 0.16; Fig. 3) showed a similar pattern to the univariate analysis. All communities are clearly separated, with community 1 the most distinct but more variable of the six communities identified from the classification (Fig. 2).

**Table 4**

Mean values for soil chemistry parameters for each plant community (measured in mg kg<sup>-1</sup> except pH and EC [mS m<sup>-1</sup>]). Differences between ranked values were tested using Kruskal–Wallis nonparametric analysis of variance. Standard errors in parentheses. Superscript a, b and c represent significant differences between community types at p < 0.05 determined by Dunns post-hoc test (n = number of quadrats, p = probability).

n	Community 1 6	Community 2 8	Community 3 8	Community 4 5	Community 5 12	Community 6 10	p value
EC	3.5 (0.6) <sup>b</sup>	15.1 (3.7) <sup>a</sup>	3.9 (0.4) <sup>ab</sup>	13 (3.1) <sup>ab</sup>	5.4 (0.8) <sup>ab</sup>	5.5 (2.1) <sup>b</sup>	0.0014
OrgC	0.60 (0.04) <sup>ab</sup>	1.35 (0.17) <sup>c</sup>	0.48 (0.06) <sup>a</sup>	0.82 (0.05) <sup>abc</sup>	1.00 (0.10) <sup>b</sup>	0.89 (0.06) <sup>abc</sup>	<0.0001
pH	4.3 (0.0) <sup>a</sup>	6.7 (0.2) <sup>b</sup>	5.7 (0.1) <sup>abc</sup>	6.7 (0.4) <sup>bc</sup>	5.6 (0.0) <sup>ac</sup>	5.8 (0.1) <sup>bc</sup>	<0.0001
Al	476.7 (26.8) <sup>a</sup>	608.8 (25.4) <sup>ab</sup>	528.8 (27.6) <sup>a</sup>	490 (42.1) <sup>a</sup>	774.2 (26.5) <sup>b</sup>	714 (21.5) <sup>b</sup>	<0.0001
N	0.046 (0.003) <sup>a</sup>	0.106 (0.0113) <sup>b</sup>	0.052 (0.006) <sup>ac</sup>	0.084 (0.004) <sup>abc</sup>	0.088 (0.008) <sup>bc</sup>	0.082 (0.004) <sup>bc</sup>	<0.0001
B	0.09 (0.02) <sup>a</sup>	0.89 (0.29) <sup>b</sup>	0.14 (0.03) <sup>ab</sup>	0.3 (0.11) <sup>ab</sup>	0.26 (0.06) <sup>ab</sup>	0.26 (0.06) <sup>ab</sup>	0.0195
Ca	119.5 (30.1) <sup>a</sup>	2838 (706.3) <sup>b</sup>	550 (62.6) <sup>ac</sup>	1940 (496.6) <sup>b</sup>	1008 (70.8) <sup>bc</sup>	1093 (71.8) <sup>bc</sup>	<0.0001
Cd	0.005 (0) <sup>a</sup>	0.014 (0.002) <sup>ab</sup>	0.017 (0.003) <sup>b</sup>	0.018 (0.006) <sup>ab</sup>	0.016 (0.001) <sup>b</sup>	0.02 (0.003) <sup>b</sup>	0.0036
Co	0.19 (0.05) <sup>a</sup>	2.11 (0.23) <sup>b</sup>	5.63 (0.81) <sup>c</sup>	4.52 (1.42) <sup>bc</sup>	3.57 (0.28) <sup>bc</sup>	3.57 (0.32) <sup>bc</sup>	<0.0001
Cu	1.78 (0.57)	3.13 (0.46)	4.25 (0.71)	3.18 (0.43)	3.48 (0.32)	4.01 (0.74)	0.1241
Fe	33.0 (2.7) <sup>a</sup>	61.1 (4.4) <sup>b</sup>	58.0 (4.2) <sup>b</sup>	55.4 (2.1) <sup>b</sup>	50.0 (1.2) <sup>ab</sup>	52.6 (2.0) <sup>ab</sup>	0.0003
K	78.8 (5.5) <sup>a</sup>	277.5 (17.3) <sup>b</sup>	193.8 (15.7) <sup>ab</sup>	244.0 (23.4) <sup>ab</sup>	242.5 (14.4) <sup>b</sup>	259.0 (11.1) <sup>b</sup>	0.0002
Mg	30.5 (9.1) <sup>a</sup>	498.8 (72.1) <sup>b</sup>	407 (72.3) <sup>b</sup>	270 (26.7) <sup>ab</sup>	275 (23.6) <sup>b</sup>	248 (21.5) <sup>ab</sup>	0.0002
Mn	17.2 (1.5) <sup>a</sup>	78.4 (15.1) <sup>ab</sup>	139.1 (15.0) <sup>b</sup>	82.8 (11.4) <sup>ab</sup>	143.5 (8.0) <sup>b</sup>	128.5 (8.1) <sup>b</sup>	<0.0001
Mo	0.005 (0)	0.011 (0.004)	0.005 (0)	0.005 (0)	0.015 (0.004)	0.0175 (0.005)	0.064
Na	6.5 (2.0) <sup>a</sup>	49.1 (7.9) <sup>b</sup>	28.9 (2.3) <sup>ab</sup>	52.0 (22.7) <sup>b</sup>	32.3 (2.7) <sup>b</sup>	24.9 (3.4) <sup>ab</sup>	0.0006
Ni	0.3 (0.1) <sup>a</sup>	2.2 (0.7) <sup>b</sup>	3.4 (0.9) <sup>b</sup>	3.8 (2.1) <sup>b</sup>	1.1 (0.2) <sup>ab</sup>	1.2 (0.3) <sup>ab</sup>	0.0002
P	4.2 (0.4) <sup>ab</sup>	5.9 (0.6) <sup>b</sup>	3.8 (0.5) <sup>ab</sup>	5.0 (1.3) <sup>ab</sup>	2.8 (0.3) <sup>a</sup>	3.3 (0.2) <sup>a</sup>	0.003
S	17.5 (1.7) <sup>b</sup>	10.8 (3.8) <sup>ab</sup>	5.0 (0.9) <sup>a</sup>	7.2 (2.1) <sup>ab</sup>	6.3 (0.6) <sup>ab</sup>	5.7 (1.3) <sup>a</sup>	0.004
Zn	0.95 (0.17) <sup>a</sup>	1.65 (0.24) <sup>ab</sup>	3.73 (0.97) <sup>b</sup>	1.48 (0.22) <sup>ab</sup>	1.82 (0.13) <sup>ab</sup>	1.76 (0.16) <sup>ab</sup>	0.0255

**Table 5**

Mean values for physical site parameters for each plant community: aspect (degrees); slope (degrees); latitude and longitude (decimal degrees); morphology type (1 – crest, 2 – mid slope, 3 – lower slope, 4 – simple slope, 5 – hillock); landform (1 – hillcrest, 2 – hill slope, 3 – footslope, 4 – mound); maximum size of coarse fragments (CF Max) (1 – fine gravely to 6 – boulders); coarse fragment (CF) abundance (0 – no coarse fragments to 6 – very abundant coarse fragments); rock outcrop (RO) abundance (0 – no bedrock exposed to 4 – very rocky); Runoff (0 – no runoff to 4 – rapid), soil depth (1 – skeletal, 2 – shallow, 3 – deep), leaf litter (cover classes 1 – <10%, 2 – 10–30%, 3 – 30–70%, 4 – > 70%). Differences between ranks were tested using Kruskal–Wallis nonparametric analysis of variance. Standard errors in parentheses.

n	Comm. 1 6	Comm. 2 8	Comm. 3 8	Comm. 4 5	Comm. 5 12	Comm. 6 10	p value
Aspect	4.7 (1.4)	5 (0.8)	5.3 (0.9)	4 (1.3)	4.1 (0.8)	4.4 (0.9)	0.9463
Latitude	-29.0375 (0.0065) <sup>c</sup>	-29.18103 (0.0259) <sup>ab</sup>	29.07081 (0.0142) <sup>bc</sup>	-29.0467 (0.0136) <sup>bc</sup>	-29.1957 (0.0142) <sup>a</sup>	-29.1942 (0.0192) <sup>a</sup>	0.0001
Longitude	117.2065 (0.0104) <sup>bc</sup>	116.9495 (0.0281) <sup>ab</sup>	117.2074 (0.01553) <sup>c</sup>	117.1754 (0.0397) <sup>bc</sup>	116.9343 (0.0216) <sup>a</sup>	116.9193 (0.0241) <sup>a</sup>	0.0001
Slope	2.58 (0.74)	2.13 (0.54)	3.19 (0.64)	4.1 (1.36)	4.21 (0.71)	2.95 (0.63)	0.4135
Morph Type	1.8 (0.4)	3.1 (0.1)	2.4 (0.3)	1.6 (0.4)	1.8 (0.2)	1.6 (0.3)	0.0127
Landform	1.5 (0.2)	2 (0)	1.8 (0.2)	1.4 (0.2)	1.6 (0.1)	1.3 (0.2)	0.0593
CFMax	3.2 (0.5) <sup>ab</sup>	3.1 (0.2) <sup>a</sup>	4.3 (0.3) <sup>ab</sup>	4.6 (0.4) <sup>b</sup>	4.1 (0.2) <sup>ab</sup>	4.3 (0.2) <sup>ab</sup>	0.0054
CFAbundance	3.5 (0.4) <sup>ab</sup>	2.9 (0.4) <sup>a</sup>	4.6 (0.3) <sup>b</sup>	3.6 (0.2) <sup>ab</sup>	3.8 (0.2) <sup>ab</sup>	3.4 (0.2) <sup>ab</sup>	0.0093
ROAbund	0.7 (0.3)	0.3 (0.2)	0.6 (0.3)	1.4 (0.6)	0.3 (0.1)	0.3 (0.2)	0.3582
Soil Depth	1.7 (0.3) <sup>b</sup>	2.8 (0.2) <sup>a</sup>	1.8 (0.2) <sup>b</sup>	1.8 (0.2) <sup>ab</sup>	2 (0.2) <sup>ab</sup>	2 (0.2) <sup>ab</sup>	0.0192
Bare Ground	3.3 (0.2)	3.4 (0.2)	3.6 (0.2)	3.2 (0.2)	3.2 (0.1)	3.1 (0.1)	0.1899
Leaf Litter	1.3 (0.2) <sup>ab</sup>	2.1 (0.1) <sup>a</sup>	1 (0) <sup>b</sup>	1.2 (0.2) <sup>ab</sup>	1.7 (0.2) <sup>ab</sup>	1.7 (0.2) <sup>ab</sup>	0.0026

The BEST analysis indicated that the best correlation with the species resemblance matrix was obtained with five environmental variables: coarse fragment abundance, pH, Al, Mn and S ( $r = 0.651$ ). Nine of the 33 environmental variables correlated with the MDS ( $r > 0.6$ ; Fig. 3). Latitude and longitude, used as surrogates for climate, correlated with the communities located on Bullajungadeah Hills, the communities further north and east. Al and Mn were positively correlated with community 5, while K, N, organic C, pH and Ca were positively correlated with community 2 but negatively correlated with community 1.

## DISCUSSION

The greenstone hills within the Warriedar Fold Belt have a rich flora, with 286 taxa identified, including a high number of endemic flora. Similar patterns of species have been observed in other greenstone ranges predominantly composed of banded ironstone (Gibson et al. 2011), especially those ranges within the boundary of the South West Australian Floristic Region (SWAFR; Hopper & Gioia 2004). High species richness and endemism is not restricted to the banded ironstone but has been found on other greenstone ranges such as Digger Hatter's Hill and the Ravensthorpe Range, where greenstone and banded ironstone flora were both sampled along the SWAFR boundary (Gibson 2004; Markey et al. 2012).

Several of the endemic and priority species, such as *Grevillea scabrada* and *Acacia diallaga*, were found only on the basalt and not on the nearby ironstones. Their distribution tended to centre on the greenstone of Rothsay and Mulgine and nearby Mount Singleton, ~50 km south-east of Rothsay. Several taxa occurred predominantly on basalt but were occasionally found on ironstone, such as *Eremophila grandiflora*. The region around the Warriedar Fold Belt has been highlighted previously as a hotspot of species endemism (Gibson et al. 2012).

Similar species richness and turnover to this survey were found in the adjacent banded ironstone ranges within the Warriedar Fold Belt (Markey & Dillon 2008). A high species turnover from north to south along the ranges, in addition to many distinct communities and a significant number of endemic and priority taxa, were recorded on the banded ironstone formations of the Blue Hills and Gnows Nest Range (Markey & Dillon 2008). Despite the proximity of these banded ironstone ranges to the basalt hills of this survey, the species and communities are very different. In a combined flora list, only 205 species out of 460 species, including annuals, were common between the greenstones and banded ironstone. In addition, similar numbers of perennial taxa were recorded from both surveys (~200 vs. 150 taxa) but there was a difference in species richness between lithologies, with banded ironstone more species-rich than the greenstone. Both surveys covered similar areas, with the Blue Hills and Gnows Nest Range extending further north while the basalt hills in this survey extend further east, with both ironstone and basalt hills traversing a climatic gradient. It

is more probable that the lithologies are influencing this difference in species richness.

In addition to high species richness, the survey also highlighted the high species turnover that is also common to greenstone ranges within the arid zone (Gibson et al. 2012). Even though the dominant communities on the basalt hills occur in similar positions in the landscape and have soils with similar chemistry, there was a clear distinction between the communities occurring on the Rothsay and Mulgine hills (communities 5 and 6) and the Bullajungadeah Hills (communities 3 and 4). Markey & Dillon (2008) found a similar species turnover heading northwards into more arid conditions. Likewise, Payne et al. (1998) also noted different land systems on the Bullajungadeah Hills compared to Rothsay and Mulgine. The Warriedar Fold Belt lies between the 250 and 300 mm rainfall isohyets and there is a gradual decrease in rainfall heading north and east into the interior. The increasing aridity appears to influence vegetation, as evidenced by the absence of the *Eucalyptus* communities on the lower slopes of the Bullajungadeah Hills, which is indicative of a shift from a more South West flora to a more Eremaean arid flora (Beard 1990).

With respect to the other communities present on the basalt hills, the laterite community (community 1) was very distinct when compared with the other communities found on the greenstones. Laterite soils are generally less fertile than other soils (Meissner & Wright 2010) as they are extremely weathered and the more mobile elements, such as Mg, are leached and transported out of the soil rapidly (Britt et al. 2001). Conversely, the soils of the *Eucalyptus* communities found on the lower slopes had higher fertility, a result of the deposition of the fertile elements and high organic matter produced by the *Eucalyptus* leaf litter. The high soil fertility and location of this community on the lower slopes is consistent with other *Eucalyptus* communities found on other arid ranges (Meissner & Wright 2010).

## Conservation

The high number of priority and endemic taxa present on the Warriedar Fold Belt makes it an area of high conservation value. Currently the majority of the mafic hills are within ex-pastoral leases purchased for the purpose of conservation; however, there are many exploration and mining tenements within the area which could provide potential land use conflicts in the future.

## ACKNOWLEDGEMENTS

We would like to thank the following people: Katrina Walton, WA Chemcentre for soil analysis; and the staff at the Western Australian Herbarium and Neil Gibson for their advice and support. Permits for flora collection were issued by the (then) Western Australian Department of Environment and Conservation. This project is part of the Special Nature Conservation Projects funded by the Department of Parks and Wildlife, Western Australia.

## REFERENCES

- Anon (1894) 'The Murchison Mine.', *The Advertiser* (Adelaide, SA : 1889–1931), 17 November, p. 5. Available at <http://nla.gov.au/nla.news-article25742061>. [Accessed 13 June 2012]
- Baxter JL, Lipple SL (1985) *Perenjori, Western Australia, 1:250,000 Geological Series – Explanatory Notes, Sheet SH/50-6*. Geological Survey of Western Australia, Perth.
- Beard JS (1976) *Murchison 1:1,000,000 Vegetation Series. Explanatory Notes to Sheet 6*. University of Western Australia Press, Perth.
- Beard JS (1990) *Plant Life of Western Australia*. Kangaroo Press, Kenthurst, NSW.
- Britt AF, Smith RE, Gray DJ (2001) Element mobilities and the Australian regolith: a mineral exploration perspective. *Marine and Freshwater Research* **52**, 25–39.
- Brown AP, Buirchell B (2007) *Eremophila densifolia* subsp. *erecta* and *E. grandiflora* (Myoporaceae), two new taxa from south-west Western Australia. *Nuytsia* **17**, 81–86.
- Bureau of Meteorology (2012) Climate Data Online <http://www.bom.gov.au/climate/data/> [Accessed 2 May 2012]
- CALM (2004) '2003–2004 Annual Report'. Department of Conservation and Land Management.
- Clarke KR, Gorley RN (2006) *PRIMER v6: User Manual/Tutorial*. PRIMER-E, Plymouth.
- Clarke KR, Warwick RM (2001) *Change in Marine Communities: An Approach to Statistical Analysis and Interpretation*, 2nd ed. PRIMER-E, Plymouth.
- De Cáceres M, Legendre P (2009) Associations between species and groups of sites: indices and statistical inference. *Ecology* **90**, 3566–3574.
- De Cáceres M, Legendre P, Moretti M (2010) Improving indicator species analysis by combining groups of sites. *Oikos* **119**, 1674–1684.
- Department of Sustainability, Environment, Water, Population and Communities (2012) Interim Biogeographic Regionalisation for Australia, Version 7. Available at <http://www.environment.gov.au/parks/nrs/science/bioregion-framework/ibra/maps.html>. [Accessed 10 August 2012]
- Gibson N (2004) Flora and vegetation of the eastern goldfields ranges: Part 7. Middle and South Ironcap, Digger Rock and Hatter Hill. *Journal of the Royal Society of Western Australia* **87**, 49–62.
- Gibson N, Meissner R, Markey AS, Thompson WA (2012) Patterns of plant diversity in ironstone ranges in arid south western Australia. *Journal of Arid Environments* **77**, 25–31.
- Gibson N, Coates DJ, Thiele KR (2007) Taxonomic research and the conservation of flora in the Yilgarn Banded Iron Formation ranges. *Nuytsia* **17**, 1–12.
- Hennig P (1998) Soils. In *An Inventory and Condition Survey of the Sandstone – Yalgoo – Paynes Find Area, Western Australia*. Technical Bulletin No. 90 (eds AL Payne, AME Van Vreeswyk, HJR Pringle, K A Leighton, P Hennig), pp. 95–118. Agriculture Western Australia, South Perth.
- Lipple SL, Baxter JL, Marston RJ (1983) *Ninghan, Western Australia, 1:250,000 Geological Series – Explanatory Notes, Sheet SH/50-7*. Geological Survey of Western Australia, Perth.
- Markey AS, Dillon SJ (2008) Flora and vegetation of the banded iron formations of the Yilgarn Craton: the central Tallering Land System. *Conservation Science Western Australia* **7**, 121–149.
- Markey AM, Kern S, Gibson N (2012) Floristic communities of the Ravensthorpe Range, Western Australia. *Conservation Science Western Australia* **8**, 187–239.
- Maslin BR, Buscumb C (2007) Two new *Acacia* species (Leguminosae: Mimosoideae) from banded ironstone ranges in the Midwest region of south-west Western Australia. *Nuytsia* **17**, 263–272.
- Maslin BR, Buscumb C (2008a) *Acacia diallaga* (Leguminosae: Mimosoideae), a new geographically restricted species with diallagous phyllodes from the Midwest Region of south-west Western Australia. *Nuytsia* **18**, 127–132.
- Maslin BR, Buscumb C (2008b) A review of *Acacia coolgardiensis* (Leguminosae: Mimosoideae) and closely related species in Western Australia. *Nuytsia* **18**, 107–125.
- McDonald RC, Isbell RE, Speight JG, Walker J, Hopkins MS (1990) *Australian Soil and Land Survey: Field Handbook*, 2nd ed. Inkata Press, Melbourne.
- Meissner R, Caruso Y (2008) Flora and vegetation of banded iron formations of the Yilgarn Craton: Mount Gibson and surrounding area. *Conservation Science Western Australia* **7**, 105–120.
- Meissner R, Wright J (2010) Flora and vegetation of banded iron formations of the Yilgarn Craton: south Illaara greenstone belt. *Conservation Science Western Australia* **7**, 605–646.
- Murray I, Bianchi P, Bloomfield M, Bridge C (2011) *West Australian Gold Towns and Settlements Volume 1*. Hesperian Press, Carlisle, WA.
- Palmer A (1999) *Yalgoo*. Hesperian Press, Carlisle, WA.
- Payne AL, Van Vreeswyk AME, Pringle HJR, Leighton KA, Hennig P (1998) *An Inventory and Condition Survey of the Sandstone – Yalgoo – Paynes Find Area, Western Australia*. Agriculture Western Australia, Technical Bulletin No. 90, South Perth.

- Shepherd KA, Rye BL, Meissner RA, West JG (2007) Two new Western Australian species of *Dodonaea* (Sapindaceae) from northern Yilgarn ironstones. *Nuytsia* **17**, 375–384.
- Smith M (2012) *Declared Rare and Priority Flora List for Western Australia*. Department of Environment and Conservation, Perth.
- Western Australian Herbarium (1998–). FloraBase—the Western Australian Flora. Department of Parks and Wildlife. Available at <http://florabase.dec.wa.gov.au> [accessed 1 July 2012].

## APPENDIX

Flora list for the Warriedar Fold Belt, including all taxa from the sampling quadrats and adjacent areas. Nomenclature follows the Western Australian Herbarium (1998–) and Conservation Codes follows Smith (2012). \* indicates an introduced species.

**Aizoaceae***\*Cleretum papulosum**Gunnioopsis rubra**\*Mesembryanthemum nodiflorum***Amaranthaceae***Ptilotus aervoides**Ptilotus exaltatus**Ptilotus gaudichaudii* subsp. *eremita**Ptilotus gaudichaudii* var. *gaudichaudii**Ptilotus helipteroides**Ptilotus macrocephalus**Ptilotus obovatus**Ptilotus schwartzii***Apiaceae***Daucus glochidiatus**Xanthosia bungei***Apocynaceae***Alyxia buxifolia***Araliaceae***Hydrocotyle pilifera* var. *glabrata**Hydrocotyle* sp. Warriedar

(PG Wilson 12267)

P1

*Trachymene cyanopetala**Trachymene ornata***Asparagaceae***Arthropodium dyeri**Thysanotus manglesianus**Thysanotus pyramidalis***Asteraceae***Actinobole uliginosum**Asteridea athrixioides**Bellida graminea**Blennospora drummondii**Brachyscome ciliaris**Brachyscome cillocarpa**Calocephalus* aff. *multiflorus* (Markey & Dillon 3464)*Calocephalus multiflorus**Calotis hispidula**Calotis multicaulis**Cephalopterum drummondii**Ceratogyne obionoides**Chthonocephalus pseudevax**Erymophyllum glossanthus**Gilruthia osbornei**Gnephosis arachnoidea**Gnephosis brevifolia**Gnephosis eriocephala**Gnephosis tenuissima**Helipterum craspedioides**Hyalosperma demissum**Hyalosperma glutinosum* subsp. *venustum**Hyalosperma zacchaeus**\*Hypochoeris glabra**Isoetopsis graminifolia**Lawrencella rosea**Lemooria burkittii**Millotia dimorpha*

P1

*Millotia myosotidifolia**Myriocephalus guerinae**Olearia humilis**Olearia pimeleoides**Podolepis canescens**Podolepis gardneri**Podolepis lessonii**Podotheca gnaphalioides**Pogonolepis stricta**Rhodanthe battii**Rhodanthe chlorocephala* subsp. *rosea**Rhodanthe chlorocephala* subsp. *splendida**Rhodanthe citrina**Rhodanthe collina*

P1

*Rhodanthe laevis**Rhodanthe manglesii**Rhodanthe maryonii**Rhodanthe oppositifolia* subsp. *oppositifolia**Rhodanthe polycephala**Rhodanthe stricta**Schoenia cassiniana**Senecio lacustrinus**\*Sonchus oleraceus**Trichanthodium skirrophorum**Triptilodiscus pygmaeus**Vittadinia humerata**Waitzia acuminata* var. *acuminata**Waitzia nitida***Boraginaceae***Halgania cyanea* var. Allambi Stn (BW Strong 676)*Omphalolappula concava***Boryaceae***Borya sphaerocephala***Brassicaceae***\*Brassica toumefortii**Lepidium oxytrichum**Menkea australis**Stenopetalum anfractum**Stenopetalum filifolium**Stenopetalum lineare* var. *lineare***Campanulaceae***Lobelia rhytidosperma**Lobelia winfridae**Wahlenbergia gracilentia**Wahlenbergia preissii***Caryophyllaceae***\*Silene nocturna**Stellaria filiformis***Casuarinaceae***Allocasuarina acutivalvis* subsp. *prinsepiana**Allocasuarina dielsiana**Allocasuarina tessellata*

P1

**Celastraceae***Stackhousia muricata*

Chenopodiaceae

*Dysphania glandulosa**Enchylaena lanata**Enchylaena* sp.*Enchylaena tomentosa*

## Appendix (cont.)

<i>Enchylaena tomentosa</i> × <i>Maireana georgei</i>		<i>Acacia tetragonophylla</i>	
<i>Eriochiton sclerolaenoides</i>		<i>Acacia umbraculiformis</i>	
<i>Maireana carnosa</i>		<i>Gastrolobium laytonii</i>	
<i>Maireana georgei</i>		<i>Leptosema aphyllum</i>	
<i>Maireana marginata</i>		* <i>Medicago minima</i>	
<i>Maireana planifolia</i>		<i>Mirbelia bursarioides</i>	
<i>Maireana thesioides</i>		<i>Mirbelia microphylla</i>	
<i>Maireana trichoptera</i>		<i>Senna artemisioides</i> subsp. <i>filifolia</i>	
<i>Rhagodia drummondii</i>		<i>Senna artemisioides</i> subsp. <i>helmsii</i>	
<i>Salsola australis</i>		<i>Senna charlesiana</i>	
<i>Sclerolaena densiflora</i>		<i>Senna glaucifolia</i>	
<i>Sclerolaena diacantha</i>		<i>Senna glutinosa</i> subsp. <i>chatelainiana</i>	
<i>Sclerolaena fusiformis</i>		<i>Senna</i> sp. Austin (A Strid 20210)	
<i>Sclerolaena gardneri</i>		<i>Senna</i> sp. Meekatharra (E Bailey 1-26)	
<i>Sclerolaena patentiscuspis</i>		<i>Senna stowardii</i>	
<b>Colchicaceae</b>		<b>Geraniaceae</b>	
<i>Wurmbea</i> sp. Paynes Find (CJ French 1237)		<i>Erodium cygnorum</i>	
<b>Convolvulaceae</b>		<b>Goodeniaceae</b>	
* <i>Cuscuta planiflora</i>		<i>Brunonia australis</i>	
<i>Duperreya sericea</i>		<i>Goodenia berardiana</i>	
<b>Crassulaceae</b>		<i>Goodenia krauseana</i>	
<i>Crassula closiana</i>		<i>Goodenia mimuloides</i>	
<i>Crassula colorata</i> var. <i>acuminata</i>		<i>Goodenia occidentalis</i>	
<i>Crassula colorata</i> var. <i>colorata</i>		<i>Goodenia pinnatifida</i>	
<i>Crassula tetramera</i>		<i>Scaevola spinescens</i>	
<b>Cyperaceae</b>		<i>Velleia hispida</i>	
<i>Lepidosperma</i> sp. Blue Hills (A Markey & S Dillon 3468)	P1	<i>Velleia rosea</i>	
<i>Schoenus nanus</i>		<b>Haloragaceae</b>	
<b>Dilleniaceae</b>		<i>Gonocarpus nodulosus</i>	
<i>Hibbertia arcuata</i>		<i>Haloragis odontocarpa</i> forma <i>rugosa</i>	
<i>Hibbertia exasperata</i>		<i>Haloragis trigonocarpa</i>	
<b>Ericaceae</b>		<b>Hemerocallidaceae</b>	
<i>Astroloma serratifolium</i>		<i>Caesia</i> sp. Wongan (KF Kenneally 8820)	
<i>Leucopogon</i> sp. Clyde Hill (MA Burgman 1207)		<i>Dianella revoluta</i> var. <i>divaricata</i>	
<b>Euphorbiaceae</b>		<i>Tricoryne</i> sp. Morawa (GJ Keighery & N Gibson 6759)	P3
<i>Calycopeplus paucifolius</i>		<b>Juncaginaceae</b>	
<i>Euphorbia boophthona</i>		<i>Triglochin isingiana</i>	
<i>Euphorbia drummondii</i>		<b>Lamiaceae</b>	
<i>Euphorbia tannensis</i> subsp. <i>eremophila</i>		<i>Hemigenia benthamii</i>	
<b>Fabaceae</b>		<i>Hemigenia</i> sp. Yalgoo (AM Ashby 2624)	
<i>Acacia acanthoclada</i> subsp. <i>glauescens</i>		<i>Hemigenia</i> sp. Yuna (AC Burns 95)	
<i>Acacia acutaria</i>		<i>Prostanthera althoferi</i>	
<i>Acacia andrewsii</i>		<i>Prostanthera patens</i>	
<i>Acacia anthochaera</i>		<b>Loganiaceae</b>	
<i>Acacia assimilis</i> subsp. <i>assimilis</i>		<i>Phyllangium sulcatum</i>	
<i>Acacia burkittii</i>		<b>Malvaceae</b>	
<i>Acacia caesaneura</i>		<i>Abutilon oxycarpum</i> subsp. <i>prostratum</i>	
<i>Acacia caesaneura</i> hybrid		<i>Alyogyne hakeifolia</i>	
<i>Acacia diallaga</i>	P2	<i>Brachychiton gregorii</i>	
<i>Acacia effusifolia</i>		<i>Sida</i> sp. dark green fruits (S van Leeuwen 2260)	
<i>Acacia erinacea</i>		<i>Sida</i> sp. Golden calyces glabrous (HN Foote 32)	
<i>Acacia exocarpoides</i>		<b>Myrtaceae</b>	
<i>Acacia incurvaneura</i>		<i>Aluta aspera</i> subsp. <i>hesperia</i>	
<i>Acacia karina</i>	P2	<i>Calothamnus gilesii</i>	
<i>Acacia kochii</i>		<i>Chamaelaucium</i> sp. Warriedar (AP Brown & S Patrick APB 1100)	P1
<i>Acacia mulganeura</i>		<i>Eucalyptus clelandii</i>	
<i>Acacia pteraneura</i>		<i>Eucalyptus loxophleba</i> subsp. <i>supralaevis</i>	
<i>Acacia ramulosa</i> var. <i>ramulosa</i>		<i>Eucalyptus salubris</i>	
<i>Acacia sibina</i>		<i>Melaleuca eleuterostachya</i>	
<i>Acacia subsessilis</i>	P3		
<i>Acacia sulcaticaulis</i>	P1		

<i>Melaleuca hamata</i>			
<i>Melaleuca nematophylla</i>			
<i>Melaleuca radula</i>			
<i>Micromyrtus acuta</i>	P3		
<i>Micromyrtus clavata</i>			
<i>Micromyrtus trudgenii</i>	P3		
<i>Thryptomene costata</i>			
<i>Thryptomene decussata</i>			
<b>Orchidaceae</b>			
<i>Cyanicula fragrans</i>	P3		
<i>Pterostylis</i> sp. dainty brown (N Gibson & M Lyons 3690)			
<b>Orobanchaceae</b>			
* <i>Parentucellia latifolia</i>			
<b>Phyllanthaceae</b>			
<i>Poranthera leiosperma</i>			
<i>Poranthera microphylla</i>			
<b>Pittosporaceae</b>			
<i>Cheiranthra simplicifolia</i>			
<b>Plantaginaceae</b>			
<i>Plantago debilis</i>			
<b>Poaceae</b>			
<i>Anthosachne scabra</i>			
<i>Aristida contorta</i>			
<i>Austrostipa blackii</i>	P3		
<i>Austrostipa elegantissima</i>			
<i>Austrostipa eremophila</i>			
<i>Austrostipa nitida</i>			
<i>Austrostipa scabra</i>			
<i>Austrostipa trichophylla</i>			
<i>Enneapogon caeruleus</i>			
<i>Eriachne pulchella</i> subsp. <i>pulchella</i>			
<i>Lachnagrostis plebeia</i>			
<i>Monachather paradoxus</i>			
* <i>Pentameris airoides</i> subsp. <i>airoides</i>			
* <i>Rostraria pumila</i>			
<i>Rytidosperma caespitosum</i>			
* <i>Schismus barbatus</i>			
<i>Tripogon loliformis</i>			
<b>Polygalaceae</b>			
<i>Comesperma integerrimum</i>			
<b>Polygonaceae</b>			
* <i>Acetosa vesicaria</i>			
<b>Portulacaceae</b>			
<i>Calandrinia calyptrata</i>			
<i>Calandrinia creethiae</i>			
<i>Calandrinia eremaea</i>			
<i>Calandrinia</i> sp. Warriedar (F Obbens 04/09)	P2		
<i>Calandrinia translucens</i>			
<b>Primulaceae</b>			
* <i>Lysimachia arvensis</i>			
<b>Proteaceae</b>			
<i>Grevillea hakeoides</i> subsp. <i>stenophylla</i>			
<i>Grevillea obliquistigma</i>			
subsp. <i>obliquistigma</i>			
<i>Grevillea scabrata</i>		P3	
<i>Grevillea subtiliflora</i>		P3	
<i>Hakea preissii</i>			
<i>Persoonia pentasticha</i>		P3	
<b>Pteridaceae</b>			
<i>Cheilanthes adiantoides</i>			
<i>Cheilanthes brownii</i>			
<i>Cheilanthes sieberi</i> subsp. <i>sieberi</i>			
<b>Rhamnaceae</b>			
<i>Cryptandra micrantha</i>			
<i>Stenanthemum poecilum</i>		P3	
<b>Rutaceae</b>			
<i>Philotheca brucei</i> subsp. <i>brucei</i>			
<i>Philotheca sericea</i>			
<b>Santalaceae</b>			
<i>Exocarpos aphyllus</i>			
<i>Santalum acuminatum</i>			
<i>Santalum spicatum</i>			
<b>Sapindaceae</b>			
<i>Dodonaea amplisemina</i>		P4	
<i>Dodonaea inaequifolia</i>			
<i>Dodonaea rigida</i>			
<b>Scrophulariaceae</b>			
<i>Eremophila clarkei</i>			
<i>Eremophila eriocalyx</i>			
<i>Eremophila forrestii</i> subsp. <i>forrestii</i>			
<i>Eremophila georgei</i>			
<i>Eremophila glutinosa</i>			
<i>Eremophila grandiflora</i>		P3	
<i>Eremophila granitica</i>			
<i>Eremophila latrobei</i>			
<i>Eremophila oldfieldii</i> subsp. <i>oldfieldii</i>			
<i>Eremophila oppositifolia</i> subsp. <i>angustifolia</i>			
<i>Eremophila pantonii</i>			
<i>Eremophila platycalyx</i> subsp. <i>platycalyx</i>			
<i>Eremophila</i> sp. (Meissner & Coppen 4312)			
<b>Solanaceae</b>			
<i>Nicotiana rotundifolia</i>			
<i>Solanum ellipticum</i>			
<i>Solanum lasiophyllum</i>			
<i>Solanum nummularium</i>			
<i>Solanum orbiculatum</i>			
<b>Stylidiaceae</b>			
<i>Levenhookia leptantha</i>			
<b>Urticaceae</b>			
<i>Parietaria cardiostegia</i>			
<b>Violaceae</b>			
<i>Hybanthus floribundus</i> subsp. <i>curvifolius</i>			
<b>Zygophyllaceae</b>			
<i>Zygophyllum lobulatum</i>			
<i>Zygophyllum ovatum</i>			
<i>Zygophyllum reticulatum</i>			

# Flora and vegetation of the greenstone ranges of the Yilgarn Craton: Kangaroo Hills and surrounding area

RACHEL A MEISSNER AND REBECCA COPPEN

Science and Conservation Division, Department of Parks and Wildlife Conservation,  
Locked Bag 104, Bentley Delivery Centre, Western Australia, 6983.

Corresponding author email: rachel.meissner@dpaw.wa.gov.au

## ABSTRACT

A series of timber reserves in the Coolgardie Bioregion were gazetted in the early 20th century to protect the woodlands and to ensure sufficient local supply of firewood close to towns. This paper describes the flora and vegetation on the greenstone hills within these timber reserves and their relationships with environmental variables. A total of 160 taxa were recorded from the survey, including a single taxon of conservation significance. The reserves are characterised by four different *Eucalyptus* woodland communities, with the most widespread community (community 3) occurring on the slopes and crests of the greenstone ranges. This community is dominated by *Eucalyptus lesouefii*, *E. torquata*, *E. griffithsii* and *E. celastroides* subsp. *celastroides*, and is consistently associated with soils that are more alkaline and higher in Mg and Ca compared with soils of other communities. Floristically, this woodland community is different to other eucalypt communities occurring on the crests of the greenstone ranges in the region.

