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Flora and vegetation of greenstone formations of the Yilgarn Craton: south-west Ravensthorpe Greenstone Belt

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ABSTRACT

A quadrat-based survey of the flora of the south-west region of the Ravensthorpe Greenstone Belt identified 321 taxa, including six taxa of conservation significance and three weed species. All of the conservation-listed taxa were known to the area. Range extensions were recorded for three taxa and additional collections of two *Austrostipa* species currently under taxonomic description were made. Six community types were derived from statistical classification of the 50 quadrats. These community types were similar to those described from other parts of the Ravensthorpe Greenstone Belt. As with the other greenstone belts of the Yilgarn Craton, soil chemical parameters and site physical characteristics were influential in delineating community types. Only a small portion of the study area is in the conservation estate; mining and exploration pressures remain the primary threat to this species-rich area.

Keywords: classification, Esperance Plains, Fitzgerald Biosphere, floristic diversity, ultramafics, vegetation communities

INTRODUCTION

Recent surveys of the flora and vegetation of the Yilgarn Craton have identified patterns of high beta-diversity between banded ironstone ranges and associated greenstone belts (Gibson et al. 2007). The greenstone belts of the Yilgarn Craton have long been of interest for pastoral settlement and resource exploration. The south-west region of the Ravensthorpe Greenstone Belt has received attention for its mineral deposits, yet scant attention in terms of systematic description of its flora and vegetation, despite being part of the UNESCO Fitzgerald Biosphere Reserve. This study is part of a survey effort to document the flora, vegetation communities and associated environmental parameters of the greenstone belts in the Yilgarn Craton (see Gibson et al. 2012).

STUDY SITE

The south-western region of the Ravensthorpe Greenstone Belt is situated in the centre of the Esperance Plains Bioregion (IBRA; Thackway & Cresswell 1995). The belt begins c. 25 km south of the South Coast Highway near the West River, trending north-north-east toward Ravensthorpe township (Fig. 1). The greenstone belt covers c. 45 km from north to south and c. 20 km west to east. The latitudinal and longitudinal boundaries of the target area of the Ravensthorpe Greenstone Belt are roughly 33° 30' S, 33° 50' S and 119° 45' E, 120° 05' E, respectively. The land tenure for the greenstone belt, located within the Ravensthorpe Shire, includes freehold, unallocated crown land and crown land, including the Fitzgerald River National Park, Cocanarup Timber Reserve and Crown Reserve 12324 (recreation).

Land use history

The Ravensthorpe area was first surveyed in 1848, with the Dunn brothers taking up land in 1868 at Cocanarup. Following the discovery of gold in Annabel Creek, development occurred in association with gold and copper mines. Ravensthorpe was the state's main copper-producing area until the closure of major operations in 1971 (Thom et al. 1977). Mineral exploration and mining has continued sporadically in the Ravensthorpe area, with particular interest in deposits of gold, copper, nickel and tantalum. At present, the Galaxy Resources Ltd operation is focused on tantalum extraction north of Ravensthorpe, and Tectonic Resources has two operations centred on gold, copper, lead and zinc, primarily south of Ravensthorpe. A nickel mine operation in the Ravensthorpe Range, which was placed in 'care and maintenance' in 2009, has been acquired by First Quantum, with annual production estimated to be between 28,000–39,000 tonnes per annum (First Quantum 2010). In addition to the mineral interest, the area is farmed by a mixture of free- and lease-hold sheep

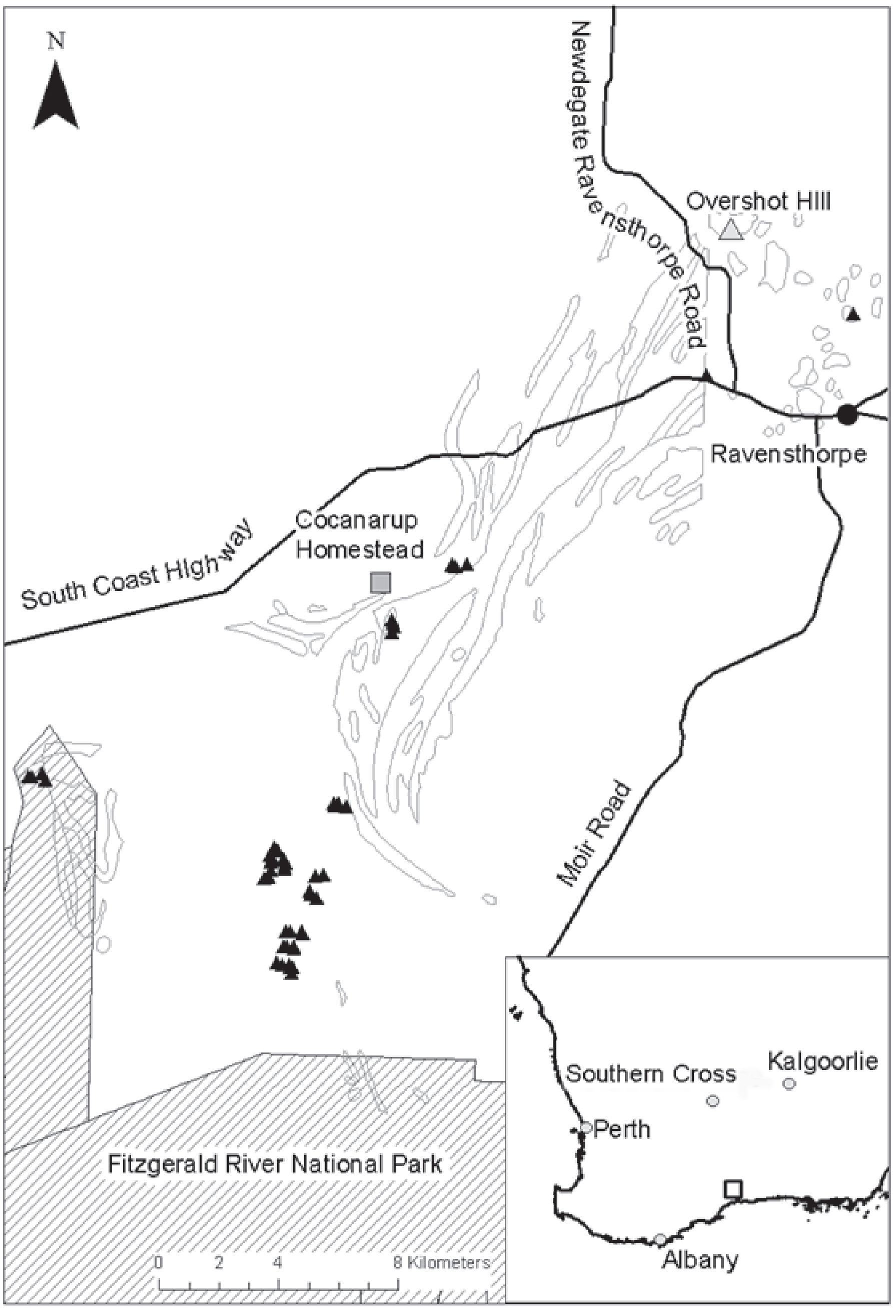


Figure 1. Map showing the location of the south-west region of the Ravensthorpe Greenstone Belt survey area, with major landforms and landmarks indicated. The locations of the 50 permanent quadrats are marked by solid triangles (▲).

and cereal producers. Fitzgerald River National Park sits in the south-west of the study area. The park and study area are within the UNESCO Fitzgerald River Biosphere Reserve. The area is recognised internationally as a biodiversity hotspot that is biologically rich in both flora and fauna (Myers et al. 2000).

Climate

The south-west region of the Ravensthorpe Greenstone Belt sits in the central portion of the Esperance Plains Bioregion, which has a temperate Mediterranean climate with warm to hot summers and mild winters. Rain falls throughout the year, with a slight increase in average monthly rainfall between May and September (mean >40 mm per month; Bureau of Meteorology 2010). Average annual rainfall at Ravensthorpe township (c. 10 km north-east of the survey area) is 425.1 mm (based on records from 1901 to 2010), with the months of July and December having the highest and lowest mean monthly rainfall, respectively. The mean annual maximum and mean minimum temperatures recorded between 1962 and 2010 are 22.7 °C and 10.4 °C, respectively. The warmest months are from November through to March, with average maximum daily temperatures above 25 °C. The lowest daily minimum temperatures occur between May and October, where mean daily minimum temperatures are below 10 °C. Temperatures below zero are an infrequent occurrence.

Geology

The south-west region of the Ravensthorpe Greenstone Belt has been mapped and described on the Newdegate (Thom et al. 1984) and Ravensthorpe (Thom et al. 1977) 1:250,000 geological sheets and straddles the 1:100,000 Cocanarup and Ravensthorpe map sheets (Witt 1994, 1995). This region of the greenstone belt is characterised by relatively low relief, and is surrounded by low granite hills. The dominant feature in the landscape is the Ravensthorpe Range, a north-west trending band of hills that rises c. 400 m above sea level, north-east of the Ravensthorpe township (Thom et al. 1984).

The Ravensthorpe Greenstone Belt, part of the Yilgarn Craton, occurs at the southern extent of the Southern Cross Domain within the Youanmi Terrane (Cassidy et al. 2006). The Archaean-aged Yilgarn Craton is an example of the intact, tectonically stable crusts that occur in the central portion of the Pre-Cambrian Western Shield of Australia (Anand & Paine 2002). The craton contains a series of greenstone belts within vast areas of granitoid and gneiss, believed to have formed between 3000 Ma and 2600 Ma (Myers 1993; Myers & Swagers 1997). Greenstone refers to the surface expression of ultramafic and mafics associated with Archaean meta-volcanic and meta-sedimentary rock sequences in Western Australia, occurring as outcrops or ranges (Cole 1992).

The majority of the Ravensthorpe Greenstone Belt is composed of tonalite and volcanic associations with the western edge dominated by strongly deformed meta-sedimentary rocks (Witt 1997). The principal geologic units of the study area belong to Archaean Annabelle volcanics (metamorphosed mafics to intermediate tuffs), Manyutup tonalite (metamorphosed tonalite and quartz diorite complex) and gneissic granitoids (Witt 1994). Other geologic components include amphibolites, garnetiferous mixed schist and banded quartz-amphibole-plagioclase rock, which constitute the western edge of the greenstone belt (Witt 1994).