**Keywords:** greenstone, floristics, ranges, vegetation communities, Yilgarn

## INTRODUCTION

Previous surveys of greenstone ranges in south-west Western Australia have highlighted the significance of the greenstone ranges within the South Western Interzone as areas of high plant endemism (Gibson et al. 2012). The greenstone ranges contain the rich deposits of nickel and gold found in the Western Australian goldfields. The recent boom in exploration and mining has led to a potential conflict between resource development and conservation values within the region. This paper is part of a continuing series investigating the flora and vegetation occurring on greenstone ranges within the Yilgarn Craton of Western Australia.

Several timber reserves, state forests and nature reserves are located within the Great Western Woodlands within the Coolgardie IBRA Bioregion. Many of these occur in the area south of Coolgardie and there are also significant areas of forest within the Norseman–Wiluna Greenstone Belt. This greenstone belt is expressed in the landscape as north-north-west trending ranges that lie between the towns of Coolgardie and Widgiemooltha (Fig. 1). The highest peak within the range, Comet Hill (508 m), occurs within Kangaroo Hills Timber Reserve. Surrounding the ranges are Quaternary-aged colluvial deposits derived from the greenstone range.

The objective of this paper is to describe the flora and vegetation of the greenstone ranges within the Kangaroo

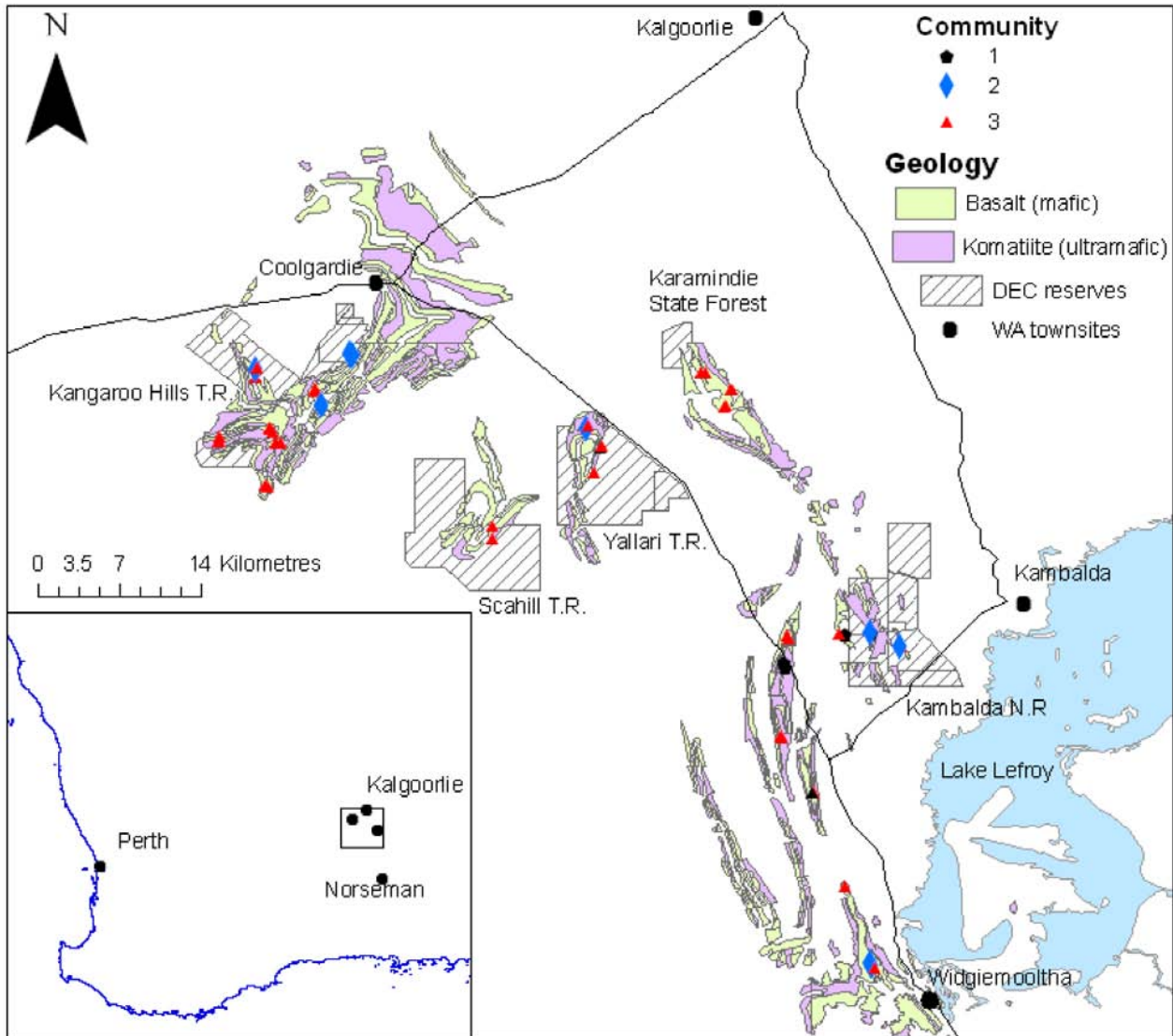
Hills Timber Reserve and the surrounding Coolgardie area and to examine whether the patterns in community composition can be explained by any of the environmental variables. This information will provide baseline information for future management of the greenstone ranges in the area.

## Land use

Kangaroo Hills Timber Reserve is located in the woodlands surrounding Kalgoorlie and Coolgardie. These woodlands are part of the Great Western Woodlands, the largest extant area of Mediterranean-climate woodland in the world (Department of Environment and Conservation 2011). There has been a long association of the area with timber and mining since gold was first discovered in 1892 (Blatchford 1899). Timber was felled and used domestically for firewood, as timber supports in underground mining, and as a source of fuel in the steam boilers (Keally 1991). After clearfelling, the woodlands were then left to regenerate naturally from seed and coppicing (Beard 1990). The reserves were established to control the extent of cutting, to protect the woodlands and to ensure sufficient local supply of firewood (Keally 1991). Current land tenure surrounding the reserves is a combination of unallocated crown land and pastoral leases, with much of the area covered by mining tenements.

## Climate

The climate of the region is classified as semi-arid and characterised by hot, dry summers and mild winters.



**Figure 1.** Location of the 52 quadrats (▲) established on the greenstone ranges on the Kangaroo Hills timber reserves (T.R.) and other reserves (hatched areas) within the Coolgardie Bioregion. The Archaean mafic and ultramafic geology are shown in green and purple respectively.

Rainfall is bimodal, with peaks occurring in summer (January to March) and winter (May to August). The highest mean monthly rainfall at Coolgardie occurs in June (29.6 mm) with the highest daily rainfall of 181.4 mm occurring in January 1967. Mean annual rainfall at Coolgardie is 270.7 mm, with a large variation (169.3 mm, 1st decile; 373.8 mm, 9th decile; recorded 1893–2012). The highest maximum temperatures occur during summer, with January the hottest month (mean maximum temperature 33.3 °C; 1897–1953). Winters are mild, with lowest mean maximum temperatures recorded for July of 5.2 °C.

### Geology

The greenstone ranges occur within the Kalgoorlie Terrane and form the western boundary of the Norseman–Wiluna Greenstone Belt. The Norseman–Wiluna Greenstone Belt

is composed of a series of mafic to ultramafic volcanic flows, which were formed approximately 2.8 to 2.5 billion years ago during the Proterozoic eon (Griffin 1989) and then underwent metamorphism, including folding, fracturing and intrusion. Sedimentary rock, such as banded ironstones and cherts, are often associated with other greenstone belts and are interlayered with the volcanic flows. The name greenstone is derived from the greenish colour that some of the metamorphic minerals give to the volcanic rocks. The Norseman–Wiluna Greenstone Belt is high in komatiite, a type of ultramafic volcanic rock low in Si, K and Al, and high to extremely high in Mg content, and the site of the rich nickel deposits in the area (Anand & Butt 2010). Basalts are also present, interlayered with the komatiite, and are generally classified as mafic rocks (high in Mg and Fe). Both komatiite and basalt are referred to as greenstone rocks.

## Vegetation

Despite the amount of mining and pastoral activity in the region and the number of collections in the Western Australian Herbarium, there have been few detailed botanical surveys of the vegetation within the reserves and surrounding areas south of Coolgardie. The area was first broadly mapped by Beard (1976), with the greenstone ranges part of his Coolgardie system, which is characterised by mainly sclerophyll woodlands with some mallee and broombush thicket. Beard (1990) later described the vegetation of greenstone ranges as woodlands predominantly of *Eucalyptus torquata* – *Eucalyptus lesouefii*, with associated *Casuarina cristata*, *Eucalyptus campaspe* and *Eucalyptus clelandii*, with an open shrub understorey of common species such as *Eremophila scoparia*, *E. glabra*, *E. oldfieldii*, *Dodonaea lobulata*, *Senna cardiosperma* and *Acacia* spp.

The vegetation on the greenstone ranges around Kambalda and Widgiemooltha, in the southern part of our study area (Fig. 1), was described in more detailed geobotanical studies by Cole (1973, 1992). The communities on the basalt around Kambalda were characterised as open woodlands dominated by *Eucalyptus lesouefii* associated with *E. salmonophloia*, *Santalum acuminatum* and *S. spicatum* on deeper soils. On skeletal soils on the hill crests, the woodland is replaced by tall shrubland of *Acacia quadrimarginea*, *A. tetragonophylla*, *Dodonaea lobulata*, *Eremophila duttonii* and *Scaevola spinescens* over *Ptilotus obovatus*. *Eucalyptus foecunda* and *E. torquata* were also common eucalypts on the deeper soils. Around Widgiemooltha, Cole (1973) described the communities as woodlands of relatively tall *Eucalyptus griffithsii*, *E. oleosa* and *E. salmonophloia* associated with the tall shrubs *Alyxia buxifolia*, *Acacia hemiteles*, *Eremophila glabra*, *E. interstans*, *E. ionantha*, *E. scoparia* and *Scaevola spinescens* over low shrubs of *Acacia colletioides*, *Maireana georgei* and *Olearia muelleri*. Of note, she highlighted *Hybanthus floribundus* and *Trymalium myrtillus* as shrubs that are confined to skeletal soils with high concentrations of Cr and Ni, with *H. floribundus* a hyper-accumulator of Ni (see also Severne & Brooks 1972).

## METHODS

The methods used in this survey follow the standard procedure used in previous vegetation surveys of other ironstone and greenstone ranges in Western Australia (Markey & Dillon 2008; Meissner & Caruso 2008). Fifty-two 20 × 20 m quadrats were established on the stony crests, slopes and footslopes of the greenstone ranges within the reserves and on unallocated crown land (UCL) during October 2011 (Fig. 1). The reserves were Kangaroo Hills, Seahill, Kambalda and Yallari timber reserves, Karamindie State Forest and Kamabalda Nature Reserve, all managed by the Department of Parks and Wildlife. The placement of quadrats was stratified based on the broad variation in geology and topography, with quadrats

located across the hills in a toposequence from crests to footslopes and plains, in the least disturbed vegetation available in the area sampled, avoiding areas heavily grazed or cleared. Each quadrat was permanently marked with four steel fence droppers and their positions determined using a Garmin GPS MAP 60CSx. All vascular plants within the quadrat were recorded and collected, in addition to opportunistic collections outside the quadrats, for later identification at the Western Australian Herbarium. Nomenclature follows the Western Australian Herbarium (1998–).

Data were recorded on the following: aspect, slope, morphology type (1 – crest, 2 – mid slope, 3 – lower slope, 4 – simple slope); landform (1 – hill crest, 2 – hill slope); disturbance (0 – no effective disturbance, 1 – no effective disturbance except grazing by hoofed animals); maximum size of coarse fragments (CF size; 1 – fine gravelly to 6 – boulders); coarse fragment (CF) abundance (0 – no coarse fragments to 6 – very abundant coarse fragments); rock outcrop (RO) abundance (0 – no bedrock exposed to 4 – very rocky); runoff (0 – no runoff to 4 – rapid); soil depth (1 – skeletal, 2 – shallow, 3 – deep); cover of leaf litter and proportion of bare ground (McDonald et al. 1990). Additionally, growth form, height and cover were recorded for the dominant taxa in each strata (upper, mid and lower). Cover was estimated as one of six cover classes: dense (> 70%), mid-dense (30–70%), sparse (10–30%), very sparse (<10%), isolated plants (< 1%) and isolated clumps (<1%) (McDonald et al. 1990). Growth form of the plant was classified as either a tree, tree mallee (>8 m), shrub mallee (<8 m), shrub, chenopod shrub, sedge, forb or fern. Cover and growth form for each strata were used to describe the plant communities following McDonald et al. (1990).

Twenty soil samples were collected from the upper 10 cm of the soil profile within each quadrat. The samples were bulked and the 2 mm fraction analysed for Al, B, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, S and Zn using an Inductively Coupled Plasma – Atomic Emission Spectrometer (ICP–AES). Electrical conductivity (EC), organic C, N and pH were determined using alternative methods, which are fully described in Meissner and Wright (2010).

Quadrats were classified on the basis of similarity in species composition using perennial species only and excluding single occurrences. This removed any temporal variation associated with the presence of annual species that may confound comparisons with other greenstone and banded ironstone ranges (Markey & Dillon 2008; Meissner & Caruso 2008 and references therein). The quadrat and species classifications were undertaken using the Bray–Curtis coefficient on presence/absence data followed by hierarchical clustering (using group-average linking) in PRIMER (Clarke & Gorley 2006). Quadrat classification was followed by similarity profile (SIMPROF) testing to determine the significance of internal group structures using permutation testing (Clarke & Gorley 2006). Vegetation communities were assigned based upon the SIMPROF results. Indicator species for vegetation communities were determined following De

Cáceres et al. (2010) using ‘indicspecies’ in the R language (De Cáceres & Legendre 2009). Indicator species are taxa that, due to niche preferences, can be used as ecological indicators of community types (De Cáceres & Legendre 2009) and can be used to identify community types during further surveys. Following the classification, the quadrat data was ordinated using non-metric multidimensional scaling (nMDS), a nonparametric approach not based upon the assumptions of linearity or presumption of any underlying model of species response gradients (Clarke & Gorley 2006).

To determine the environmental variables that best explained the community pattern, the BEST analysis using BIOENV algorithm in PRIMER v6 (Clarke & Gorley 2006) was undertaken on a Euclidean distance resemblance matrix based on normalised environmental data. The BEST routine selects environmental variables that best explain the community pattern, by maximising a rank correlation between their respective resemblance matrices (Clarke & Warwick 2001). In the BIOENV algorithm, all permutations of the environmental variables were tried and the five best variables selected. The environmental variables were then fitted to the nMDS ordination and Pearson rank correlation values ( $r > 0.6$ ) were calculated to determine linear relationships between the variables and the vegetation communities.

## RESULTS

### Flora

A total of 160 taxa (species, subspecies, varieties and forms) were recorded from all the quadrats and opportunistic collections. The most common families were Chenopodiaceae (18 taxa), Asteraceae (17), Scrophulariaceae (17) and Myrtaceae (16), and the most common genera were *Eremophila* (17 taxa), *Eucalyptus* (12), *Acacia* (10) and *Austrostipa* (7). Forty-five annuals were recorded, including all five introduced taxa (Table 1). None of the introduced taxa were declared weeds and no endemic taxa were recorded for the range.

### Priority flora

A single priority taxon (Smith 2012) was collected from five quadrats spread across the survey area. *Austrostipa*

**Table 1**

Summary of the number of families, genera and taxa, including numbers of introduced taxa, recorded from the survey.

	Total	Dicotyledons	Monocotyledons	Pteridophytes
Families	38	33	4	1
Genera	78	68	7	1
Taxa	160	143	14	3
Native	155	139	13	3
Introduced	5	4	1	-

*blackii* (P3) is a perennial tufted grass found mainly in the eastern states of Australia. It has a distinctive lemma with a long coma at the base of the awn. It is found in disjunct locations from Paynes Find to Widgiemooltha.

### Flora of taxonomic interest

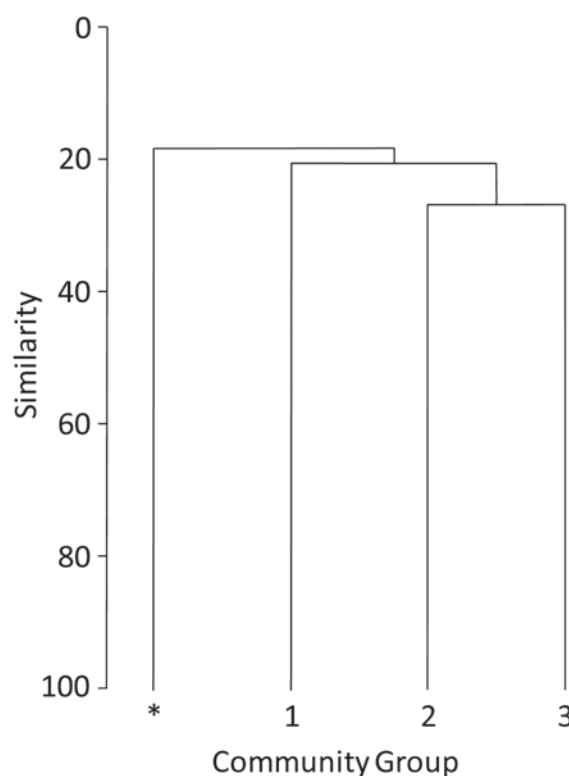
Two taxa collected require either taxonomic study to determine their taxonomic status or were determined to be new species:

*Acacia coatesii* was found at a single site within the Kangaroo Hills Timber Reserve, and is known from only two other localities within the Kangaroo Hills. This taxon has a distinctive small, compact, low-domed habit to 20 to 40 cm tall and has short, pungent phyllodes (Maslin 2014).

*Lepidosperma* aff. *diurnum* was collected at several sites, mostly opportunistically, and growing on laterised greenstone. It appears to have close affinities to *L. diurnum*, found on Mount Day on the Bremer Range, and possesses similar red ciliate leaf margins. In this survey, it was collected from Saddle Hills, the same location as the only other known specimen in the Western Australian Herbarium.

### Vegetation

Three vegetation communities were determined from the classification (Fig. 2). The dendrogram shows a stepwise division of the four communities. The first division consisted of two sites only, a sample too small to describe



**Figure 2.** Dendrogram of the vegetation communities derived from the 52 quadrats established on the Kangaroo Hills and surrounding area. (\* represents two species-poor quadrats.)

**Table 2**

Two-way table of quadrat and species classification of the three communities found on the Kangaroo Hills timber reserve and surrounding areas. Taxa shaded black within a community are indicator species determined by 'indicspecies' ( $p < 0.05$ ; De Cáceres & Legendre 2009). (\* represents 2 species poor quadrats.)

Species Groups	*	1	2	3
<b>Group a</b>				
<i>Acacia burkittii</i>				
<b>Group b</b>				
<i>Dampiera lateolata</i>				
<i>Pimelea microcephala</i> subsp. <i>microcephala</i>				
<i>Acacia</i> sp. narrow phyllode (B.R. Maslin 7831)				
<i>Prostanthera incurvata</i>				
<i>Eremophila gibbosa</i>				
<i>Senna artemisioides</i> subsp. <i>x artemisioides</i>				
<i>Austrostipa eremophila</i>				
<i>Solanum lasiophyllum</i>				
<i>Acacia</i> sp. Norseman (B. Archer 1554)				
<i>Marsdenia australis</i>				
<i>Cheilanthes sieberi</i> subsp. <i>sieberi</i>				
<i>Austrostipa blackii</i>				
<i>Prostanthera althoferi</i> subsp. <i>althoferi</i>				
<i>Chrysocephalum putale</i>				
<i>Eremophila clarkii</i>				
<i>Sida calyxymenia</i>				
<b>Group c</b>				
<i>Sida spodochroma</i>				
<i>Grevillea nematophylla</i> subsp. <i>nematophylla</i>				
<i>Olearia pimeleoides</i>				
<i>Eriochiton sclerolaenoides</i>				
<i>Austrostipa trichophylla</i>				
<i>Austrostipa platychaeta</i>				
<i>Zygophyllum apiculatum</i>				
<b>Group d</b>				
<i>Solanum nummularium</i>				
<i>Maireana tomentosa</i> subsp. <i>tomentosa</i>				
<i>Sclerolaena drummondii</i>				
<b>Group e</b>				
<i>Eremophila caerulea</i> subsp. <i>caerulea</i>				
<i>Eremophila ionantha</i>				
<i>Sclerolaena fusiformis</i>				
<b>Group f</b>				
<i>Eremophila dempsteri</i>				
<i>Allocasuarina helmsii</i>				
<i>Acacia pachypoda</i>				
<i>Dodonaea stenozyga</i>				
<i>Melaleuca pauperiflora</i> subsp. <i>fastigiata</i>				
<i>Ricinocarpos stylosus</i>				
<i>Halgalina andromedifolia</i>				
<i>Eremophila clavata</i>				
<i>Eucalyptus lesouefii</i>				
<i>Grevillea acuarina</i>				
<i>Pomaderris forrestiana</i>				
<i>Eremophila psilocalyx</i>				
<i>Eucalyptus torquata</i>				
<b>Group g</b>				
<i>Eremophila interstans</i> subsp. <i>interstans</i>				
<i>Chenopodium curvispicatum</i>				
<i>Sclerolaena obliquicuspis</i>				
<i>Enchylaena tomentosa</i>				
<i>Maireana trichoptera</i>				
<i>Rhagodia drummondii</i>				
<i>Atriplex vesicaria</i>				
<i>Eucalyptus griffithsii</i>				
<i>Acacia tetragonophylla</i>				
<i>Austrostipa scabra</i>				
<i>Pterostylis</i> sp. dainty brown (N. Gibson & M. Lyons 3690)				
<i>Rytidosperma caespitosum</i>				
<i>Eremophila alternifolia</i>				
<i>Thysanotus manglesianus</i>				
<i>Maireana georgei</i>				
<i>Maireana pentatropis</i>				
<i>Eucalyptus celastroides</i> subsp. <i>celastroides</i>				
<i>Atriplex nummularia</i> subsp. <i>spatulata</i>				
<i>Sclerolaena diacantha</i>				
<i>Austrostipa nitida</i>				
<i>Acacia hemiteles</i>				
<i>Eremophila scoparia</i>				
<i>Dodonaea microzyga</i> var. <i>acrolobata</i>				
<i>Eremophila oldfieldii</i> subsp. <i>angustifolia</i>				
<i>Dodonaea labulata</i>				
<i>Ptilotus obovatus</i>				
<i>Eremophila glabra</i> subsp. <i>glabra</i>				
<i>Senna artemisioides</i> subsp. <i>filifolia</i>				
<i>Santalum spicatum</i>				
<i>Trymalium myrtillus</i> subsp. <i>myrtillus</i>				
<i>Austrostipa elegantissima</i>				
<i>Eremophila oppositifolia</i> subsp. <i>angustifolia</i>				
<i>Acacia erinacea</i>				
<i>Westringia rigida</i>				
<i>Alyxia buxifolia</i>				
<i>Exocarpos aphyllus</i>				
<i>Olearia muelleri</i>				
<i>Scaevola spinescens</i>				
<b>Group h</b>				
<i>Eucalyptus oleosa</i> subsp. <i>oleosa</i>				
<i>Santalum acuminatum</i>				
<i>Eremophila rugosa</i>				
<i>Eucalyptus campaspe</i>				
<i>Eucalyptus clelandii</i>				
<i>Acacia andrewsii</i>				
<i>Casuarina pauper</i>				
<i>Eremophila parvifolia</i> subsp. <i>auricampa</i>				

as a community, followed by community 1, found on the crests of hills in an area around Kambalda Nature Reserve. Communities 2 and 3 were widespread across the study area and were most similar to each other.

Community 1 was characterised by woodlands (10–30% cover) or open forest (30–70% cover) of *Eucalyptus torquata* (coral gum) over sparse shrubland (<10% cover) of *Ricinocarpos stylosus*, *Dodonaea stenozyga*,

*Eremophila* spp. (*E. dempsteri*, *E. psilocalyx*), over low shrubland (30–70% cover) of *Westringia rigida*, *Halgania andromedifolia* and *Acacia pachypoda*. Quadrats contained in this group (n = 4) were located on the basalt crests occurring in the Kambalda Nature Reserve and the basalt hills to the west. Indicator species were *Acacia pachypoda*, *Dodonaea stenozyga*, *Melaleuca pauperiflora* subsp. *fastigiata*, *Ricinocarpos stylosus*, *Eremophila psilocalyx* and *Eucalyptus torquata* (Table 1). Mean species richness was 17.8 ( $\pm 1.9$  SE) perennial taxa per plot.

Community 2 was characterised by mallee woodlands and shrublands (10–30% cover) to open mallee woodlands and shrublands (<10% cover) of *Eucalyptus griffithsii* and *Acacia* sp. Norseman (B Archer 1554) over shrublands (30–70% cover) of *Dodonaea lobulata*, *Eremophila* spp. (*Eremophila oldfieldii* subsp. *angustifolia*, *Eremophila glabra* subsp. *glabra*, *Eremophila clarkei* and *Eremophila alternifolia*), *Scaevola spinescens* over low shrubland (30–70% cover) of *Ptilotus obovatus*. The quadrats in this community (n = 10) were located mainly on the crests of the greenstone hills throughout the study area. Indicator species were *Acacia* sp. Norseman (B Archer 1554), *Ptilotus obovatus*, *Marsdenia australis* and *Austrostipa blackii* (Table 1). The mean species richness was 19.0 ( $\pm 1.1$  SE) perennial taxa per plot.

Community 3 was characterised as an open forest to open woodland complex of *Eucalyptus* spp. (*E. lesouefii*, *E. torquata*, *E. griffithsii*, or *E. celastroides* subsp. *celastroides*) over open shrublands of *Scaevola spinescens*,

*Eremophila oldfieldii* subsp. *angustifolia*, *Senna artemisioides* subsp. *filifolia* and *Halgania andromedifolia*. The quadrats characterising this community (n = 36) occurred across all positions within the landscape across the study area. There were no unique indicator species for this community, but *Olearia muelleri* and *Senna artemisioides* subsp. *filifolia* were indicator species for both communities 2 and 3 (Table 1). Mean species richness was 17.4 ( $\pm 0.8$  SE) perennial taxa per plot.

## Environmental correlates

The topography of the greenstone ranges is characterised by gentle hills with moderate to gentle slopes, with the elevations of sampled sites ranging from 348 to 510m. Soils at these quadrats were predominantly shallow to skeletal soils of red-brown sandy clay loam.

The nonparametric analysis of variance on communities 1, 2 and 3 found that while 12 of the 20 soil parameters were significantly different (Table 4), none of the 13 site attributes were significantly different between the three communities (Table 3). Soils associated with community 2, confined to the crests of the range, had significantly lower concentrations of B, Ca, Cd and Mg and had lower soil pH than communities 1 and 3, but significantly greater concentrations of Al, Co, Cu and Mn (Table 4). EC and Na were only significantly greater in the soils of community 3 than those of community 2. Sites that were more alkaline also had higher Ca and Mg concentrations.

The BIOENV analysis indicated that the best correlation between the quadrat and environmental similarity matrices was obtained with five soil variables: pH, Al, B, Fe and Mn ( $r = 0.406$ ). The two dimensional MDS (stress = 0.17; Fig. 3) clearly showed that all four communities were separated on the MDS. Four soil variables correlated with the MDS ( $r > 0.6$ ; Fig. 3). B, pH and Mg were positively correlated with communities 1 and 3 while Al was positively correlated with community 2.

## DISCUSSION

### Flora

The flora of the greenstone ranges of the Kangaroo Hills and surrounding areas is not as rich as floras found on other greenstone ranges closer to the boundary of the South-West Interzone, a transitional region between the South-West and Eremaean flora (Beard 1990). For example, the Helena and Aurora ranges, 180 km north-west of the current survey area, supports a flora of 324 taxa (of which 45% are annuals) with a high degree of endemism (Gibson et al. 1997, 2007). Similarly, the Parker Range (150 km south-west) supports a flora of 253 taxa (Gibson & Lyons 1998). Both these ranges include mafic as well as banded ironstone geologies and are in areas of higher annual rainfall. More comparable to this survey is the greenstone range north-west of Bullfinch,

**Table 3**

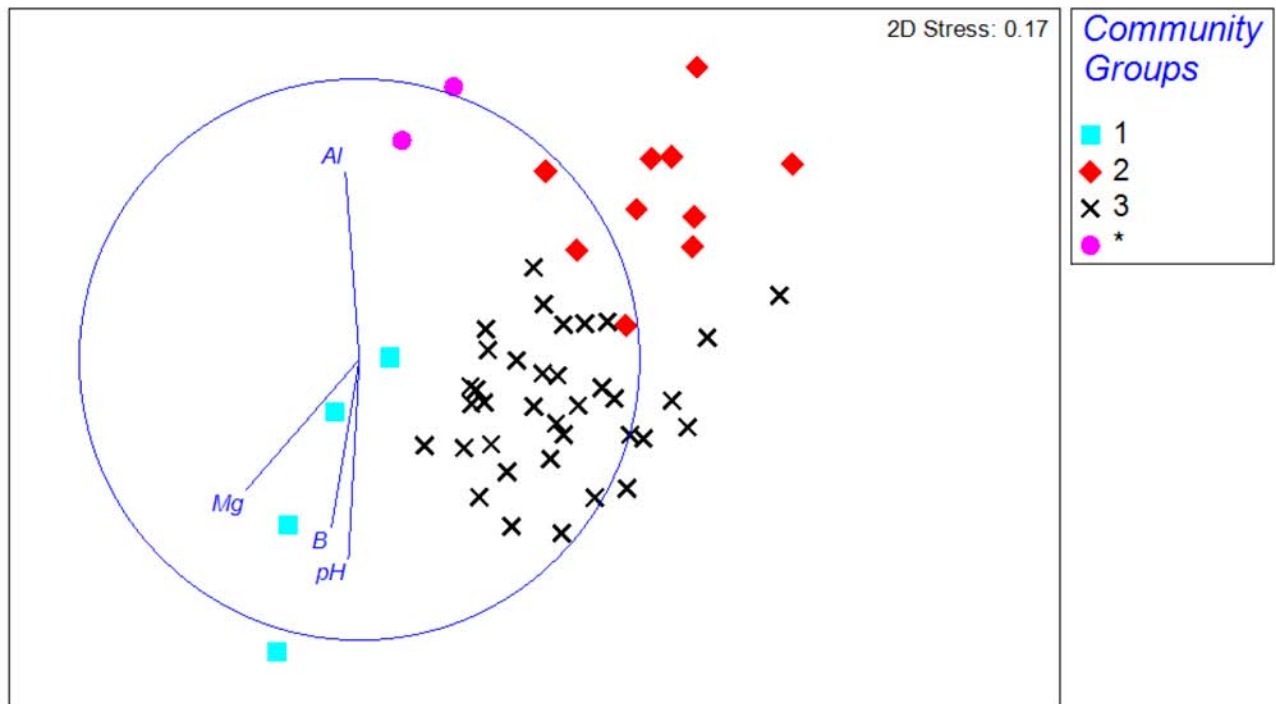
Mean values for site attributes by plant community type: aspect (degrees); slope (degrees); morphology type (1 – crest, 2 – mid slope, 3 – lower slope, 4 – simple slope); landform (1 – hill crest, 2 – hill slope); disturbance (0 – no effective disturbance, 1 – no effective disturbance except grazing by hoofed animals); maximum size of coarse fragments (CF size; 1 – fine gravely to 6 – boulders); coarse fragment (CF) abundance (0 – no coarse fragments to 6 – very abundant coarse fragments); rock outcrop (RO) abundance (0 – no bedrock exposed to 4 – very rocky); runoff (0 – no runoff to 4 – rapid); soil depth (1 – skeletal, 2 – shallow, 3 – deep). Differences between ranks were tested using Kruskal–Wallis nonparametric analysis of variance. Standard error in parentheses (n = number of quadrats, p = probability).

Community	1	2	3	p value
n	4	10	36	
Aspect	4.8 (1.3)	5.4 (0.6)	5.4 (0.4)	0.8495
Slope	2.8 (0.5)	5.3 (1.2)	3.4 (0.4)	0.2965
MorphType	1.8 (0.8)	2.5 (0.3)	2.4 (0.2)	0.6318
Landform	1.3 (0.3)	1.7 (0.2)	1.5 (0.1)	0.3075
Disturbance	0 (0)	0.3 (0.2)	0.9 (0.2)	0.0634
CFAbund	4.3 (0.3)	4 (0.3)	4.1 (0.2)	0.8473
CFMaxSize	3.5 (0.5)	3.6 (0.2)	3.8 (0.1)	0.6207
ROAbund	0.5 (0.5)	0.7 (0.3)	0.3 (0.1)	0.5385
Soil Depth	2.5 (0.3)	2.2 (0.1)	2.3 (0.1)	0.5762
Bare Ground	3 (0)	3 (0)	3.1 (0.1)	0.4542
Leaf Litter	2.5 (0.3)	1.7 (0.2)	2.0 (0.1)	0.0725

**Table 4**

Mean values for soil attributes (measured in mg kg<sup>-1</sup> except pH and EC [mS m<sup>-1</sup>]) by plant community type. Differences between ranked values were tested using Kruskal–Wallis nonparametric analysis of variance, and differences between communities determined using Dunn’s post-hoc comparison. Standard error of the mean in parentheses. Superscript a and b represent significant differences between community types at p < 0.05 (n = number of quadrats; p = probability). Significant results are in bold font.

Comm.	1	2	3	p value
n	4	10	36	
EC	15.3 (1.7) <sup>ab</sup>	8.5 (1.9) <sup>a</sup>	16.2 (2.0) <sup>b</sup>	<b>0.009</b>
pH	8.0 (0.1) <sup>b</sup>	6.4 (0.2) <sup>a</sup>	7.5 (0.1) <sup>b</sup>	<b>&lt;0.0001</b>
Org C	2.3 (0.5)	1.7 (0.2)	2.0 (0.1)	0.2653
N	0.1375 (0.0224)	0.1173 (0.0101)	0.1327 (0.0062)	0.4053
P	7.0 (0.9)	5.8 (0.5)	8.7 (0.7)	0.0667
K	203 (9) <sup>a</sup>	257 (22) <sup>ab</sup>	306 (17) <sup>b</sup>	<b>0.0245</b>
Mg	1500 (0) <sup>b</sup>	428 (47) <sup>a</sup>	873 (68) <sup>b</sup>	<b>0.0001</b>
Al	301 (102) <sup>b</sup>	720 (32) <sup>a</sup>	484 (35) <sup>b</sup>	<b>0.0004</b>
B	3.0 (0.7) <sup>b</sup>	0.7 (0.2) <sup>a</sup>	2.3 (0.2) <sup>b</sup>	<b>0.0001</b>
Ca	6700 (800) <sup>b</sup>	2890 (565) <sup>a</sup>	5596 (384) <sup>b</sup>	<b>0.0018</b>
Cd	0.03 (0.0108) <sup>ab</sup>	0.011 (0.0016) <sup>a</sup>	0.027 (0.004) <sup>b</sup>	<b>0.0255</b>
Co	1.22 (0.47) <sup>b</sup>	3.5 (0.43) <sup>a</sup>	1.94 (0.13) <sup>b</sup>	<b>0.0005</b>
Cu	2.25 (0.23) <sup>a</sup>	6.91 (0.98) <sup>b</sup>	4.77 (0.32) <sup>b</sup>	<b>0.0031</b>
Fe	100.8 (17.4)	75.3 (4.4)	67.1 (3.0)	0.1044
Mn	49 (8) <sup>b</sup>	110 (9) <sup>a</sup>	81 (4) <sup>b</sup>	<b>0.0016</b>
Mo	0.0063 (0.0013)	0.007 (0.0008)	0.0111 (0.0012)	0.1322
Na	30.8 (2.9) <sup>ab</sup>	21.9 (2.6) <sup>a</sup>	68.9 (24.2) <sup>b</sup>	<b>0.0182</b>
Ni	6.55 (1.73)	4.46 (1.92)	4.59 (0.70)	0.1763
S	14.8 (3.0)	9.3 (2.3)	16.4 (3.0)	0.0813
Zn	1.03 (0.09)	1.87 (0.23)	1.83 (0.20)	0.0715



**Figure 3.** Two dimensional MDS ordination of the 52 quadrats established on Kangaroo Hills and surrounding areas. The three communities and two quadrats not assigned to a community (\*) are shown. The lines represent the strength and direction of the four soil variables correlated with the MDS using Pearson rank correlation ( $r > 0.6$ ).

approximately 200 km west of the Kangaroo Hills area, with a flora of 218 taxa (Thompson & Allen 2013) and on Credo station, 70 km north of Coolgardie, with a flora of 186 taxa recorded (Meissner & Coppen 2013).

The overall species richness within this survey is consistent with values recorded in a previous survey by Bamford et al. (1991), who similarly recorded  $17 \pm 2$  perennial taxa per 20 x 20 m quadrat within the communities found on the basalt hill. The presence of dominant genera such as *Eucalyptus*, *Acacia* and *Eremophila* is also consistent with Bamford et al. (1991) and with those found elsewhere in the South-West Interzone (Gibson et al. 1997). The only difference between this study and others was the greater presence of taxa from Chenopodiaceae. However, this finding is unsurprising, given that chenopods are commonly found on more alkaline sites within the South-West Interzone (Beard 1990).

In addition, the floristic patterns found during this survey were largely consistent with the geobotanical work undertaken by Cole (1973) on the greenstone ranges at Widgiemooltha, also surveyed in our study. Cole (1973) examined the relative relationship between vegetation communities and ultramafic bedrock and found that the replacement of *Eucalyptus* woodland by a shrub community dominated by *Hybanthus floribundus* coincided with high Ni and Cu in the soil. In our study, we recorded *H. floribundus* subsp. *curvifolius* in a few quadrats on ultramafic geology, but too few to confirm Cole's (1973) observations. In addition, herbarium records show that *H. floribundus* subsp. *curvifolius* has a wide geographic distribution, largely associated with greenstone ranges but also occurring in other habitats, so it is unlikely to be an ultramafic endemic. As well as these observations, Cole (1973) also found that *Trymalium myrtillus* was restricted to skeletal soils associated with strong outcrops of ultramafic rocks. Again, our findings disagree with Cole (1973), as *T. myrtillus* was widespread on mafic and ultramafic geology and not restricted to any community type.

## Vegetation communities

The communities described in this study are consistent with a similar survey within the Kangaroo Hills. Bamford et al. (1991) described several communities dominated by *Eucalyptus griffithsii* occurring in the Kangaroo Hills timber reserve. Community 2, the *Acacia* sp. Norseman shrubland found on the crests of the greenstones, is similar to the community described by Bamford et al. (1991), and occupies a band near the top of the greenstone ridges in Kangaroo Hills. Soils associated with this community tended to be higher in Al but lower in Ca, Mg and Na. It was highly suggestive that the soils that this community occupies are highly weathered, since weathering results in the more mobile elements being leached down to the colluvial soils on the lower slopes (Britt et al. 2001).

The differences in mafic and ultramafic geologies were not as sharply reflected by differences in the vegetation communities as suggested by Cole (1992). The chemical

composition of the soil analysed from the ranges was consistent with the chemistry of mafic and ultramafic rocks. Mafic rocks are high in Mg, Ca and iron oxides (generally 20–30%) and ultramafic rocks are even higher (generally >30%; Gray & Murphy 2002). While Cole (1992) concluded that there were distinctive plant assemblages on particular substrates around Widgiemooltha, there was no distinctive flora associated with serpentinite (or ultramafic) geology across the Goldfields region. Our data supports this interpretation and we agree with Cole's (1992) suggestion that the plant communities in the eastern Goldfields are complex and involve the interaction of many environmental factors and not just geology. The regional differences in vegetation highlights the high species turnover characteristic of the South-West Interzone, as shown for the vegetation communities on the banded ironstone ranges (Gibson et al. 2012).

## Conservation

The Kangaroo Hills and the surrounding areas have a long history of mining and timber clearfelling, and the impact of these activities is still evident today within the reserves. The results of this survey found no endemic taxa associated with the greenstone ranges of Kangaroo Hills and the surrounding areas. The main vegetation community (community 3) is well represented in state forest, nature reserves or timber reserves throughout the survey area; however, all three communities are not represented on the nearest greenstone ranges at Credo Station to the north (Meissner & Coppen 2013). The greenstone ranges show the same pattern as the banded ironstone ranges, where each range has unique vegetation communities, with a decrease in endemics as aridity increases (Gibson et al. 2012). Although the communities are well represented within the gazetted conservation estate, all the reserves either have exploration permits or mining lease tenements overlying them.

## ACKNOWLEDGEMENTS

We would like to thank the following people: Katrina Walton, WA Chemcentre for soil analysis; the staff at the Western Australian Herbarium; and Neil Gibson for his advice and support. Permits for flora collection were issued by the Western Australian Department of Parks and Wildlife. This project was part of the Special Nature Conservation Projects, and has been funded by the Department of Parks and Wildlife, Western Australia.

## REFERENCES

- Anand RR, Butt CRM (2010) A guide for mineral exploration through the regolith in the Yilgarn Craton, Western Australia. *Australian Journal of Earth Sciences* **57**, 1015–1114.
- Bamford MJ, Davies SJJE, Ladd PG (1991) 'Biological

- survey of Kangaroo Hills and Calooli Timber Reserve, Coolgardie, Western Australia'. Unpublished report.
- Beard JS (1976) *The Vegetation of the Boorabbin and Lake Johnston Areas, Western Australia. Maps and Explanatory Memoir 1:250,000 Series*. 2nd ed. VegMap Publications, Perth.
- Beard JS (1990) *Plant Life of Western Australia*. Kangaroo Press, Kenthurst, NSW.
- Blatchford T (1899) The geology of the Coolgardie Goldfield. *Geological Survey of Western Australia Bulletin* No. 3.
- Britt AF, Smith RE, Gray DJ (2001) Element mobilities and the Australian regolith – a mineral exploration perspective. *Marine Freshwater Research* **52**, 25–39.
- Clarke KR, Gorley RN (2006) *PRIMER v6: User Manual/Tutorial*. PRIMER-E, Plymouth.
- Clarke KR, Warwick RM (2001) *Change in Marine Communities: An Approach to Statistical Analysis and Interpretation*. 2nd ed. PRIMER-E, Plymouth.
- Cole MM (1973) Geobotanical and biogeochemical investigations in the sclerophyllous woodland and shrub associations of the eastern goldfields area of Western Australia, with particular reference to the role of *Hybanthus floribundus* (Lindl.) F. Muell. as a nickel indicator and accumulator plant. *Journal of Applied Ecology* **10**, 269–320.
- Cole MM (1992) The vegetation of the greenstone belts of Western Australia. In *The Ecology of Areas with Serpentinized Rocks, A World View* (eds BA Roberts, J Proctor), pp. 343–373. Luwer Academic Publisher, Netherlands.
- De Cáceres M, Legendre P (2009) Associations between species and groups of sites: indices and statistical inference. *Ecology* **90**, 3566–3574.
- De Cáceres M, Legendre P, Moretti M (2010) Improving indicator species analysis by combining groups of sites. *Oikos* **119**, 1674–1684.
- Department of Environment and Conservation (2011) *A Biodiversity and Cultural Conservation Strategy for the Great Western Woodlands*. Department of Environment and Conservation, Perth.
- Gibson N, Lyons MN (1998) Flora and vegetation of the eastern goldfields ranges: Part 3. Parker Range. *Journal of the Royal Society of Western Australia* **81**, 119–117.
- Gibson N, Coates DJ, Thiele KR (2007) Taxonomic research and the conservation of flora in the Yilgarn Banded Iron Formation ranges. *Nuytsia* **17**, 1–12.
- Gibson N, Lyons MN, Lepschi BJ (1997) Flora and vegetation of the eastern goldfield ranges, 1 Helena and Aurora Range. *CALMScience* **2**, 231–246.
- Gibson N, Meissner R, Markey AS, Thompson WA (2012) Patterns of plant diversity in ironstone ranges in arid south western Australia. *Journal of Arid Environments* **77**, 25–31.
- Gray J, Murphy B (2002) Parent material and soil distribution. *Natural Resource Management* **5**, 2–12.
- Griffin TJ (1989) *Widgiemooltha, Western Australia 1:250 000 Geological Series – Explanatory Notes, Sheet SH 51–14*. Geological Survey of Western Australia, Perth.
- Hunter WM (1991) *Boorabbin Western Australia 1:250 000 Geological Series – Explanatory Notes, Sheet SH 51–13*. 2nd ed. Geological Survey of Western Australia, Perth.
- Keally I (1991) Management of inland arid and semi-arid woodland forest of Western Australia. In *Forest Management in Australia* (eds FH McKinnell, ER Hopkins, JED Fox), pp. 286–295. Surrey Beatty & Sons, Chipping Norton, NSW.
- Markey AS, Dillon SJ (2008) Flora and vegetation of the banded iron formations of the Yilgarn Craton: the central Tallering Land System. *Conservation Science Western Australia* **7**, 121–149.
- Maslin BR (2014) Miscellaneous new species of *Acacia* (Fabaceae: Mimosoideae) from south-west Western Australia. *Nuytsia* **24**, 139–159.
- McDonald RC, Isbell RF, Speight JG, Walker J, Hopkins MS (1990) *Australian Soil and Land Survey: Field Handbook*. 2nd ed. Inkata Press, Melbourne.
- Meissner R, Caruso Y (2008) Flora and vegetation of banded iron formations of the Yilgarn Craton: Mount Gibson and surrounding area. *Conservation Science Western Australia* **7**, 105–120.
- Meissner R, Coppen R (2013) Flora and vegetation of the greenstone ranges of the Yilgarn Craton: Credo Station. *Conservation Science Western Australia* **8**, 333–343.
- Meissner R, Wright J (2010) Flora and vegetation of banded iron formations of the Yilgarn Craton: Barloweerie and Twin Peaks Greenstone Belts. *Conservation Science Western Australia* **7**, 557–570.
- Severne BC, Brooks RR (1972) A nickel-accumulating plant from Western Australia. *Planta* **103**, 91–94.
- Smith M (2012) *Declared Rare and Priority Flora List for Western Australia*. Department of Environment and Conservation, Perth.
- Thompson WA, Allen J (2013) Flora and vegetation of greenstone formations of the Yilgarn Craton: southern Bullfinch Greenstone Belt. *Conservation Science Western Australia* **8**, 295–312.
- Western Australian Herbarium (1998–). FloraBase—the Western Australian Flora. Department of Parks and Wildlife. <http://florabase.dpaw.wa.gov.au/>
- Woodall R, Travis GA (1979) Nickel. In *Mining in Western Australia*. (ed RT Prider) pp. 87–100. University of Western Australia Press, Perth.

## APPENDIX

Flora list for the greenstone ranges on the Kangaroo Hills and other timber reserves, including all taxa from the sampling quadrats and adjacent areas. Nomenclature follows Western Australian Herbarium (1998–).

**Amaranthaceae**

*Ptilotus exaltatus* var. *villosus*  
*Ptilotus gaudichaudii* var. *parviflorus*  
*Ptilotus holosericeus*  
*Ptilotus obovatus*

**Apiaceae**

*Daucus glochidiatus*

**Apocynaceae**

*Alyxia buxifolia*  
*Marsdenia australis*

**Araliaceae**

*Hydrocotyle pilifera* var. *glabrata*  
*Trachymene ornata*

**Asparagaceae**

*Thysanotus manglesianus*  
*Thysanotus speckii*

**Asteraceae**

*Asteridea athrixoides*  
*Brachyscome ciliaris*  
*Calotis hispidula*  
*Cephalopterum drummondii*  
*Chrysocephalum puteale*  
*Cratystylis conocephala*  
*Isoetopsis graminifolia*  
*Leucochrysum fitzgeraldii*  
*Millotia myosotidifolia*  
*Olearia muelleri*  
*Olearia pimeleoides*  
*Podolepis canescens*  
*Podolepis capillaris*  
*Podolepis lessonii*  
*Rhodanthe oppositifolia* subsp. *oppositifolia*  
 \**Sonchus oleraceus*  
*Waitzia acuminata* var. *acuminata*

**Boraginaceae**

*Halgania andromedifolia*

**Brassicaceae**

\**Carrichtera annua*  
*Stenopetalum filifolium*  
*Stenopetalum lineare*

**Campanulaceae**

*Wahlenbergia gracilentia*

**Casuarinaceae**

*Allocasuarina campestris*  
*Allocasuarina helmsii*  
*Casuarina pauper*

**Celastraceae**

*Stackhousia* sp. Mt Keith (G Cockerton & G O'Keefe 11017)

**Chenopodiaceae**

*Atriplex nummularia* subsp. *spathulata*  
*Atriplex vesicaria*  
*Chenopodium curvispicatum*  
*Enchylaena tomentosa*  
*Eriochiton sclerolaenoides*  
*Maireana* aff. *planifolia*

*Maireana georgei*  
*Maireana pentatropis*  
*Maireana radiata*  
*Maireana tomentosa* subsp. *tomentosa*  
*Maireana trichoptera*  
*Rhagodia drummondii*  
*Rhagodia* sp. (R Meissner & R Coppen 3958)  
*Sclerolaena cuneata*  
*Sclerolaena diacantha*  
*Sclerolaena drummondii*  
*Sclerolaena fusiformis*  
*Sclerolaena obliquicuspis*

**Crassulaceae**

*Crassula colorata* var. *acuminata*  
*Crassula colorata* var. *colorata*  
*Crassula tetramera*

**Cyperaceae**

*Lepidosperma* aff. *diurnum* (R Meissner & R Coppen 3792)

**Euphorbiaceae**

*Ricinocarpos stylosus*

**Fabaceae**

*Acacia acuminata*  
*Acacia andrewsii*  
*Acacia burkittii*  
*Acacia erinacea*  
*Acacia hemiteles*  
*Acacia pachypoda*  
*Acacia pritzeliana*  
*Acacia* sp. (R Meissner & R Coppen 3720)  
*Acacia* sp. Norseman (B Archer 1554)  
*Acacia tetragonophylla*  
*Daviesia pachyloma*  
 \**Medicago minima*  
*Senna artemisioides* subsp. *filifolia*  
*Senna artemisioides* subsp. \**artemisioides*

**Geraniaceae**

*Erodium cygnorum*

**Goodeniaceae**

*Dampiera latealata*  
*Goodenia havilandii*  
*Scaevola spinescens*  
*Velleia rosea*

**Haloragaceae**

*Haloragis trigonocarpa*

**Lamiaceae**

*Prostanthera althoferi* subsp. *althoferi*  
*Prostanthera incurvata*  
*Westringia rigida*

**Loganiaceae**

*Phyllangium sulcatum*

**Malvaceae**

*Brachychiton gregorii*  
*Sida calyxhymania*  
*Sida spodochroma*  
*Calothamnus gilesii*

**Myrtaceae**

*Eucalyptus campaspe*  
*Eucalyptus celastroides* subsp. *celastroides*  
*Eucalyptus* cf. *ravida*  
*Eucalyptus clelandii*  
*Eucalyptus gracilis*  
*Eucalyptus griffithsii*  
*Eucalyptus lesouefii*  
*Eucalyptus oleosa* subsp. *oleosa*  
*Eucalyptus salmonophloia*  
*Eucalyptus stricklandii*  
*Eucalyptus torquata*  
*Eucalyptus websteriana* subsp. *websteriana*  
*Melaleuca hamata*  
*Melaleuca pauperiflora* subsp. *fastigiata*  
*Melaleuca sheathiana*

**Orchidaceae**

*Pterostylis* sp. dainty brown (N Gibson & M Lyons 3690)

**Pittosporaceae**

*Pittosporum angustifolium*

**Poaceae**

*Aristida contorta*  
*Austrostipa blackii* P3  
*Austrostipa elegantissima*  
*Austrostipa eremophila*  
*Austrostipa nitida*  
*Austrostipa platychaeta*  
*Austrostipa scabra*  
*Austrostipa trichophylla*  
 \**Pentameris airoides* subsp. *airoides*  
*Rytidosperma caespitosum*

**Portulacaceae**

*Calandrinia calyptrata*  
*Calandrinia eremaea*  
*Calandrinia* sp. Blackberry

**Primulaceae**

\**Lysimachia arvensis*

**Proteaceae**

*Grevillea acuaria*  
*Grevillea nematophylla* subsp. *nematophylla*

**Pteridaceae**

*Cheilanthes adiantoides*  
*Cheilanthes lasiophylla*  
*Cheilanthes sieberi* subsp. *sieberi*

**Rhamnaceae**

*Cryptandra* sp. (R Meissner & R Coppen 3900)  
*Pomaderris forrestiana*  
*Trymalium myrtillus* subsp. *myrtillus*

**Santalaceae**

*Exocarpos aphyllus*  
*Santalum acuminatum*  
*Santalum spicatum*

**Sapindaceae**

*Dodonaea lobulata*  
*Dodonaea microzyga* var. *acrolobata*  
*Dodonaea stenozyga*

**Scrophulariaceae**

*Eremophila alternifolia*  
*Eremophila caerulea* subsp. *caerulea*  
*Eremophila* cf. *deserti*  
*Eremophila clarkei*  
*Eremophila clavata*  
*Eremophila dempsteri*  
*Eremophila gibbosa*  
*Eremophila glabra* subsp. *glabra*  
*Eremophila interstans* subsp. *interstans*  
*Eremophila ionantha*  
*Eremophila oldfieldii* subsp. *angustifolia*  
*Eremophila oppositifolia* subsp. *angustifolia*  
*Eremophila parvifolia* subsp. *auricampa*  
*Eremophila psilocalyx*  
*Eremophila rugosa*  
*Eremophila saligna*  
*Eremophila scoparia*

**Solanaceae**

*Solanum ellipticum*  
*Solanum lasiophyllum*  
*Solanum nummularium*

**Thymelaeaceae**

*Pimelea microcephala* subsp. *microcephala*

**Violaceae**

*Hybanthus floribundus* subsp. *curvifolius*

**Zygophyllaceae**

*Zygophyllum apiculatum*  
*Zygophyllum compressum*  
*Zygophyllum eremaeum*  
*Zygophyllum ovatum*  
*Zygophyllum reticulatum*

# The status and distribution of alien plants on the islands of the south coast of Western Australia

MT LOHR<sup>1</sup> AND G KEIGHERY<sup>2</sup>

<sup>1</sup>Department of Parks and Wildlife, Woodvale Research Centre, PO Box 51, Wanneroo WA 6946, Australia

<sup>2</sup>Department of Parks and Wildlife, Keiran McNamara Conservation Science Centre, 17 Dick Perry Avenue, Technology Park, Western Precinct, Kensington WA 6151, Australia

email: Michael.Lohr@dpaw.wa.gov.au

## ABSTRACT

Alien plants pose a substantial threat to island ecosystems in Australia and worldwide. A better understanding of weed distributions is necessary to more effectively manage natural resources on islands. To address this need for Western Australian islands, we created a database of all available records of alien plants on these islands. Here we report on records from all islands located along the south coast of Western Australia. From 789 individual records, a total of 116 alien plant species were recorded on the 43 islands with existing weed records. A disproportionately large number of weed species were recorded on estuarine islands and islands with a history of intensive human activity. Some of the species are known to be serious environmental weeds, including bridal creeper (*Asparagus asparagoides*), pig's ear (*Cotyledon orbiculata*), sea spurge (*Euphorbia paralias*), cleavers (*Galium aparine*), African boxthorn (*Lycium ferocissimum*), tree mallow (*Malva arborea*), arum lily (*Zantedeschia aethiopica*), and the annual grasses *Avena*, *Bromus*, *Ehrharta*, *Hordeum*, *Lolium* and *Vulpia*. Developing management plans to address these species, as well as surveying islands adjacent to known infestations, should be a conservation priority for south coast islands. Improved biosecurity procedures and enforcement could prevent the establishment of new island weed populations and reduce future costs associated with the management of active infestations.

**Keywords:** biogeography, distribution maps, introduced plants, weeds

## INTRODUCTION

Deleterious effects of introduced plants on native biodiversity and ecosystem function have been documented worldwide (Vila et al. 2011). Introductions of alien species represent a substantial component of anthropogenic global environmental change and disproportionately affect islands (Vitousek 1997). The Conservation Commission of Western Australia (2009) identified the establishment of weeds on conservation reserve islands as a significant issue affecting island biodiversity. Among the major knowledge gaps that the Conservation Commission listed as impairing effective management of island natural resources was a lack of review of weed occurrence and control methods.

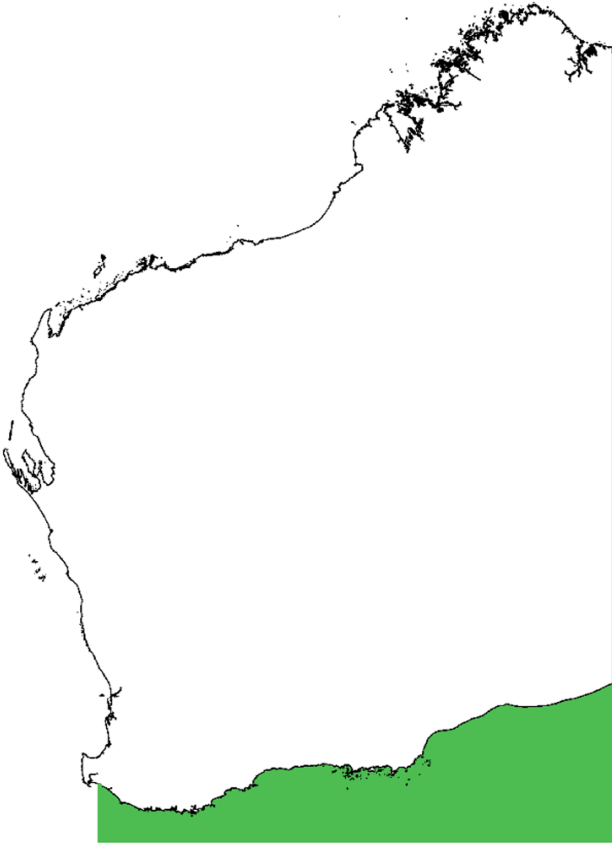
Islands along the south coast of Western Australia have a long history of disturbance and deliberate plant introductions. Islands in this region range from unnamed, occasionally submerged rocks to Middle Island, which covers 1080 ha. Most islands along the south coast are steep-sloped granite domes with relatively few beaches. Many of these islands are difficult to access, even in good weather conditions, and have not been formally surveyed

by biologists. However, more accessible islands have been documented as plant introduction sites, starting in 1791 with Vancouver who planted grape vines, watercress, and sowed various seeds on Michelmas Island, although these species were not evident when searched for by Flinders in 1801 (Flinders 1814; Lamb 1984).

Several south coast islands were occupied either briefly or for longer periods by sealers, including the settlement on Middle Island by the 'pirate' Black Jack Anderson in 1827 (Dickson 2007; Forrestal 2008). A brief settlement for salt extraction occurred on Middle Island in 1890 (Bechervaise 1972). Little evidence of any gardens or resulting naturalised plants remains from these activities, although doubtlessly they resulted in some weed introductions.

A tourist development on Woody Island, which includes permanent structures and campsites, has facilitated continual introductions over a long period of time. Along with disturbance associated with human activities, this has led to Woody Island being the 'weediest' of all the Recherche Archipelago islands, even surpassing Cull Island with its resident feral goats (DEC 2012).

Lighthouses were constructed on Breaksea Island in 1858 and manned until 1926, with a second tower in 1902 (Cumming et al. 1995). Another was erected on



**Figure 1.** Our study area included all islands within the tenure of the Department of Parks and Wildlife Warren and South Coast regions (shaded). This area stretched from Black Point to the South Australia border.

Eclipse Island in 1926 and manned until 1976 (Cumming et al. 1995). At both sites, vegetable and ornamental gardens were established leading to the introduction of many potential weeds, some of which (e.g. arum lilies, *Zantedeschia aethiopica*) still remain.

Vegetables were planted on Green Island in 1826 (Shellam 2009). Soon after the first settlement of Albany, a gardener's hut was constructed on the island in 1830 (Shellam 2009). A grazing lease for the island was granted in 1918 but has been since discontinued (Garden 1977). This long history of clearing and disturbance has added many garden escapes to the flora of this small island.

New potential weeds on islands will continue to arrive as visitation increases. For example, five new weed records for Daw Island were noted at the campsite established after the Sanko Harvest oil spill (Keighery 1995). This is a worldwide trend (Drost & Junak 2009). While many of these weeds will not persist, the constant re-introductions suggest that any program to reduce weed impacts on offshore islands needs to focus on monitoring access sites.

To provide a baseline for such monitoring and address the knowledge gap in island weed occurrences identified by the Conservation Commission of Western Australia, we collated baseline information summarizing current knowledge of the distributions of introduced plants on the islands along the south coast of Western Australia. This information will help to facilitate and direct future

research and management efforts, as well as identify more specific gaps in existing knowledge of weed distributions. Additionally, we list exotic plant species that pose a particular risk to island biodiversity and conservation values that should be prioritized accordingly in management plans for the islands, where these plans exist.

We expected that islands with a more extensive history of human use would have more records of weeds. We also expected to see a higher number of weed species on estuarine islands than their oceanic counterparts due to increased propagule pressure from upstream sources.

## METHODS

We gathered data on the distribution and prevalence of weeds on south coast islands from a variety of sources and entered and processed it using Microsoft Access. We defined south coast islands as all islands within the tenure of the WA Department of Parks and Wildlife's (DPaW) South Coast and Warren regions. This area covers all the islands in Western Australian waters from Black Point to the South Australian border. We used a list of 88 named and gazetted South Coast islands to guide the search for records. Sources included Western Australian Herbarium records, published journal articles, government and contractor reports, personal accounts from experts and surveys. We excluded records that did not contain taxonomic identification to the species level (i.e. specimens only identified to genus).

We cross-referenced weeds present on the islands against existing weed lists and prioritizations to help clarify the current or potential negative environmental impacts of the weeds. These lists included:

- the Department of Parks and Wildlife Regional Weed Prioritization for both the South Coast and Warren regions;
- the IUCN's '100 of the World's Worst Invasive Alien Species' list (<http://www.issg.org/database/species/search.asp?st=100ss>);
- the Department of Agriculture and Food's (WA) Western Australian Organism List (<http://www.agric.wa.gov.au/bam/western-australian-organism-list-waol>), which enumerates the state's declared and prohibited plants;
- the federal Department of the Environment and Heritage National Environmental Alert List (<http://www.environment.gov.au/biodiversity/invasive/weeds/weeds/lists/alert.html>);
- a list of all weed species officially targeted for biocontrol;
- a list of weed risk rankings from Groves et al.'s (2003) Weed Categories for Natural and Agricultural Ecosystem Management; and
- the Pacific Island Ecosystems at Risk's list of risk assessments for plants in Australia.

Statuses in these lists are reported for each species recorded on south coast islands.

While some records were associated with specific coordinates, the coordinates were often inaccurate enough that the coordinates did not fall within the boundaries of the island the record was associated with. For this reason, we used island centroid coordinates to depict the known ranges of weeds with records on five or more south coast islands. For each species, we provide data on distribution, plant listings, abundance and the potential ecological threats posed by the plant when available.

## RESULTS

We collected a total of 789 individual records of weeds on islands. A total of 116 species of weeds were recorded

on all islands in the region (Appendix 1). Of the 88 named and gazetted islands we searched for, only 43 islands had records of introduced plants being present.

Islands with the most weed species recorded were Woody Island (57), Boxer Island (31), Bald Island (29), Green Island (26) and Middle Island (22; Table 2). Three south coast islands have been described in the literature as being completely free of weeds: Coffin (Smith & Kolchis 1980), Six Mile (Keighery 1995) and Spindle (Keighery 1995). However, a subsequent publication from a year later (Abbott 1981) listed eight weed species as present on Coffin Island.

Despite accounting for less than 7% of islands with records of weeds, the three estuarine islands (Green Island, Gull Rock and Honeymoon Island) collectively had 77 weed species (66.4% of all species recorded). Twenty-two weed species (almost 19% of all weeds species recorded) were observed solely on the three estuarine islands.

**Table 1**

Key to weed ranking and recommended management actions from Department of Parks and Wildlife regional weed prioritizations.

Code	Weed ranking
VH	Very high (objective is eradication)
H	High (objective is eradication or control to reduce)
M	Medium (objective is control to reduce or containment)
L	Low (objective is containment at key sites only)
N	Negligible (no action to be undertaken but may include monitoring only)
Code	Recommended management action
A	No action (the weed species ranking is so low as to not warrant any investment in regional strategic management actions)
B	Monitor only (aims to detect any significant changes in the species' weed risk or management ability)
C	Improve general weed management (aims to minimise weed impact and maintain the overall biodiversity, social, cultural and economic values in the region through improved general weed management)
D	Protect priority sites (aims to prevent spread of weed species to key sites/assets of high biodiversity, social, cultural or economic value)
E	Targeted control to reduce infestations at priority sites (may include biocontrol) (aims to significantly reduce the impact of a weed species on key sites/assets of high biodiversity, social, cultural or economic value through targeted management)
F	Contain regional spread (aims to prevent the ongoing spread of the weed species in the region)
G	Reduce regional infestations (may include biocontrol) (aims to significantly reduce the extent of the weed species in the region)
H	Regional eradication (aims to remove the weed species from the region)
I	State-wide eradication (aims to remove the weed species from the state)

## Annotated list

The regions named below refer to the management regions of the Department of Parks and Wildlife. Codes for regional weed prioritizations and recommended management actions are given in Table 1.

*Aira caryophylla* – Recorded on nine islands (Fig. 2a). Prioritized as L (B, C) in the South Coast Region. Widespread environmental weed in south-west WA found in bushland and degraded pasture (Hussey et al. 2007).

*Aira cupaniana* – Recorded on Bald, Coffin, Mondrain and Woody islands. Widespread environmental weed in south-west WA found in bushland and degraded pasture (Hussey et al. 2007). Prioritized as L (B, C) in the South Coast Region.

*Aira praecox* – Recorded on Bald and Woody islands. Widespread environmental weed in south-west WA found in bushland and degraded pasture (Hussey et al. 2007). Recorded on Woody Island as an early colonizer of areas that were severely disturbed by fire in 1950. Prioritized as L (B, C) in the South Coast Region.

*Ammophila arenaria* – One record from Sandy Island in Windy Harbour. Prioritized as L (C) in the South Coast Region and L (B, C, D) in the Warren Region. Modifies coastal dune ecosystems by increasing dune stabilization and outcompeting native dune vegetation (Western Australian Herbarium 2014). Preventing this plant from establishing in areas where it is not already present should be a priority for islands with dunes.

*Arctotheca calendula* – Recorded on five islands (Fig. 2b). Prioritized as N (B) in the South Coast Region. Primarily a weed of disturbed areas but can impact native vegetation once established (Western Australian Herbarium 2014). Records from Woody Island note that it is found within the settlement area.

*Arctotheca populifolia* – Recorded on Woody, Sandy, Gull Rock and Middle islands. Primarily a threat on islands with coastal dune ecosystems where it can colonize rapidly,

**Table 2**

Number of weed records per island, recorded number of weed species, and island type and for islands on the south coast of Western Australia.

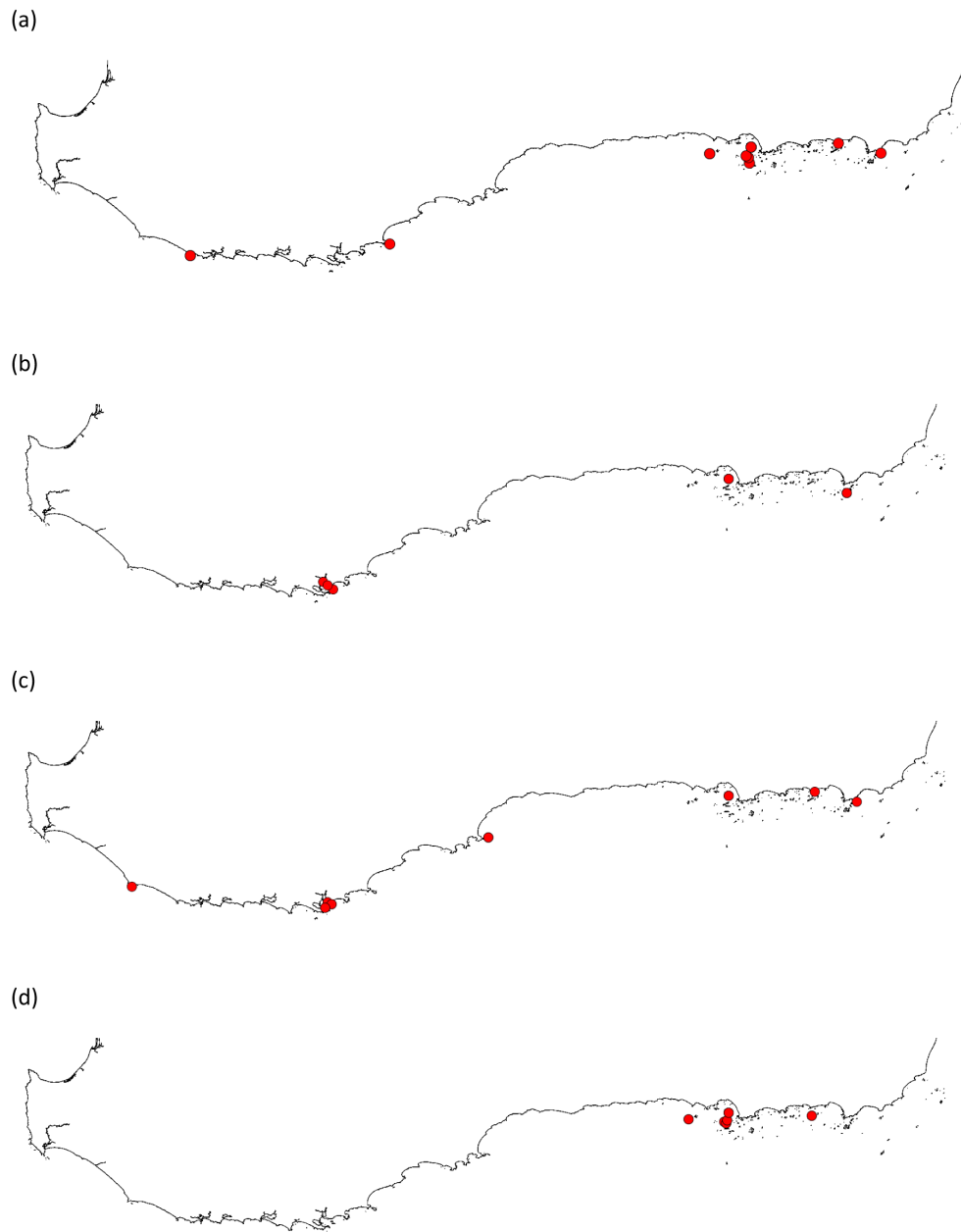
Island name	No. weed records	No. species recorded	Type of island
Anvil	2	2	continental
Bald	49	29	continental
Bellinger	6	5	continental
Boxer	42	31	continental
Breaksea	27	19	continental
Cave	1	1	continental
Chatham	6	4	continental
Coffin	12	8	continental
Cull	2	1	continental
Daw (= Christmas)	22	10	continental
Doubtful Islands	33	18	continental
Eclipse	19	16	continental
Figure of Eight	25	19	continental
Green (Oyster Harbour)	31	26	estuarine
Gull Rock (King George Sound)	19	16	continental
High (Duke of Orleans Bay)	1	1	continental
Honeymoon (Wilson Inlet)	9	9	estuarine
Kermadec (= Wedge)	3	2	continental
Long (Recherche)	13	9	continental
MacKenzie	1	1	continental
Michaelmas	20	16	continental
Middle (Recherche)	72	22	continental
Mistaken	23	19	continental
Mistaken (nearby islet)	9	9	continental
Mondrain	30	19	continental
New Year	1	1	continental
North Twin Peaks	15	11	continental
Observatory	2	2	continental
Pasco (Recherche)	5	4	continental
Quagering (= Flat)	1	1	continental
Remark	12	9	continental
Round (Recherche)	2	2	continental
Saddle	13	7	continental
Sandy (Windy Harbour)	13	13	continental
Sandy Hook	14	7	continental
Seal (King George Sound)	14	9	continental
Shelter (= Mutton Bird)	5	5	continental
South Twin Peaks	8	6	continental
Taylor	10	9	continental
Westall (= Combe)	1	1	continental
Wickham (= Stanley)	12	9	continental
Wilson	11	7	continental
Woody	173	57	estuarine

increase dune biomass, and decrease native plant diversity (Western Australian Herbarium 2014). Prioritized as N (B) in the South Coast Region.

*Asparagus asparagoides* – One record from Daw Island (also known as Christmas Island) in 1988 and one record from Honeymoon Island in Wilson Inlet in 1992. Bridal creeper is listed as a Weed of National Significance and as a declared pest organism in WA. It is officially listed as a biocontrol target. It is prioritized as L (D, E) in the Warren Region and L (D) in the South Coast Region. These low rankings are likely the result of the widespread range of bridal creeper in south-west WA and a largely successful biocontrol program that has substantially reduced the prevalence and impacts of bridal creeper across its

introduced range. While biocontrol agents are likely to spread to Honeymoon Island unassisted because of its close proximity to the mainland, they may not spread to the more distant Daw Island unassisted. Efforts should be made to assess the population of bridal creeper on Daw Island and translocate biocontrol agents if necessary as bridal creeper can substantially alter native ecosystems and could potentially be dispersed to adjacent islands by frugivorous birds.

*Atriplex prostrata* – One record from Middle Doubtful Island in April 1977. Common weed of estuarine and salty areas in south-west WA (Hussey et al. 2007). Prioritized as L (B, C, D) in the Warren Region and FAR in the South Coast Region.



**Figure 2.** Recorded distribution of (a) *Aira caryophyllca*, (b) *Arctotheca calendula*, (c) *Avena barbata* and (d) *Avena fatua* on islands of the south coast of Western Australia.

*Avena barbata* – Recorded on eight islands (Fig. 2c). Prioritized as N (B) in the South Coast Region. Allelopathic competitor with native grasses but possibly requires disturbance to establish (Western Australian Herbarium 2014).

*Avena fatua* – Recorded on six islands (Fig. 2d). Prioritized as N (B) in the South Coast Region. A weed in both crops and bushland. Dense stands of up to 8 ft (2.44 m) in height were recorded in areas of Woody Island that had been severely disturbed by fire (Willis 1953).