The soils of the Esperance Plains Bioregion are typically clay and ironstone gravels overlain by sands (Beard 1990). Where valleys have been carved in the area, the yellow-mottled soils are generally neutral to alkaline (Beard 1990). The soils of the Ravensthorpe Range have been described as shallow calcareous loams on the greenstone uplands, with cracking clays found further downslope and on the adjacent plains (Beard 1981).

Vegetation

The Ravensthorpe Greenstone Belt occurs within the Eyre Botanical District in the South West Botanical Province (Beard 1990). The greenstone belt, particularly the Ravensthorpe Range, is known for its high biodiversity values and is recognised for being floristically rich (Chapman & Newbey 1995a; Craig et al. 2008; Kern et al. 2008). Vegetation surveys and mapping have occurred across the greenstone belt and survey area, principally focusing on the Fitzgerald River National Park (Alpin & Newbey 1990; Chapman & Newbey 1995b) and the Ravensthorpe Range (Chapman & Newbey 1995a; Craig et al. 2008; Kern et al. 2008; Markey et al. 2012).

The area is dominated by scrub- and mallee-heath sandplains, characterised by the presence of *Eucalyptus pleurocarpa* (formerly *E. tetragona*; Beard 1990). Beard (1981) mapped the south-west portion of the Ravensthorpe Greenstone Belt as predominantly *E. nutans* mallee on greenstone, with pockets of *E. loxophleba* and *E. occidentalis* woodlands and *E. redunca* scrub in the south. The western boundary of the study area, encompassing some of the Fitzgerald River National Park, is chiefly mallee and mallee-heath.

The Ravensthorpe Greenstone Belt belongs to the Ravensthope Vegetation System (Beard 1981). Vegetation associations tend to change with changes in topography and soil depth. Recent surveys have focused on the flora and vegetation of the Ravensthorpe Range (Craig et al. 2008; Kern et al. 2008; Markey et al. 2012), a narrow range of hills with subdued relief occupying much of the north-east area of the greenstone belt. The Ravensthorpe Range is dominated by thicket communities on the uplands, including *E. preissiana* and *E. lehmannii* with *Banksia heliantha* (formerly *Dryandra quercifolia*; Beard 1981). Mallee communities tend to be found further downslope, with *E. loxophleba* and *E. salmonophloia* woodlands occurring on the deeper valley soils (Beard 1981).

Following detailed vegetation mapping (1:10,000), Craig et al. (2008) identified 70 vegetation units associated with the Ravensthorpe Range between Mt. Short and Kundip. Two-hundred permanent vegetation quadrats were established on the Ravensthorpe Range in 2007, and 627 taxa representing 59 families were recorded (Kern et al. 2008). Recently, Markey et al. (2012) analysed the Kern et al. (2008) survey data in conjunction with additional survey quadrats from the Ravensthorpe Range and described 21 community types, predominantly influenced by topographical position, substrate and altitude. Dominant families containing the 698 taxa identified during the survey included Myrtaceae, Fabaceae, Proteaceae and Cyperaceae, with 45 taxa of conservation significance recorded (6 Declared Rare Flora and 39 priority-listed species; Markey et al. 2012).

No systematic surveys have examined the floristic diversity of the south-west Ravensthorpe Greenstone Belt, with prior flora and vegetation surveys focused on the Ravensthorpe Range. This study aimed to alleviate the gap in information on the flora and vegetation of the south-western region of the Ravensthorpe Greenstone Belt. The timing was particularly important as interest in the mineral-rich belt has not dissipated in recent decades. The objective of the study was to record the floristic diversity, describe vegetation patterns and examine environmental correlates associated with this region.

METHODS

Between 21 October and 2 November 2009, fifty 20 × 20 m permanent quadrats were established across the south-west region of the Ravensthorpe Greenstone Belt. The greenstone belt was sampled using an environmentally stratified, biased (non-random) strategy: bias occurred due to various limitations in sampling capacity, including access restrictions, human settlement and associated clearing, and recent wildfire through the central survey area. Quadrats were located to represent the topographical, geological and geomorphological variation across the length and breadth of the range, which also allowed the capture of associated vegetation communities. The methods used followed those of previous surveys on greenstone belts in the Yilgarn Craton (e.g. Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008a, 2008b, 2008c). The landscape positions of the sites encompassed a broad topological sequence from hill crests downslope to the colluvial deposits. Quadrats were located in areas that had minimal disturbance or modification following burning or from pastoral agriculture. Thus, sites where there was evidence of disturbance were avoided (e.g. heavy grazing, fire scars, clearing or exploration-related activities). Much of the north-north-eastern portion of the defined survey area is cleared and the central-western portion had been burnt in a wildfire (<2 years) prior to the survey; therefore, fewer quadrats were located in these areas.

The quadrats were marked by four steel fence droppers and their location recorded using a Garmin Map76 GPS. Photographs were taken at a set distance of 5 m from each corner. Site physical characteristics (landform, slope, aspect, litter and bare ground cover, size of coarse fragments, cover of surface rock fragments and bedrock, soil colour and texture) were recorded as a series of descriptive attributes and semi-quantitative scales, as defined by McDonald et al. (1998). Landform description was based on topographical position (crest, upper slope, mid-slope, lower slope or flat) and landform element type (e.g. hillcrest, hillslope, breakaway; McDonald et al. 1998). Coarse fragments and rock outcrop data were recorded as specific geologies and as part of a seven-class scale representing percent (%) cover. The seven cover classes were: zero % cover (0); <2% cover (1); 2–10% (2); 10–20% (3); 20–50% (4); 50–90% (5); >90% (6). Site disturbance was ranked between zero and three, with zero (0) representing no effective disturbance and three (3) being extensively cleared. Runoff was assigned to a scale of six classes (0 = no runoff, 1 = very slow, 2 = slow, 3 = moderately rapid, 4 = rapid, 5 = very rapid; McDonald et al. 1998).

Vegetation structure was determined by assigning the dominant taxa to each stratum found in the landscape, noting emergent taxa where appropriate, based on McDonald et al. (1998). All vascular plants were recorded from within the plot and assigned a cover class (D >70%, M 30–70%, S 10–30%, V<10%, I = isolated plants and L = isolated clumps); material was collected for verification and vouchering at the Western Australian Herbarium (WA Herbarium). Additional specimens were collected adjacent to the plots, contributing to the overall species list for the range. When sufficient representative plant material was available, it was lodged at the WA Herbarium. Nomenclature generally follows Florabase (Western Australian Herbarium 2010). For this study, 'weed' refers to an invasive species, recognised as introduced or alien to the area, in accordance with the WA Herbarium.

Soil chemical attributes were analysed for each quadrat. Soil was collected from 20 regularly-spaced intervals across the quadrat, bulked and sieved. The <2 mm fraction was analysed by an Inductively Coupled Plasma – Atomic Emission Spectrometer (ICP–AES) for B, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, S and Zn using the Mehlich No. 3 procedure (Mehlich 1984). Soil pH was measured on 1:5 soil-water extracts in 0.01 M $CaCl_2$ (method S3; Rayment & Higginson 1992). Organic carbon content was determined using a modified Walkley–Black method (method 6A1) and calculation of soil nitrogen (N) was based on a modified Kjeldahl digest (method S10; Rayment & Higginson 1992).

The classification and ordination analyses were undertaken on a presence/absence data matrix of 195 perennial taxa occurring in more than a single quadrat, which was consistent with previous greenstone belt studies (Gibson et al. 2012). The dissimilarity between quadrats was determined using the Bray–Curtis measure and the Resemblance routine in PRIMER v6 (Clarke & Gorley 2006). The Bray–Curtis measure is a widely-used assessment of ecological distance, which reflects differences in compositional change (Legendre & Legendre 1998; Anderson & Robinson 2003), providing quantitative output for similarity between samples (Faith et al. 1987).Using the Bray–Curtis similarity matrix, the quadrats were classified based on the flexible unweighted pair-group mean average method (UPGMA, $\beta = -0.1$), using PATN v3.11 (Belbin 1989). The resulting dendrogram provided the basis for grouping of taxa into ecological groups. A two-way table was created based on the classification. Non-metric Multi-dimensional Scaling (NMS) was performed on the species–site similarity matrix, and stress values for both the 2D and 3D ordination were determined. An environmental data matrix that included soil chemical properties and site physical characteristics was created. The continuous variables in the environmental matrix were normalised prior to fitting environmental vectors to the NMS ordination. The environmental vectors are lines of 'best-fit' in multi-dimensional space, with stronger correlations corresponding to those lines extending closer to the edge of the circle (see Fig. 3).

The similarity percentages (SIMPER) analyses provided information on those species typically found within each community. The SIMPER routine in PRIMER determines those taxa contributing the greatest similarity within a community and dissimilarity amongst communities (Clarke & Warwick 2001). Those taxa contributing 10% or more to the similarity within each community type were initially selected. However, given the high species richness of the area, this was not applicable for most groups. Therefore, taxa that contributed to a cumulative 50% similarity between community types were included. Where individual species contributions were tied at the 50% level, all taxa in the tie were reported.

The relationships between environmental variables were examined using the nonparametric Spearman's rank correlation routine in Statistix 7.1 (Analytical Software, Tallahassee, Florida). The environmental variables were subjected to Kruskal–Wallis nonparametric one-way analysis of variance and post-hoc significance testing of means at $\alpha = 0.05$ (Sokal & Rolf 1995), using the community types determined by the site dendrogram.

RESULTS

Summary information

A total of 313 taxa were collected from within the quadrats in the south-west Ravensthorpe Greenstone Belt and an additional eight taxa were identified from areas adjacent to the quadrats (Appendix 1). There were 49 families represented, principally Myrtaceae (62 taxa), Fabaceae (39), Cyperaceae (30), Proteaceae (22) and Poaceae (14). There were 131 genera recorded, with *Eucalyptus* (22 species), *Acacia* (20 species), *Lepidosperma* (19 species) and *Melaleuca* (17 species) having the highest representation. Five weed species (Table 1), representing 9 collections, were identified. All weed species, except *Pentatschistis airoides* subsp. *airoides*, were known to the Ravensthorpe area. No new taxa were identified during the survey.

Table 1

Weed taxa recorded during the survey of the south-west region of the Ravensthorpe Greenstone Belt.