*Brassica rapa* – One record from Green Island in Oyster Harbour from 1986 noting that it was abundant on the island. Not known to be present on any other islands on

the south coast. Groves et al. (2003) assigned ratings of 1 to 4 for different *B. rapa* subspecies (Table 3). It is not known which subspecies was present on Green Island but subspecies readily hybridize and are not easily distinguishable.

*Briza maxima* – Recorded as present on Coffin and Mistaken islands. Prioritized as N (B) in the South Coast Region. A common weedy grass in south-west WA.

*Briza minor* – Recorded on seven islands (Fig. 3a). Prioritized as N (B) in the South Coast Region. A common weedy grass in south-west WA.

*Bromus diandrus* – Recorded from nine islands (Fig. 3b) and noted as occurring frequently on Saddle Island. No

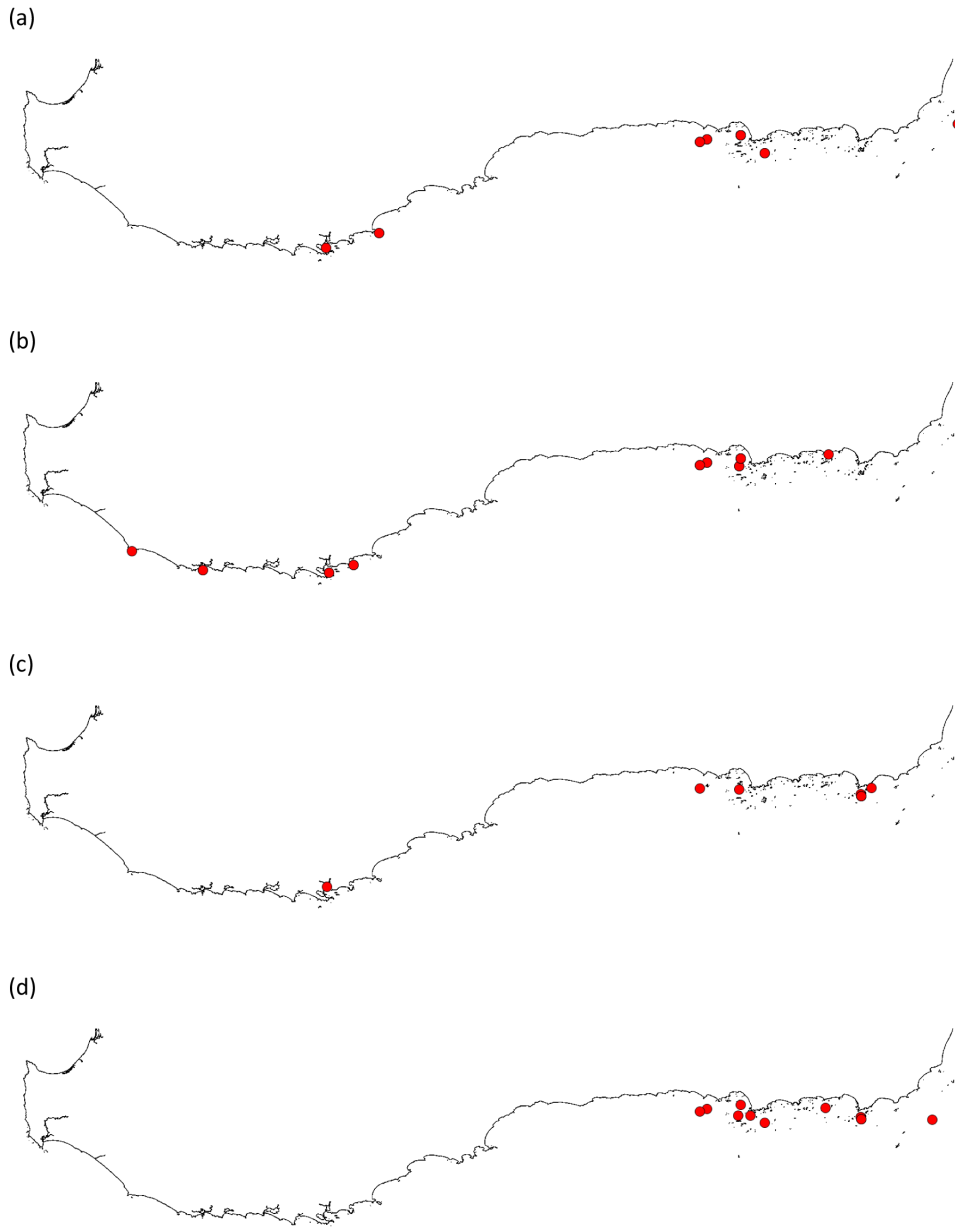


Figure 3. Recorded distribution of (a) *Briza minor*, (b) *Bromus diandrus*, (c) *Cakile maritima* and (d) *Centaurium erythraea* on islands of the south coast of Western Australia.

available records identified the particular variety of *B. diandrus* present on south coast islands but *B. diandrus* var. *diandrus* is cited as being a frequently occurring and serious weed on offshore islets in WA (Hussey et al. 2007). Prioritized as N (B) in the South Coast Region.

*Bromus hordeaceus* – Recorded on Boxer and Woody islands. Prioritized as N (B) in the South Coast Region. A common weedy grass found on damp soils across south-west WA (Hussey et al. 2007).

*Bromus rubens* – Recorded once in 2003 growing on granite on Bald Island. Prioritized as N (B) in the South Coast Region. Common on disturbed ground in the wheatbelt (Hussey et al. 2007) but less so along the south coast.

*Cakile maritima* – Recorded on six islands (Fig. 3c). Common weed of beaches in WA. Prioritized as N (B) in the South Coast Region.

*Carpobrotus aequilaterus* – One WA Herbarium specimen from Wilson Island in 1960 and another from Middle Island in 1974. Prioritized as L (C) in the South Coast Region and FAR in the Warren Region. A mat-forming succulent that is commonly found in coastal heathland and beaches in WA.

*Catapodium rigidum* – Recorded from Boxer Island and a WA Herbarium specimen from Woody Island in 1998. The Woody Island specimen was noted to have been from a disturbed area near a campsite. A weedy grass of disturbed areas. Prioritized as L (B, C) in the South Coast Region.

**Table 3**

Rankings from Groves et al. (2003) of Australia-wide impacts of weed species in natural ecosystems for all recorded weed species on islands along the south coast of Western Australia. Potential rankings range from 0 (lowest risk) to 5 (known problematic weed). \* indicates multiple rankings for different subspecies.

Species	Groves et al. ranking	Species	Groves et al. ranking
<i>Aira caryophylla</i>	4	<i>Lagurus ovatus</i>	4
<i>Aira cupaniana</i>	4	<i>Leontodon saxatilis</i>	3
<i>Aira praecox</i>	4	<i>Lepidium bonariense</i>	4
<i>Ammophila arenaria</i>	5	<i>Lolium loliaceum</i>	4
<i>Arctotheca calendula</i>	5	<i>Lolium rigidum</i>	5
<i>Arctotheca populifolia</i>	3	<i>Lotus subbiflorus</i>	4
<i>Asparagus asparagoides</i>	5	<i>Lycium ferocissimum</i>	5
<i>Atriplex prostrata</i>	5	<i>Lycopersicon esculentum</i>	2
<i>Avena barbata</i>	5	<i>Lysimachia arvensis</i>	4
<i>Avena fatua</i>	5	<i>Malva arborea</i>	5
<i>Brassica rapa</i>	*	<i>Malva parviflora</i>	4
<i>Briza maxima</i>	5	<i>Medicago polymorpha</i>	4
<i>Briza minor</i>	5	<i>Melilotus indicus</i>	4
<i>Bromus diandrus</i>	5	<i>Oxalis corniculata</i>	4
<i>Bromus hordeaceus</i>	4	<i>Oxalis pes-caprae</i>	5
<i>Bromus rubens</i>	3	<i>Parapholis incurva</i>	4
<i>Cakile maritima</i>	5	<i>Parentucellia latifolia</i>	4
<i>Carpobrotus aequilaterus</i>	4	<i>Parentucellia viscosa</i>	4
<i>Catapodium rigidum</i>	4	<i>Pelargonium capitatum</i>	5
<i>Centaurium erythraea</i>	4	<i>Petrorhagia dubia</i>	4
<i>Centaurium tenuiflorum</i>	4	<i>Phytolacca octandra</i>	4
<i>Cerastium glomeratum</i>	4	<i>Poa annua</i>	4
<i>Chenopodium album</i>	5	<i>Polycarpon tetraphyllum</i>	5
<i>Chenopodium murale</i>	4	<i>Polypogon maritimus</i>	4
<i>Cirsium vulgare</i>	5	<i>Polypogon monspeliensis</i>	4
<i>Conyza bonariensis</i>	4	<i>Raphanus raphanistrum</i>	5
<i>Conyza sumatrensis</i>	4	<i>Romulea rosea</i>	5
<i>Corrigiola litoralis</i>	2	<i>Rostraria cristata</i>	3
<i>Cotula bipinnata</i>	3	<i>Rumex crispus</i>	4
<i>Cotula coronopifolia</i>	3	<i>Sagina apetala</i>	4
<i>Cotyledon orbiculata</i>	3	<i>Silene gallica</i>	4
<i>Crassula natans</i>	3	<i>Silene nocturna</i>	3
<i>Cynodon dactylon</i>	4	<i>Sisymbrium orientale</i>	5
<i>Cyrtomium falcatum</i>	2	<i>Solanum nigrum</i>	5
<i>Dactylis glomerata</i>	4	<i>Sonchus asper</i>	*
<i>Disa bracteata</i>	3	<i>Sonchus oleraceus</i>	4
<i>Dischisma arenarium</i>	2	<i>Sparaxis bulbifera</i>	5
<i>Dittrichia graveolens</i>	3	<i>Spergularia diandra</i>	3
<i>Ehrharta longiflora</i>	5	<i>Spergularia rubra</i>	4
<i>Erodium cicutarium</i>	4	<i>Sporobolus africanus</i>	5
<i>Euphorbia paralias</i>	5	<i>Stellaria media</i>	4
<i>Euphorbia peplus</i>	4	<i>Stellaria pallida</i>	3
<i>Fumaria capreolata</i>	4	<i>Trachyandra divaricata</i>	5
<i>Fumaria muralis</i>	4	<i>Trifolium campestre</i>	4
<i>Galium aparine</i>	3	<i>Trifolium cernuum</i>	4
<i>Galium murale</i>	4	<i>Trifolium glomeratum</i>	4
<i>Geranium molle</i>	4	<i>Trifolium tomentosum</i>	4
<i>Gladiolus floribundus</i>	1	<i>Triticum aestivum</i>	2
<i>Holcus lanatus</i>	4	<i>Tropaeolum majus</i>	3
<i>Hordeum leporinum</i>	5	<i>Urtica urens</i>	4
<i>Hordeum murinum</i>	4	<i>Vellereophyton dealbatum</i>	4
<i>Homungia procumbens</i>	4	<i>Vulpia bromoides</i>	5
<i>Hypochaeris glabra</i>	4	<i>Vulpia fasciculata</i>	3
<i>Isolepis marginata</i>	3	<i>Vulpia muralis</i>	5
<i>Juncus bufonius</i>	5	<i>Vulpia myuros</i>	*
<i>Lactuca serriola</i>	3	<i>Zantedeschia aethiopica</i>	5

*Centaureum erythraea* – Recorded from 10 islands (Fig. 3d). Prioritized as L (B, C) in the South Coast Region. All but two records are from 1950 and were listed under the synonym *Erythraea centaureum*. Given that this species has few WA Herbarium collections from areas of the adjacent mainland and is similar in appearance to the native plant *Schenkia australis*, the presence of this species on south coast islands is suspect.

*Centaureum tenuiflorum* – One WA Herbarium specimen collected on Bald Island in 1963. Prioritized as L (B, C) in the South Coast Region. Frequently found on disturbed sites (Hussey et al. 2007).

*Cerastium glomeratum* – Recorded on nine islands (Fig. 4a). Prioritized as L (B, C) in the South Coast Region. One WA Herbarium specimen collected on Middle Island in 1973 was found on burnt ground and noted to be rare on the island at the time. On Woody Island, it was found in 1950 and 2003 but Goodsell et al. (1976) noted that it was absent during their survey.

*Chenopodium album* – One WA Herbarium specimen collected from Honeymoon Island in 1992 noted that it was common in the area. Prioritized as N (B) in the South Coast Region. Highly allelopathic and competes aggressively with other plants in disturbed areas with high nitrate levels. These traits make this species potentially problematic on islands that support colonies of seabirds (Western Australian Herbarium 2014).

*Chenopodium murale* – Recorded on six islands (Fig. 4b). Prioritized as N (B) in the South Coast Region. A herbarium specimen from 1991 notes that it was common on Honeymoon Island. Another specimen was collected on Middle Island in 1973 with notes that multiple growth habits (both prostrate and erect) were present on and near areas that had recently been burnt. As with its congeners, disturbance events like fire probably facilitate the spread of this weed.

*Cirsium vulgare* – Recorded on Middle, Bald, Eclipse and West Doubtful islands. Prioritized as L (D) in the South Coast Region and L (B, C) in the Warren Region, but this species has a high Pacific Island Ecosystems at Risk (PIER) ranking of 21 for Australia. A serious weed in disturbed areas (Western Australian Herbarium 2014).

*Conyza bonariensis* – Recorded on Middle, Eclipse, Middle Doubtful and West Doubtful islands. Prioritized as L (B, C) in the South Coast Region and M (D, E, F) in the Warren Region. A WA Herbarium specimen was collected from Eclipse Island in 1988 with notes that it was abundant there, and a specimen was collected on Middle Island in 1974 with notes that it was common in the area surrounding a hut.

*Conyza sumatrensis* – One WA Herbarium specimen was collected from Honeymoon Island in 1992. Prioritized as L (B, C) in the South Coast Region and M (D, E, F) in the Warren Region. Removal of island populations of a plant prioritized at the level of 'medium' would normally be recommended. However, the close proximity of

Honeymoon Island to the mainland and this plant's capability to disperse long distances via wind-borne seeds makes it likely that the island would be quickly re-invaded following any control efforts.

*Corrigiola litoralis* – One WA Herbarium specimen collected from Wickham Island (also known as Stanley Island) in 1991. Noted as being abundant in shallow claypans. Prioritized as L (B, C) in the South Coast Region.

*Cotula bipinnata* – One WA Herbarium specimen was collected from Woody Island in 2005. This plant was from a population of 2–5 plants in a recently disturbed area beside a track. Prioritized as FAR in the South Coast Region; however, there are few WA Herbarium records from this part of the coastline and eradication of this island population while it is still small might be of benefit to the Esperance area in general.

*Cotula coronopifolia* – Recorded on eight islands (Fig. 4c). Prioritized as L (B, C) in the South Coast Region. Collections are usually from damp disturbed areas or areas near a lake or spring.

*Cotyledon orbiculata* – Present on Breaksea Island. Naturalized garden escape that has become abundant on the island. Believed to be spreading and difficult to control (J Lavers, pers. comm., 5 December 2013). This species is prioritized as L (B, C, D) in the South Coast Region.

*Crassula natans* – Recorded on Bald and Mondrain islands. One WA Herbarium specimen collected from Mondrain Island in 2002 was found growing in a pan gnamma hole and was identified as the variety *Crassula natans* var. *minus*. Prioritized as L (B, C) in the South Coast Region.

*Cynodon dactylon* – Recorded on Woody Island in 1950. Later publications disagree on whether it was absent (Goodsell et al. 1976) or present (Abbott 1992). Prioritized as L (B, C) in the South Coast Region. Common lawn grass that frequently escapes cultivation.

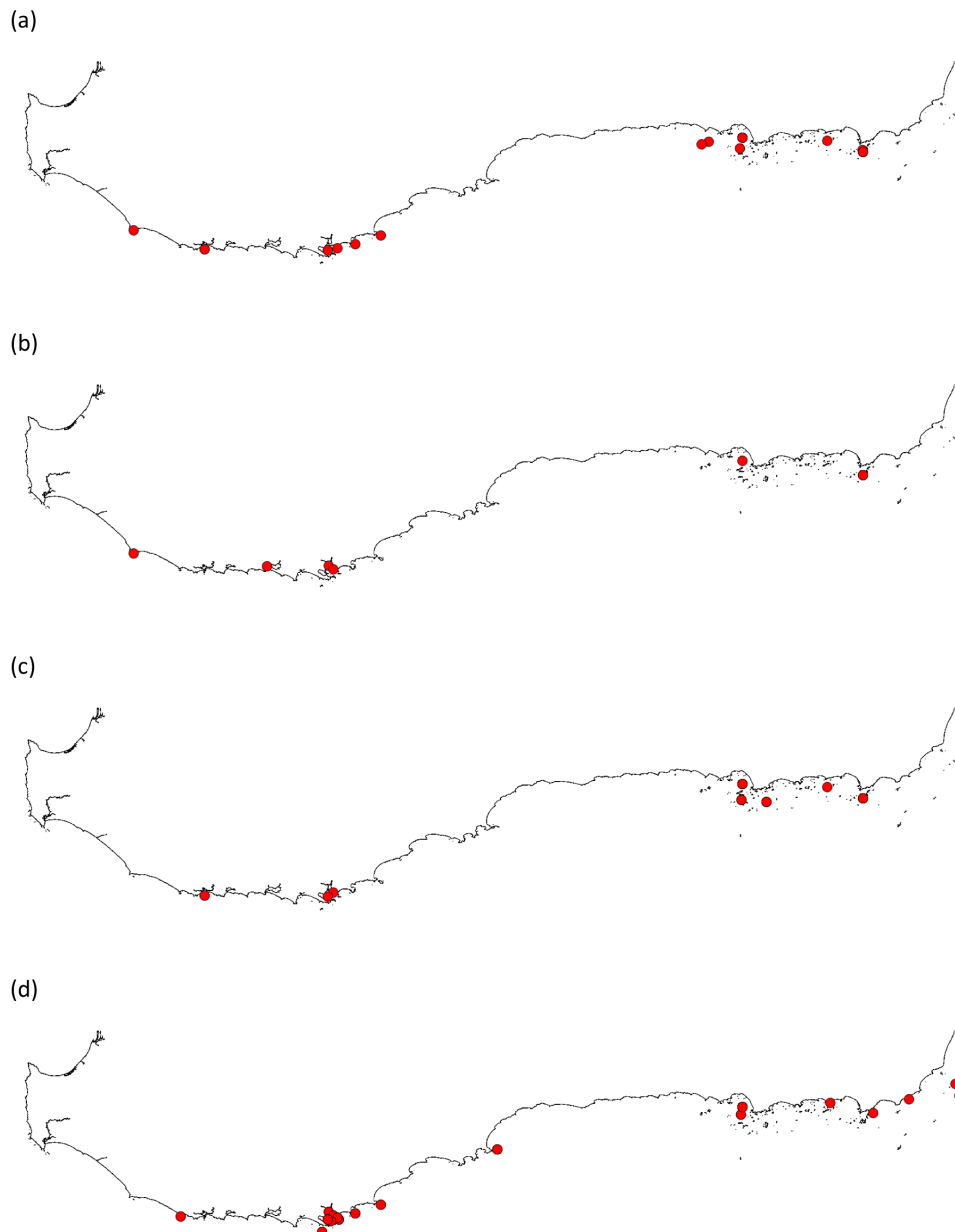
*Cyrtomium falcatum* – One WA herbarium specimen from Breaksea Island in 1999. Noted as being rare and occurring in crock crevices. Prioritized as L (B, C, D) in the South Coast Region.

*Dactylis glomerata* – One WA herbarium specimen from Honeymoon Island in 1992. Noted as being rare at the time. Prioritized as L (B, C, D) in the South Coast Region and L (C) in the Warren Region with a very low PIER ranking of 2. Grown as a pasture grass.

*Dischisma arenarium* – Recorded on the north coast of Boxer Island in 1950 and on Sandy Island in 1980. Prioritized as L (B, C) in the South Coast Region. Common in coastal areas of WA.

*Disa bracteata* – Recorded on Taylor and Bald islands. Prioritized as L (B, C) in the South Coast Region. Escaped garden plant found more commonly in disturbed areas (Hussey et al. 2007).

*Dittrichia graveolens* – Recorded on Eclipse and West



**Figure 4.** Recorded distribution of (a) *Cerastium glomeratum*, (b) *Chenopodium murale*, (c) *Cotula coronopifolia* and (d) *Ehrharta longiflora* on islands of the south coast of Western Australia.

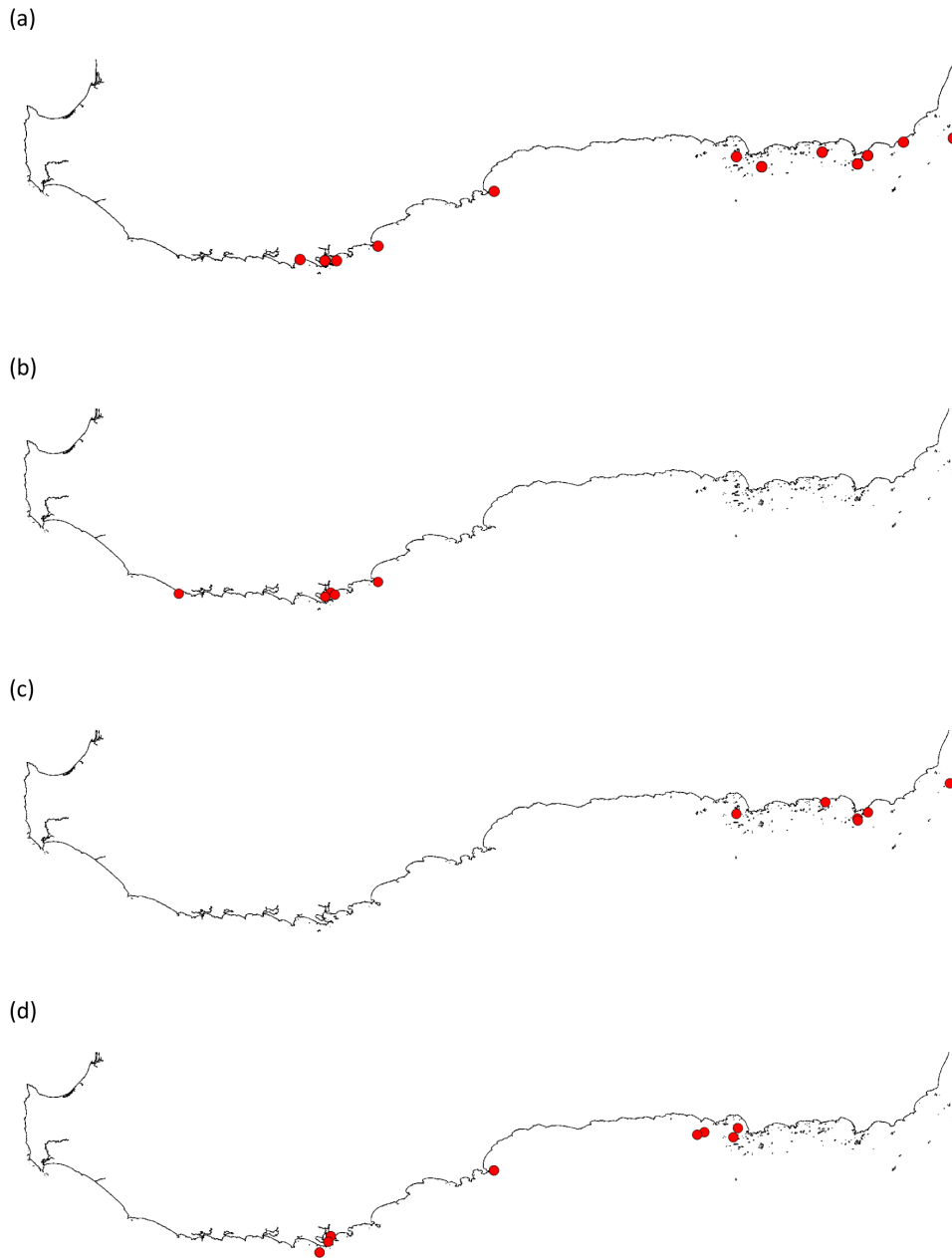
Doubtful islands. Prioritized as L (B, C) in the South Coast Region and FAR in the Warren Region. Primarily a weed of disturbed areas.

*Dysphania pumilio* – Native to WA but recorded once as a weed on Woody Island. Considered a weed in agricultural areas.

*Ehrharta longiflora* – Recorded on 18 islands (Fig. 4d). Prioritized as L (B, C) in the South Coast Region. Weedy grass commonly found in coastal areas and offshore islands (Hussey et al. 2007).

*Erodium cicutarium* – Recorded on Eclipse, Seal and Woody islands. Prioritized as N (B) in the South Coast Region. Common weed of sandy soils in WA.

*Euphorbia paralias* – Recorded on 13 islands (Fig. 5a). While specific islands are not mentioned, published literature indicates that *E. paralias* is present on all islands with beaches in the Recherche Archipelago (Keighery & Dodd 1997). An environmental weed which forms dense monocultures on beaches and foredunes. Believed to alter beach and dune shape and formation (Heylingers 1985), and negatively impact seabird populations by reducing the amount of bare ground available for nesting (Rudman 2003). Also an amenity weed because exposure to its sap can cause dermatitis in some individuals. Prioritized as L (B, C) in the South Coast Region and N (B) in the Warren Region. This species has been officially targeted for biocontrol but no biocontrol agents have been developed or released yet (Scott 2012). Success at controlling related



**Figure 5.** Recorded distribution of (a) *Euphorbia paralias*, (b) *Geranium molle*, (c) *Helichrysum luteoalbum* and (d) *Hordeum leporinum* on islands of the south coast of Western Australia.

*Euphorbia* species in North America suggest that it is possible for an effective agent to be developed for *E. paralias* in the future (Scott 2012).

*Euphorbia pepus* – Recorded on Bald and Woody islands. Largely a weed of disturbed areas. The Woody Island record is associated with a 2003 WA Herbarium specimen that came from a population of 6–20 plants on disturbed soil in the settlement. Prioritized as L (B, C) in the South Coast Region.

*Fumaria capreolata* – Recorded on Bald and Green islands. A 1986 WA Herbarium specimen from Green Island noted that this species was abundant. Prioritized as L (C) in the South Coast Region.

*Fumaria muralis* – Recorded on Breaksea and Green islands. The Green Island record is from a WA Herbarium specimen collected in 1986 that was identified at a finer taxonomic level and belongs to subspecies *muralis*. Prioritized as L (C) in the South Coast Region.

*Galium aparine* – One record from 1950 on Boxer Island. Listed by DAFWA as a prohibited plant in WA due to its negative impacts on canola production. An alert species for DPaW-managed lands in the South Coast Region. Some taxonomic uncertainty exists regarding the identity of WA specimens that have been identified as either *Galium aparine* or *Galium spurium*. Assessment and identification of the Boxer Island population is recommended in order

to determine whether it poses serious agricultural or environmental risks.

*Galium murale* – Recorded on Bald and Woody Islands. One WA Herbarium specimen collected on Woody Island in 2003 beside a track near the settlement. Prioritized as L (B, C) in the South Coast Region.

*Geranium molle* – Recorded on six islands including a small unnamed islet near Mistaken Island (Fig. 5b). Prioritised as FAR in the South Coast Region. Mostly a weed of disturbed areas.

*Gladiolus floribundus* – One record from Mistaken Island (Abbot 1981). Not currently accepted as being naturalized in WA. It is unclear what species this record actually represents. Given that some *Gladiolus* species are problematic invaders of bushland in WA, efforts should be made to determine the identity of this population.

*Helichrysum luteoalbum* – Recorded on six islands (Fig. 5c). Currently listed as native to WA but its status is ambiguous. Prioritised as FAR in the South Coast Region.

*Holcus lanatus* – One record from Green Island in Oyster Harbour from a WA herbarium specimen collected in 1986. Prioritized as L (B, C, D) in the South Coast Region with a relatively high PIER ranking of 15 for Australia. A serious weed on the edges of freshwater wetlands (Western Australian Herbarium 2014). Unlikely to spread to oceanic islands.

*Hordeum leporinum* – Recorded on eight islands (Fig. 5d). Prioritised as N (B) for the South Coast Region. Common weedy grass across south-west WA.

*Hordeum murinum* – Recorded on Woody, Long, Boxer and Figure of Eight islands. Not known to be naturalized in WA. All records are from one early source (Willis 1953) and may be due to misidentification of *Hordeum leporinum*, which is recorded on all four of these islands. One later account specifically lists *Hordeum murinum* as absent on Woody Island (Goodsell et al 1976).

*Hornungia procumbens* – Two records from WA Herbarium specimens on Middle Island in 1973 and Breaksea Island in 1975. Noted as being rare on Middle Island. Prioritized as L (C) in the South Coast Region. Hussey et al. (2007) note that it is commonly found in coastal areas and on offshore islands in WA.

*Hypochaeris glabra* – Recorded on 20 islands (Fig. 6a). Prioritized as L (B, C) in the South Coast Region. Common wind-dispersed weed found throughout south-west WA.

*Isolepis marginata* – Recorded on six islands (Fig. 6b). Sometimes considered a native plant but is currently listed as introduced by the WA Herbarium. It is believed to have been introduced from South Africa (Hussey et al. 2007). Prioritized as L (B, C) in the South Coast region. Noted as being common near the marsh east of Pink Lake on Middle Island.

*Juncus bufonius* – Recorded on six islands (Fig. 6c). Prioritized as L (C) in the South Coast region. Both native

and naturalized forms may be present in WA (Hussey et al. 2007). A WA Herbarium record from 1973 indicated that both cushion and non-cushion forms were present on Middle Island. Additional research on the taxonomy and origins of taxa currently classified as *Juncus bufonius* could help clarify the status of plants present on south coast islands.

*Lactuca serriola* – Recorded on Mondrain, West Doubtful and Middle Doubtful islands. The record from Mondrain Island was from a single plant seen in 2002 that was dispatched at the time of observation (S Hopper, pers. comm., 16 April 2014). Prioritized as FAR in the South Coast Region. Primarily found in disturbed areas (Hussey et al. 2007).

*Lagurus ovatus* – Recorded on Sandy, Shelter, Taylor and Woody islands. The Taylor Island record is from 2011 and describes the population as consisting of over 50 plants. On Woody Island it was described as locally common in 1998, and in 2002 it was noted that there were ‘many scattered plants’. Common across Shelter Island. Usually in sandy soils (Hussey et al. 2007). Prioritized as L (B, C) in the South Coast Region.

*Leontodon saxatilis* – Recorded on Honeymoon Island in 1992 from one WA Herbarium specimen. Mostly found in lawns and highly disturbed areas (Hussey et al. 2007). Prioritized as L (D) in the South Coast Region but no prioritization for the Warren Region.

*Lepidium bonariense* – Recorded on Honeymoon Island in 1992 from one WA Herbarium specimen. Prioritized as L (B, C, D) in the South Coast Region but no prioritization for the Warren Region.

*Lolium loliaceum* – Recorded on five islands (Fig. 6d). Prioritized as N (B) in the South Coast Region. More common along the coast than currently recognized.

*Lolium rigidum* – Recorded on Boxer, Figure of Eight, Green and Woody islands. Prioritized as N (B) in the South Coast Region. Notes associated with a WA Herbarium specimen collected in 2005 state that there was a population of 21–50 plants on the east end of Woody Island.

*Lotus subbiflorus* – Recorded on Gull Rock and Mistaken Island. Prioritized as L (B, C, D) in the South Coast Region. Primarily a weed of disturbed winter-wet areas (Hussey et al. 2007).

*Lycopersicon esculentum* – One record from Middle Island. Prioritized as an alert species in the South Coast Region. Low PIER rating of 2. Occasional garden escape.

*Lycium ferocissimum* – Recorded on seven islands (Fig. 7a). African Boxthorn is listed as a Weed of National Significance and is a declared weed in all states and territories except for Western Australia (Australian Weeds Committee 2013). It is prioritized as M (D, E, F) in the South Coast Region. African boxthorn was recorded on Boxer, Sandy Hook and Woody islands as early as 1950 and Middle Doubtful Island in 1980, with many of these

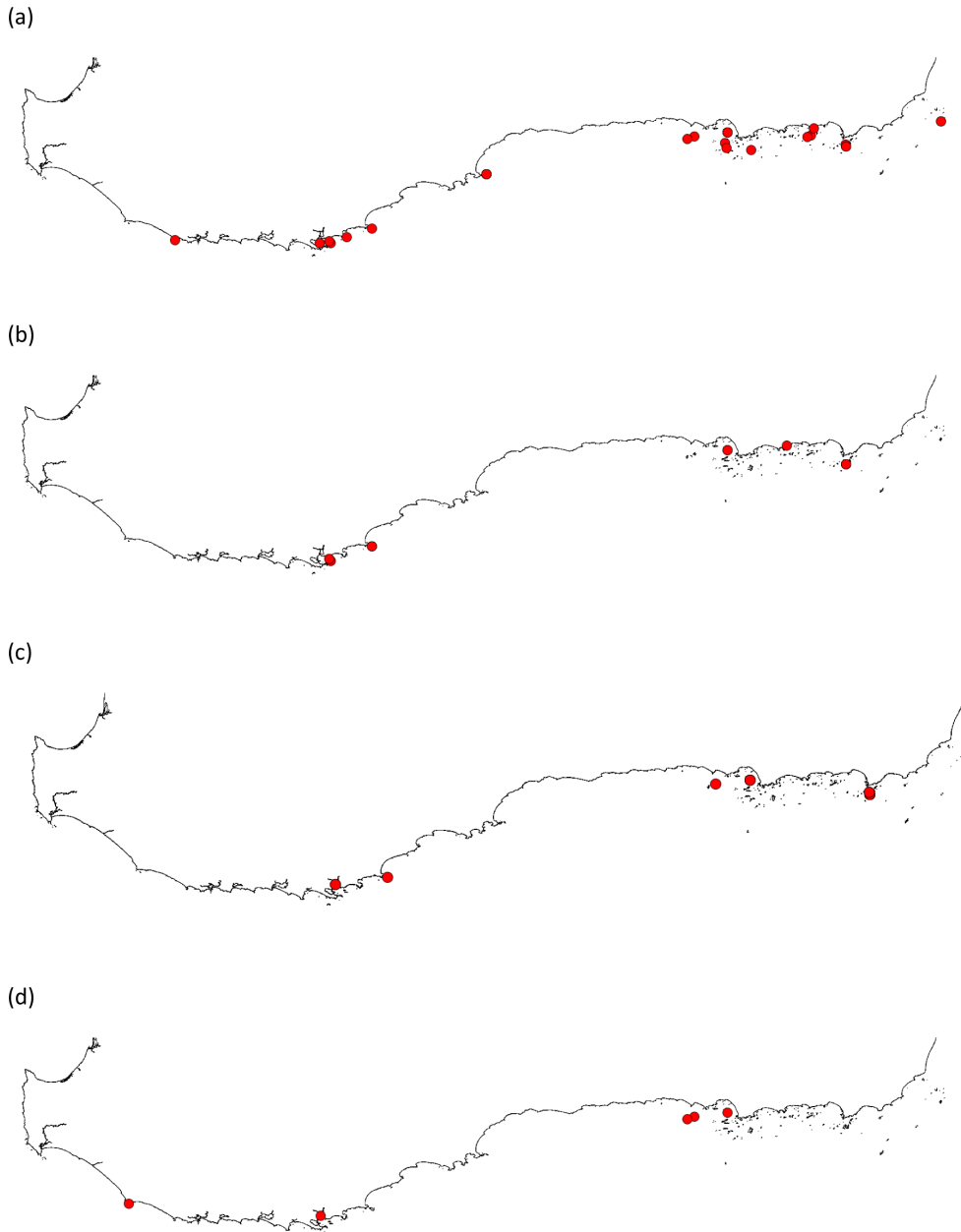


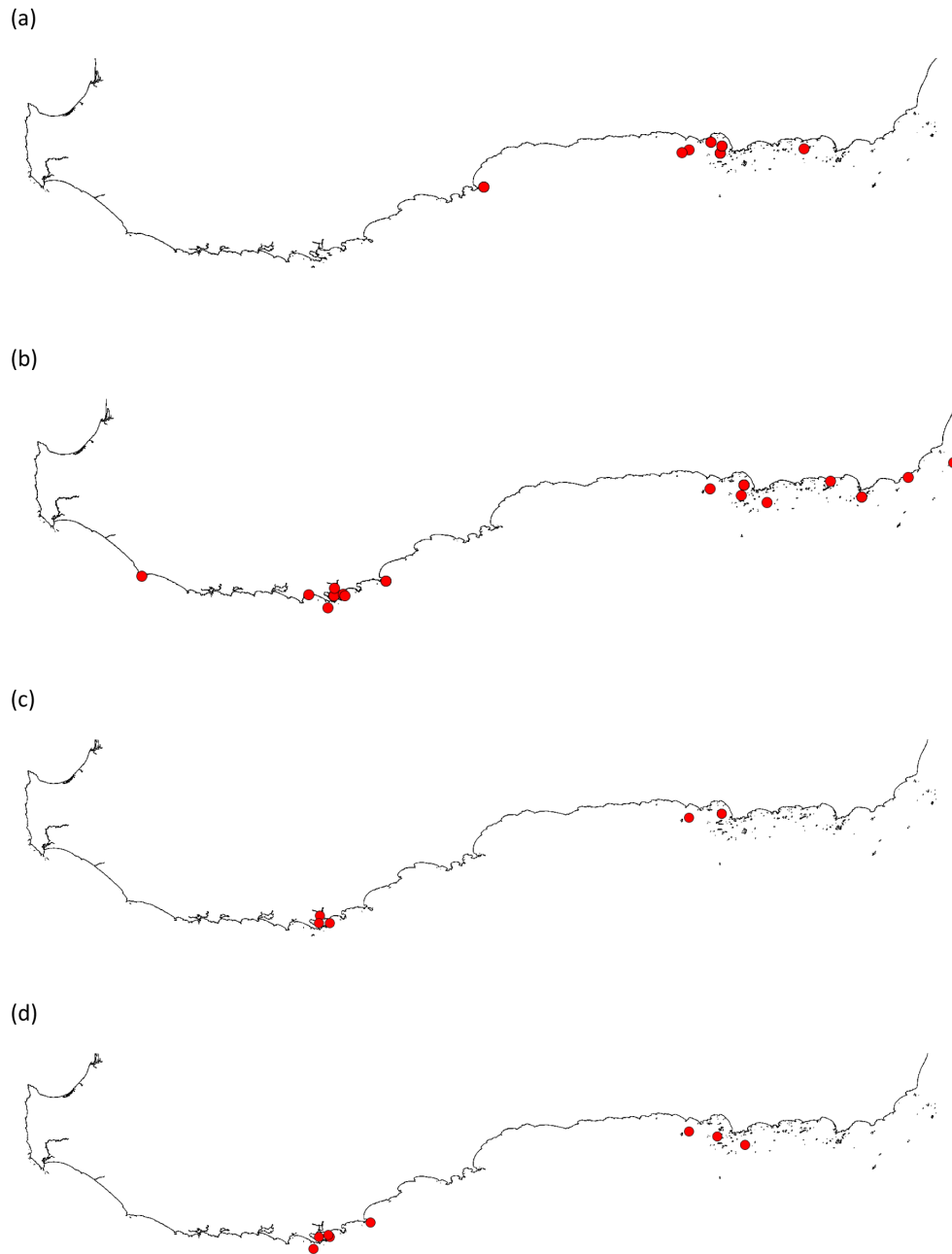
Figure 6. Recorded distribution of (a) *Hypochaeris glabra*, (b) *Isolepis marginata*, (c) *Juncus bufonius* and (d) *Lolium loliaceum* on islands of the south coast of Western Australia.

islands having more recent records. A serious infestation is also present on Cull Island where grazing by feral goats has removed most other vegetation from the island (J Lavers, pers. comm., 5 December 2013). African boxthorn is known to severely impede nesting by burrowing seabirds and breeding of seals and sea lions on offshore islets (Western Australian Herbarium 2014). It has also been observed to entangle and kill flesh-footed shearwaters (*Puffinus carneipes*) on islands off the coast of South Australia (J Lavers, pers. comm., 5 December 2013). Its threat to marine mammal and seabird populations, coupled with its ability to displace native vegetation in intact bushland, suggests that it should be removed when feasible. Allowing infestations to persist

on islands, or the adjacent mainland, increases the chance of spread to other adjacent islands because seeds are often dispersed by frugivorous birds.