Family	Taxon	No. Records
Asparagaceae	*Asparagus asparagoides*	1
Malvaceae	*Malva parviflora*	1
Poaceae	*Ehrharta longiflora*	2
Poaceae	*Pentaschistis airoides* subsp. *airoides*	3
Primulaceae	*Lysimachia arvensis*	2

Species richness varied from 10 to 53 species per quadrat, with a mean species richness of 28.7 ± 9.1 SD. The majority of the taxa recorded were perennials, with only 14 annuals identified. Twenty taxa were amalgamated into nine species complexes during analyses. This occurred for taxa where a lack of sufficient material (i.e. flowering or fruiting specimens) prevented identification to sub-species level and for *Senna artemisioides* integrades. The final species matrix used in the classification and ordination routines consisted of 190 species × 50 sites. All annuals, singletons and specimens unidentifiable below generic level were removed from the data matrix prior to the analyses.

Priority taxa

Six taxa of conservation significance, represented in 16 populations, were identified during the survey (Table 2). All priority-listed taxa recorded were known to occur in the Ravensthorpe area. Two undescribed taxa of interest, *Austrostipa* sp. Carlingup Road (S Kern & R Jasper LCH18459) and *A.* sp. Ravensthorpe Range (A Markey & J Allen 6261), described below, have been classified Priority 1 (P1). A single collection of the former was made and 10 populations of the latter were recorded. Fifteen collections of *Lepidosperma diurnum* (formerly P1) were made during the survey. *L. diurnum* is widespread in the Ravensthorpe region and has been delisted, based on recommendations (Barrett el al. 2009). Only isolated individuals were collected of the following priority taxa: *Cassinia arcuata* (P2), *Eucalyptus desmondensis* (P4) and *Melaleuca penicula* (P4). Two collections were made of *Acacia bifaria* (P3).

Range extensions

Range extensions were recorded for three taxa collected during the survey. A single collection of *A. brumalis* represented a c. 100 km range extension to the south-east of its current distribution. *Acacia brumalis* occurs as a shrub or tree and is predominantly known from the Avon Wheatbelt Bioregion; this is the first record for the Esperance Plains Bioregion. A slight range extension eastward (c. 40 km) was recorded for *Schoenus* sp. Cape Riche Cushion (GJ Keighery 9922), a small perennial sedge. A single collection of *M. sparsiflora* was made

Table 2

Priority taxa recorded from the south-west region of the Ravensthorpe Greenstone Belt. Bioregion abbreviations: COO = Coolgardie, MAL = Mallee, ESP = Esperance Plains.

Family	Taxon	Priority Status	Distribution
Poaceae	*Austrostipa* sp. Carlingup Road	P1	ESP, MAL, COO
Poaceae	*Austrostipa* sp. Ravensthorpe Range	P1	ESP, MAL
Asteraceae	*Cassinia arcuata*	P2	ESP, MAL
Fabaceae	*Acacia bifaria*	P3	ESP
Myrtaceae	*Eucalyptus desmondensis*	P4	ESP
Myrtaceae	*Melaleuca penicula*	P4	ESP, MAL

opportunistically from outside of the survey quadrat boundaries. This record represents a small range extension of c. 50 km. The shrub is principally known from the Mallee Bioregion, north of the survey area.

Taxa of interest

Two species of *Austrostipa* that were collected during the survey are of taxonomic interest, as they represented new taxa currently undergoing formal description. *Austrostipa* sp. Carlingup Road (S Kern & R Jasper LCH18459) and *Austrostipa* sp. Ravensthorpe Range (A Markey & J Allen 6261) were initially collected from the Ravensthorpe Range area (north-west of this survey effort), with a single collection of each lodged at the WA Herbarium. The survey efforts in the south-west Ravensthorpe Greenstone Belt resulted in a single additional collection of *Austrostipa* sp. Carlingup Road (S Kern & R Jasper LCH18459) and four new populations of *Austrostipa* sp. Ravensthorpe Range (A Markey & J Allen 6261). Both taxa are currently listed as Priority 1.

Floristic communities

Hierarchical clustering separated the taxa into 13 species groups (A–M). Species group B was associated with more neutral to alkaline soils and group E contained the most ubiquitous taxa, with representation across all sites. Species group H was associated with more acidic soils. Six broad community types were defined from the site dendrogram (Fig. 2). The dendrogram highlighted the close relationship between particular communities as well as less well-defined community types with low representation of quadrats. Community types were characterised by similarity in species groups (Table 3) as well as similarity in edaphic factors such as soil pH and soil cation concentrations (Ca, K, Mg, Na; Table 4). However, separation of community types was not distinctly along gradients of soil pH (acidic vs. alkaline) or soil cation concentrations. Community types 2 and 4 were characterised by highly acidic soils with relatively low cation concentrations compared with the community types on more moderately acidic to neutral soils, but had low numbers of representative quadrats (i.e. 2–4 quadrats). This is a reflection of the limitations of the survey sampling and not necessarily a representation of the extent of these community types within the greenstone belt. By comparison, community types 1, 3 and 5a had more moderately acidic to neutral soils, with comparatively higher soil cation concentrations.

The NMS output (2D stress = 0.16, 3D stress = 0.12) displays the relationship between the sites, based on the resemblance matrix with environmental vectors overlain (Fig. 3). Vectors extending close to the edge of the circle indicate stronger correlation to those communities. The environmental vectors overlain on the NMS ordination highlight the influence of edaphic factors on vegetation communities, suggesting a greater influence on community composition than site physical characteristics such as position in the landscape.

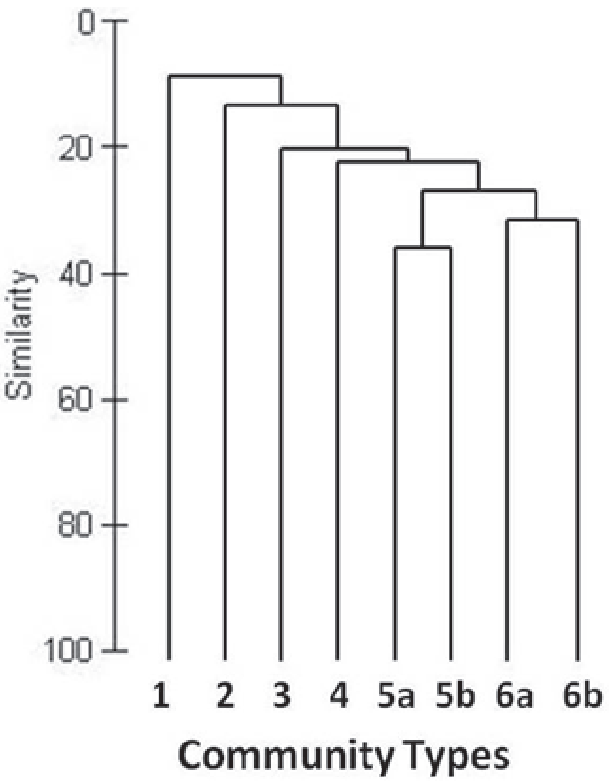


Figure 2. Summary dendrogram of community types for the Ravensthorpe Greenstone Belt. The six community types displayed in the dendrogram are derived from the classification analyses of the 195 taxa from 50 sites.

One pair of sites (SWRV 23 and 49) are discussed below as a community type (community type 4), despite only being recorded within two quadrats. Further regional survey will potentially clarify the status of these sites as a distinct community type.

Community type 1 was identified from ten quadrats with moderate species richness (14–28 taxa per quadrat, mean 23.2 ± 2.7 SD). They were *Eucalyptus* woodland sites, with either *E. myriadena* or *E. salmonophloia* as the dominant eucalypt species. A single quadrat with low species richness was included as the taxa recorded fitted the pattern of species grouping and other site physical characteristics. Although the survey area was not characterised by significant gradients, community type 1 contained sites classified predominantly as upland, with variable slopes. Taxa were principally from species groups A, B and E; no representative taxa were recorded from groups F–J and L–M (Table 3). Typical taxa of this community included the shrubs *Dodonaea ptarmicaefolia*, *Enchylaena tomentosa* var. *tomentosa*, *Eremophila decipiens* subsp. *decipiens*, *Rhagodia crassifolia*, *Senna artemisioides* subsp. *filifolia* and the grass *Austrostipa* sp. Ravensthorpe Range (A Markey & J Allen 6261).

Soils were principally red-brown slightly acidic to alkaline (pH 5.1–7.8) sandy clay loams. Ca concentrations were high, particularly in the alkaline soils (Table 4). Other soil cation concentrations were also high (K, Mg, Na).

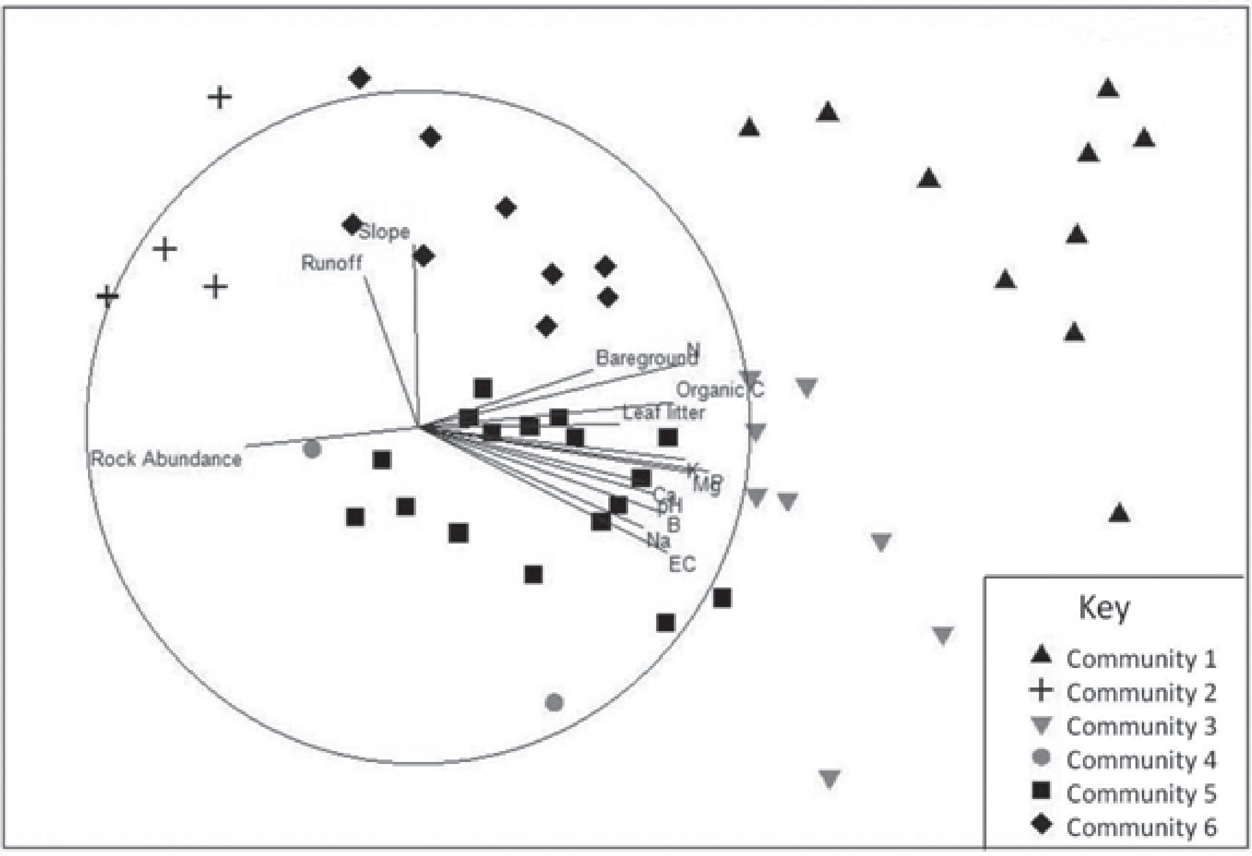


Figure 3. 2D graph of the first two axes of the NMS ordination (stress value = 0.16) of survey quadrats from the Ravensthorpe Greenstone Belt. Data are a matrix of 195 perennial species from 50 survey sites. Survey quadrats are presented as community groups overlain with environmental vectors; the closer the line of 'best-fit' approaches the circle boundary, the stronger the correlation. The soil parameters (soil pH, electrical conductivity, organic C, B, Ca, K, Mg, Na and P) that had the strongest correlation ($r_s \geq 0.7$) using Spearman rank correlation coefficient are shown. For comparison, the top five site physical characteristic vectors are shown (abundance of coarse fragments, leaf litter, runoff, slope and bare ground).

Organic carbon concentrations were relatively high for the survey area. Coarse rock fragments, leaf litter and bare ground were generally abundant.

Community type 2 was a group of species-rich quadrats (23–43 taxa per quadrat, mean 35.7 ± 9 SD) on moderate slopes. Taxa were principally allied with species groups E, H, I and J. Sites were typically mallee *Eucalyptus pleurocarpa* with a rich shrub layer including *Acacia mimica* var. *angusta*, *Calothamnus quadrifidus* subsp. *quadrifidus*, *Calytrix leschenaultia*, *Daviesia pachyphylla*, *Hakea verrucosa*, *Leptospermum spinescens*, *Leucopogon cuneifolius*, *Melaleuca villosisepala*, *Petrophile seminuda*, *Platysace deflexa*, plus *Conostylis argentea* and *Mesomelaena stygia* subsp. *stygia* (Table 3).

Soils were strongly acidic (pH 4.5–5.3) yellow-brown loamy sands or sandy loams. Cation concentrations were low, with Ca concentrations concomitantly low in the quadrats with more acidic soil (Table 4). Coarse rock fragments were very abundant, predominantly medium gravel-sized quartzite and mixed metasediment with minimal surface exposure of any bedrock.

Community type 3 consisted of quadrats characterised by heterogeneous topography, gentle to moderate slopes and variable species richness (10–39 taxa per quadrat, mean 21.2 ± 9.8 SD). Taxa were principally allied with species groups B and E, with minimal representation in group D and no representative taxa from groups F–J (Table 3). Typical taxa were *Eucalyptus extensa*, *E. oleosa* subsp. *corvina* with *Melaleuca cucullata* over *Acacia glaucoptera* and the *Senna artemisioides* subsp. × *artemisioides* group.

Soils were mildly acidic to alkaline (pH 6.2–7.8) sandy loams and sandy clay loams. Soil cation concentrations were high, with higher concentrations associated with higher soil pH (Table 4). High Na values were recorded at sites with correspondingly high electrical conductivity (EC) values. Coarse rock fragments were moderate to abundant in cover, with minimal exposed bedrock recorded.

Community type 4 was recorded within a pair of quadrats in open mallee shrubland, particularly distinguished by their soil characteristics. Soils were highly acidic (pH 4.3–4.7) orange-brown sandy clay loams and loamy sands. Species richness was 21 and 42 taxa per quadrat. Taxa were associated with species groups E, H, L and M (Table 3). Typical taxa of these sites were *E. pluricaulis* subsp. *pluricaulis* and *E. suggrandis* subsp.

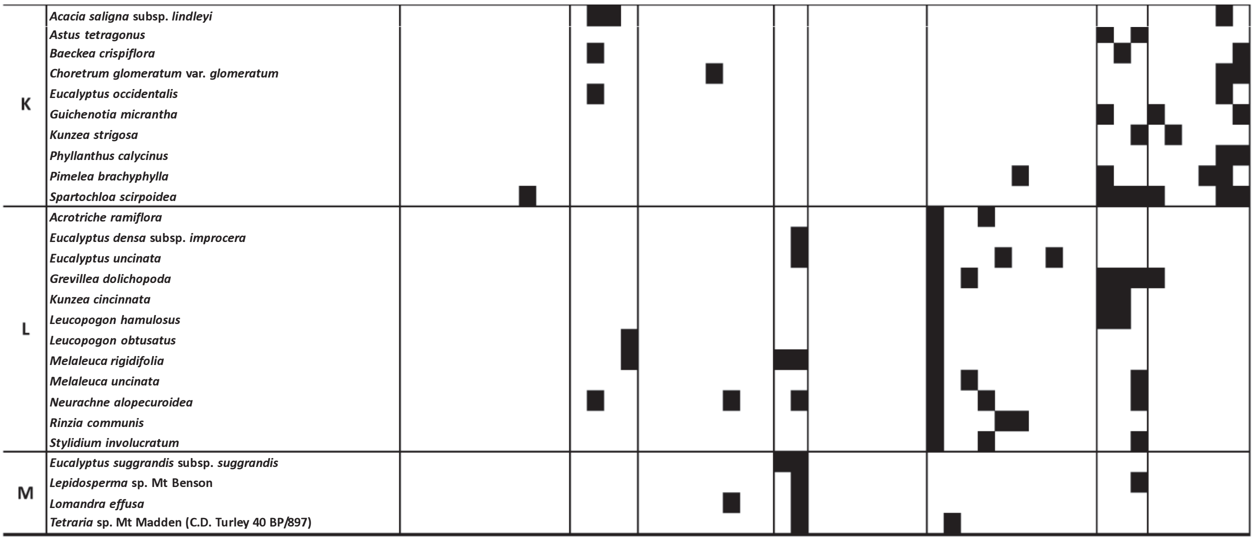
Table 3

Two-way table of community types (columns) and species (rows) groups for the south-west Ravensthorpe Greenstone Belt. Taxa are sorted within species groups. The squares represent the presence of the specific taxon in the corresponding quadrat.

		1	2	3	4	5a	5b	6a	6b
A	*Acacia acuminata*	■							
A	*Acacia bifaria*	■							
A	*Acacia brumalis*	■							
A	*Acacia erinacea*	■							
A	*Acacia lachnophylla*	■		■					
A	*Atriplex semibaccata*	■							
A	*Austrostipa elegantissima*	■							
A	*Austrostipa* sp. Ravensthorpe Range	■		■					
A	*Chenopodium desertorum* subsp. *microphyllum*	■							
A	*Comesperma integerrimum*	■							
A	*Daviesia nematophylla*	■							
A	*Dianella brevicaulis*	■							
A	*Enchylaena tomentosa* var. *tomentosa*	■							
A	*Eremophila decipiens* subsp. *decipiens*	■							
A	*Eucalyptus myriadena*	■							
A	*Eucalyptus salmonophloia*	■							
A	*Goodenia affinis*	■							
A	*Ptilotus holosericeus*	■							
A	*Rhagodia crassifolia*	■							
A	*Santalum spicatum*	■							
A	*Sclerolaena diacantha*	■							
A	*Senecio quadridentatus*	■							
A	*Templetonia battii*	■							
B	*Acacia cyclops*	■		■					■
B	*Acacia* sp. narrow phyllode (B.R. Maslin 7831)	■							
B	*Alyxia buxifolia*	■		■					
B	*Austrodanthonia setacea*	■		■	■	■			■
B	*Austrostipa variabilis*	■		■					■
B	*Dodonaea ptarmicaefolia*	■		■					■
B	*Eucalyptus brachycalyx*	■		■		■			
B	*Eucalyptus extensa*	■		■		■			■
B	*Eucalyptus oleosa* subsp. *corvina*	■		■		■			
B	*Glischrocaryon flavescens*	■							■
B	*Glycocystis beckeri*	■		■		■			
B	*Olearia muelleri*	■		■		■			
B	*Oxalis perennans*	■		■					
B	*Rhagodia preissii*	■		■		■			
B	*Senna artemisioides* subsp. *filifolia*	■		■		■			
B	*Teucrium sessiliflorum*	■							
C	*Eucalyptus cernua*	■							■
C	*Lepidosperma* sp. Carracarrup Creek			■					■
C	*Lepidosperma* sp. Mt Chester						■		■
C	*Maireana suaedifolia*	■							■
C	*Melaleuca acuminata* subsp. *acuminata*	■	■	■					
C	*Pimelea erecta*			■					
D	*Austrostipa acrociliata*			■		■			
D	*Billardiera coriacea*		■			■			■
D	*Eucalyptus redunca*				■	■			
D	*Goodenia laevis* subsp. *humifusa*			■		■	■		
D	*Grevillea concinna* subsp. *lemanniana*					■			
D	*Hakea commutata*			■	■	■			
D	*Halgania andromedifolia*	■				■			
D	*Lepidosperma fimbriatum*			■		■			
D	*Lepidosperma gahnioides*			■		■			
D	*Lomandra micrantha* subsp. *teretifolia*		■			■			
D	*Melaleuca undulata*			■		■	■		
	Acacia binata	■				■	■		
	Acacia glaucoptera			■	■	■	■	■	■
	Acacia ingrata			■		■	■		■
	Acacia sulcata	■	■	■		■	■	■	■
	Acacia tetanophylla				■	■	■	■	■
	Allocasuarina campestris		■				■	■	■
	Astroloma epacridis	■		■			■		■
	Baeckea corynophylla				■	■	■	■	■
	Boronia inornata subsp. *inornata*	■		■		■	■		
	Boronia scabra subsp. *scabra*					■	■	■	■
	Callitris drummondii			■	■		■		■
	Calothamnus quadrifidus subsp. *quadrifidus*		■		■	■	■	■	■
	Cassytha melantha	■		■	■	■	■		■
	Daviesia anceps		■			■	■		■
	Daviesia benthamii subsp. *benthamii*					■	■		
	Daviesia incrassata subsp. *incrassata*				■	■	■		
	Dianella revoluta var. *revoluta*	■	■	■	■	■	■		■
	Dodonaea concinna	■		■		■	■		
	Dodonaea pinifolia	■	■	■		■	■	■	■
	Eucalyptus calycogona subsp. *calycogona*	■				■	■		■
	Eucalyptus flocktoniae subsp. *flocktoniae*			■		■	■		■
	Eucalyptus phenax subsp. *phenax*	■		■	■	■	■		■
	Eucalyptus pluricaulis subsp. *pluricaulis*				■		■		■
	Eucalyptus proxima	■		■		■	■		■
	Eutaxia cuneata					■	■	■	■
	Exocarpos aphyllus			■		■	■		■