*Lysimachia arvensis* – Recorded on 16 islands (Fig. 7b). Noted as being common on Goose Island in 1950. Populations of over 50 plants were present on Woody Island in 2003. Prioritized as L (B, C, D) in both Warren and South Coast Regions.

*Malva arborea* – Recorded entirely from estuarine islands: Green Island in Oyster Harbour as well as Gull Rock and Seal Island in King George Sound. Prioritized as M (D, E, F, G) in the Warren Region and listed as an alert species in the South Coast Region. Known to be a serious weed



**Figure 7.** Recorded distribution of (a) *Lycium ferocissimum*, (b) *Lysimachia arvensis*, (c) *Medicago polymorpha* and (d) *Oxalis corniculata* on islands of the south coast of Western Australia.

on islands in Shoalwater Bay and other seabird islands in Victoria and South Australia (Ripley et al. 2002). Outcompetes native plant species, reduces seabird nesting opportunities, and increases erosion (Ripley et al. 2002). Increased nitrogen from guano deposition on seabird islands seems to facilitate growth and increase the invasive properties of *M. arborea*. On Rottnest Island, grazing by quokkas has kept this weed from establishing in all areas except for a small island in a lake and a few offshore islets that are inaccessible to quokkas. When rats established on Penguin Island (about 50 km south of Perth), they seriously damaged or killed most individuals by ring-barking and near-total defoliation. There has been some

suggestion that this species may facilitate the persistence of rats in seabird colonies within its native range by providing an additional water source (Ripley et al. 2002). These anecdotes suggest that this species may be a good candidate for control via the introduction of native mammalian herbivores.

*Malva parviflora* – Recorded on Gull Rock and Woody Island. Prioritized as FAR in the South Coast Region. Prefers areas with high light and nutrient levels (Western Australian Herbarium 2014). These traits could lead to it becoming problematic on seabird islands.

*Medicago polymorpha* – Recorded on five islands (Fig.

7c). Prioritized as L (B, C) in the South Coast Region. It was noted as being present on Woody Island in 1950 (Willis 1953) but it was not detected in a later, more intensive survey of the island's flora (Goodsell et al. 1976). This probably reflects the fact that there had been a major fire on the island prior to the earlier expedition. The fire would have created an open disturbed area for *Medicago polymorpha* to establish, while subsequent regrowth could have limited its ability to persist in most areas.

*Melilotus indicus* – Recorded on Boxer and Woody islands. Prioritized as L (B, C) in the South Coast Region. Very common on Boxer in 1950 according to Willis (1953). A WA Herbarium specimen from 1998 notes it was locally common on Woody Island.

*Oxalis corniculata* – Recorded on eight islands (Fig. 7d). Prioritized as N (B) in the South Coast Region. Usually a weed in lawns and gardens (Western Australian Herbarium 2014).

*Oxalis pes-caprae* – Recorded only once from a small unnamed islet off Mistaken Island. Prioritized as N (B) in the South Coast Region.

*Parapholis incurva* – Recorded on Bellinger, Boxer, Figure of Eight and Woody islands. Prioritized as L (C) in the South Coast Region. Common weed of offshore islands and other areas with highly saline soil (Hussey et al. 2007).

*Parentucellia latifolia* – Two WA Herbarium specimens from granite areas on Bald Island in 2003. Prioritized as N (B) in the South Coast Region. Widespread weed on granite outcrops throughout the south-west of WA (Hussey et al. 2007).

*Parentucellia viscosa* – One record on Mistaken Island. Widespread weed in south-west WA. Prioritized as N (B) in the South Coast Region.

*Pelargonium capitatum* – Recorded on Saddle Island and Quagering Island (also known as Flat Island). Notes with a 2005 WA Herbarium specimen record indicate that its occurrence on Saddle Island was frequent. Prioritized as L (B, C, D) in the South Coast Region and L (B, C) in the Warren Region. A major weed of coastal heathland and beach dunes that is facilitated by disturbance (Western Australian Herbarium 2014).

*Petrorhagia dubia* – Recorded on West Doubtful Island. Prioritized as L (B, C) in the South Coast Region. Known to be a weed of granite rocks (Hussey et al. 2007).

*Phytolacca octandra* – Recorded on Green and Honeymoon islands. Notes with a 1992 WA Herbarium sample state that it was common on Honeymoon Island at the time. Prioritized as N (A, B) in the South Coast Region and L (B, C, D) in the Warren Region. A weed of disturbed areas. Could potentially colonize other islands as its seeds are dispersed by frugivorous birds.

*Poa annua* – Recorded on six islands (Fig. 8a). Prioritized as L (C) in the South Coast Region. Usually present in disturbed areas and has little impact on native vegetation (Hussey et al. 2007).

*Polycarpon tetraphyllum* – Recorded on ten islands, including one small islet (Fig. 8b). Prioritized as L (C) in the South Coast Region. Several records note that it was growing in disturbed soil. On Daw Island it was recorded as common near the camp site. Multiple records from Woody Island describe it as locally common.

*Polypogon maritimus* – One record on Eclipse Island. Prioritized as an alert species for the South Coast Region. No other records for the south coast. Possibly a misidentification of *P. monspeliensis* but needs confirmation.

*Polypogon monspeliensis* – Recorded on five islands (Fig. 8c). Notes with a WA Herbarium specimen record from 1998 state that it was locally common in areas about 20 m from the shoreline on Woody Island. Prioritized as L (C) in the South Coast Region and L (B, C) in the Warren Region. Common weed in fresh and brackish wetlands that have been disturbed (Hussey et al. 2007).

*Raphanus raphanistrum* – Recorded on Green Island in Oyster Harbour. One WA Herbarium record notes that it was common on the island. Prioritized as N (B) in the South Coast Region. Significant agricultural weed in WA.

*Romulea rosea* – Recorded on Mistaken Island. Prioritized as L (B, C) in the South Coast Region and N (B) in the Warren Region. Common weed across south-west WA.

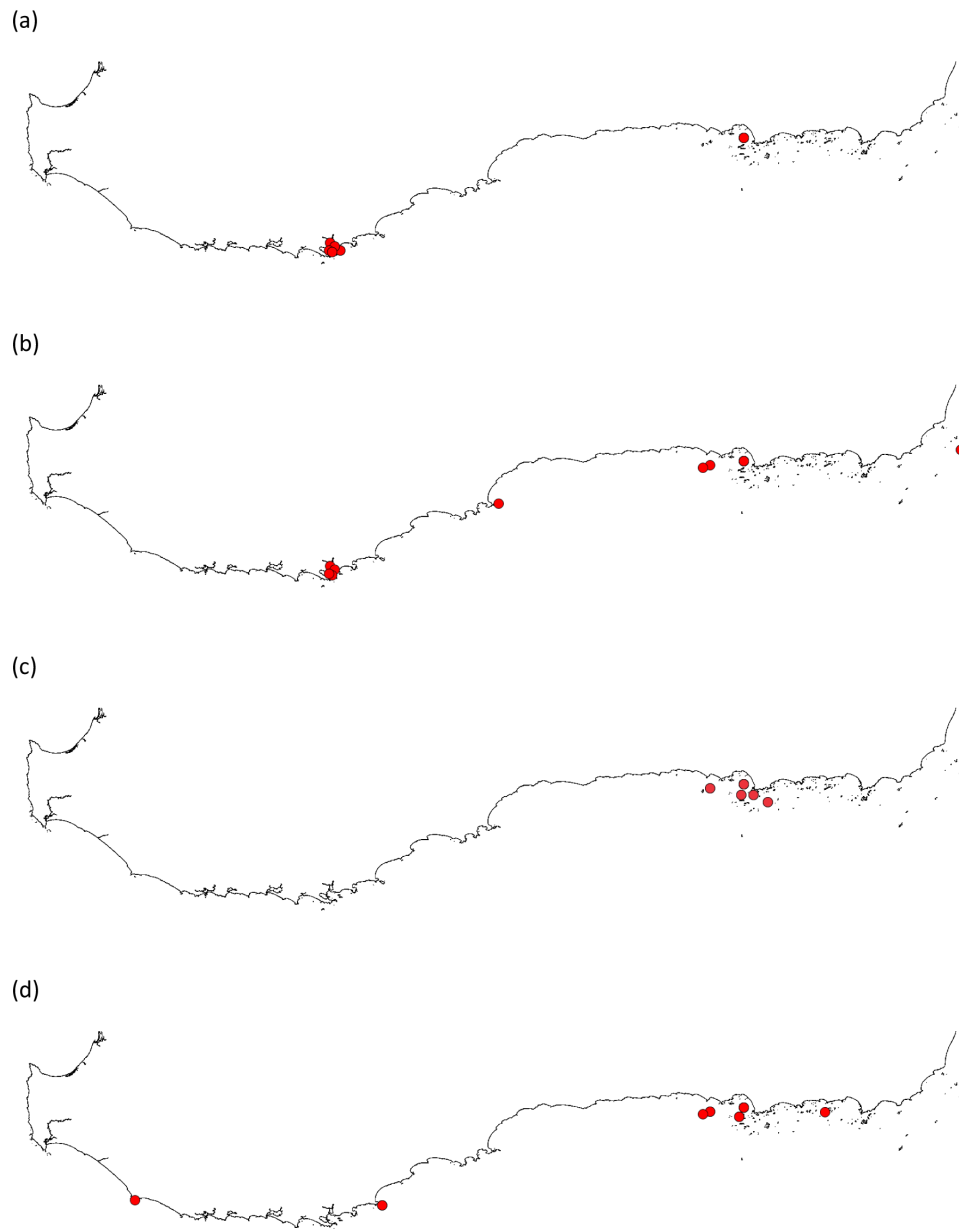
*Rostraria cristata* – Recorded on seven islands (Fig. 8d). Prioritized as L (B, C) in the South Coast Region. Weedy grass found on coastal heath and offshore islands.

*Rumex crispus* – Recorded on Woody Island and Sandy Island in Windy Harbour. Prioritized as N (B) in the South Coast Region and L (B, C, D) in the Warren Region. Has been officially targeted for biocontrol and has a moderate to high PIER ranking of 16. Both the Woody Island and Sand Island records are from prior to the release of a biocontrol moth (*Pyropteron chrysidiformis*), which has caused substantial reductions in the density of *R. crispus* across WA (Strickland et al. 2012). Surveys to investigate whether or not *R. crispus* populations are still present and whether the moth has already established could be helpful in determining whether translocation is necessary.

*Sagina apetala* – Recorded on seven islands (Fig. 9a). Prioritized as L (B, C) in the South Coast Region. Notes with a WA Herbarium specimen collected on Middle Island in 1978 state that it was 'apparently rare' but it was subsequently collected on Middle Island again at two different locations in 2004.

*Silene gallica* – Three records from Woody Island. The most recent, WA Herbarium specimen from 2003, indicates that 2–3 plants were present and that they were of the variety *Silene gallica* var. *gallica*. Prioritized as L (C) in the South Coast Region.

*Silene nocturna* – A single record from Middle Doubtful Island. Prioritized as L (B, C, D) in the South Coast Region. Typically found in disturbed areas (Hussey et al. 2007).



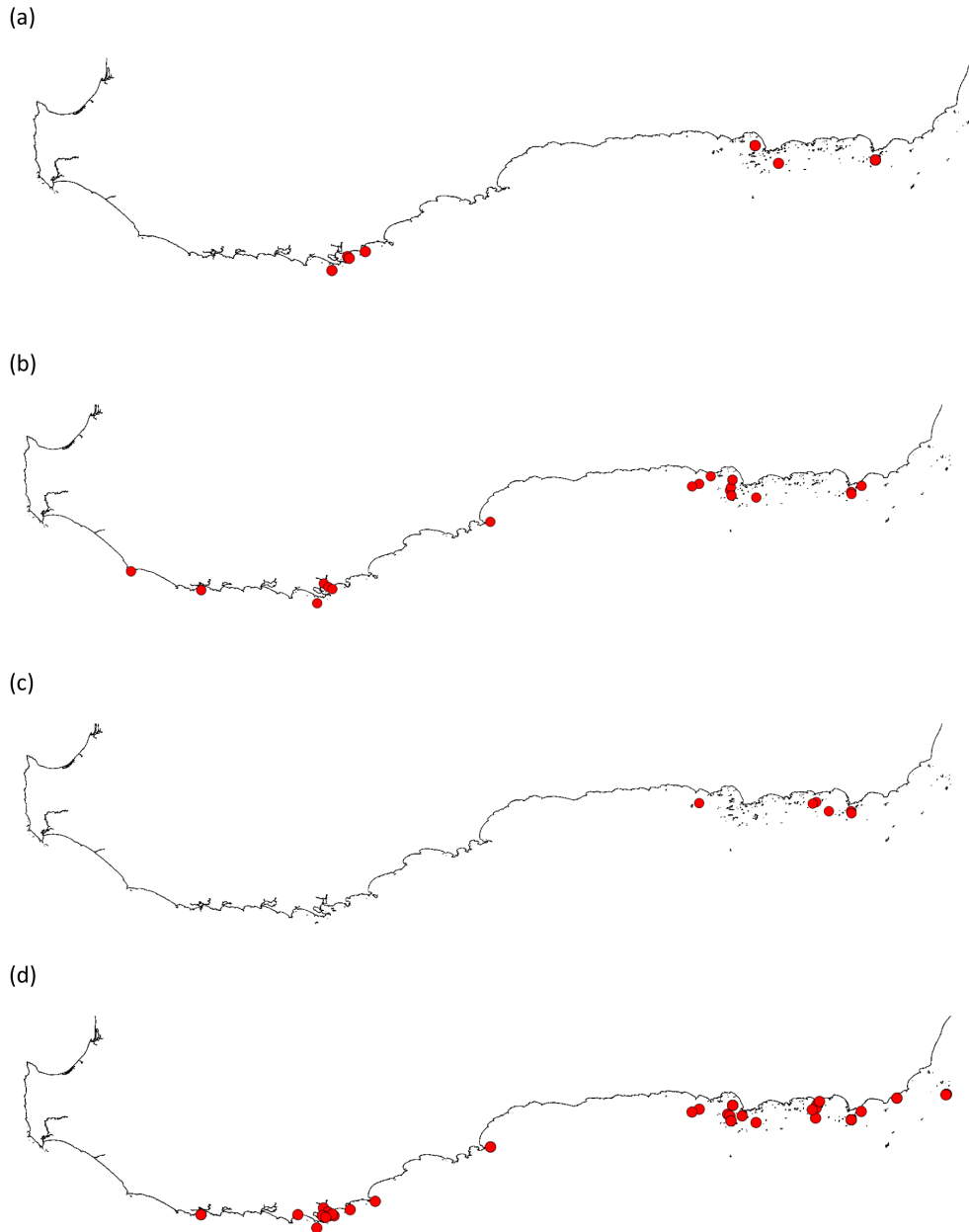
**Figure 8.** Recorded distribution of (a) *Poa annua*, (b) *Polycarpon tetraphyllum*, (c) *Polypogon monspeliensis* and (d) *Rostraria cristata* on islands of the south coast of Western Australia.

*Sisymbrium orientale* – A single record from Green Island in Oyster Harbour. Prioritized as L (B, C) in the South Coast Region.

*Solanum nigrum* – Recorded on 18 islands (Fig. 9b). Notes with a 2005 specimen collected on Saddle Island state that it was locally abundant, but another 2005 specimen from Woody Island was recorded as being the only individual present. However, this species was recorded on Woody Island as early as 1950 and is likely to still be present on the island. Prioritized as L (B, C) in the South Coast Region. Dispersal by frugivorous birds is probably responsible for this species' presence on many south coast islands. Common weed in bushland across many parts of WA.

*Sonchus asper* – Recorded on six islands (Fig. 9c). Referred to as common on Goose Island in 1950 (Willis 1953). Prioritized as L (B, C) in the South Coast Region. Groves et al. (2003) assign rankings of 3 and 4 to the two subspecies of *Sonchus asper*, however, these subspecies are no longer recognized as valid in Western Australia. Although not an official biocontrol target, this species is closely related to the agricultural weed *Sonchus oleraceus*. Biocontrol techniques in development for *S. oleraceus* are likely to be effective at controlling *S. asper* as well (Scott & McCarren 2012).

*Sonchus oleraceus* – Recorded on 31 islands (Fig. 9d). Extremely common weed across WA. Long distance dispersal of seeds by wind and an early introduction date



**Figure 9.** Recorded distribution of (a) *Sagina apetala*, (b) *Solanum nigrum*, (c) *Sonchus asper* and (d) *Sonchus oleraceus* on islands of the south coast of Western Australia.

to WA has probably allowed it to colonize more south coast islands than any other weed. Already known from 12 islands by 1950 (Willis 1953). Surprisingly, it was listed as absent on Woody Island by Goodsell et al. (1976), but was listed as present in 1950 (Willis 1953) and recorded as common on Woody Island in the notes with a WA Herbarium specimen from 1998. Prioritized as L (B, C) in the South Coast Region. Although not officially listed as a biocontrol target, a mycoherbicide is in development overseas and several potentially useful agents have already been identified within Australia (Scott & McCarren 2012).

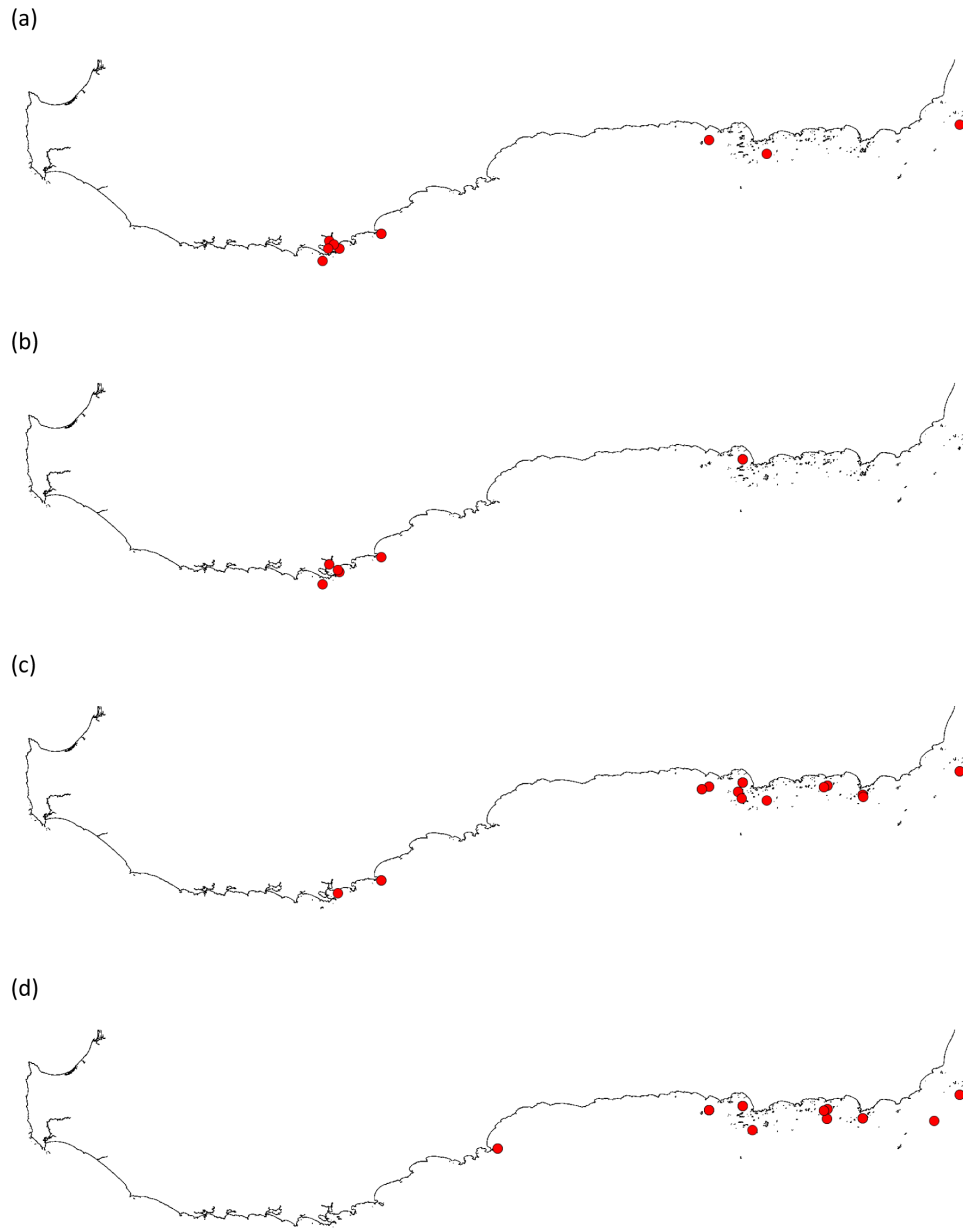
*Sparaxis bulbifera* – A population of 4–5 plants recorded on Green Island in Oyster Harbour from a WA Herbarium collection. Serious invader of clay wetlands (Hussey et al.

2007). Prioritized as L (B, C, D) in the South Coast Region and L (B, C, D) in the Warren Region.

*Spergularia diandra* – Recorded once on Saddle Island. Prioritized as L (B, C) in the South Coast Region. Scattered weed of disturbed wetlands (Hussey et al. 2007).

*Spergularia marina* – One WA Herbarium specimen collected on Woody Island in 2003. The record noted that it was from a population of 2–5 plants in a small oily puddle near the jetty. While previously listed as an alien species, *Spergularia marina* is now considered to be native to WA.

*Spergularia rubra* – Recorded on seven islands. Although it was listed as present on Woody Island in 1950 (Willis



**Figure 10.** Recorded distribution of (a) *Stellaria media*, (b) *Urtica urens*, (c) *Vulpia bromoides* and (d) *Vulpia fasciculata* on islands of the south coast of Western Australia.

1953) it was said to be absent during a later survey (Goodsell et al. (1976). Prioritized as L (B, C) in the South Coast Region.

*Sporobolus africanus* – One WA Herbarium collection from Honeymoon Island in Wilson Inlet in 1992. Invades wet swampy areas and outcompetes other vegetation (Western Australian Herbarium 2014). Currently an official biocontrol target. Two potential control agents were identified but not found to be suitable for introduction to Australia (Palmer 2012). Prioritized as L (C) in the Warren Region.

*Stellaria media* – Recorded on nine islands (Fig. 10a). Prioritized as L (B, C) in the South Coast Region. A WA Herbarium specimen from Bald Island describes it as being in disturbed areas.

*Stellaria pallida* – One WA Herbarium specimen from Woody Island in 2003. Prioritized as L (B, C) in the South Coast Region. The sample came from a population of 21–50 plants growing in the camp.

*Trachyandra divaricata* – One record from Michaelmas Island. Prioritized as N (B) in the South Coast Region and M (D, E, F) in the Warren Region. A problematic weed in areas with coastal dunes (Western Australian Herbarium 2014).

*Triticum aestivum* – Two records from Eclipse Island. Important crop plant that is not usually considered a weed. Possibly from feed used for chickens during operation of the lighthouse.

*Trifolium campestre* – One record on Woody Island.

Prioritized as N (B) in the South Coast Region. Widespread in a variety of disturbed habitats (Hussey et al. 2007).

*Trifolium cernuum* – One WA Herbarium specimen collected on Woody Island in 2003 from a population of over 50 plants in a disturbed area near the restaurant. Prioritized as N (B) in the South Coast Region.

*Trifolium glomeratum* – Recorded on Woody Island and West Doubtful Island. Prioritized as N (B) in the South Coast Region.

*Trifolium tomentosum* – One record from Woody Island. Prioritized as N (B) in the South Coast Region. Found in waterlogged and moderately saline soils and around granite rocks (Hussey et al. 2007), habitat present on many south coast islands.

*Tropaeolum majus* – Recorded only on Green Island in Oyster Harbour. Notes with a WA Herbarium specimen from 1986 describe it as abundant on Green Island. Prioritized as FAR in the South Coast Region and N (A, B) in the Warren Region. Garden escape that is only likely to colonize estuarine islands.

*Urtica urens* – Recorded on six islands (Fig. 10b). A serious amenity weed covered in hairs that produce a painful stinging or burning sensation with light contact. Often associated with high-nutrient soils such as in seabird colonies (Hussey et al. 2007). A 2003 WA Herbarium specimen was taken from a population of 6–20 plants in a disturbed area near the restaurant on Woody Island. This population probably warrants some degree of control to prevent negative impacts on user experience of the island. Prioritized as L (B, C, D) in the South Coast Region and FAR in the Warren Region.

*Vellereophyton dealbatum* – Recorded on Mondrain, Wickham and Woody islands. Notes with WA Herbarium specimens state that it was locally common near the shoreline on the west end of Woody Island in 1998, and a population of 2–5 plants was recorded from the east end in 2003. One WA Herbarium specimen was collected on Mondrain Island in 2004. Prioritized as L (B, C) in the South Coast Region.

*Vulpia bromoides* – Recorded on 13 islands (Fig. 10c) with records on eight islands as early as 1950 (Willis 1953). Prioritized as N (B) in the South Coast Region. Common weed of coastal areas along the south coast (Hussey et al. 2007).

*Vulpia fasciculata* – Recorded on 10 islands (Fig. 10d). Records on nine islands as early as 1950 (Willis 1953). Prioritized as N (B) in the South Coast Region.

*Vulpia muralis* – One WA Herbarium specimen from Woody Island from a population of 21–50 plants near a path. Prioritized as N (B) in the South Coast Region.

*Vulpia myuros* – Recorded on Breaksea, Michaelmas, Woody and Observatory islands. One WA Herbarium specimen collected on Observatory Island in 1974 was noted to be of the form *Vulpia myuros* forma *myuros*.

Other specimens from islands could belong to *Vulpia myuros* forma *megalura* as both forms are common throughout the south-west of WA. Groves et al. (2003) assign a rank of 5 to *Vulpia myuros* forma *myuros* and a rank of 4 to *Vulpia myuros* forma *megalura*. Prioritized as N (B) in the South Coast Region.

*Zantedeschia aethiopica* – Recorded on Breaksea, Eclipse, Green and Shelter islands. Eclipse Island, in particular, has dense monotypic stands of this plant (Abbott 1981). A single dead specimen was observed on Shelter Island in 2014 and its fruit was removed. A declared pest in WA with a control category of C3 and moderately high PIER ranking of 13. Prioritized as L (B, C, D) in the South Coast Region and L (D) in the Warren Region. Although it is not an official biocontrol target, some work has been done toward developing a mycoherbicide to help control this species (Scott 2012). A serious invader of freshwater wetlands that should be removed wherever possible to prevent formation of dense monocultures.

## DISCUSSION

The five islands with the highest number of recorded weed species all exhibit attributes we expected would facilitate weed invasion. Woody Island had the largest number of recorded weed species and is the only island in the Recherche Archipelago with public access. It is also a popular recreational location, and it has had extensive botanical surveys. The second, third, and fifth largest counts came from Boxer, Bald and Middle islands, respectively. All three of these islands are large relative to other islands along the south coast. Boxer and Middle islands both have a history of human use and occupation and have been the focus of several biological surveys. Though small, Green Island (ranked fourth) is located in an estuary near a major population centre and has been farmed in the past. The high proportion of weeds exclusively present on estuarine islands is probably partially due to differences in soil and other abiotic factors. Easier colonisation of weeds from mainland source populations probably plays an important role as well. Maintaining the integrity of natural barriers to weed dispersal via improved biosecurity protocols and enforcement will help to minimize new anthropogenic weed introductions to continental islands and decrease future costs associated with active management of established populations.

Due to practical difficulties in accessing many islands in the Recherche Archipelago, as well as an historical focus on native plants in flora surveys, there are probably many populations of weeds present on islands that have not yet been recorded. Some islands in the Recherche Archipelago have never been formally surveyed by biologists and represent a gap in our knowledge of the alien flora of the area. Efforts should be made to assess populations of weeds on islands that have not been surveyed or lack recent data. Priority should be given to islands of high conservation value and islands adjacent to areas known to harbor dangerous high-priority weeds.

The weeds that pose the greatest threat to the integrity of south coast island ecosystems are bridal creeper (*Asparagus asparagoides*), pig's ear (*Cotyledon orbiculata*), sea spurge (*Euphorbia paralias*), cleavers (*Galium aparine*), African boxthorn (*Lycium ferocissimum*), tree mallow (*Malva arborea*), arum lily (*Zantedeschia aethiopica*), and the annual grasses *Avena*, *Bromus*, *Ehrharta*, *Hordeum*, *Lolium* and *Vulpia*. These species have already been observed substantially impacting some islands along the south coast or, in the case of *Asparagus asparagoides* and *Galium aparine*, are known to be serious environmental weeds in similar habitats on mainland Australia. Developing management plans for these species and further clarifying their distributions will be an important step in mitigating the impacts of introduced plants on south coast islands.

The Conservation Commission Island Management Audit recommended that an online database system be developed for recording and extraction of information on biodiversity and management issues on islands (Conservation Commission of Western Australia 2009). The database of introduced plants on the islands of Western Australia that was created as part of this assessment of south coast islands substantially contributes to this goal. Efforts are currently underway to make this database more readily available to conservation professionals in Western Australia.

## ACKNOWLEDGEMENTS

Department of Parks and Wildlife staff have generously contributed their time to this project. Kellie Passeretto provided much helpful assistance regarding the regional prioritization list. Keith Morris, Sophie Moller and Paul Gioia all contributed valuable suggestions that helped develop the structure of the database underpinning this work. Our manuscript was improved by the contributions of an anonymous reviewer as well as by Steve Hopper who both reviewed the manuscript and contributed additional weed records.

## REFERENCES

- Abbott I (1981) Vegetation maps of four large islands near Albany, Western Australia. *Western Australian Herbarium Research Notes* 5, 5–18.
- Abbott I (1992) Biogeography of grasses (Poaceae) on islands of southwestern Australia. *Australian Journal of Ecology* 17, 289–296.
- Australian Weeds Committee (2013) 'Weeds of National Significance: African Boxthorn (*Lycium ferocissimum*) Strategic Plan'. Australian Weeds Committee, Canberra.
- Bechervaise JM (1972) General history. In *The Archipelago of the Recherche*, Australian Geographic Society Report 1 (ed JH Willis), pp. 3–7. Australian Geographic Society, Melbourne.
- Conservation Commission of Western Australia (2009) *Status Performance Assessment: Biodiversity Conservation on Western Australian Islands, Phase 1*. Conservation Commission of Western Australia, Perth.
- Cumming DA, Glasson M, McCarthy M (1995) 'Lighthouses of the Western Australian coast and offshore islands'. Report 100, Western Australian Maritime Museum, Department of Maritime Archeology, Fremantle.
- Department of Environment and Conservation (2012) 'Esperance and Recherche Parks and Reserves: Draft management Plan'. Department of Environment and Conservation, Perth.
- Dickson R (2007) *The History of the Whalers on the South Coast of New Holland from 1800–1888*. Hesperian Press, Carlisle, WA.
- Drost CA, Junak SA (2009) Colonizers, waifs and stowaways: arrival of new plant species on Santa Barbara Island over a 30 year period. In *Proceedings of the 7th Californian Islands Symposium* (eds CC Damiana, DK Garcelon), pp. 215–228. Institute for Wildlife Studies, Arcata, California.
- Flinders M (1814) *A Voyage to Terra Australis. Vol. 1*. G and W Nicol, London.
- Forrestal E (2008) *Black Jack Anderson*. Penguin Books, Melbourne.
- Garden DS (1977) *Albany: A Panorama of the Sound from 1827*. Nelson, Melbourne.
- Goodsell J, Tingay A, Tingay S (1976) 'A resource survey of Woody Island, Archipelago of the Recherche'. Unpublished report of Department of Fisheries and Wildlife, Perth.
- Groves RH, Hosking JR, Batiannoff GN, Cooke DA, Cowie ID, Johnson RW, Keighery GJ, Lepschi BJ, Mitchell AA, Moerkerk M, Randall RP, Rozefelds AC, Walsh NG, Waterhouse BM (2003) *Weed Categories for Natural and Agricultural Ecosystem Management*. Bureau of Rural Sciences, Canberra.
- Heyligers PC (1985) The impact of introduced plants on foredune formation in south eastern Australia. In *Proceedings of the Ecological Society of Australia* 14, 23–41.
- Hussey BMJ, Keighery GJ, Dodd J, Lloyd SG, Cousens RD (2007) *Western Weeds. A Guide to the Weeds of Western Australia*, 2nd ed. Weeds Society of WA Inc., Victoria Park, WA.
- Keighery G (1995) Additions to the flora of the Recherche Archipelago. *Western Australian Naturalist* 20, 133–138.
- Keighery GJ, Dodd J (1997) Occurrence and spread of sea spurge (*Euphorbia paralias*) along the west coast of Western Australia. *Nuytsia* 11, 285–286.