E
Exocarpos sparteus
Gahnia ancistrophylla
Gastrolobium musaceum
Gastrolobium tetragonophyllum
Goodenia concinna
Grevillea oligantha
Grevillea pectinata
Hakea verrucosa
Hibbertia exasperata
Hybanthus floribundus subsp. adpressus
Lepidosperma diurnum
Lepidosperma sp. A2 Inland Flat (G.J. Keighery 7000)
Lepidosperma sp. Bandalup Scabrid
Lepidosperma sp. Ravensthorpe (G.F. Craig 5188)
Melaleuca cliffortioides
Melaleuca cucullata
Melaleuca glaberrima
Melaleuca lateriflora subsp. lateriflora
Melaleuca pomphostoma
Melaleuca scalena
Melaleuca torquata
Santalum acuminatum
Senna artemisioides subsp. x artemisioides complex
Stylidium albomontis
Templetonia neglecta
Templetonia retusa
Thysanotus patersonii
Wilsonia humilis
F
Austrostipa hemipogon
Boronia inconspicua
Goodenia scapigera subsp. scapigera
Lasiopetalum compactum
Leptospermum erubescens
G
Acacia gonophylla
Acacia pravifolia
Acrotriche cordata
Cassytha glabella
Coopernookia strophiolata
Cryptandra nutans
Eucalyptus leptocalyx
Gahnia aristata
Lasiopetalum rosmarinifolium
Lepidosperma sp. Saltbush Hill (K.R. Newbey 4118)
Logania stenophylla
Marianthus microphyllus
Microcorys glabra
Siegfriedia darwinioides
Spyridium cordatum
H
Acacia mimica var. angusta
Amphipogon turbinatus
Astroloma serratifolium
Calytrix leschenaultii
Conostylis argentea
Daviesia pachyphylla
Eucalyptus pleurocarpa
Hakea lissocarpha
Hibbertia gracilipes
Kunzea affinis
Lepidosperma sp. Clathrate
Lepidosperma sp. Tibialate
Leucopogon cuneifolius
Leucopogon lloydiorum
Leucopogon sp. Newdegate (M. Hislop 3585)
Lysinema pentapetalum
Melaleuca hamata
Melaleuca villosisepala
Mesomelaena stygia subsp. stygia
Olax benthamiana
Petrophile seminuda
I
Lepidosperma sp. Mt Short
Lepidosperma sp. Shoemaker Levy
J
Allocasuarina microstachya
Banksia nivea subsp. nivea
Chamelaucium ciliatum
Eucalyptus perangusta
Hakea incrassata
Hakea laurina
Lepidosperma carphoides
Leptospermum oligandrum
Leptospermum spinescens
Lomandra mucronata
Melaleuca hamulosa
Melaleuca pentagona var. pentagona
Platysace deflexa
Schoenus subflavus
Synaphea interioris
Verticordia chrysantha

Table 3 (cont.)



suggrandis over *Melaleuca hamata*, *Daviesia incrassata* subsp. *incrassata*, *Dianella revoluta* var. *revoluta* and *Gastrolobium musaceum* with *Lepidosperma* sp. A2 Inland Flat (GJ Keighery 7000), *Lepidosperma* sp. Ravensthorpe (GF Craig 5188) and the parasitic climber *Cassytha melantha*.

The plots primarily had low soil cation concentrations, and one plot had very high electrical conductivity and Na concentrations (Table 4). Coarse rock fragments were highly abundant on the surface, predominantly weathered ironstone and laterite with undifferentiated greenstone of large gravel size.

Community type 5 was recorded in a group of quadrats in mallee woodland with relatively high species richness (23–53 taxa per quadrat, mean 34.7 ± 7.8 SD). The community was dominated by *E. flocktoniae* subsp. *flocktoniae* and *E. phenax* subsp. *phenax*, with a typical understorey of *Acacia glaucoptera*, *A. ingrata*, *Boronia inornata* subsp. *inornata* and *Dodonaea* sp. (Table 3). Two sub-types are discussed, as species associations outside of the ubiquitous group E diverged strongly. Sites typically had high abundance of rock fragments and variable amounts of exposed bedrock (Table 4).

Community type 5a was characterised by the aforementioned taxa and *Grevillea pectinata*. Taxa were allied with species groups B, D and F, with no representatives from groups I–M. Soils were more alkaline (pH 5.8–7.8) and typically red-brown sandy loams and sandy clay loams with relatively higher soil cation concentrations.

Taxa in community type 5b also included the mallee *E. proxima*, understorey shrubs *Daviesia benthamii* subsp. *benthamii*, *Hakea verrucosa*, *Hibbertia exasperata*, *Melaleuca lateriflora* subsp. *lateriflora* and the sedge *Gahnia ancistrophylla*. Taxa were allied with species groups G, H, I and L. Soils were typically strongly acidic to slightly alkaline (pH 4.9–7.6) light brown sandy clay loams and sandy loam. Soil cation concentrations, organic carbon content and electrical conductivity values were generally lower than those recorded in type 5a.

Community type 6 was characterised by quadrats containing *Allocasuarina campestris* with *Dodonaea pinifolia* and *Hakea verrucosa*. Soils were typically sandy clay loams with a high cover of coarse rock fragments and some exposed bedrock at the surface. Two sub-types are discussed, as site characteristics and taxa associations diverged outside of the ubiquitous species group E.

Community type 6a was characterised by strongly acidic yellow-brown sandy loam soils (pH 5.3–5.4; Table 4). Additional species fidelity included groups H, K and L, with a noticeable absence of taxa from groups A–D, F and G (Table 3). Typical taxa included *A. campestris*, with additional shrubs of *Calothamnus quadrifidus* subsp. *quadrifidus* and *Grevillea dolichopoda* and the tussock grass *Spartochloa scirpoidea*. Soils had lower cation concentrations, particularly Ca, than community type 6b.

Community type 6b had moderately acidic (pH 5.5–6.7) red-brown sandy clay loam soils (Table 4). Typical taxa included *A. campestris*, with *Exocarpos aphyllus* and *Santalum acuminatum* over *Hibbertia exasperata*, with *Gahnia ancistrophylla* and *Lepidosperma diurnum*. Taxa were principally allied with species group B, H and K, with no representative taxa from groups A, J, L and M (Table 3).

Environmental variables

Survey quadrats were located on altitudes ranging from 111 to 273 m above sea level (mean 182.6 ± 36.5 SD; Table 4). The predominant soil textures were sandy loam and sandy clay loams, with only eight sites characterised by loamy sands, loams or clay loams. All sites had coarse fragments present, with a mean surface cover score of 4.6, which corresponded to 20–50% cover. Surface bedrock was recorded in over half of the quadrats, with 21 quadrats having no outcrops. The sites typically had a high

Table 4

Summary statistics for environmental variables, separated by community type, for the south-west Ravensthorpe Greenstone Belt. Mean values with standard deviation are listed for community types recorded in more than one quadrat. Differences were determined using Kruskal–Wallis nonparametric one-way analysis of variance. Significance values are indicated by * ($p < 0.05$ = *, $p < 0.01$ = **, $p < 0.001$ = ***, $p < 0.0001$ = ****) and $^{+}$ indicates no significant difference of means. Post-hoc differences were set at $\alpha = 0.05$. Units of measurements for the parameters are: soil chemicals = mg/kg; abundance of fragments and outcrop abundance = categorical maximum (0 = 0%, 1 = <2%, 2 = 2–10%, 3 = >10–20 %, 4 = >20–50 %, 5 = >50–90 %, 6 = >90%); topographical position: 1 = crest, 2 = upper slope, 3 = mid-slope, 4 = lower slope, 5 = flat; species richness = number of taxa/quadrat.

	Community Types					
Soil Parameters	**1**	**2**	**3**	**4**	**5**	**6**
B***	1.5 ± 0.9 ^{a}	0.1 ± 0.1 ^{b}	2.0 ± 1.4 ^{a}	0.6 ± 0.0 ^{ab}	0.5 ± 0.6 ^{ab}	0.3 ± 0.6 ^{b}
Ca***	3300.0 ± 1298.7 ^{a}	365.0 ± 157.8 ^{b}	4412.5 ± 1840.4 ^{a}	375.0 ± 134.4 ^{ab}	2435.9 ± 1963.6 ^{ab}	1785.6 ± 1278.4 ^{ab}
Cd^{NS}	0.006 ± 0.002	0.005 ± 0.00	0.005 ± 0.00	0.005 ± 0.00	0.005 ± 0.00	0.013 ± 0.025
Co***	2.2 ± 1.3 ^{ac}	0.1 ± 0.1 ^{b}	1.5 ± 1.3 ^{abc}	0.6 ± 0.3 ^{abc}	0.8 ± 0.5 ^{bd}	1.8 ± 1.4 ^{acd}
Cu***	4.5 ± 2.8 ^{a}	0.2 ± 0.2 ^{b}	4.1 ± 1.2 ^{a}	1.6 ± 0.1 ^{ab}	2.3 ± 1.7 ^{ab}	3.1 ± 3.2 ^{ab}
EC***	17.0 ± 5.5 ^{a}	2.0 ± 0.8 ^{b}	20.9 ± 10.9 ^{a}	72.0 ± 96.2 ^{ab}	11.2 ± 7.5 ^{ab}	4.9 ± 1.8 ^{b}
Fe*$^{+}$	92.2 ± 39.6	111.5 ± 42.8	80.8 ± 25.6	120.0 ± 14.1	116.5 ± 38.4	140.1 ± 40.5
K***	351.0 ± 113.8 ^{ac}	71.8 ± 24.7 ^{b}	433.8 ± 131.3 ^{a}	140.5 ± 84.1 ^{abc}	190.8 ± 131.2 ^{bc}	188.9 ± 88.8 ^{abc}
Mg***	932.0 ± 233.5 ^{a}	66.8 ± 31.2 ^{b}	935.0 ± 305.6 ^{a}	350.0 ± 183.9 ^{ab}	553.5 ± 312.9 ^{ab}	438.9 ± 271.9 ^{ab}
Mn*$^{+}$	76.1 ± 29.3	27.3 ± 24.2	88.8 ± 58.9	8.0 ± 1.7	49.6 ± 47.4	83.4 ± 64.9
N (Total)****	0.26 ± 0.07 ^{a}	0.05 ± 0.02 ^{b}	0.15 ± 0.06 ^{ab}	0.08 ± 0.03 ^{ab}	0.10 ± 0.04 ^{b}	0.11 ± 0.03 ^{b}
Na***	168.3 ± 89.2 ^{ac}	11.8 ± 2.8 ^{b}	246.4 ± 129.3 ^{a}	582.5 ± 731.9 ^{ab}	99.2 ± 55.2 ^{ab}	64.6 ± 46.3 ^{bc}
Ni***	4.9 ± 3.5 ^{a}	0.2 ± 0.1 ^{b}	2.5 ± 0.7 ^{ac}	1.2 ± 0.6 ^{abc}	1.6 ± 1.9 ^{bc}	3.4 ± 3.8 ^{abc}
Organic C (%)***	3.6 ± 0.7 ^{a}	0.8 ± 0.3 ^{c}	2.6 ± 1.1 ^{ab}	2.0 ± 1.0 ^{abc}	1.8 ± 0.7 ^{bc}	1.9 ± 0.6 ^{bc}
P****	5.7 ± 1.6 ^{a}	1.1 ± 0.6 ^{b}	5.3 ± 3.1 ^{ac}	2.5 ± 2.1 ^{abc}	2.5 ± 1.3 ^{bc}	1.2 ± 0.8 ^{b}
pH***	6.9 ± 0.9 ^{ac}	5.0 ± 0.3 ^{b}	7.2 ± 0.6 ^{a}	4.5 ± 0.3 ^{bc}	6.4 ± 1.0 ^{abc}	6.0 ± 0.6 ^{abc}
S**	13.0 ± 5.9 ^{a}	3.3 ± 1.9 ^{b}	15.5 ± 10.9 ^{ab}	82.5 ± 109.6 ^{ab}	8.1 ± 5.8 ^{ab}	5.7 ± 1.7 ^{ab}
Zn**	3.0 ± 1.0 ^{a}	0.5 ± 0.3 ^{b}	1.6 ± 0.5 ^{ab}	1.3 ± 0.1 ^{ab}	1.9 ± 1.2 ^{ab}	2.3 ± 1.7 ^{ab}
Site Physical Parameters						
Altitude (m)*	194.8 ± 31.4 ^{ab}	225.8 ± 19.8 ^{a}	178.1 ± 40.6 ^{ab}	202.0 ± 80.6 ^{ab}	178.1 ± 31.8 ^{ab}	158.1 ± 26.3 ^{b}
Bare ground (%)*$^{+}$	94.0 ± 2.2	91.0 ± 1.2	94.5 ± 1.4	90.0 ± 7.1	90.9 ± 3.7	92.2 ± 3.2
Abundance fragments***	3.7 ± 0.9 ^{ab}	4.8 ± 0.5 ^{ab}	3.6 ± 0.9 ^{a}	5.5 ± 0.7 ^{ab}	5.1 ± 0.6 ^{b}	5.0 ± 0.5 ^{ab}
Leaf litter (%)**	55.0 ± 27.0 ^{a}	9.0 ± 2.6 ^{c}	42.9 ± 21.0 ^{ab}	25.0 ± 14.1 ^{abc}	19.4 ± 13.2 ^{bc}	20.2 ± 14.5 ^{abc}
Topographical position^{NS}	2.5 ± 1.0	3.3 ± 0.5	2.8 ± 1.6	1.5 ± 0.7	2.6 ± 1.1	2.6 ± 0.9
Outcrop abundance^{NS}	0.7 ± 0.8	0.3 ± 0.5	0.5 ± 0.8	1.0 ± 1.4	1.2 ± 1.0	1.2 ± 0.8
Slope*$^{+}$	5.6 ± 3.8	4.4 ± 1.3	2.7 ± 1.2	2.0 ± 1.4	3.3 ± 2.0	6.2 ± 3.6
Species Richness	23.2 ± 4.7	35.8 ± 9.0	21.3 ± 9.9	31.5 ± 14.8	34.7 ± 7.8	26.4 ± 5.2
Number of quadrats:	10	4	8	2	17	9

Table 5

Spearman rank correlation coefficients for select soil parameters and species richness for the south-west Ravensthorpe Greenstone Belt. The upper value for each correlation is the correlation coefficient and the lower value represents significance at $p < 0.05$. Bold values represent highly significant correlations at $p < 0.0001$. Where no lower value is reported, the relationship is not significant ($p > 0.05$).

	B	CA	CO	CU	EC	FE	K	MG	MN	N	NA	NI	ORG C	P	pH	S
CA	**0.7773**															
	0															
CO	0.3107	0.4478														
	0.0284	0.0012														
CU	**0.5595**	**0.7093**	**0.6587**													
	0	**0**	**0**													
EC	**0.8376**	**0.7955**	0.3293	0.5106												
	0	**0**	0.0199	0.0002												
FE	-0.6054	-0.5822	-0.0865	-0.5055	-0.4912											
	0	0		0.0002	0.0003											
K	**0.8309**	**0.8861**	0.5096	**0.7661**	**0.7906**	-0.5935										
	0	**0**	0.0002	**0**	**0**	0										
MG	**0.8794**	**0.9054**	0.5244	**0.68**	**0.8802**	-0.5381	**0.9099**									
	0	**0**	0.0001	**0**	**0**	0.0001	**0**									
MN	0.3375	0.5396	**0.7255**	**0.603**	0.3212	-0.1429	**0.5703**	0.49								
	0.0169	0.0001	**0**	**0**	0.0233		**0**	0.0004								
N	**0.6934**	**0.7286**	**0.5657**	**0.6165**	**0.7091**	-0.434	**0.8024**	**0.797**	0.5326							
	0	**0**	**0**	**0**	**0**	0.0018	**0**	**0**	0.0001							
NA	**0.746**	**0.6637**	0.2764	0.4857	**0.848**	-0.5473	**0.7197**	**0.7794**	0.211	**0.6018**						
	0	**0**		0.0004	**0**	0.0001	**0**	**0**		**0**						
NI	**0.5607**	**0.6527**	**0.8295**	**0.6081**	**0.5637**	-0.2243	**0.6695**	**0.7302**	**0.6066**	**0.6898**	0.4873					
	0	**0**	**0**	**0**	**0**		**0**	**0**	**0**	**0**	0.0004					
ORG C	**0.7249**	**0.7209**	0.5052	**0.5896**	**0.7794**	-0.4101	**0.7816**	**0.797**	0.4674	**0.9373**	**0.713**	**0.671**				
	0	**0**	0.0002	**0**	**0**	0.0033	**0**	**0**	0.0007	**0**	**0**	**0**				
P	**0.6843**	**0.5921**	0.4609	0.506	**0.733**	-0.472	**0.7069**	**0.7365**	0.4493	**0.6976**	**0.6187**	0.5237	**0.6846**			
	0	**0**	0.0009	0.0002	**0**	0.0006	**0**	**0**	0.0012	**0**	**0**	0.0001	**0**			
pH	0.7647	0.8919	0.4508	0.5539	0.7478	-0.4869	**0.7819**	**0.8645**	0.5101	**0.6305**	**0.558**	**0.5859**	**0.5755**	**0.6216**		
	0	0	0.0011	0	0	0.0004	**0**	**0**	0.0002	**0**	**0**	**0**	**0**	**0**		
S	0.8193	0.7377	0.3158	0.5775	0.8831	-0.4256	**0.8066**	**0.8332**	0.3824	**0.7618**	**0.6932**	0.5357	**0.8132**	**0.6485**	**0.6243**	
	0	0	0.0259	0	0	0.0022	**0**	**0**	0.0064	**0**	**0**	0.0001	**0**	**0**	**0**	
ZN	0.3131	0.4051	0.4693	0.3444	0.332	-0.068	0.3267	0.4375	0.2766	0.4596	0.3716	0.4787	0.4806	0.2982	0.3539	0.2828
	0.0272	0.0038	0.0007	0.0147	0.0189		0.021	0.0016		0.0009	0.0082	0.0005	0.0005	0.0358	0.0121	0.0469
RICHNESS	**-0.5627**	-0.4451	-0.1737	-0.341	-0.5471	0.3002	**-0.6009**	-0.5443	-0.2562	-0.5733	-0.4453	-0.308	**-0.5492**	-0.4825	-0.4573	-0.5928
	0	0.0013		0.0158	0.0001	0.0345	**0**	0.0001		0	0.0013	0.03	**0**	0.0005	0.0009	0

proportion of bare ground (mean 92.3% ± 3.3 SD) and sparse to moderate leaf litter (29.8% ± 23.2 SD).

Soils ranged from very strongly acidic (pH 4.3) to mildly alkaline (pH 7.8). Mean soil pH was 6.4 ± 1 SD, with an equal number of sites characterised as slightly to moderately acidic (pH 5.6–6.5, 18 sites) or neutral to moderately alkaline (pH 6.6–7.8, 18 sites; Bruce & Rayment 1982). Typical of greenstone belt soils, soil cation concentrations (Ca, K, Mg, Na) were predominantly moderate to high.

Significant intercorrelations occurred between environmental variables (Table 5). Soil pH, electrical conductivity, organic carbon and the elements B, Ca, Cu, K, Mg, N, Na, Ni, P and S were all positively intercorrelated ($p < 0.01$). These strongly intercorrelated soil parameters were negatively correlated with species richness and Fe ($p < 0.05$), except for Ni, which was not significantly correlated with Fe ($p > 0.05$). Species richness was negatively correlated with disturbance and percentage leaf litter ($p < 0.05$) but positively correlated with the abundance of surface coarse fragments ($p < 0.01$). Site physical parameters exhibited fewer significant correlations with any other environmental parameters than the soil chemical characteristics. Bare ground was positively correlated ($p < 0.05$) with the same large group of intercorrelated soil chemical characteristics (soil pH, electrical conductivity, organic carbon, B, Ca, Cu, K, Mg, N, Na, Ni, P and S), but negatively correlated with Fe ($p < 0.05$). Slope and runoff were highly positively correlated ($r_s = 0.78$, $p < 0.0001$).