- Lamb WK, ed (1984) *The Voyage of George Vancouver 1791–1795, Vol. 1*. Hakluyt Society, London.
- Palmer B (2012) *Sporobolus* spp. – weedy sporobolus grasses. In *Biological Control of Weeds in Australia*. (eds JK Scott, M Julien, R McFadyen, J Cullen), pp. 569–575. CSIRO Publishing, Collingwood, Victoria.
- Ripley E, Hislop MC, Dodd J (2003) Reassessment of the vascular flora of Rottnest Island. *Journal of the Royal Society of Western Australia* **86**, 7–23.
- Ripley E, Ripley JJ, Dunlop N (2002) Management of indigenous and alien Malvaceae on islands near Perth, Western Australia. In *Turning the Tide: The Eradication of Invasive Species* (eds CR Veitch, MN Clout), pp. 254–259. IUCN SSC Invasive Species Specialist Group, IUCN, Gland, Switzerland and Cambridge UK.
- Rudman T (2003) ‘Tasmanian beach weed strategy for marram grass, sea spurge, sea wheatgrass, pyp grass and beach daisy’. Nature Conservation Report 3(2). Tasmania Department of Primary Industries, Parks, Water and Environment, Hobart.
- Scott JK (2012) *Euphorbia paralias* L. – sea spurge. In *Biological Control of Weeds in Australia*. (eds JK Scott, M Julien, R McFadyen, J Cullen), pp. 259–262. CSIRO Publishing, Collingwood, Victoria.
- Scott JK (2012) *Zantedeschia aethiopica* (L.) Spreng. – arum lily. In *Biological Control of Weeds in Australia*. (eds JK Scott, M Julien, R McFadyen, J Cullen), pp. 609–613. CSIRO Publishing, Collingwood, Victoria.
- Scott JK, McCarren K (2012) *Sonchus oleraceus* L. – sowthistle. In *Biological Control of Weeds in Australia*. (eds JK Scott, M Julien, R McFadyen, J Cullen), pp. 563–567. CSIRO Publishing, Collingwood, Victoria.
- Shellam T (2009) *Shaking Hands on the Fringe. Negotiating the Aboriginal World of King George’s Sound*. University of Western Australia Press, Nedlands.
- Storr GM (1962) Annotated flora of Rottnest Island, Western Australia. *The Western Australian Naturalist* **8**, 109–124.
- Strickland GR, Fogliani R, Scott JK (2012) *Rumex* spp. – docks. In *Biological Control of Weeds in Australia*. (eds JK Scott, M Julien, R McFadyen, J Cullen), pp. 510–517. CSIRO Publishing, Collingwood, Victoria.
- Willis JH (1953) Land flora. In *The Archipelago of the Recherche, Australian Geographic Society Report 1*, (ed JH Willis), pp. 3–35. Australian Geographic Society, Melbourne.
- Vilà M, Espinar JL, Hejda M, Hulme PE, Jarošík V, Maron JL, Pergl J, Schaffner U, Sun Y, Pyšek P (2011) Ecological impacts of invasive alien plants: a meta-analysis of their effects on species, communities and ecosystems. *Ecology Letters* **14**, 702–708.
- Vitousek PM, D’Antonio CM, Loope LL, Rejmanek M, Westbrooks R (1997) Introduced species: a significant component of human-caused global change. *New Zealand Journal of Ecology* **21**, 1–16.
- Western Australian Herbarium (2014) FloraBase—the Western Australian Flora. Department of Parks and Wildlife. Available at <http://florabase.dpaw.wa.gov.au/>. [Accessed 13 February 2014]

# An annotated checklist of intertidal reef invertebrates from Marmion and Shoalwater Islands marine parks

ALAN J KENDRICK & MICHAEL J RULE

Science and Conservation Division, Department of Parks and Wildlife,  
Locked Bag 104, Bentley Delivery Centre, Western Australia, 6983.

Email: alan.kendrick@dpaw.wa.gov.au

## ABSTRACT

An annotated checklist of 71 invertebrate species recorded from intertidal reefs in Marmion and Shoalwater Islands marine parks in the temperate south-west of Western Australia (WA) is presented, with information on their relative prevalence in the reserves and the habitats in which they were found. Most of the species have temperate distributions that extend across southern Australia and few are primarily tropical (at the southern limits of their distribution in the study area) to the study area. Twelve species are endemic to WA. This checklist will assist the development and implementation of long-term intertidal reef monitoring across WA's temperate marine parks.

**Keywords:** checklist, intertidal, marine protected area, monitoring

## INTRODUCTION

The coastal geomorphology of the Perth region comprises sandy beaches and rocky headlands with a complex system of offshore islands, emergent rocks and subtidal reefs formed by eroded limestone (Searle & Semeniuk 1985). The process of erosion has also formed shoreline and offshore intertidal platform reefs that are a distinctive feature of this region (Playford 1988). Shoreline intertidal reefs comprise a relatively flat limestone platform that may be at the shore, backed by a distinctive notched cliff or ramp. Similarly flat intertidal platform reefs that occur as part of reef systems up to 10 km offshore from the mainland in this area may be associated with emergent rocks or lack any permanently exposed feature. The size and structure of intertidal platform reefs vary widely; those at Rottneest Island commonly exceed 50 m in width and are typically larger than those at the adjacent mainland, which are generally less than 20 m wide.

Biological communities associated with intertidal reefs are strongly influenced by physical conditions such as tidal range and exposure to wave action (Hodgkin 1959a). Changes in the algal and invertebrate communities are usually obvious on shoreline reefs that slope upward towards the land, and the drier upper intertidal area is populated by organisms with a higher resistance to desiccation. Offshore intertidal reefs that are comparatively flat generally lack such obvious differences. Intertidal reefs can also be influenced by periodic events like sand burial or prolonged exposure to heat stress at low tide, which may lead to the mortality of organisms and processes of

succession as the reefs are recolonised (Hodgkin 1959b; Kohn 1993).

Intertidal reef research has been carried out in the Perth region since the 1950s, with initial focus on Rottneest and Carnac Islands (Marsh 1955; Hodgkin et al. 1959; Marsh & Hodgkin 1962). Scientific interest in intertidal organisms at Rottneest Island has continued as it provides numerous accessible study sites and the biota is influenced by the Leeuwin Current, as illustrated by the presence of tropical species with different life history traits at the west end of the island (see Black & Johnson 1983; Wells & Walker 1993). Only a few community-level studies have been carried out on intertidal reefs of the mainland coast adjacent to the Perth metropolitan area (Marsh 1955; Wells et al. 1987, 2007), although additional ecological research has examined particular species or functional groups, such as grazers (Wells & Keesing 1987; Wells & Sellers 1987; Scheibling 1994; Wells & Keesing 1990; Hancock 2000).

Coastal waters adjacent to the Perth metropolitan area feature two marine protected areas, Marmion Marine Park (MMP) and Shoalwater Islands Marine Park (SIMP), which are managed by WA's Department of Parks and Wildlife (DPAW). Although intertidal reefs are recognized as key ecological values of both marine parks (CALM 1992; DEC 2007), the current ecological knowledge of these communities is considered to be inadequate for effective reserve management. Here we present a checklist of invertebrate species which has been compiled from research undertaken to determine spatial and temporal patterns in the structure of intertidal reef communities in these marine parks from 2010–2012. In addition to examining spatial and temporal patterns in the distribution of intertidal invertebrates, the broader study also aimed

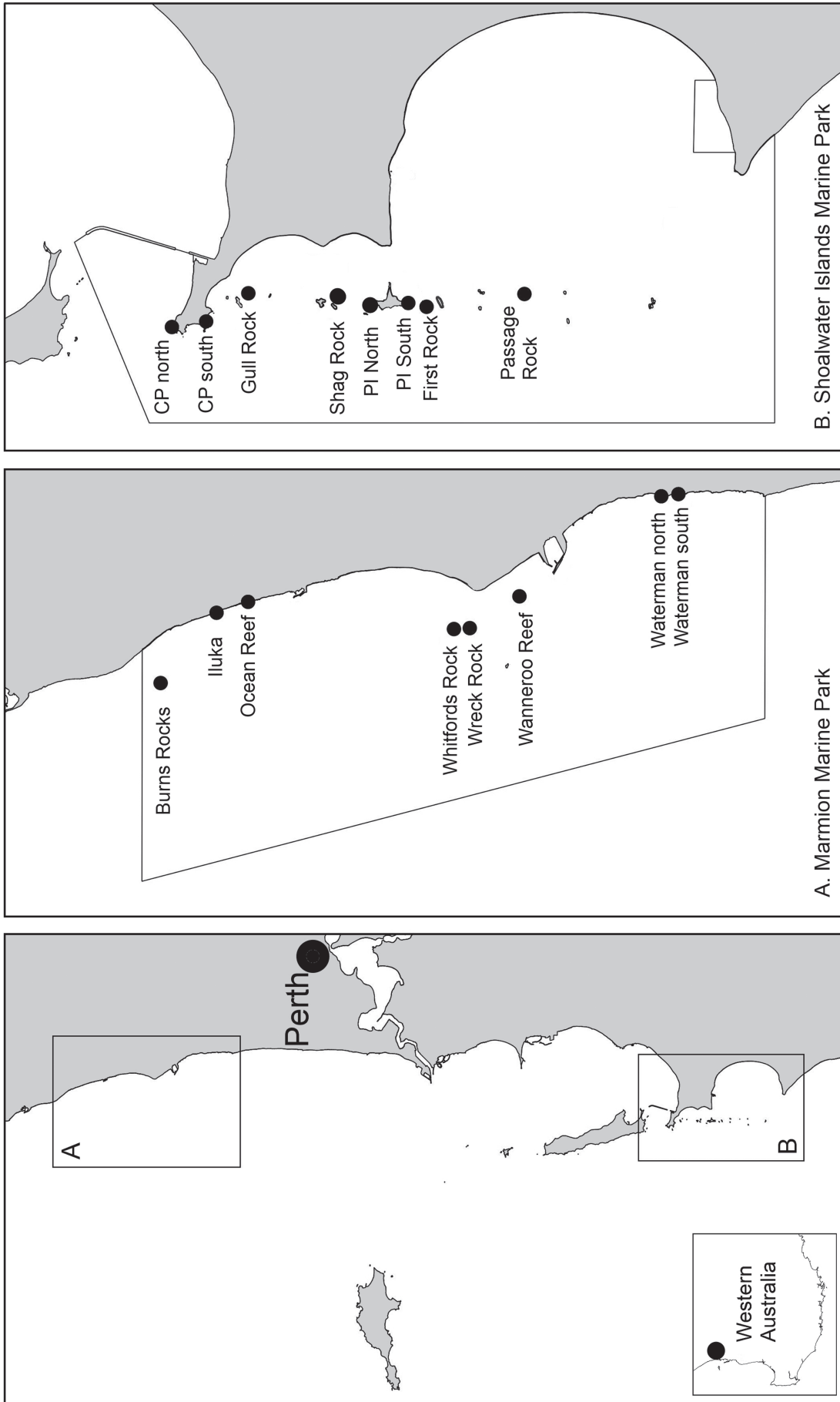


Figure 1. The study area in Western Australia. Insets show the positions of A) Marmion Marine Park and B) Shoalwater Islands Marine Park. Sites sampled during the study are indicated by dots. PI = Penguin Island; CP = Cape Peron.

to inform the development of long-term monitoring that could be used to assess the 'condition' of intertidal communities in MMP and SIMP over time. This checklist will complement more detailed ecological analyses by providing information on most of the species recorded during this research, with notes on their relative prevalence across the different sampling locations, to assist future monitoring of intertidal reef communities in MMP and SIMP.

## SAMPLING LOCATIONS, SITES AND METHODS

Located on the coast of metropolitan Perth, MMP extends from north of Burns Rocks (31° 43.45' S) to Trigg (31° 52.63' S) and SIMP extends from north of Cape Peron (32° 14.85' S) to south of Becher Point (32° 22.58' S). Sampling was conducted at four shoreline and four offshore intertidal reefs at both MMP and SIMP (n = 16 sites, Fig. 1). Shoreline reefs were those adjacent to land and thus included reefs fringing Penguin Island in SIMP. A spatial study comprising all sixteen sites was undertaken in 2011, while seven of the sites were sampled in each of three consecutive years from 2010–2012 to examine temporal patterns.

To accommodate major differences across shoreline reefs, samples were collected at inner (i.e. shoreward) and outer (i.e. seaward) areas of the platform. In most instances, these areas conformed to broadly visible changes in the algal community with the inner part of the reef supporting canopy-forming macro-algae (e.g. *Sargassum*) while the outer part was relatively bare (Wells et al. 2007). In contrast, offshore reefs were typically more homogenous with few obvious differences across the platform. At shoreline reefs, ten 1 m<sup>2</sup> sampling quadrats were haphazardly placed approximately parallel to the shore in each of the inner and outer areas, while at offshore reefs ten 1 m<sup>2</sup> quadrats were haphazardly placed across the platform. Anemones, molluscs and echinoderms greater than 5 mm in size were sampled by searching the substratum within each quadrat by hand and by removing the algal canopy, which was thoroughly washed in a 5 mm sieve to remove animals. While these groups were not specifically targeted by this study, many other groups (e.g. crabs, barnacles) were rarely encountered. Likewise, highly mobile or cryptic organisms (e.g. some crabs, brittle stars, holothurians) were not included as their presence was inconsistently observed. The number of individuals of each species was recorded and voucher specimens of unknown species were retained or photographed for later identification. The scientific names and authorities of species presented here are consistent with the Codes for Australian Aquatic Biota (CAAB Code; <http://www.marine.csiro.au/caab/>) as of March 2014. The CAAB code for each species has been included here to allow for the checking and tracking of current names in the CAAB database.

For this checklist, the relative prevalence of each species was designated as rare (n = 1 individual), occasional (n

= 2–10 individuals), frequent (n = 11–100 individuals), common (n = 101–1000 individuals) or abundant (> 1000 individuals) across the 16 sites. Broader species distributions were collated from published works (Lamprell & Whitehead 1992; Lamprell & Healy 1998; Wilson 1993, 1994; Wells & Bryce 1988; Miskelly 2002; Edgar 2008; Gowlett-Holmes 2008). This checklist is not exhaustive and does not include some taxa, such as holothurians and ophiuroideans, which were not identified to species during the surveys. Some species, such as high-shore littorinids, that were recorded in pilot sampling at SIMP and MMP have been included in the checklist although they were not observed during the actual surveys. In such cases, their relative prevalence was not assessed.

## RESULTS AND DISCUSSION

A total of 71 species, comprising three anemones, 59 molluscs and nine echinoderms, are presented here. This large number of species compared to previous intertidal reef studies in the same region (Marsh 1955; Marsh & Hodgkin 1962; Wells et al. 2007; Irvine et al. 2008), is most likely a consequence of the relatively intensive sampling effort associated with this study. The species documented here are mostly biogeographically temperate (n = 56 or ca. 79%), with distributions that extend across southern Australia. Relatively few species (n = 5 or ca. 7%), such as *Rhinoclavis* (*Rhinoclavis*) *bituberculata* and *Monetaria caputserpentis*, have predominantly tropical distributions that extend southwards to the study area. Some, like *Stomatella impertusa*, are widespread across temperate and tropical regions. This outcome is consistent with the results of previous analyses of intertidal fauna in this region and contrasts with the marine fauna of nearby Rottnest Island, where the influence of the Leeuwin Current has led to the occurrence of a higher proportion of tropical species compared with the adjacent mainland coast (Wells 1985). Twelve (ca. 17%) of the species recorded here are endemic to WA. The geographic range of these endemic species varies greatly, with some being solely temperate (e.g. *Turbo kenwilliamsi*) while others (e.g. *Echinolittorina australis*) range widely across temperate and tropical regions of the state.

Few of the species recorded here are exclusively intertidal and most also inhabit the subtidal reefs of MMP and SIMP. Indeed, some recorded in low numbers in this study, such as *Campanile symbolicum* and *Phyllacanthus irregularis*, are much more abundant on adjacent subtidal reefs. It should also be noted that some obligate intertidal species, such as neritids, littorinids, siphonariids, that inhabit the high intertidal (or 'splash zone') were generally attached to rocks above the inner shoreline reef area where samples were collected. Although their relative prevalence was not assessed as they were only recorded in pilot sampling, some of these high intertidal species (e.g. *Nerita atramentosa* and *Austrolittorina unifasciata*) were very common across rocky shores of MMP and SIMP.

With regard to implementing long-term monitoring of intertidal reef communities in MMP and SIMP and

other marine parks and reserves in temperate WA, this checklist highlights the fact that organisms inhabit a range of habitats on the reefs and efforts to monitor the overall intertidal fauna should ensure these different areas, such as the rock surface, sand patches and the algal canopy, are representatively sampled. This is particularly the case with regard to shoreline reefs, which are commonly more heterogeneous than offshore reefs because they frequently have a high intertidal area towards the shore and can also be subject to sand deposition from adjacent beaches. In both instances, these habitats support species not typically found on other parts of the reef.

Another focus of monitoring should be on species that are subject, or potentially subject, to human impacts. The most obvious direct impact is the collection of organisms, such as the abalone *Haliotis roei*, which is subject to a managed fishery in an area that includes MMP and SIMP (Hancock & Caputi 2006). However, other species are also taken from intertidal reefs for bait or food (Kingsford et al. 1991; Keough et al. 1993), and such activity has previously been documented in MMP (Farrell 1986). More broadly, sites that are established to monitor the condition of intertidal reefs in MMP and SIMP should also be chosen with consideration of other impacts, such as locations where sustained access has led to trampling effects or where pollutants or nutrients are discharged from drains into intertidal or nearshore areas (DoW 2007). Some intertidal species can be useful indicators of contamination, as indicated by the occurrence of imposex in molluscs like *Dicathais orbita* and *Conus* spp. due to the presence of pollution from the antifouling additive tributyltin in coastal waters near Perth (Kohn et al. 1999; Reitsemma et al. 2003).

## ACKNOWLEDGEMENTS

Thanks to the marine operational staff from DPaW's Swan Coastal District for their assistance in the field and to Anne Brearley, Karen Gowlett-Holmes and Loisetta Marsh for taxonomic advice. This paper benefited from the comments of two anonymous referees.

## REFERENCES

- ABRS (2014) Australian Faunal Directory, Australian Biological Resources Study. Department of Environment. Available at [http://www.environment.gov.au/biodiversity/abrs/online-resources/fauna/afd/taxa/Siphonaria\\_kurracheensis](http://www.environment.gov.au/biodiversity/abrs/online-resources/fauna/afd/taxa/Siphonaria_kurracheensis) [Accessed 12 February 2014].
- Black RW, Johnson MS (1983) Marine biological studies on Rottnest Island. *Journal of the Royal Society of Western Australia* **66**, 24–28.
- CALM (1992) *Marmion Marine Park Management Plan 1992–2002*. Department of Conservation and Land Management, Perth.
- DEC (2007) *Shoalwater Islands Marine Park Management Plan 2007–2017*. Department of Environment and Conservation, Perth.
- DoW (2007) *Contaminants in Stormwater Discharge, and Associated Sediments, at Perth's Marine Beaches*. Department of Water, Perth.
- Edgar GJ (2008) *Australian Marine Life*, 2nd ed. Reed New Holland, Sydney.
- Farrell JM (1986) Amateur fishing in the M10 area. In *Seminar on the Proposed M10 Marine Park* (eds JR Ottaway, RB Humphries), pp 139–148. Bulletin 256, Department of Conservation and Environment, Perth.
- Gowlett-Holmes K (2008) *A Field Guide to the Marine Invertebrates of South Australia*. Notomares, Hobart.
- Hancock B (2000) Genetic subdivision of Roe's abalone, *Haliotis roei* Grey (Mollusca: Gastropoda), in south-western Australia. *Marine and Freshwater Research* **51**, 679–687.
- Hancock B, Caputi N (2006) The Roes's abalone fishery near the Perth metropolitan area, Western Australia. *Journal of Shellfish Research* **25**, 167–178.
- Hodgkin EP (1959a) Patterns of life on rocky shores. *Journal of the Royal Society of Western Australia* **43**, 35–43.
- Hodgkin EP (1959b) Catastrophic destruction of the littoral fauna and flora near Fremantle January 1959. *Western Australian Naturalist* **7**, 6–11.
- Hodgkin EP, Marsh LM, Smith GG (1959) The littoral environment of Rottnest Island. *Journal of the Proceedings of the Royal Society of Western Australia* **42**, 85–88.
- Irvine TR, Keesing JK, Wells FE (2008) 'Assessment of invertebrate populations on intertidal platforms at Rottnest Island, Western Australia'. Report to the Swan Catchment Council, Perth.
- Keough MJ, Quinn GP, King A (1993) Correlations between human collecting and intertidal mollusc populations on rocky shores *Conservation Biology* **7**, 378–390.
- Kingsford MJ, Underwood AJ, Kennelly SJ (1991) Humans as predators on rocky reefs in New South Wales, Australia. *Marine Ecology Progress Series* **72**, 1–14.
- Kohn AJ (1993) Episodic mortality of limpets on a shore platform at Rottnest Island, Western Australia. In *The Marine Flora and Fauna of Rottnest Island, Volume 2* (eds FE Wells, DI Walker, H Kirkman, R Lethbridge), pp. 497–508. Western Australian Museum, Perth.
- Kohn AJ, Lalli CM, Wells FE (1999) Imposex in *Conus* at Rottnest Island, Western Australia: five years after the first report. In *The Seagrass Flora and Fauna of Rottnest Island, Western Australia* (eds DI Walker, FE Wells), pp. 199–209. Western Australian Museum, Perth.

- Lamprell K, Healy J (1998) *Bivalves of Australia, Volume 2*. Backhuys Publishers, Leiden.
- Lamprell K, Whitehead T (1992) *Bivalves of Australia, Volume 1*. Crawford House Press, Bathurst.
- Marsh LM (1955) 'Ecology of the Western Australian limestone reefs'. MSc thesis, University of Western Australia, Perth.
- Marsh LM, Hodgkin EP (1962) A survey of the fauna and flora of rocky shores of Carnac Island, Western Australia. *The Western Australian Naturalist* **8**, 62–72.
- Miskelly A (2002) *Sea Urchins of Australia and the Indo-Pacific*. Capricornia Publications, Sydney.
- Playford PE (1988) *Guidebook to the Geology of Rottnest Island*. Geological Society of Australia, Western Australian Division, Perth.
- Reitsemá TJ, Field S, Spickett JT (2003) Surveying imposex in the coastal waters of Perth, Western Australia, to monitor trends in TBT contamination. *Australasian Journal of Exotoxicology* **9**, 87–92.
- Scheibling RE (1994) Molluscan grazing and macroalgal zonation on a rocky intertidal platform at Perth, Western Australia. *Australian Journal of Ecology* **19**, 141–149.
- Scheibling RE, Black R. (1993) The ecology of the giant limpet *Patella laticostata* on intertidal limestone platforms at Rottnest Island, Western Australia. In *The Marine Flora and Fauna of Rottnest Island, Volume 2* (eds FE Wells, DI Walker, H Kirkman, R Lethbridge R), pp. 565–582. Western Australian Museum, Perth.
- Scheibling RE, Evans T, Mulvay P, Lebel T, Williamson D, Holland S (1990) Commensalism between an epizoic limpet, *Patelloida nigrosulcata*, and its gastropod hosts, *Haliotis roei* and *Patella laticostata*, on intertidal platforms off Perth, Western Australia. *Australian Journal of Marine and Freshwater Research* **41**, 647–655.
- Searle DJ, Semeniuk V (1985) The natural sectors of the inner Rottnest Shelf coast adjoining the Swan Coastal Plain. *Journal of the Royal Society of Western Australia* **67**, 116–136.
- Spencer HG, Waters JM, Eichhorst TE (2007). Taxonomy and nomenclature of black nerites (Gastropoda: Neritimorpha: *Nerita*) from the South Pacific. *Invertebrate Systematics* **21**, 229–237.
- Wells FE (1985) Zoogeographical importance of tropical marine mollusc species at Rottnest Island, Western Australia. *Western Australian Naturalist* **16**, 40–45.
- Wells FE, Bryce CW (1988) *Seashells of Western Australia*. Western Australian Museum, Perth.
- Wells FE, Keesing JK (1987) Population characteristics of the gastropod *Cantharidus pulcherrimus* on intertidal platforms in the Perth area of Western Australia. *Journal of the Malacological Society of Australia* **8**, 23–36.
- Wells FE, Keesing JK (1990) Population characteristics of the abalone *Haliotis roei* on intertidal platforms in the Perth metropolitan area. *Journal of the Malacological Society of Australia* **11**, 65–71.
- Wells FE, Keesing JK, Irvine TR (2007) 'Assessment of invertebrate populations on intertidal platforms in the Perth metropolitan area'. Swan Catchment Council, Perth.
- Wells FE, Keesing JK, Sellers RJ (1987) The 1986 survey of mollusc and echinoderm assemblages on intertidal beachrock platforms in the Perth metropolitan area. In *Collected Technical Reports on the Marmion Marine Park, Perth, Western Australia* (ed E Moore), pp. 125–161. Technical Series **19**, Environmental Protection Authority, Perth.
- Wells FE, Sellers RJ (1987) Reproductive periodicity of the chiton *Acanthopleura hirtosa* on intertidal platforms in the Perth area. *Journal of the Malacological Society of Australia* **8**, 87–92.
- Wells FE, Walker DI (1993) Introduction to the marine environment of Rottnest Island, Western Australia. In *The Marine Flora and Fauna of Rottnest Island, Volume 1* (eds FE Wells, DI Walker, H Kirkman, R Lethbridge), pp. 1–10. Western Australian Museum, Perth.
- Wilson B (1993) *Australian Marine Shells, Part 1*. Odyssey Publishing, Kallaróo.
- Wilson B (1994) *Australian Marine Shells, Part 2*. Odyssey Publishing, Kallaróo.

## APPENDIX 1

Annotated checklist of intertidal reef species collected at Marmion and Shoalwater Islands marine parks from 2010–2012.

### Phylum Cnidaria

#### Family Actiniidae

*Actinia tenebrosa* Farquhar, 1898.

CAAB Code: 11 232001.

Distribution: Southern Australia including Tasmania, from Shark Bay (WA) to Heron Island in Queensland (Edgar 2008; Gowlett-Holmes 2008).

Prevalence: Abundant.

Notes: This species occurred widely on shoreline and offshore reefs at MMP and SIMP, but was only occasionally recorded at the inner area of shoreline reefs. Densities of *A. tenebrosa* at the outer area of shoreline reefs at MMP commonly exceeded 10 m<sup>-2</sup>, in contrast to SIMP where they more typically occurred at 1–2 m<sup>-2</sup>. Higher densities of >20 m<sup>-2</sup> commonly occurred at offshore reefs, including at Burns Rocks in MMP where the highest density of 92 m<sup>-2</sup> was recorded in one quadrat. This species was most commonly found on exposed rock surfaces and hollows without dense algae.

*Aulactinia veratra* (Drayton in Dana, 1846).

CAAB Code: 11 232003.

Distribution: Southern Australia including Tasmania, from Rottnest Island (WA) to southern Queensland (Edgar 2008; Gowlett-Holmes 2008).

Prevalence: Common.

Notes: This species occurred widely on shoreline and offshore reefs at MMP and SIMP, and was present at both inner and outer areas on shoreline reefs. While densities of this species rarely exceeded 5 m<sup>-2</sup> at shoreline reefs, densities of >10 m<sup>-2</sup> occurred frequently at MMP offshore reefs.

*Oulactis mcmurrichi* (Lager, 1911).

CAAB Code: 11 232021.

Distribution: Southern Australia from Perth (WA) to Coffin Bay in South Australia (Edgar 2008).

Prevalence: Common.

Notes: This species mostly occurred at the inner and outer areas of shoreline reefs in MMP and SIMP and was far less common on offshore reefs. It was, however, recorded at Passage Rock and Shag Rock in SIMP and at Wreck Rock in MMP. When present, densities of this species only occasionally exceeded 2 m<sup>-2</sup>, although a maximum of 11 m<sup>-2</sup> was recorded on two instances at inner areas at Cape Peron south (SIMP) and at Iluka (MMP). This species often occurred in sand-filled hollows.

### Phylum Mollusca

#### Family Chitonidae

*Liolophura hirtosa* (Blainville, 1825).

CAAB Code: 23 118005.

Distribution: Endemic to WA, from Shark Bay to Albany (Edgar 2008).

Prevalence: Abundant.

Notes: This species occurred mostly on the outer area of shoreline reefs and on offshore reefs, and was more common at MMP than at SIMP. At MMP, *L. hirtosa* was most abundant at the outer areas of Iluka and Ocean Reef, where densities of >10 m<sup>-2</sup> were common and much higher densities of about 100 m<sup>-2</sup> were occasionally recorded. In contrast, densities of *L. hirtosa* at SIMP only exceeded 10 m<sup>-2</sup> at First Rock, where a maximum of 39 m<sup>-2</sup> was recorded.

#### Family Cryptoplacidae

*Cryptoplax iredalei* Ashby, 1923.

CAAB Code: 23 121002.

Distribution: Southern Australia, including Tasmania (Gowlett-Holmes 2008).

Prevalence: Rare.

Notes: A single specimen was recorded at Gull Rock (SIMP).

#### Family Haliotidae

*Haliotis roei* Gray, 1826.

CAAB Code: 24 038005.

Distribution: Southern Australia, from Shark Bay (WA) to western Victoria (Edgar 2008).

Prevalence: Abundant.

Notes: This was the second most abundant species recorded in this study. It occurred mostly at MMP offshore reefs and the outer area of shoreline reefs, where densities frequently exceeded 100 m<sup>-2</sup>. At SIMP, *H. roei* occurred primarily at Passage and First rocks, but less frequently than the high densities often recorded at MMP reefs. This species was also consistently present at Penguin Island south at lower densities of <10 m<sup>-2</sup>. It was most typically found on exposed rock surfaces and hollows with little or no macroalgae. Large *H. roei* (up to ca. 120 mm) were one of the most prominent species in the study area and are an important recreational fishery species on MMP and SIMP intertidal reefs.

*Haliotis scalaris* (Leach, 1814).

CAAB Code: 24 038015.

Distribution: Southern Australia, including northern Tasmania, from Dongara (WA) to Cape Liptrap in Victoria (Edgar 2008).

Prevalence: Rare.

Notes: A single specimen was recorded at the outer area at Penguin Island north (SIMP).

#### Family Fissurellidae

*Macroschisma productum* Adams, 1850.

CAAB Code: 24 040031.

Distribution: Southern Australia, including Tasmania, from Dongara (WA) to New South Wales (Wells & Bryce 1988).

Prevalence: Common.

Notes: This species was present at both MMP and SIMP, but was

recorded only at the inner area of MMP shoreline reefs. In contrast, at SIMP it was found at the inner and outer areas of shoreline reefs and also at Gull Rock and Shag Rock. Although this species most commonly occurred at low densities of 1–2 m<sup>-2</sup>, abundances of about 10 m<sup>-2</sup> were occasionally recorded. It was typically concealed amongst sand and turfing algae and in rock hollows.

*Macroschisma baikiei* (A Adams, 1855).

CAAB Code: 24 040026.

Distribution: Endemic to WA, from Geraldton to Esperance (Wilson 1993; Wells & Bryce 1988).

Prevalence: Rare.

Notes: A single specimen was recorded at the inner area at Penguin Island north (SIMP).

*Amblychilepas oblonga* (Menke, 1843).

CAAB Code: 24 040024.

Distribution: Southern Australia, from Geraldton (WA) to Western Port in Victoria (Edgar 2008).

Prevalence: Frequent.

Notes: This species was only recorded at the inner areas at Ocean Reef and Iluka (MMP). Although recorded on relatively few instances, 13 individuals were found in a single quadrat. It was typically concealed amongst sand and turf algae.

*Amblychilepas nigrita* (GB Sowerby, 1835).

CAAB Code: 24 040023.

Distribution: Southern Australia, including Tasmania, from Geraldton (WA) to Caloundra in Queensland (Edgar 2008).

Prevalence: Occasional.

Notes: A small number of this species were recorded from the inner areas at Iluka and Waterman south (MMP).

#### Family Patellidae

*Scutellastra peronii* (Blainville, 1825).

CAAB Code: 24 005004.

Distribution: Southern Australia, including Tasmania, from Shark Bay (WA) to New South Wales (Edgar 2008).

Prevalence: Abundant.

Notes: This species occurred mostly at the outer area of MMP shoreline reefs, where densities frequently exceeded 100 m<sup>-2</sup> and on several instances exceeded 200 m<sup>-2</sup>. It was only recorded in low densities at First Rock (SIMP). This species was typically found attached to bare rock surfaces or those with low sparse algae.

*Scutellastra laticostata* (Blainville, 1825).

CAAB Code: 24 005003.

Distribution: Southern Australia from Shark Bay (WA) to Port Lincoln in South Australia (Edgar 2008).

Prevalence: Occasional.

Notes: A small number of this species was recorded at First Rock (SIMP). This particularly large (up to ca. 110 mm) limpet is locally abundant on intertidal reefs at the west end of Rottnest Island (Scheibling & Black 1993) and, together with *H. roei*, acts as a host for the commensal limpet *P. nigrosulcata* (Scheibling et al. 1990).

#### Family Lottidae

*Patelloida alticostata* (Angas, 1865).

CAAB Code: 24 010002.

Distribution: Southern Australia, including Tasmania, from Kalbarri (WA) to The Entrance in New South Wales (Edgar 2008).

Prevalence: Abundant.

Notes: This was the most abundant species recorded in this study. It was most prevalent at the outer area of MMP shoreline reefs, where densities commonly exceeded 100 m<sup>-2</sup> and occasionally exceeded 500 m<sup>-2</sup>. It was considerably less abundant at SIMP, where it occurred mostly at Passage and First rocks at densities of typically <50 m<sup>-2</sup>. This species was usually found attached to bare rock surfaces or those with low sparse algae.

*Lottia onychitis* (Menke, 1843).

CAAB Code: 24 010008.

Distribution: Southern Australia, from Point Quobba (WA) to South Australia (Wells & Bryce 1988).

Prevalence: Abundant.

Notes: This species occurred mostly at the outer area of MMP shoreline reefs, where densities frequently exceeded 50 m<sup>-2</sup> and on several instances approached 100 m<sup>-2</sup>. It was recorded in far lower densities at the Cape Peron south inner area (SIMP). This species was typically found attached to bare rock surfaces.

*Patelloida nigrosulcata* (Reeve, 1855).

CAAB Code: 24 010022.

Distribution: Endemic to WA, from the Houtman Abrolhos to Esperance (Wells & Bryce 1988).

Prevalence: Frequent.

Notes: This species was only recorded attached to the shells of living *H. roei* and *S. laticostata*. Individual numbers were not recorded, but it occurred at all locations where the host species were present.

#### Family Trochidae

*Austrocochlea rudis* (Gray, 1826).

CAAB Code: 24 046071.

Distribution: Southern Australia, from Kalbarri (WA) to South Australia (Wells & Bryce 1988).

Prevalence: Occasional.

Notes: A small number of this species were recorded at inner and outer areas at Iluka (MMP).

*Stomatella impertusa* (Burrow, 1815).

CAAB Code: 24 046068.

Distribution: Indo-west Pacific, circum-Australian (Wilson 1993; Gowlett-Holmes 2008). Prevalence: Common.

Notes: This species occurred mostly at inner and outer areas of SIMP shoreline reefs, but was only occasionally recorded at SIMP offshore reefs and at MMP. Densities only occasionally exceeded 5 m<sup>-2</sup> and it was most commonly found amongst turf algae, in rock hollows and on algal fronds.

*Cantharidus pulcherrimus* (Wood, 1828).

CAAB Code: 24 046095.

Distribution: Southern Australia, from Jurien Bay (WA) to Victoria (Wilson 1993).

Prevalence: Abundant.

Notes: This species was most abundant at shoreline reefs and markedly less so at offshore reefs. While densities at the inner areas of MMP shoreline reefs commonly exceeded 50 m<sup>-2</sup> and occasionally exceeded 150 m<sup>-2</sup>, densities at the inner and outer areas of SIMP shoreline reefs were rarely >15 m<sup>-2</sup>. This species was most commonly found attached to algal fronds.

*Clanculus* spp.

CAAB Code: 24 046915.

Distribution: Widespread across temperate and tropical regions (Wilson 1993).

Prevalence: Common.

Notes: These juvenile shells with undeveloped features of the umbilicus, columella and aperture were recorded widely across shoreline and offshore reefs at MMP and SIMP but in relatively low densities that never exceeded 7 m<sup>-2</sup>. They were typically found attached to the fronds of tall algae such as *Sargassum*.

*Prothalotia lehmanni* (Menke, 1843).

CAAB Code: 24 046094.

Distribution: Southern Australia from Kalbarri (WA) to Victoria (Edgar 2008).

Prevalence: Common.

Notes: This species occurred widely across shoreline and offshore reefs at MMP and SIMP but in low densities that only occasionally exceeded 2 m<sup>-2</sup>. This species was typically found attached to the fronds of algae.

*Thalotia chlorostoma* (Menke, 1843).

CAAB Code: 24 046112.

Distribution: Southern Australia from the Houtman Abrolhos (WA) to Victoria (Wells & Bryce 1988).

Prevalence: Occasional.

Notes: A small number of this species were recorded at inner and outer areas at Iluka (MMP) and at Cape Peron North and Penguin Island south (SIMP). It was typically found attached to the fronds of algae.

*Notogibbula preissiana* (Philippi, 1848).

CAAB Code: 24 046092.

Distribution: Southern Australia, from Fremantle (WA) to Victoria (Wilson 1993).

Prevalence: Occasional.

Notes: This species was recorded only twice at the outer area of Penguin Island south (SIMP).

#### Family Turbinidae

*Lunella torquata* (Gmelin, 1791).

CAAB Code: 24 045003.

Distribution: Southern Australia from Port Gregory (WA) to eastern

South Australia and from Green Cape to Brunswick Heads in New South Wales (Edgar 2008).

Prevalence: Abundant.

Notes: This species was widespread on shoreline and offshore reefs in MMP and SIMP. Larger individuals were usually found attached to the reef surface while smaller shells were often concealed in turf algae or among the fronds of algae. While the density of large shells (up to ca. 100 mm) rarely exceeded 10 m<sup>-2</sup>, juveniles were occasionally recorded at densities of >20 m<sup>-2</sup>. Large *L. torquata* are one of the most prominent species on intertidal reefs of MMP and SIMP. The commensal bonnet limpet *H. conicus* was commonly attached to this species.