Kruskal–Wallis one-way analysis of variance revealed significant differences between community groups for the site physical and chemical characteristics. (Table 4). Community types 1 and 3 had significantly higher mean values than community type 2 for many of the soil parameters, including soil pH, electrical conductivity, organic carbon, B, Ca, Cu, K, Na, Ni and P. Community type 1 also had significantly higher mean values of N, P and organic carbon than both community types 5 and 6. Community type 4 had the lowest mean soil pH values, which were significantly different from community type 3. For site physical parameters, there were significant differences of means for altitude (community type 6 found at lower altitudes on average than community type 2), abundance of coarse fragments (community type 5 had higher cover than community type 3) and percentage cover of leaf litter (community type 1 had greater cover than community types 2 and 5; community type 3 greater cover than community type 2).

DISCUSSION

Flora and vegetation communities

The 321 taxa recorded from this survey (313 from within quadrats) represent a markedly lower total than previously recorded in the Ravensthorpe Greenstone Belt. Flora and vegetation surveys on the northern Ravensthorpe Greenstone Belt, encompassing the Ravensthorpe Range, recorded 698 taxa from within and adjacent to 266 quadrats (Kern et al. 2008; Markey et al. 2012). The significant difference in the number of taxa recorded is attributed to the variation in surveying effort. This survey was based on collecting within 50 quadrats and adjacent areas, while the WA Herbarium holds over 1300 records for the broader survey polygon. This is to be expected for an area that corresponds to the eastern region of the Fitzgerald Biosphere Reserve, a UNESCO-recognised hotspot for biodiversity.

Previous surveys of the flora of the Ravensthorpe Greenstone Belt have identified at least 56 taxa of conservation significance, including six declared as rare taxa (Craig et al. 2008; Kern et al. 2008; Markey et al. 2012). This survey of the south-western region of the greenstone belt recorded six priority-listed taxa and no Declared Rare Flora (DRF). All of the priority-listed taxa were known to the Ravensthorpe area. There are five Priority Ecological Communities (all Priority 1) currently recognised in the Ravensthorpe Greenstone Belt (see Markey et al. 2012), all of which are associated with the Ravensthorpe Range and were not recorded during this survey.

Community types described from this study were comparable with the communities recognised by Craig et al. (2008) and Markey et al. (2012). Overlapping suites of species have been observed between surveys and provided guidance as to where the species groups in the south-west portion of the belt fit within the more well-defined vegetation communities of the northern and eastern areas of the Ravensthorpe Greenstone Belt (see Craig et al. 2008; Markey et al. 2012). However, further sampling and meta-analysis of the data are required to clarify the status of the broad community types described from this study. Analogous communities are addressed below, referring primarily to Markey et al. (2012), as their study incorporated the corresponding mapping codes of Craig et al. (2008).

Community type 1 contained a similar suite of understorey species to Markey et al.'s (2012) community type 1 (lowland *Eucalyptus flocktoniae* – *E. phenax* – *E. calycogona* woodlands), particularly the presence of chenopod shrubs; however, the prevalent eucalypt was *E. salmonophloia*, which was described in Markey et al.'s community type 2 (*E. salmonophloia* woodlands on lower hillslopes). Similarly, community type 2 corresponded with two community types from Markey et al. (2012): both lateritic *E. pleurocarpa* mallee shrubland communities, separated by geographic extent (northern vs. southern) and the suite of other eucalypt species present. As community type 2 was only represented by four quadrats, with no additional eucalypt species present and the understorey species from both of Markey et al.'s communities, no further interpretation is possible without additional survey and analysis. Community type 3 was closely matched to that of Markey et al.'s (2012) *Eucalyptus oleosa* subsp. *corvina* tall open mallee shrubland and open forest, with similar species composition including *E. oleosa* subsp. *corvina*, *E.*

extensa, *Acacia glaucoptera* and *Senna artemisioides* subsp. x *artemisioides*.

Community type 4 contained taxa similar to Markey et al.'s (2012) community type 20, defined as *Eucalyptus uncinata*, *E. incrassata*, *E.* spp. mallee shrublands. Markey et al. (2012) noted that *E. pluricaulis* subsp. *pluricaulis* and *E. suggrandis* subsp. *suggrandis* occurred in the south-eastern portion of the Raventhorpe Range and a north-to-south species gradation may exist within this community. The pair of sites from this study may represent the southern gradation of this eucalypt mallee shrubland community. Craig et al. (2008) and Markey et al. (2012) both recognised the *E. flocktoniae* – *E. phenax* mallee woodlands, which are analogous to community type 5 from this study. Community type 6 was similar to Markey et al.'s (2012) community type 21 (*E. desmondensis* – *Allocasuarina* spp. tall mallee shrubland), recorded in the southern part of the range, which would be at similar latitudes as this survey. Both communities shared the dominant taxa of *A. campestris* and *Melaleuca hamata*.

Environmental correlates

The south-west Ravensthorpe Greenstone Belt was characterised primarily by sandy clay loam and sandy loam soils with varying soil pH, typical of the greenstone belts of the Yilgarn Craton. The locations where low soil pH values were recorded are indicative of extensive weathering (Slattery et al. 1999). This has been widely documented in the greenstone belts throughout the Yilgarn Craton (Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008a, 2008b, 2008c; Thompson & Sheehy 2011a, 2011b, 2011c), although it is more pronounced across the greenstone belts further north. Ca concentrations are closely linked with soil pH, with more alkaline values typically associated with lowland communities (Anand et al. 1997), as lower slopes and adjacent areas are enriched by the movement of mobile elements from the upland regions (Ben-Shahar 1990) This pattern holds true in the survey area, the one exception being that the highest Ca concentrations were recorded across varying, but subtle, topographical gradients. This inconsistency in Ca concentrations relative to topographical position may be indicative of different rates of weathering, as studies have shown that sulphides and carbonates are readily leached from the profile (Butt et al. 2000; Anand 2005). The prevalence of high Mg concentrations was expected, given the presence of mafic and ultra-mafic rocks within the greenstone belt.

Variations in vegetation community types were related to environmental parameters, particularly soil chemistry. The link between vegetation patterns and soil parameters has been widely documented on greenstone belts in the Yilgarn Craton (Gibson 2004b; Markey & Dillon 2008a, 2008b, 2009; Meissner & Caruso 2008a, 2008b, 2008c; Meissner et al. 2009a, 2009b, 2009c) and within the Ravensthorpe Greenstone Belt (Craig et al. 2008; Kern et al. 2008; Markey et al. 2012). The strongest correlations were between the community types and the soil chemical characteristics of soil pH, electrical conductivity, and concentrations of organic carbon, B, Ca, K, Mg, Na and P. In particular, communities types 1 and 3 had significantly higher mean values for many of the soil parameters compared with community type 2, which was characterised by low soil pH and cation concentrations (Ca, K, Mg and Na). The strong relationship between soil chemical parameters was likely due to rates of weathering and the variable underlying geology, as weathering of the regolith influences the concentration of trace elements in the soils.

Previous greenstone belt studies have found that distinct vegetation associations are found at particular topographical positions in the landscape (i.e. gradients from crests to colluvial footslopes and outwash; Gibson 2004b; Gibson & Lyons 2001; Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008a, 2008b, 2008c), especially in the Ravensthorpe Range (Markey et al. 2012). However, much of the topographical gradient in the south-west region of the Ravensthorpe Greenstone Belt is subtle. There were significant differences between community types with respect to altitude but not topographical position. Community type 2 was recorded at the highest mean altitude, which was only significantly different from the lowest mean altitude recorded for community type 6. The NMS ordination highlighted that environmental site characteristics were influencing community groups. However, edaphic factors were more strongly correlated with the ordination, suggesting they had a greater influence on community composition than position in the landscape. Higher concentration of some soil cations (e.g. Ca, K, Mg) have been linked with lowland communities (Thompson & Sheehy 2011c). There were some correlations between communities and environmental variables seen in the south-west Ravensthorpe Greenstone Belt, with community types 1 and 3 having the highest values for the soil cations and covering a range of topographical positions, but all in areas with gentle to moderate slopes. Another consideration is the complex underlying geologic sequences and variation in weathering confounding the relationship between topographical position and vegetation communities: our soil samples and site physical parameters do not provide a complete substrate or geologic profile. Stronger associations with topographical position are more likely to occur with significant topographical gradients, as was found in many of the banded ironstone formations (BIF) and associated ranges that constitute significant elements of many greenstone belts in the Yilgarn Craton.

Conservation significance

The poor representation of greenstone belts in the conservation estate has been long recognised (Henry-Hall 1990; Chapman & Newbey 1995a) and highlighted in other greenstone belt flora surveys in the Yilgarn Craton, particularly with respect to the BIF ranges (Gibson 2004a, 2004b; Gibson et al. 1997; Gibson & Lyons 2001; Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008a, 2008b, 2008c; Thompson & Sheehy 2011a, 2011b, 2011c). Recent papers (e.g. Gibson et al. 2010; Gibson et al. 2012) have reiterated the urgency for adequate conservation of greenstone belts, particularly because of the lack of conservation status over the main portion of the Ravensthorpe Range (Markey et al. 2012). These areas are hotspots of plant species richness, with high beta-diversity (species turnover) between greenstone belts within the Yilgarn Craton.

A small portion of the far south-west region of the greenstone belt survey area is held within the conservation estate as part of the Fitzgerald River National Park, and the middle area is part of the Cocanarup Timber Reserve (Fig. 1). Much of the northern portion of the study area is freehold and used for agricultural and pastoral purposes. This study highlights the high species richness and diverse substrates of this region and suggests the need for further systematic survey of the flora in the south-west portion of the Ravensthorpe Greenstone Belt. The scope of this study was limited in scale, as large areas of the belt were recovering from fire. Therefore, further surveying of the area is required, which may provide further detailed description of the diversity and associated communities. This is particularly important, given the continuing mineral interest in the area, with both live and pending mining tenements held over the study area.