*Turbo kenwilliamsi* Williams, 2008.

CAAB Code: 24 045052.

Distribution: Endemic to WA, from Point Quobba to Esperance (Edgar 2008).

Prevalence: Occasional.

Notes: This large species (up to ca. 80 mm) was recorded at the inner and outer areas of shoreline reefs at Ocean Reef (MMP), Cape Peron north and south and Penguin Island north (SIMP).

#### Family Neritidae

*Nerita atramentosa* Reeve, 1855.

CAAB Code: 24 057001.

Distribution: Southern Australia from Western Australia to New South Wales, including Tasmania (Spencer 2007). Prevalence: Not assessed.

Notes: This species was recorded during pilot sampling at SIMP. It occurred across the study area at sites that provide a mid to high intertidal area, which was typically above the shoreline reef inner area sampling conducted during this study.

#### Family Littorinidae

*Austrolittorina unifasciata* (Gray, 1826).

CAAB Code: 24 095001.

Distribution: Southern Australia, including Tasmania, from North West Cape (WA) to Yeppoon in Queensland (Edgar 2008).

Prevalence: Not assessed.

Notes: This species was recorded during pilot sampling at Ocean Reef (MMP). It occurred across the study area at sites that provide a high intertidal area, which was typically above the shoreline reef inner area sampling conducted during this study.

*Echinolittorina australis* (Quoy and Gaimard, 1826).

CAAB Code: 24 095024.

Distribution: Endemic to WA, from Kimberley to Esperance (Edgar 2008).

Prevalence: Not assessed.

Notes: This species was recorded during pilot sampling at Ocean Reef (MMP). It occurred across the study area at sites that provide a high intertidal area, which was typically above the shoreline reef inner area sampling conducted during this study.

**Family Phasianellidae**

*Phasianella ventricosa* Swainson, 1822.

CAAB Code: 24 042006.

Distribution: Southern Australia, including Tasmania, from the Houtman Abrolhos (WA) to Noosa (Qld) (Edgar 2008).

Prevalence: Occasional.

Notes: A small number of this species were recorded at inner areas at Iluka and Waterman north (MMP) and at Shag Rock (SIMP). They were found attached to the fronds of algae.

*Phasianella variegata* Lamarck, 1822.

CAAB Code: 24 042005.

Distribution: Endemic to WA, from Cheyne Beach to Dampier (Wilson 1993).

Prevalence: Occasional.

Notes: A small number of this species were recorded at the outer area at Penguin Island south (SIMP), where they were found attached to fronds of algae.

**Family Cerithiidae**

*Rhinoclavis (Rhinoclavis) bituberculata* (Sowerby, 1865).

CAAB Code: 24 076048.

Distribution: Northern Australia, extending southwards to Cape Leeuwin (WA) and southern Queensland (Wilson 1993, Edgar 2008).

Prevalence: Frequent.

Notes: This species was only collected from shoreline reef inner areas at MMP, where it was found concealed in sand patches and sand-filled hollows. On several instances it was recorded at densities of 6–7 m<sup>-2</sup> but was usually less common.

**Family Campanilidae**

*Campanile symbolicum* Iredale, 1917.

CAAB Code: 24 090001.

Distribution: Endemic to WA, from Geraldton to Esperance (Edgar 2008).

Prevalence: Occasional.

Notes: A small number of this large species (up to ca. 230 mm) were recorded at Shag Rock and the outer area at Cape Peron north (SIMP). This and other large gastropod species, such as *D. orbita* and *L. torquata*, act as hosts for the bonnet limpet *H. conicus*.

**Family Hipponicidae**

*Hipponix australis* (Lamarck, 1819).

CAAB Code: 24 130001.

Distribution: Around southern Australia, from NSW to Shark Bay, including Tasmania (Gowlett-Holmes, 2008).

Prevalence: Common.

Notes: This species occurred only on the shells of large molluscs such as *D. orbita*, *L. torquata* and *C. symbolicum*. Individual numbers were not recorded, but it occurred at all locations where the host species were present. More than ten could occur on a

single host shell, where they typically cluster near the aperture and feed on faecal pellets produced by the host.

**Family Epitoniidae**

*Opalia granosa* (Quoy & Gaimard, 1834).

CAAB Code: 24 191006.

Distribution: Southern Australia, including Tasmania, from Fremantle (WA) to Victoria (Wells & Bryce 1988).

Prevalence: Occasional.

Notes: A small number of this species were recorded from the inner area of shoreline reefs at Iluka and Waterman north (MMP) and Penguin Island north (SIMP). They were typically buried in sand.

**Family Cypraeidae**

*Monetaria caputserpentis* (Linnaeus, 1758).

CAAB Code: 24 155018.

Distribution: Indo-west Pacific and southwards to Albany (WA) and New South Wales (Wilson 1993; Wells & Bryce 1988).

Prevalence: Rare.

Notes: A single specimen was recorded at Passage Rock (SIMP).

**Family Muricidae**

*Dicathais orbita* (Gmelin, 1791).

CAAB Code: 24 200008.

Distribution: Southern Australia, including Tasmania, from Barrow Island (WA) to southern Queensland (Edgar 2008).

Prevalence: Common.

Notes: This large species (up to ca. 75 mm) was widespread across shoreline inner and outer areas and offshore reefs in both MMP and SIMP. Larger individuals were usually found attached to the reef surface and smaller shells were often concealed in hollows. While it most commonly occurred at 1–3 m<sup>-2</sup>, densities of 10–15 m<sup>-2</sup> were occasionally recorded. The commensal bonnet limpet *H. conicus* was often attached to this species. Along with *H. roei* and *L. torquata*, larger *D. orbita* were among the most prominent species in the study area. The presence of imposex in this species has been used to monitor the impact of tributyltin contamination in coastal waters near Perth (Reitsemá et al. 2003).

*Lepsiella (Bedeva) paivae* (Crosse, 1864).

CAAB Code: 24 200003.

Distribution: Southern Australia, including Tasmania, from Shark Bay (WA) to Queensland (Wells & Bryce 1988).

Prevalence: Rare.

Notes: A single specimen was recorded at the inner area at Iluka (MMP).

*Murexsul planiliratus* (Reeve, 1845).

CAAB Code: 24 200152.

Distribution: Southern Australia, from Fremantle (WA) to central Victoria (Wilson 1993).

Prevalence: Not assessed.

Notes: This species was recorded during pilot sampling at MMP.

*Cronia avellana* (Reeve, 1846).

CAAB Code: 24 200005.

Distribution: Endemic to WA, from the Kimberley to Cheynes Beach (Wilson 1993).

Prevalence: Frequent.

Notes: Most individuals of this species were recorded at Burns Rocks (MMP), with smaller numbers also occurring at Gull Rock (SIMP) and the inner areas of Waterman south (MMP) and Penguin Island north (SIMP).

#### Family Buccinidae

*Cominella eburnea* (Reeve, 1846).

CAAB Code: 24 202001.

Distribution: Southern Australia, including Tasmania, from Geraldton (WA) to Moreton Bay in Queensland (Edgar 2008).

Prevalence: Rare.

Notes: A single specimen was recorded at the inner area at Iluka (MMP).

#### Family Nassariidae

*Nassarius glans particeps* (Hedley, 1915).

CAAB Code: 24 202006.

Distribution: Southern Australia, including Tasmania, from North West Cape (WA) to southern Queensland (Wilson 1993; Gowlett-Holmes 2008).

Prevalence: Rare.

Notes: A single specimen was recorded at Shag Rock (SIMP).

#### Family Ranellidae

*Ranella australasia* (Perry, 1811).

CAAB Code: 24 176002.

Distribution: Southern Australia, including Tasmania, from the Houtman Abrolhos (WA) to Tin Can Bay in Queensland (Edgar 2008).

Prevalence: Rare.

Notes: A single specimen was recorded at the outer area at Penguin Island south (SIMP).

#### Family Columbelloidea

*Euplica scripta* (Lamarck, 1822).

CAAB Code: 24 203051.

Distribution: Indo-west Pacific, from North West Cape (WA) to northern New South Wales (Wilson 1993).

Prevalence: Common.

Notes: This species was widespread across shoreline and offshore reefs at MMP and SIMP. It was frequently recorded at densities of >10 m<sup>-2</sup> and occasionally exceeded 50 m<sup>-2</sup>. This species most commonly occurred in the fronds of large brown algae like *Sargassum*.

*Euplica bidentata* (Menke, 1843).

CAAB Code: 24 203045.

Distribution: Southern Australia, from North West Cape (WA) to South Australia (Edgar 2008).

Prevalence: Common.

Notes: This species was widespread across shoreline and offshore reefs at MMP and SIMP. It was recorded in similar densities to *E. scripta* was also most commonly found on the fronds of large brown algae like *Sargassum*.

*Mitrella austrina* (Gaskoin, 1851).

CAAB Code: 24 203027.

Distribution: Southern Australia, including Tasmania, from Fremantle (WA) to southern New South Wales (Edgar 2008).

Prevalence: Common.

Notes: This species was widespread across shoreline and offshore reefs at MMP and SIMP. Like *Euplica* spp., it was most commonly found among the fronds of large brown algae, but in the case of this species densities only occasionally exceeded 10 m<sup>-2</sup>.

*Mitrella menkeana* (Reeve, 1858).

CAAB Code: 24 203025.

Distribution: Southern Australia from the Houtman Abrolhos (WA) to Victoria (Wells & Bryce 1988).

Prevalence: Frequent.

Notes: This species was recorded at the inner and outer areas of shoreline reefs at Iluka and Waterman north (MMP) and at Cape Peron south and Penguin Island south (SIMP). When present, it mostly occurred at densities of 1–2 m<sup>-2</sup>.

*Mitrella lincolnensis* (Reeve, 1859).

CAAB Code: 24 203002.

Distribution: Southern Australia, including Tasmania, from the Houtman Abrolhos (WA) to Victoria (Wells & Bryce 1988).

Prevalence: Frequent.

Notes: This species was recorded at the inner and outer areas of shoreline reefs at Iluka and Waterman north (MMP) and at Penguin Island north and south (SIMP). When present, it mostly occurred at densities of 1–2 m<sup>-2</sup>.

#### Family Conidae

*Conus anemone* Lamarck, 1810.

CAAB Code: 24 222010.

Distribution: Southern Australia, including Tasmania, from Port Gregory (WA) to southern Queensland (Edgar 2008).

Prevalence: Frequent.

Notes: This species occurred mostly at the inner and outer areas of shoreline reefs at SIMP. It was rarely recorded at SIMP offshore reefs or at MMP, where only single specimens were recorded at the inner areas at Iluka and Ocean Reef. When present, it only occurred at densities of 1–2 m<sup>-2</sup> and was usually concealed in turf algae.

*Conus dorensis* Péron, 1807.

CAAB Code: 24 222044.

Distribution: Endemic to WA, from the Montebello Islands to Albany (Edgar 2008).

Prevalence: Frequent.

Notes: This species occurred mostly at the inner and outer areas of shoreline reefs at SIMP with a lesser number being recorded at the inner areas of shoreline reefs at MMP. Among offshore reefs, it was only recorded at Gull Rock and Shag Rock (SIMP). This species was most commonly concealed under turf algae or sand. When present, it typically occurred at densities of 1–2 m<sup>-2</sup>, although on one occasion eight were recorded from an inner area quadrat at Penguin Island north (SIMP). The presence of imposex in this species as a consequence of tributyltin contamination has been recorded at intertidal reefs at Rottneest Island near Perth (Kohn et al. 1999).

#### Family Olividae

*Ancillista cingulata* (GB Sowerby I, 1830).

CAAB Code: 24 208003.

Distribution: Northwards from Albany (WA) to north Qld (Wilson 1993).

Prevalence: Rare.

Notes: A single specimen was recorded from the inner area at Cape Peron north (SIMP).

#### Family Mitridae

*Mitra chalybeia* Reeve, 1844.

CAAB Code: 24 211011.

Distribution: Endemic to WA, from Shark Bay to Alexander Bay (Edgar 2008).

Prevalence: Occasional.

Notes: This species was mostly recorded at inner and outer areas of shoreline reefs at MMP and SIMP, with only recorded from an offshore reef at Gull Rock (SIMP). This species was usually concealed in rock hollows, sand or turf algae.

#### Family Costellariidae

*Vexillum (Pusia) marrowi* Cernohorsky, 1973.

CAAB Code: 24 213059.

Distribution: Endemic to WA, from Kalbarri to Hopetoun (Wilson 1993).

Prevalence: Occasional.

Notes: A small number of this species were recorded at inner and outer areas of shoreline reefs at Iluka and Ocean Reef (MMP) and at Penguin Island north and south (SIMP).

#### Family Siphonariidae

*Siphonaria zelandica* Quoy & Gaimard, 1833.

CAAB Code: 24 488002.

Distribution: Broome (WA) to Keppel Bay (Qld) (Edgar 2008).

Prevalence: Frequent.

Notes: This species was only recorded at the inner area at Cape Peron south (SIMP), where it was attached to bare rock at the mid to high intertidal.

*Siphonaria kurracheensis* Reeve, 1856.

CAAB Code: 24 488007.

Distribution: Endemic to temperate WA (ABRS 2014). Prevalence: Occasional.

Notes: A small number of this species were recorded at the inner area at Cape Peron south (SIMP), where it was attached to bare rock at the mid to high intertidal.

#### Family Bullidae

*Bulla quoyii* Gray in Dieffenbach, 1843.

CAAB Code: 24 335001.

Distribution: Southern Australia, including Tasmania, from Carnarvon (WA) to southern Queensland (Edgar 2008).

Prevalence: Frequent.

Notes: This species was only recorded at the inner area of shoreline reefs at Iluka and Ocean Reef (MMP) and Penguin Island south (SIMP). It was typically concealed under turf algae or sand.

#### Family Mytilidae

*Brachidontes ustulatus* (Lamarck, 1819).

CAAB Code: 23 220081.

Distribution: Kimberley (WA) to South Australia (Wells & Bryce 1988).

Prevalence: Abundant.

Notes: This species occurred mostly at the inner and outer areas of shoreline reefs at Ocean Reef and Waterman north (MMP) and Cape Peron north and south and Penguin Island south (SIMP). It occurred individually, in clusters, or as dense habitat-forming beds that covered the rock surface. While individual numbers of this species were not recorded, it occasionally occurred at densities of >100 m<sup>-2</sup> where dense beds had formed.

*Xenostrobus securis* (Lamarck, 1819).

CAAB Code: 23 220014.

Distribution: Moore River (WA) to Queensland (Wells & Bryce 1988).

Prevalence: Not assessed.

Notes: This species was recorded during pilot sampling at MMP.

*Septifer bilocularis* (Linnaeus, 1758).

CAAB Code: 23 220029.

Distribution: Indo-west Pacific, from Rottneest Island (WA) to New South Wales (Wells & Bryce 1988).

Prevalence: Common.

Notes: This species was widespread across shoreline and offshore reefs at MMP and SIMP. Unlike *B. ustulatus* it did not form dense clusters or beds and was typically found as individuals. The highest densities of >10 m<sup>-2</sup> were recorded occasionally at offshore reefs at MMP, and particularly at Wanneroo Reef.

#### Family Malleidae

*Malleus meridianus* Cotton, 1930.

CAAB Code: 23 237001.

Distribution: Southern Australia, from Fremantle (WA) to the Gulf of St Vincent in South Australia (Edgar 2008).

Prevalence: Occasional.

Notes: This species was recorded only twice at offshore reefs at Gull Rock (SIMP) and Wreck Rock (MMP).

**Family Veneridae**

*Irus carditoides* (Lamarck, 1818).

CAAB Code: 23 380016.

Distribution: Southern Australia, including Tasmania, from south WA to Victoria (Lamprell & Whitehead 1992).

Prevalence: Occasional.

Notes: A small number of this species was recorded at the inner areas of Waterman north and south (MMP).

*Venerupis galactites* (Lamarck, 1818).

CAAB Code: 23 380156.

Distribution: Southern Australia, including Tasmania, from south WA to New South Wales (Lamprell & Whitehead 1992).

Prevalence: Not assessed.

Notes: This species was recorded during pilot sampling at Waterman north (MMP).

**Family Chamidae**

*Chama ruderalis* Lamarck, 1819.

CAAB Code: 23 301002.

Distribution: Southern Australia, from south WA to New South Wales (Lamprell & Whitehead 1992).

Prevalence: Not assessed.

Notes: This species was recorded during pilot sampling at MMP.

**Phylum Echinodermata****Family Asterinidae**

*Meridiastra occidentalis* (O'Loughlin, Waters & Roy, 2003).

CAAB Code: 25 140042.

Distribution: Southern Australia, from Kalbarri (WA) to Port Fairy in Victoria (Edgar 2008).

Prevalence: Abundant.

Notes: This species was widespread across shoreline and offshore reefs at MMP and SIMP, but occurred at higher densities at shoreline than at offshore reefs and was more abundant at SIMP than at MMP. While densities ranging from 20–80 m<sup>-2</sup> were frequently recorded at SIMP shoreline reefs, densities of >20 m<sup>-2</sup> occurred only occasionally at MMP shoreline reefs. At offshore reefs, densities at SIMP and MMP rarely exceeded 15 and 10 m<sup>-2</sup>, respectively. This species was often found adhering to the rock surface in hollows or amongst low algae.

*Meridiastra calcar* (Lamarck, 1816).

CAAB Code: 25 140028.

Distribution: Southern Australia including Tasmania, from Albany (WA) to Currumbin in Queensland (Edgar 2008).

Prevalence: Frequent.

Notes: This species was recorded mostly at shoreline reefs in SIMP and MMP, while a small number were also recorded at SIMP offshore reefs. This species was less abundant than *M. occidentalis* and densities of >2 m<sup>-2</sup> occurred only occasionally, and only at SIMP.

*Meridiastra gunnii* (Gray, 1840).

CAAB Code: 25 140027.

Distribution: Southern Australia, including Tasmania, from the Houtman Abrolhos (WA) to eastern Victoria (Edgar 2008).

Prevalence: Frequent.

Notes: This species was mostly recorded at the inner and outer areas at Penguin Island south (SIMP) with additional single records at Cape Peron south and Shag Rock (SIMP) and Iluka (MMP). This species was less common than *M. occidentalis* and *M. calcar*.

*Coscinasterias muricata* Verrill, 1867.

CAAB Code: 25 154011.

Distribution: Southern Australia, including Tasmania, from the Houtman Abrolhos (WA) to southern Queensland (Edgar 2008).

Prevalence: Common.

Notes: This relatively large (up to ca. 250 mm) sea-star occurred widely across shoreline and offshore reefs in MMP and SIMP, but typically occurred in relatively low densities of 1–2 m<sup>-2</sup> when it was present. Higher densities (i.e. >10 m<sup>-2</sup>) of smaller individuals were recorded in some instances, mainly at SIMP shoreline reefs.

**Family Echinometridae**

*Helicoidaris erythrogramma* (Valenciennes, 1846).

CAAB Code: 25 247001.

Distribution: Southern Australia, including Tasmania, from Shark Bay (WA) to Caloundra in Queensland (Edgar 2008).

Prevalence: Abundant.

Notes: This species was widespread across shoreline and offshore reefs at MMP and SIMP, but was particularly abundant only at Cape Peron north and south (SIMP) and, to a lesser extent, at Iluka (MMP). Densities ranging from 10 to ca. 130 m<sup>-2</sup> were frequently recorded at the inner and outer areas at Cape Peron north and south, while densities of 10–43 m<sup>-2</sup> were occasionally recorded at the inner area at Iluka. In contrast, densities of >3 m<sup>-2</sup> were rare at all other sites. This species was typically found in rock hollows.

**Family Toxopneustidae**

*Nudechinus scotiopremnus* HL Clark, 1912.

CAAB Code: 25 242007.

Distribution: Indian Ocean and Red Sea, from Yallingup to Broome in WA (Miskelly 2002; Coleman 2007).

Prevalence: Frequent.

Notes: This small urchin was recorded on both shoreline and offshore reefs at MMP and SIMP, but usually occurred at relatively low densities of 1–3 m<sup>-2</sup> when it was present. This species was most commonly concealed in reef hollows or amongst turf algae, but was occasionally found amongst the fronds of branched algae.

**Family Temnopleuridae**

*Holopneustes porosissimus* L Agassiz, 1846.

CAAB Code: 25 241011.

Distribution: Southern Australia, including northern Tasmania, from the Houtman Abrolhos (WA) to Waratah Bay (Vic) (Edgar 2008).

Prevalence: Frequent.

Notes: This species occurred widely across shoreline and offshore reefs at MMP and SIMP at relatively low densities that rarely exceeded 3 m<sup>-2</sup>. They were most commonly found amongst the fronds of tall branched algae such as *Sargassum*.

*Amblypneustes leucoglobus* Döderlein, 1914.

CAAB Code: 25 241004.

Distribution: Endemic to WA, from Geraldton to Eucla (Edgar 2008).

Prevalence: Occasional.

Notes: Several specimens of this species were recorded at Wreck Rock (MMP).

#### **Family Cidaridae**

*Phyllacanthus irregularis* Mortensen, 1928.

CAAB Code: 25 202012.

Distribution: Southern Australia, from the Houtman Abrolhos (WA) to the Gulf of St Vincent in South Australia (Edgar 2008).

Prevalence: Rare.

Notes: A single small individual was recorded in a reef pothole at Gull Rock (SIMP).

# Spatial variation in the morphology of monospecific stands of the western white mangrove *Avicennia marina* var. *marina* in Shark Bay Marine Park

MICHAEL J RULE<sup>1,2\*</sup>, ALAN J KENDRICK<sup>1</sup> AND DAVID HOLLEY<sup>3</sup>

<sup>1</sup>Marine Science Program, Science and Conservation Division, Department of Parks and Wildlife, Kensington, Western Australia 6151, Australia.

<sup>2</sup>Oceans Institute, University of Western Australia, Crawley, Western Australia, Australia

<sup>3</sup>Shark Bay District, Midwest Region, Regional and Fire Services Division, Department of Parks and Wildlife, Denham, Western Australia 6537, Australia.

\* Corresponding author: michael.rule@dpaw.wa.gov.au

## ABSTRACT

Spatial variation in the morphology of mangrove stands could be expected to lead to differences in their ecological role and the ecosystem services they provide. Here we examine spatial variation in the structural morphology of stands of *Avicennia marina*, the sole mangrove inhabiting Shark Bay, Western Australia—a semi-arid environment with strong regional-scale gradients in the physical environment. Morphological variables were measured at 12 sites across a putative gradient in physical conditions from oceanic (western) to metahaline (eastern) parts of the bay and data were tested using both univariate and multivariate analyses. The multivariate analysis of the combined suite of characters found a significant difference between sites, and pairwise tests revealed significant differences for most comparisons. Changes in morphology across Shark Bay were correlated to longitude, which was used as a proxy for the salinity regime. Three distinct morphotypes associated with different salinity zones were revealed. The results suggest that the morphology of *A. marina* in Shark Bay varies across regional scales and may be influenced by background physical conditions. It is likely that the functional roles of these mangrove stands differ across the region, and thus, treating stands as uniform ‘units’ may not be appropriate for conservation management. We suggest that the conservation of *A. marina* could be enhanced by revised management zoning of Shark Bay Marine Park to include representative areas of each of the divergent morphotypes in sanctuary zones or special purpose zones configured for mangrove protection.

**Keywords:** morphology, spatial variation, structure

## INTRODUCTION

Mangroves are salt-tolerant trees that inhabit the intertidal zone of sheltered coasts and estuaries across both tropical and temperate regions (Morrisey et al. 2010). These communities can be highly productive and are ecologically and economically significant (Barbier et al. 2010; Walters et al. 2008) through providing diverse ecosystem services such as nursery habitats for fishery species, enhanced shoreline stability, food and timber (Alongi 2002; Morrisey et al. 2010). A range of physical and climatic factors, such as sediment type, tidal inundation and wave exposure, as well as temperature, rainfall and groundwater dynamics, influence whether mangrove communities can establish and how they persist in particular coastal areas (Semeniuk 1993).

Mangroves display a high level of morphological plasticity in response to environmental conditions (Feller

et al. 2010). Across small spatial scales the growth and biomass of mangroves can vary in relation to factors like rainfall and freshwater input, tidal inundation and wave action (Alongi et al. 2005). For example, within a forest, dwarf or scrub mangroves can occur at higher elevations where there is infrequent tidal inundation, greater rates of evaporation and consequently higher salinities (Naidoo 2010). In some areas, such morphological changes in mangroves may also be a result of nutrient availability, and dwarf trees have been shown to increase growth significantly when limiting nutrients have been experimentally added (Feller 1995; Lovelock et al. 2006). While many studies have sought to classify the sequential changes in forest structure and species distribution parallel to shore on the basis of local topographic features (Lugo & Snedaker 1974) or structural characteristics (Pellegrini et al. 2009), few have quantified regional-scale patterns in morphological structure (Schaeffer-Novelli et al. 1990; Ward et al. 2006), particularly in areas with strong, regional-scale environmental gradients (Agraz Hernández et al. 2011; Arreola-Lizárraga et al. 2004).

Mangroves occur prominently along coasts in the northern half of Western Australia (WA) and are listed as key ecological values in marine parks and reserves across this region. While the monsoonal and macro-tidal northern Kimberley region supports up to 19 mangrove species, they become less diverse and more fragmented further southwards in the relatively arid and micro-tidal Pilbara and Midwest regions (Duke 2006). The large, semi-enclosed embayment of Shark Bay supports the southern-most limit of extensive mangrove growth in WA, but only has a single species, *Avicennia marina* (Forsk.) Vierh. var. *marina*. Here, this mangrove occurs in numerous and often isolated stands (CALM 1996) that are typically less than 10 ha in size and rarely exceed 100

ha. Southwards from Shark Bay in WA, small and widely separated stands of this species occur at the Houtman Abrolhos Islands and Bunbury.

The semi-arid Shark Bay region has a unique marine environment where the combined influences of shallow water, high evaporation rates (Burling et al. 2003) and constrained water circulation (Nahas et al. 2005) maintain a persistent salinity gradient which ranges from oceanic (35–38 ppt) in the western and northern areas to strongly hyper-saline (60–65 ppt) in the south-eastern reaches of Hamelin Pool and L'haridon Bight (Logan & Cebulski 1970). Between these extremes, lies a distinct metahaline region and the Cape Peron and Faure salinoclines (Fig. 1). This hyper-saline environment is one of the exceptional

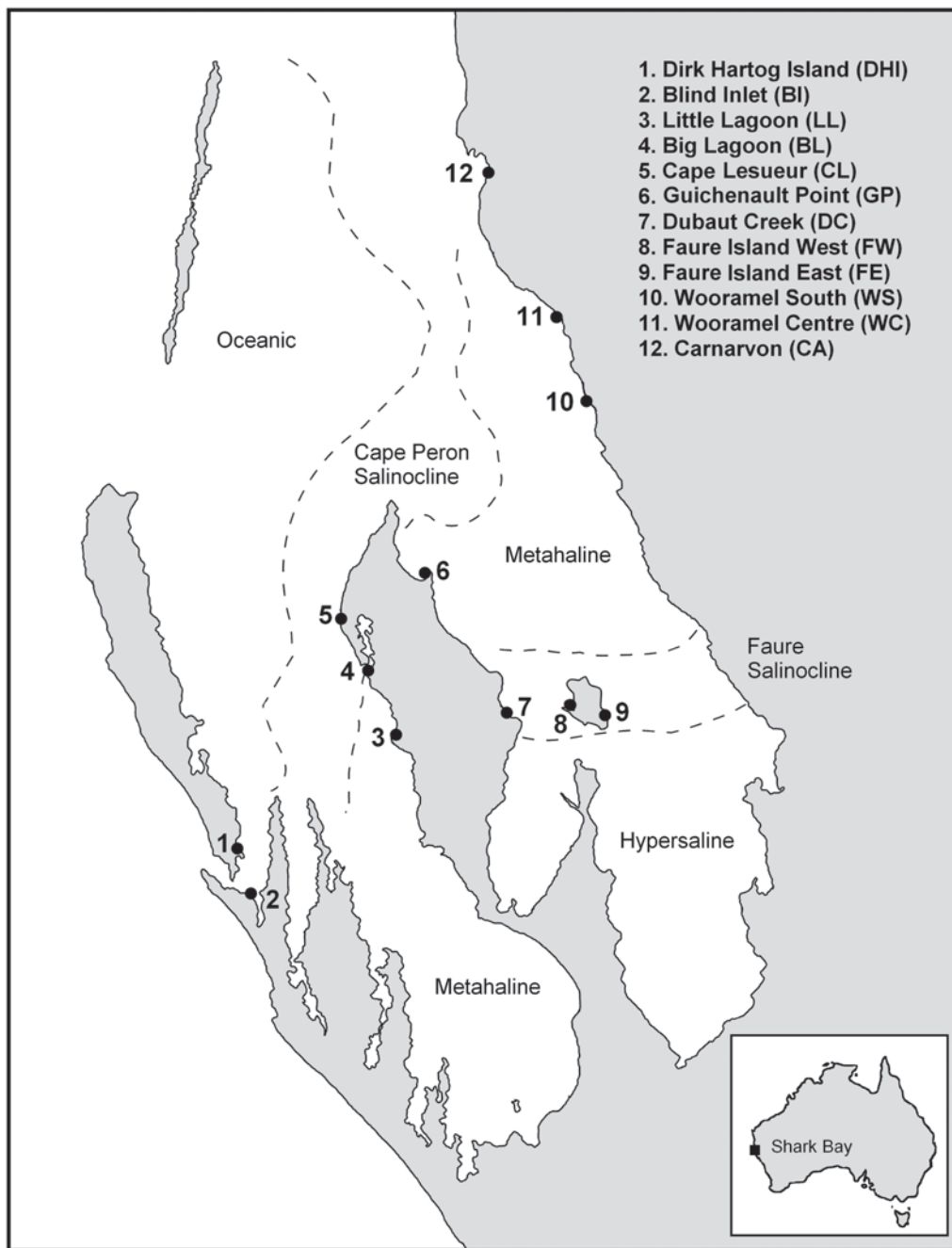


Figure 1. Mangrove sites sampled in Shark Bay. Codes used in tables are also given in parentheses.

**Table 1**

Mean ( $\pm$  SE) values for each character measured at each site. The overall mean ( $\pm$  SE) for each character is also provided. See Fig. 1 for site codes. Additional information includes: latitude and longitude of each site; aerial extent; a priori-defined salinity regime (oceanic = ocean, metahaline = meta, Cape Peron salinocline = CP sal, Faure salinocline = F sal); and conservation status (General Use = GUZ, Sanctuary = SZ, and Special Purpose = SPZ).

Character	Site												Overall mean
	DHI	BI	CL	BL	LL	GP	CA	DC	WC	FW	WS	FE	
Latitude	S26.1066	S26.1862	S25.7180	S25.7979	S25.9057	S25.6205	S24.9345	S25.8670	S25.1826	S25.8447	S25.3255	S25.8671	
Longitude	E113.2273	E113.2498	E113.4169	E113.4657	E113.5285	E113.5777	E113.6800	E113.7272	E113.8205	E113.8547	E113.8772	E113.9208	
Salinity regime	ocean	ocean	CP sal	meta	meta	meta	CP sal	F sal	meta	F sal	meta	F sal	
Conservation	GUZ	GUZ	GUZ	SPZ	GUZ	GUZ	SPZ	GUZ	SPZ	GUZ	SPZ	GUZ	
Areal extent (ha)	4.60	26.60	1.90	14.00	2.80	35.40	559.50	1.00	137.70	3.20	22.90	8.60	68.20
No. of mature trees (ha)	1120 (195.96)	960 (160.00)	9040 (1163.44)	8640 (1411.95)	2240 (530.66)	4160 (652.38)	8800 (954.99)	1520 (557.14)	6320 (598.67)	6320 (637.50)	5920 (1438.89)	7040 (1077.78)	5173 (446.75)
No. of saplings (ha)	– (521.54)	–	4000.00 (160.00)	– (160.00)	240.00 (240.00)	160.00	560.00 (97.98)	–	160.00 (632.46)	– (334.66)	2000.00 (165.72)	800.00	660.00
No. of recruits (ha)	36400 (13912.3)	6240 (3916.3)	22373.2 (18610.4)	1920 (958.3)	12720 (3430.2)	–	6720 (2964.9)	160 (160)	560 (240)	1040 (854.2)	400 (253)	1200 (357.8)	7477.77 (2291.59)
No. of pneumatophores (m)	416.00 (26.00)	363.47 (20.52)	218.13 (21.58)	340.00 (29.92)	390.40 (44.89)	256.53 (8.76)	510.93 (80.21)	59.33 (16.83)	201.33 (21.72)	518.93 (40.22)	287.73 (26.12)	259.47 (28.32)	318.52 (18.90)
Complexity	4.80 (0.58)	4.60 (0.24)	3.60 (0.40)	3.60 (0.51)	4.00 (0.55)	2.80 (0.49)	2.00 (0.63)	2.20 (0.80)	2.80 (0.49)	3.60 (0.24)	5.00 (0.45)	3.40 (0.60)	3.53 (0.18)
% cover	65.00 (2.34)	63.43 (3.72)	39.49 (4.67)	48.66 (3.63)	69.52 (3.16)	45.57 (1.82)	48.59 (4.61)	39.62 (5.29)	32.76 (7.06)	70.06 (1.87)	42.98 (3.67)	36.84 (4.21)	50.21 (1.97)
Height (cm)	370.00 (6.85)	557.50 (21.45)	118.20 (17.55)	344.00 (15.19)	414.40 (25.26)	462.40 (7.83)	311.20 (25.97)	203.71 (73.84)	118.12 (17.46)	345.60 (24.41)	188.40 (11.12)	195.20 (12.97)	302.40 (18.79)
Total diameter at 30cm (cm)	112.74 (23.46)	139.12 (25.42)	21.57 (2.72)	30.11 (4.08)	80.58 (25.71)	44.03 (3.49)	33.33 (9.32)	87.93 (28.23)	26.51 (1.53)	27.78 (1.26)	30.33 (4.17)	25.77 (3.10)	54.98 (6.37)
Total diameter at 130cm (cm)	81.05 (20.28)	114.04 (22.32)	1.52 (1.52)	20.59 (3.02)	48.77 (9.95)	31.35 (2.67)	20.63 (7.15)	31.93 (21.21)	2.44 (2.29)	18.24 (1.32)	8.51 (2.76)	7.50 (1.55)	32.21 (5.18)
No. of primary branches	2.65 (0.48)	2.75 (0.68)	2.92 (0.40)	1.56 (0.20)	3.84 (1.80)	1.28 (0.08)	1.52 (0.22)	3.28 (0.70)	1.92 (0.19)	1.20 (0.09)	2.48 (0.26)	1.56 (0.19)	2.25 (0.20)
Leaf weight (g)	1.60 (0.12)	1.72 (0.07)	1.27 (0.04)	1.37 (0.07)	1.59 (0.12)	1.70 (0.04)	1.35 (0.06)	0.94 (0.10)	1.17 (0.05)	1.34 (0.04)	1.07 (0.05)	1.27 (0.05)	1.37 (0.04)
Leaf length (cm)	12.11 (0.32)	12.32 (0.31)	9.62 (0.27)	11.56 (0.30)	10.93 (0.38)	11.88 (0.17)	10.18 (0.30)	8.63 (0.47)	10.01 (0.29)	11.16 (0.28)	8.89 (0.14)	9.20 (0.13)	10.54 (0.18)
Leaf width (cm)	3.81 (0.21)	3.66 (0.10)	3.22 (0.14)	3.49 (0.07)	3.56 (0.14)	3.78 (0.06)	3.15 (0.06)	2.82 (0.13)	2.74 (0.09)	3.54 (0.05)	3.06 (0.08)	3.32 (0.05)	3.35 (0.05)
Leaf area (cm)	27.39 (2.00)	26.79 (0.59)	20.21 (1.15)	23.92 (0.90)	25.06 (1.74)	27.00 (0.51)	19.54 (0.84)	14.60 (1.15)	16.74 (0.91)	23.86 (0.83)	16.44 (0.71)	18.83 (0.38)	21.70 (0.63)

physical and biological conservation values of Shark Bay that has led to the creation of terrestrial and marine conservation reserves in this area and its inclusion on the World Heritage List (CALM 1996; McCluskey 2008). Although the federal government has over-arching responsibility for ensuring the protection of Australia's World Heritage estate (McCluskey 2008), Shark Bay Marine Park (SBMP) was created in 1990 under the *Conservation and Land Management Act (1984)* to protect the area's important marine conservation values (CALM 1996). Management zoning is a key mechanism for ensuring the protection of ecological and social values in WA's marine parks and reserves.

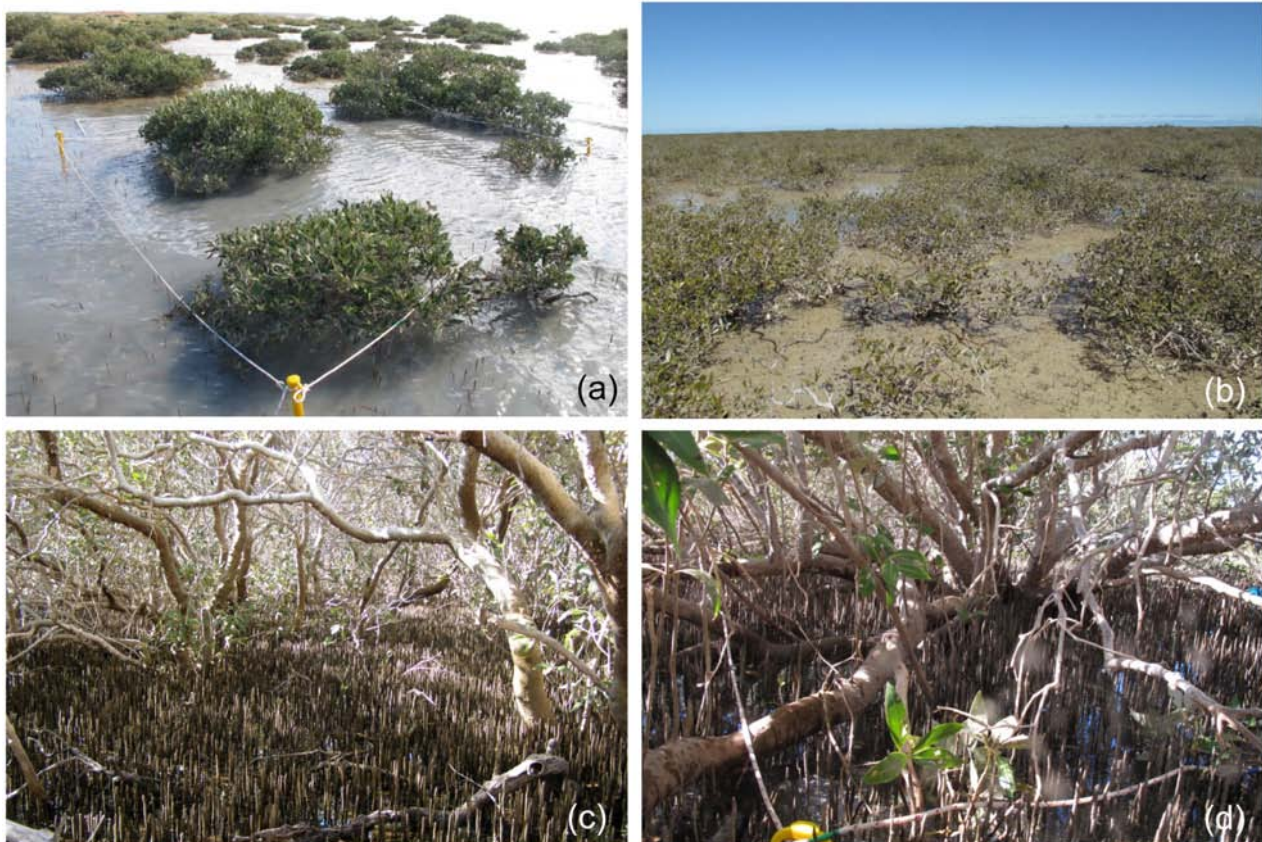
Although the ecological and conservation value of mangroves are recognised in SBMP, mangroves are poorly studied in this region (CALM 1996) and little is known, for example, about how they vary in structure in relation to Shark Bay's persistent salinity regime (Nahas et al. 2005). Managers often assume that mangroves are morphologically and ecologically uniform, such that the conservation value may be adequately preserved by the protection of 'representative' areas (Jin-Eong, 1995). However, local variations in the structure, biomass and productivity of mangroves can lead to variations in ecosystem function and habitat use across relatively small spatial scales (Lovelock et al. 2005; Twilley et al. 1986), and treating mangroves as a homogeneous unit may not be an appropriate management strategy in some areas.

Here we documented spatial variation in the morphological structure of *A. marina* stands across SBMP and investigated the potential role of the broad-scale salinity gradient in driving the observed patterns. We also assessed the adequacy of existing management zoning relating to mangroves in this distinctive marine environment.

## METHODS

### Sampling procedure

Prior to field sampling, 12 sites of relatively homogeneous mangrove cover in Shark Bay were identified from aerial imagery (Fig. 1; Table 1). Five randomly placed 5 m × 5 m plots were established at each site and the perimeter of each plot was delineated with rope suspended on stakes. A broad index of benthic structural complexity (Wilson et al. 2007) was estimated for each plot. Briefly, a semi-quantitative score (between 1 and 6) for the overall complexity of the habitat was given for each plot, based on the density and size of trees, the coverage of bare sand and the amount of woody debris present (Fig. 2). Thus, a plot composed of a small number of immature trees with little woody debris, scored low ( $c = 1$ ) while a plot composed of a range of tree-sizes (including multi-stemmed trees) with a large amount of woody debris



**Figure 2.** Examples of the variation in mangrove stand morphology across Shark Bay and the complexity scores used in this study: (a) Dubaut Creek (complexity = 1); (b) Wooramel South (complexity = 2); (c) Blind Inlet (complexity = 4); and (d) Little Lagoon (complexity = 6).

scored highly ( $c = 6$ ). While other measures of complexity have been widely used for mangroves (e.g. Arreola-Lizárraga et al. 2004), they are typically used in multi-species forests and rely on an index which is calculated from other measured variables and thus are not independent. The index used here provided an assessment of complexity which was independent of other measured characters.

Within each plot the number of mature trees (stem girth  $> 2$  cm), saplings ( $> 100$  cm in height, stem girth  $\leq 2$  cm) and recruits ( $< 100$  cm high, leaves arising directly from a single, undifferentiated stem) were counted, and the number of pneumatophores was counted within three haphazardly positioned  $1 \text{ m}^2$  quadrats. The extent of canopy cover was estimated by taking eight haphazardly selected upward-facing photographs from approximately 0.5 m above the substratum. In the few instances where the mangrove canopy was too low to use this method, downward-facing images were taken from a height of approximately 1.5 m from the substratum. The percent of foliage cover in each image was then calculated using ER Mapper software.

Within each plot, further measurements were taken on five haphazardly selected trees, or all trees if fewer than six were present. The maximum height of each tree, the trunk diameters at heights of 30 and 130 cm from the ground and the number of primary branches were counted. Where multiple primary branches were present at the heights where measurements were taken, each trunk diameter was measured and summed for the tree. Five mature leaves were collected from each tree, weighed to 0.01 g and photographed from a standard height. The maximum length, width and area of each leaf were calculated using the ImageJ software (Abramoff et al. 2004).

In order to assess the adequacy of current management zoning, the total area (ha) of mangroves within the boundary of SBMP was calculated from high-resolution (10 m pixel) ALOS (Advanced Land Observation Satellite) satellite imagery. The area of mangrove habitat was also calculated for each management zone and summed to provide a proportion of the total area of mangroves in each type of management zone.

## Statistical analyses

All data were averaged or scaled to the plot level, such that analyses were undertaken on five replicates for each variable at each site. Multivariate analyses performed using PRIMER V6 with PERMANOVA extension (Anderson et al. 2006; Clarke & Gorley 2006) were used to examine differences in the overall structure of the 12 mangrove sites. Prior to analysis, strongly correlated variables (e.g. leaf length and width) were removed from the dataset. Data were normalised as they were measured on different scales and a similarity matrix was constructed on Euclidean distances. Principal components analysis (PCA) was performed to visually assess patterns in the data and Spearman rank correlations ( $p > 0.5$ ) were used to produce eigenvectors to highlight the overall increasing

or decreasing relationships of morphological variables across the ordination. Differences in the combined suite of morphological characters between groups were examined using a one-way permutational analysis of variance (PERMANOVA; Anderson 2002) with site as a random factor. Additional, post-hoc pairwise  $t$ -tests were conducted to examine where significant differences occurred.

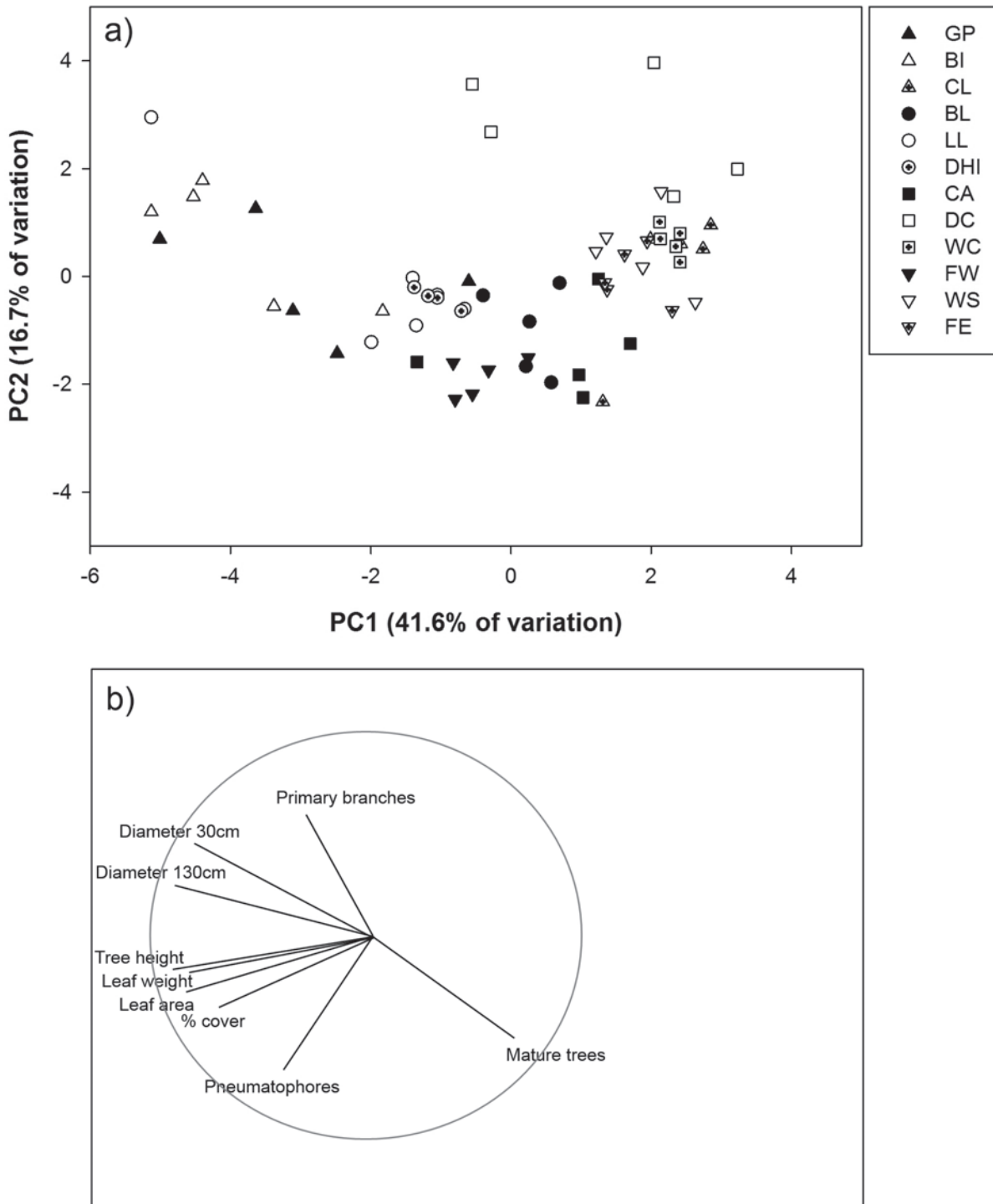
Linear regressions were performed to examine the relationships between PCA scores and the predictor variables, latitude and longitude, which provide a reasonable proxy for the strong east–west and north–south salinity gradient in Shark Bay. Prior to analysis, all variables were checked for normality and were appropriately transformed if necessary.

We tested whether the magnitude of divergence in mangrove structure between sites was related to the distance between sites. Linear distances between each site were measured and the mean dissimilarity between each pair of sites was calculated using a SIMPER analysis. The resultant dissimilarity matrix was then correlated (Pearson correlation) to the distances between sites.

A constrained canonical analysis of principal coordinates (CAP; Anderson & Willis 2003) was used to test whether mangrove structure differed between a priori-defined salinity zones (i.e. oceanic, metahaline, Cape Peron salinocline and Faure salinocline; Fig. 1; Table 1) identified in Shark Bay by Logan and Cebulski (1970). The groupings identified by the CAP analysis were formally tested using a one-way PERMANOVA using salinity zone as a fixed factor.

## RESULTS

The morphological structure of *A. marina* stands varied considerably across sites in Shark Bay (Table 1). For example, the mean density ( $\pm 1$  SE) of mature trees ranged from  $960 \pm 160.00$  trees per plot at Blind Inlet to  $9040 \pm 1163.44$  per plot at Cape Lesueur. The mean height of trees differed by  $>400$  cm between Blind Inlet ( $557.50 \pm 21.45$  cm) and Wooramel Centre ( $118.12 \pm 17.46$  cm). In the PCA based on all measured variables, PC1 and PC2 accounted for 61.0% of total variation between samples (Fig. 3a). Samples to the left of the plot (Blind Inlet and Guichenault Point, Little Lagoon) corresponded to increased tree height, diameter and larger values for leaf characteristics (Fig. 3a, b), while those to the right of the plot (Carnarvon, Wooramel South and Centre, Faure East, Dubaut Creek) corresponded with an increased number of mature trees (Fig. 3a, b). Samples from Dirk Hartog Island, Big Lagoon and Faure West formed reasonably tight site-groups in the centre of the plot. Samples from Dubaut Creek formed a disparate group at the upper right of the ordination (Fig. 3a). The vertical separation of samples in the PCA was driven by shifts in the number of primary branches, mature trees and pneumatophores (Fig. 3b). The PC1 scores were significantly correlated ( $r^2 = 0.40$ ;  $p = 0.001$ ) to longitude and also displayed a significant but weak negative ( $r^2 = -0.28$ ;  $p = 0.001$ ) correlation to



**Figure 3.** Principal components analysis (PCA) showing (a) all data and (b) a vector plot of the variables contributing to the PCA. The vector lines indicate the direction of increasing values, and the length relative to the circle indicates the strength of the correlation (Spearman). Only vectors with correlations >0.5 have been included. Site codes are given in Fig. 1.

latitude. The vertical separation of samples in the ordination (PC2 scores) was very weakly correlated ( $r^2 = 0.07$ ;  $p = 0.05$ ) to latitude.

The analysis of the combined suite of structural components by PERMANOVA returned a significant difference between sites ( $pseudo-F_{11,49} = 9.48$ ,  $p < 0.001$ ), and despite the apparent overlap in the structure of sites (Fig. 3a), pairwise comparisons revealed significant

differences for almost all comparisons (65 of 66 possible comparisons). The only comparison where morphological structure was not significantly different was for Little Lagoon and Dirk Hartog Island (Table 2).

The CAP analysis of mangrove structure in the different salinity zones (Fig. 4) separated the study sites into three distinct groups that were supported by the PERMANOVA ( $pseudo-F_{3,57} = 7.70$ ,  $p < 0.001$ ). Samples from the

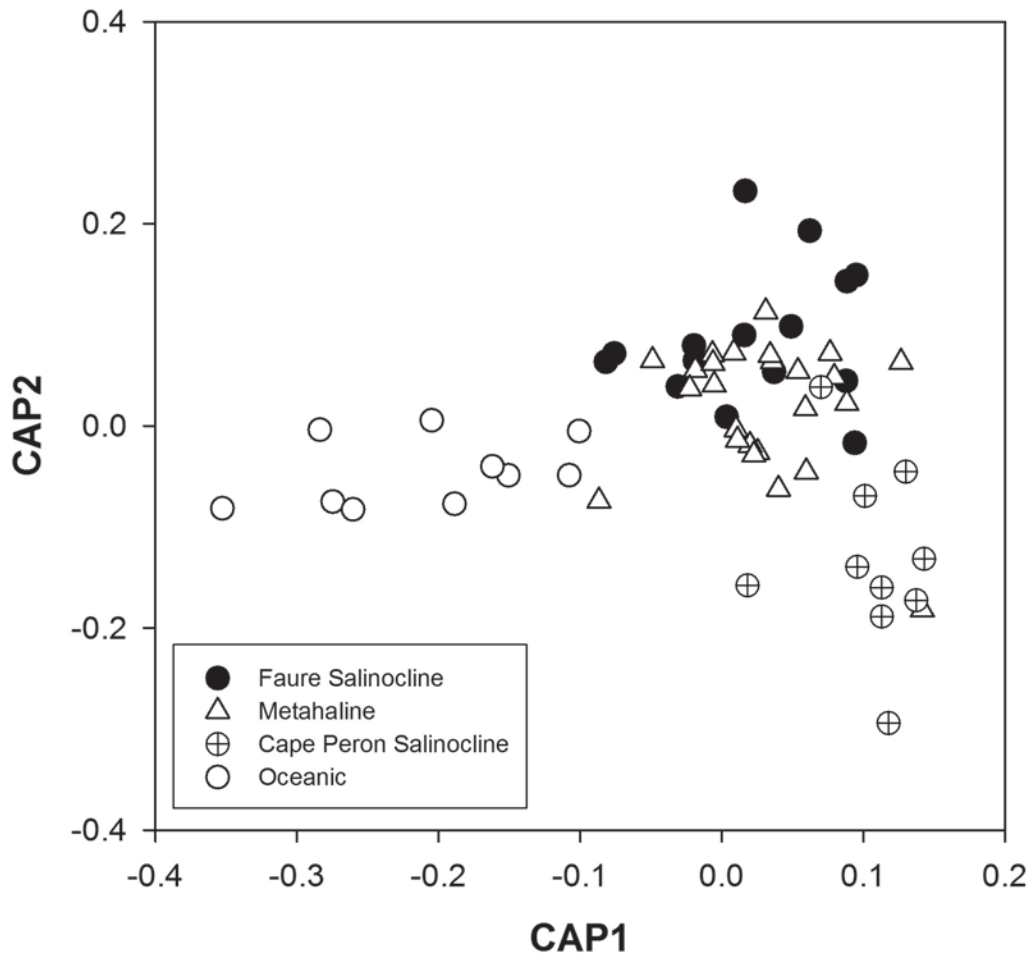


Figure 4. Results of the canonical analysis of principal coordinates (CAP) examining changes in mangrove morphology across different salinity zones.

Table 2

Summary of the pairwise comparisons (t-values) of morphological structure between sites for the single-factor PERMANOVA. Only t-values for comparisons that were significant ( $p < 0.05$ ) are shown. Tests that were not significant ( $p > 0.05$ ) are designated by 'ns'. Site codes are given in Fig. 1.

	BI	CL	BL	LL	GP	CA	DC	WN	FW	WS	FE
DHI	1.65	3.23	2.68	ns	2.40	3.09	3.55	4.22	2.56	3.81	3.70
BI		4.53	4.27	1.75	3.48	4.53	4.34	6.42	4.52	5.72	5.82
CL			2.68	2.57	3.72	2.38	2.67	2.31	3.37	1.69	1.92
BL				1.82	2.78	1.84	3.20	3.31	2.12	3.24	2.50
LL					1.80	2.11	2.70	3.02	1.60	2.66	2.55
GP						3.53	3.88	5.58	4.24	5.31	4.66
CA							2.87	2.61	2.23	2.70	2.07
DC								1.88	3.76	2.16	2.26
WN									4.88	2.29	1.79
FW										4.17	3.94
WS											1.74

oceanic salinity zone formed a discrete group to the left of the ordination, while samples from each of the other salinity classes grouped to the right. Among these samples, those from the Faure salinocline and metahaline zones formed a single group while samples from the Cape Peron salinocline zone separated clearly from this group. All

groups had a high allocation success, with 42 of 60 (70%) samples correctly classified and an overall misclassification error of 30%. Allocation success was extremely high (90%) for oceanic and Cape Peron salinocline samples while allocation was poorest among metahaline zone samples (52% correctly classified). The post-hoc pairwise tests

**Table 3**

Summary of the pairwise comparisons of morphological structure between different salinity zones derived from the one-factor PERMANOVA. Values that are significant ( $p < 0.05$ ) are shown in bold.

Test	<i>t</i>	<i>p</i> <sub>permuted</sub>
Oceanic vs Cape Peron salinocline	3.84	<b>0.001</b>
Oceanic vs metahaline	3.51	<b>0.001</b>
Oceanic vs Faure salinocline	3.71	<b>0.001</b>
Cape Peron salinocline vs metahaline	1.90	<b>0.003</b>
Cape Peron salinocline vs Faure salinocline	1.80	<b>0.009</b>
Metahaline vs Faure salinocline	1.14	0.237

revealed significant differences for all comparisons except for the comparison between metahaline samples and those from the Faure salinocline (Table 3), confirming the presence of three distinct groups; oceanic, Cape Peron salinocline, and a combined metahaline/Faure salinocline group.

## DISCUSSION

### Variation in *A. marina* structure across Shark Bay Marine Park

This study has demonstrated that the structure of *A. marina* stands varies markedly across Shark Bay, and that this variation broadly corresponds to the different salinity zones that exist in this biogeographically distinct marine environment. The suite of characters showed a negative relationship with longitude, which may be considered as a reasonable surrogate for Shark Bay's persistent salinity gradient that increases in a south-east direction into the bay. At a broad scale, the *A. marina* stands that were exposed to typically oceanic conditions were more structurally complex (Pool et al. 1977) with a lower density of tall (> 500 cm) and multi-stemmed trees, whereas stands in more saline areas were typically more dense and composed of short (< 150 cm) trees. Divergent examples of the structure of these typically discrete and isolated mangrove stands are shown in Fig. 2. Notably, mangroves are not present in the most saline parts of Shark Bay, and thus it appears that the salinity regime within Shark Bay is exerting a significant influence on the structure of mangrove stands.

The relationship between mangrove structure and salinity across Shark Bay is analogous to the variations in mangrove tree structure that occur across typically smaller spatial scales in estuaries (Lovelock et al. 2005), where physical gradients of factors like salinity and shoreline elevation can be pronounced (Agraz Hernández et al. 2011; Chen & Twilley 1999). Such environmental gradients result in the predictable zonation of estuarine mangroves, with a decline in tree height with increasing elevation from the sea (Lugo & Snedaker 1974). It is

notable that the patterns observed in this study were only moderately predictable, as illustrated by the fact that the smallest trees occurred at the Wooramel central and Cape Lesueur sites, while those at Faure Island west, which is closest to Shark Bay's persistent hypersaline zone, were of similar size to those at Big Lagoon and Dirk Hartog Island. Hence, while Shark Bay's salinity gradient is likely to influence the structure of these typically small and isolated mangrove stands, additional factors acting on mangrove growth may also contribute to the patterns observed in this study. These may include, for example, tidal inundation, elevation, differences in the recruitment and mortality of trees and the influence of sediment movement at particular sites (de Lange & de Lange 1994). In Shark Bay, such influences may occur on the eastern coast when fine sediments are episodically discharged from the Wooramel River during cyclonic floods. Subject to prevailing on-shore winds, the discharged silt is unlikely to be widely dispersed (Fraser et al. 2012) and its settlement along this shallow, low-energy coastline may significantly influence mangrove growth in this area.

We are confident that structural differences among mangrove stands observed in this study are caused by environmental conditions and do not simply reflect stands of varying ages that have recruited at different times (Fromard et al. 1998). While some sites, such as Cape Lesueur, did support a high number of apparently young trees that were relatively small with thin trunks, similarly low trees at sites like Wooramel south had comparatively thick and gnarled trunks, indicating that they were mature, but stunted, and are most likely growing in sub-optimal habitats (Naidoo 2006). For instance, mangrove growth is closely linked to nutrient availability and when trees are nutrient limited, canopy development may be retarded (Lovelock et al. 2006). Shark Bay has long been recognised as a largely P-limited system (Smith & Atkinson 1984); however, recent investigations in the area have shown that nutrient limitation is spatially variable over local scales due to differences in nutrient input and transport (Burkholder et al. 2013; Fraser et al. 2012). It is possible that spatial variability in nutrient availability interacts with the salinity regime of the area to produce the patterns in mangrove structure observed here. Additionally, while ground water availability may be particularly important to mangrove growth in areas where rainfall is limited (Susilo et al. 2005), very little information on groundwater dynamics is currently available from the region. Further research on plant and sediment nutrient content and groundwater availability would provide a more clear understanding of mangrove growth in Shark Bay.

### Implications for managing *A. marina* in Shark Bay Marine Park

Conservation management has tended to assume that mangroves along marine shorelines are structurally homogenous and ecologically similar across their spatial extent (Jin-Eong 1995). However, the wide variation in the structural complexity and density of *A. marina* across SBMP reported here suggests that these divergent

mangrove stands may function quite differently. This could include, for example, differences in primary productivity (Ewel et al. 1998) and carbon storage (Alongi 2012), their capacity to trap decomposing wrack, or the manner in which complex trunks, root structures and tree canopies provide refuge and/or feeding habitats for other organisms (Morton 1990; Storr 1990).

While the physical removal of mangroves in WA is prohibited under the *Wildlife Conservation Act (1950)* (CALM 1996), mangrove trees and their associated fauna in Shark Bay are subject to impacts from human activities such as fishing, camping and four-wheel driving. These potentially detrimental activities can be managed in SBMP by marine park zoning, as is the case in other marine reserves in WA (e.g. Mangrove Bay in Ningaloo Marine Park; CALM 2005). However, of the approximately 1500 ha of measurably dense *A. marina* identified within SBMP from satellite imagery, only about 0.54 ha (0.035%, Table 4) is currently protected in a single sanctuary zone (Big Lagoon Sanctuary Zone), which provides the highest level of conservation protection (i.e. no-take). All other mangroves in SBMP are in general use (ca. 293 ha), recreation (ca. 4.3 ha) or special purpose zones that were established for the protection of nursery areas and seagrass communities (ca. 1260 ha), which do not explicitly protect mangroves or their associated fauna from a range of potential human impacts. In addition, mangroves in many areas bridge the tenure between the SBMP boundary (which mostly extends to High Water Mark) and adjacent lands that are not all managed for conservation (CALM 1996). Thus, despite mangroves in Shark Bay being recognized for their high conservation value (CALM 1996; McCluskey 2008), the vast majority are not within management zones that confer a high level of protection.

Based on the findings of this study, we suggest that it is inappropriate to consider mangroves in Shark Bay as a single, homogeneous entity for conservation management. We identified three structurally distinct mangrove types: oceanic mangroves which comprised tall, low density mangroves with a high canopy cover (i.e. Blind Inlet and Dirk Hartog Island); mangroves associated with the Cape Peron salinocline which had high densities of both mature trees and saplings with thinner trunks (Cape Leseuer, Carnarvon); and a combined metahaline/Faure salinocline type which comprised smaller trees with reduced leaf

characteristics (Faure Island, Wooramel coast). We recommend that future conservation planning targets representative mangrove stands of each of these structural forms. This would acknowledge the fact that, for example, a relatively small area (ca. 31 ha) of tall, low density mangroves occur in association with oceanic salinities in the western parts of Shark Bay. In this context, threatening processes that may be impacting on a relatively small proportion the total mangrove area may, in fact, be impacting on a large proportion of mangroves of a particular structural form. Threatening processes that currently impact on mangroves and their associated fauna include fishing (e.g. for mud crabs, *Scylla* spp.) and damage to trees and pneumatophores caused by campers or four-wheel drive vehicles. Notably, the significance of these threatening processes will vary depending upon the structure of the mangroves and the location and size of different stands. Smaller and stunted trees are, for example, much more susceptible to damage from vehicles, while fished species like mud crabs are more likely to be significantly depleted from relatively small and isolated mangrove stands.

We suggest that future management planning for SBMP should ensure that zoning provides adequate conservation protection for a significantly greater area of mangroves than is currently the case. This could be achieved by their inclusion in sanctuary zones or appropriately configured special purpose zones aimed at mangrove protection. As a matter of priority, further research should be undertaken to increase knowledge of how Shark Bay's marine environment drives the observed differences in mangrove structure and how differently structured mangrove stands contribute to the maintenance of biodiversity and ecological processes across Shark Bay.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge Parks and Wildlife staff Kathy Murray and Bart Huntley for GIS support and image analysis, and Wayne Moroney for field support. Thanks also to Shaun Wilson and Tom Holmes (Parks and Wildlife), Ray Froend (Edith Cowan University) and Margie Mohring (University of Western Australia) for their comments on the draft. Rainfall data were provided by the Australian Bureau of Meteorology. The manuscript was improved by the comments of two anonymous reviewers.

## REFERENCES

- Abramoff MD, Magalhaes PJ, Ram SJ (2004) Image processing with ImageJ. *Biophotonics International* **11**, 36–42.
- Agraz Hernández CM, García Zaragoza C, Iriarte-Vivar S, Flores-Verdugo FJ, Moreno Casasola P (2011) Forest structure, productivity and species phenology of mangroves in the La Mancha lagoon in the Atlantic

**Table 4**

Summary of the area (ha) of and the relative proportion of mangroves in different conservation zones in the SBMP.

Conservation zone	Mangrove area	% of total mangroves in SBMP
Special Purpose Zone	1262.43	80.87
General Use Zone	293.72	18.82
Recreation Zone	4.31	0.28
Sanctuary Zone	0.54	0.04
Total	1561.00	100.00

- coast of Mexico. *Wetlands Ecology and Management* **19**, 273–293.
- Alongi DM (2002) Present state and future of the world's mangrove forests. *Environmental Conservation* **29**, 331–349.
- Alongi DM (2012) Carbon sequestration in mangrove forests. *Carbon Management* **3**, 313–322.
- Alongi DM, Clough BF, Robertson AI (2005) Nutrient-use efficiency in arid-zone forests of the mangroves *Rhizophora stylosa* and *Avicennia marina*. *Aquatic Botany* **82**, 121–131.
- Anderson MJ (2002) A new method for non-parametric multivariate analysis of variance. *Austral Ecology* **26**, 32–46.
- Anderson MJ, Gorley RN, Clarke KR (2006) *PERMANOVA + for PRIMER: Guide to software and statistical methods*. PRIMER-E, Plymouth.
- Anderson MJ, Willis TJ (2003) Canonical analysis of principal coordinates: a useful method of constrained ordination for ecology. *Ecology* **84**, 511–525.
- Arreola-Lizárraga JA, Flores-Verdugo FJ, Ortega-Rubio A (2004) Structure and litterfall of an arid mangrove stand on the Gulf of California, Mexico. *Aquatic Botany* **79**, 137–143.
- Barbier E, Hacker SD, Kennedy C, Koch EW, Stie AC, Silliman BR (2010) The value of estuarine and coastal ecosystem services. *Ecological Monographs* **81**, 169–193.
- Burkholder D, Fourqurean J, Heithaus M (2013) Spatial pattern in seagrass stoichiometry indicates both N-limited and P-limited regions of an iconic P-limited subtropical bay. *Marine Ecology Progress Series* **472**, 101–115.
- Burling MC, Pattiaratchi CB, Ivey GN (2003) The tidal regime of Shark Bay, Western Australia. *Estuarine Coastal and Shelf Science* **57**, 725–735.
- CALM (1996) *Shark Bay Marine Reserves Management Plan 1996–2006*. Department of Conservation and Land Management, Perth.
- CALM (2005) *Management Plan for the Ningaloo Marine Park and Murion Islands Marine Management Area 2005–2015*. Department of Conservation and Land Management, Perth.
- Chen R, Twilley RR (1999) Patterns of mangrove forest structure and soil nutrient dynamics along the Shark River Estuary, Florida. *Estuaries* **22**, 955–970.
- Clarke KR, Gorley RN (2006) *PRIMER v6: User Manual*. PRIMER-E, Plymouth.
- De Lange WP, de Lange PJ (1994) An appraisal of factors controlling the latitudinal distribution of mangrove (*Avicennia marina* var. *resinifera*) in New Zealand. *Journal of Coastal Research* **10**, 539–548.
- Duke NC (2006) *Australia's Mangroves*. University of Queensland Press, Brisbane.
- Ewel KC, Twilley RR, Jin-Eong O (1998) Different kinds of mangrove forests provide different goods and services. *Global Ecology and Biogeography Letters* **7**, 83–94.
- Feller IC (1995) Effects of nutrient enrichment on growth and herbivory of dwarf red mangrove (*Rhizophora mangle*). *Ecological Monographs* **65**, 477–505.
- Feller IC, Lovelock CE, Berger U, McKee KL, Joye SB, Ball MC (2010) Biocomplexity in mangrove ecosystems. *Annual Review of Marine Science* **2**, 395–417.
- Fraser MW, Kendrick GA, Grierson PE, Fourqurean JW, Vanderklift MA, Walker DI (2012) Nutrient status of seagrasses cannot be inferred from system-scale distribution of phosphorus in Shark Bay, Western Australia. *Marine and Freshwater Research* **63**, 1015–1026.
- Fromard F, Puig H, Mougin E, Marty G, Betoulle JL, Cadamuro L (1998) Structure, above-ground biomass and dynamics of mangrove ecosystems: new data from French Guiana. *Oecologia* **115**, 39–53.
- Jin-Eong O (1995) The ecology of mangrove conservation and management. *Hydrobiologia* **295**, 341–353.
- Logan BW, Cebulski DE (1970) Sedimentary environments of Shark Bay, Western Australia. *AAPG Memoir* **13**, 1–37.
- Lovelock CE, Ball MC, Choat B, Engelbrecht BMJ, Holbrook NM, Feller IC (2006) Linking physiological processes with mangrove forest structure: phosphorus deficiency limits canopy development, hydraulic conductivity and photosynthetic carbon gain in dwarf *Rhizophora mangle*. *Plant, Cell & Environment* **29**, 793–802.
- Lovelock CE, Feller IC, McKee KL, Thompson R (2005) Variation in mangrove forest structure and sediment characteristics in Bocas del Toro, Panama. *Caribbean Journal of Science* **41**, 456–464.
- Lugo AE, Snedaker SC (1974) The ecology of mangroves. *Annual Review of Ecology and Systematics* **5**, 39–64.
- McCluskey P (2008) *Shark Bay World Heritage Property Strategic Plan 2008–2020*. Prepared for the Department of Environment and Conservation, Perth and for the Department of Environment, Water, Heritage and Arts, Canberra.
- Morrisey DJ, Swales A, Dittman S, Morrison MA, Lovelock CE, Beard CM (2010) The ecology and management of temperate mangroves. *Oceanography and Marine Biology: An Annual Review* **48**, 43–160.
- Morton R (1990) Community structure, density and standing crop of fishes in a subtropical Australian mangrove area. *Marine Biology* **105**, 385–394.
- Nahas EL, Pattiaratchi CB, Ivey GN (2005) Processes controlling the position of frontal systems in Shark Bay, Western Australia. *Estuarine, Coastal and Shelf Science* **65**, 463–474.

- Naidoo G (2006) Factors contributing to dwarfing in the mangrove *Avicennia marina*. *Annals of Botany* **97**, 1095–1101.
- Naidoo G (2010) Ecophysiological differences between fringe and dwarf *Avicennia marina* mangroves. *Trees* **24**, 667–673.
- Pellegrini JAC, Soares MLG, Chaves FO, Estrada GCD, Cavalcanti VF (2009) A method for the classification of mangrove forests and sensitivity/vulnerability analysis. *Journal of Coastal Research* **SI56**, 443–447.
- Pool DJ, Snedaker SC, Lugo AE (1977) Structure of mangrove forests in Florida, Puerto Rico, Mexico, and Costa Rica. *Biotropica* **9**, 195–212.
- Schaeffer-Novelli Y, Cintrón-Molero G, Adaime RR, de Camargo TM (1990) Variability of mangrove ecosystems along the Brazilian coast. *Estuaries and Coasts* **13**, 204–218.
- Semeniuk V (1993) The mangrove systems of Western Australia: 1993 Presidential Address. *Journal of the Royal Society of Western Australia* **76**, 99–122.
- Smith SV, Atkinson MJ (1984) Phosphorus limitation of net production in a confined aquatic ecosystem. *Nature* **307**, 626–627.
- Storr GM (1990) Birds of the Shark Bay area, Western Australia. In *Research in Shark Bay: Report of the France–Australie Bicentenary Expedition Committee* (eds PF Berry, SD Bradshaw, BR Wilson). Western Australian Museum, Perth.
- Susilo A, Ridd PV, Thomas S (2005) Comparison between tidally driven groundwater flow and flushing of animal burrows in tropical mangrove swamps. *Wetlands Ecology and Management* **13**, 377–388.
- Twilley RW, Lugo AE, Patterson-Zucca C (1986) Litter production and turnover in basin mangrove forests in southwest Florida. *Ecology* **67**, 670–683.
- Walters BB, Ronnback P, Kovacs JM, Crona B, Hussain SA, Badola R, Primavera JH, Barbier E, Dahdouh-Guebas F (2008) Ethnobiology, socio-economics and management of mangrove forests: A review. *Aquatic Botany* **89**, 220–236.
- Ward GA, Smith TJ, Whelan KRT, Doyle TW (2006) Regional processes in mangrove ecosystems: spatial scaling relationships, biomass, and turnover rates following catastrophic disturbance. *Hydrobiologia* **569**, 517–527.
- Wilson SK, Graham NAJ, Polunin NVC (2007) Appraisal of visual assessments of habitat complexity and benthic composition on coral reefs. *Marine Biology* **151**, 1069–1076.