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APPENDIX 1

Flora list for the south-west Ravensthorpe Greenstone Belt, including collections made outside of the survey quadrat boundaries. Nomenclature follows Florabase (Western Australian Herbarium 2010). An * indicates a weed taxon.

Aizoaceae
- *Carpobrotus* sp.
- *Disphyma crassifolium*

Amaranthaceae
- *Ptilotus holosericeus*

Apiaceae
- *Daucus glochidiatus*
- *Platysace deflexa*

Apocynaceae
- *Alyxia buxifolia*

Asparagaceae
- **Asparagus asparagoides*
- *Chamaexeros serra*
- *Lomandra collina*
- *Lomandra effusa*
- *Lomandra micrantha* subsp. *teretifolia*
- *Lomandra mucronata*
- *Thysanotus patersonii*

Asteraceae
- *Argentipallium niveum*
- *Asteridea athrixioides*
- *Calotis hispidula*
- *Cassinia arcuata* P2
- *Lagenophora huegelii*
- *Olearia imbricata*
- *Olearia muelleri*
- *Ozothamnus lepidophyllus*
- *Podolepis rugata*
- *Senecio quadridentatus*
- *Vittadinia cervicularis*
- *Vittadinia gracilis*
- *Waitzia acuminata* var. *acuminata*

Boraginaceae
- *Halgania anagalloides* var. Southern (AE Orchard 1609)
- *Halgania andromedifolia*

Casuarinaceae
- *Allocasuarina campestris*
- *Allocasuarina huegeliana*
- *Allocasuarina humilis*
- *Allocasuarina microstachya*

Celastraceae
- *Stackhousia monogyna*

Chenopodiaceae
- *Atriplex semibaccata*
- *Chenopodium desertorum* subsp. *microphyllum*
- *Enchylaena tomentosa* var. *tomentosa*
- *Maireana erioclada*
- *Maireana marginata*
- *Maireana suaedifolia*
- *Rhagodia crassifolia*
- *Rhagodia preissii*
- *Rhagodia preissii* subsp. *preissii*
- *Sclerolaena diacantha*

Convolvulaceae
- *Wilsonia humilis*

Crassulaceae
- *Crassula colorata* var. *colorata*

Cupressaceae
- *Callitris drummondii*

Cyperaceae
- *Gahnia ancistrophylla*
- *Gahnia aristata*
- *Gahnia drummondii*
- *Lepidosperma* aff. *diurnum*
- *Lepidosperma* aff. *fimbriatum*
- *Lepidosperma* aff. *pruinosum*
- *Lepidosperma carphoides*
- *Lepidosperma diurnum*
- *Lepidosperma fimbriatum*
- *Lepidosperma gahnioides*
- *Lepidosperma* sp. A2 Inland Flat (GJ Keighery 7000)
- *Lepidosperma* sp. Bandalup Scabrid (N Evelegh 10798)
- *Lepidosperma* sp. Carracarrup Creek (S Kern, R Jasper, D Brassington LCH 16738)
- *Lepidosperma* sp. Clathrate
- *Lepidosperma* sp. K Boorabbin (KL Wilson 2579)
- *Lepidosperma* sp. Mt Benson
- *Lepidosperma* sp. Mt Chester (S Kern et al. LCH 16596)
- *Lepidosperma* sp. Mt Short (S Kern et al. LCH 17510)
- *Lepidosperma* sp. Ravensthorpe (GF Craig 5188)
- *Lepidosperma* sp. Saltbush Hill (KR Newbey 4118)
- *Lepidosperma* sp. Shoemaker Levy (L Ang & O Davies 10815)
- *Lepidosperma* sp. Tibialate
- *Mesomelaena stygia* subsp. *stygia*
- *Schoenus breviculmis*
- *Schoenus brevisetis*
- *Schoenus racemosus*
- *Schoenus* sp. Cape Riche Cushion (GJ Keighery 9922)
- *Schoenus subflavus* subsp. hispid culms (KR Newbey 8278)
- *Schoenus subflavus* subsp. subflavus
- *Tetraria* sp. Mt Madden (CD Turley 40 BP/897)

Dilleniaceae
- *Hibbertia exasperata*
- *Hibbertia gracilipes*
- *Hibbertia recurvifolia*

Ericaceae
- *Acrotriche cordata*
- *Acrotriche ramiflora*
- *Astroloma epacridis*
- *Astroloma serratifolium*
- *Leucopogon concinnus*
- *Leucopogon cuneifolius*
- *Leucopogon hamulosus*
- *Leucopogon lloydiorum*
- *Leucopogon obtusatus*
- *Leucopogon* sp. Newdegate (M Hislop 3585)
- *Leucopogon tamminensis* var. *australis*
- *Lysinema pentapetalum*
- *Styphelia pulchella*

Euphorbiaceae
- *Beyeria lechenaultii*
- *Stachystemon virgatus*

Fabaceae
- *Acacia acuminata*
- *Acacia bifaria* P3

Acacia binata
Acacia brumalis
Acacia chrysella
Acacia cyclops
Acacia erinacea
Acacia glaucoptera
Acacia gonophylla
Acacia harveyi
Acacia ingrata
Acacia lachnophylla
Acacia microbotrya
Acacia mimica var. *angusta*
Acacia pravifolia
Acacia saligna subsp. *lindleyi*
Acacia sp. narrow phyllode (BR Maslin 7831)
Acacia sulcata var. *planoconvexa*
Acacia sulcata var. *platyphylla*
Acacia tetanophylla
Daviesia anceps
Daviesia benthamii subsp. *benthamii*
Daviesia incrassata subsp. *incrassata*
Daviesia nematophylla
Daviesia pachyphylla
Eutaxia cuneata
Gastrolobium musaceum
Gastrolobium tetragonophyllum
Gompholobium confertum
Mirbelia ramulosa
Pultenaea rotundifolia
Senna artemisioides subsp. *filifolia*
Senna artemisioides subsp. x *artemisioides*
Senna artemisioides subsp. x *artemisioides* x *filifolia*
Senna sp. Pallinup River (JW Green 4847)
Templetonia aculeata
Templetonia battii
Templetonia neglecta
Templetonia retusa

Goodeniaceae
Coopernookia strophiolata
Dampiera angulata subsp. *angulata*
Goodenia affinis
Goodenia concinna
Goodenia laevis subsp. *humifusa*
Goodenia scapigera subsp. *scapigera*
Goodenia tripartita

Haemodoraceae
Conostylis argentea

Haloragaceae
Glischrocaryon aureum
Glischrocaryon flavescens

Hemerocallidaceae
Dianella brevicaulis
Dianella revoluta var. *revoluta*

Lamiaceae
Microcorys glabra
Teucrium sessiliflorum
Westringia dampieri

Lauraceae
Cassytha glabella
Cassytha melantha

Linaceae
Linum marginale

Loganiaceae
Logania stenophylla
Phyllangium divergens

Malvaceae
Alyogyne wrayae
Guichenotia ledifolia
Guichenotia micrantha
Lasiopetalum compactum
Lasiopetalum rosmarinifolium
**Malva parviflora*
Thomasia foliosa

Myrtaceae
Astus tetragonus
Baeckea corynophylla
Baeckea crispiflora
Baeckea preissiana
Beaufortia micrantha var. *micrantha*
Callistemon phoeniceus
Calothamnus quadrifidus subsp. *quadrifidus*
Calytrix aff. *leschenaultii*
Calytrix leschenaultii
Chamelaucium ciliatum
Eucalyptus brachycalyx
Eucalyptus calycogona subsp. *calycogona*
Eucalyptus cernua
Eucalyptus densa subsp. *improcera*
Eucalyptus desmondensis P4
Eucalyptus extensa
Eucalyptus flocktoniae subsp. *flocktoniae*
Eucalyptus leptocalyx
Eucalyptus myriadena
Eucalyptus myriadena subsp. *myriadena*
Eucalyptus occidentalis
Eucalyptus oleosa subsp. *corvina*
Eucalyptus perangusta
Eucalyptus phaenophylla subsp. *phaenophylla*
Eucalyptus phenax subsp. *phenax*
Eucalyptus pleurocarpa
Eucalyptus pluricaulis subsp. *pluricaulis*
Eucalyptus proxima
Eucalyptus redunca
Eucalyptus salmonophloia
Eucalyptus suggrandis subsp. *suggrandis*
Eucalyptus uncinata
Kunzea affinis
Kunzea cincinnata
Kunzea jucunda
Kunzea micrantha
Kunzea preissiana
Kunzea strigosa
Leptospermum erubescens
Leptospermum nitens
Leptospermum oligandrum
Leptospermum spinescens
Melaleuca acuminata subsp. *acuminata*
Melaleuca cliffortioides
Melaleuca cucullata
Melaleuca glaberrima
Melaleuca hamata
Melaleuca hamulosa
Melaleuca lateriflora subsp. *lateriflora*
Melaleuca penicula P4
Melaleuca pentagona var. *pentagona*
Melaleuca pomphostoma
Melaleuca rigidifolia

Appendix 1 (cont.)

Melaleuca scalena
Melaleuca sparsiflora
Melaleuca torquata
Melaleuca uncinata
Melaleuca undulata
Melaleuca villosisepala
Rinzia communis
Verticordia acerosa var. *preissii*
Verticordia chrysantha

Olacaceae
Olax benthamiana

Orchidaceae
Pterostylis aff. *spathulata*
Pterostylis platypus ms

Oxalidaceae
Oxalis perennans

Phyllanthaceae
Phyllanthus calycinus

Pittosporaceae
Billardiera coriacea
Cheiranthera brevifolia
Cheiranthera filifolia
Marianthus bicolor
Marianthus microphyllus

Plantaginaceae
Plantago hispida

Poaceae
Amphipogon turbinatus
Austrodanthonia setacea
Austrostipa acrociliata
Austrostipa elegantissima
Austrostipa hemipogon
Austrostipa pycnostachya
Austrostipa sp. Carlingup Road (S Kern & R Jasper LCH18459) P1
Austrostipa sp. Ravensthorpe Range (A Markey & J Allen 6261) P1
Austrostipa trichophylla
Austrostipa variabilis
**Ehrharta longiflora*
Neurachne alopecuroidea
**Pentaschistis airoides* subsp. *airoides*
Spartochloa scirpoidea

Polygalaceae
Comesperma integerrimum
Comesperma polygaloides
Comesperma scoparium

Polygonaceae
Muehlenbeckia adpressa

Portulacaceae
Calandrinia eremaea s.l.

Primulaceae
**Lysimachia arvensis*

Proteaceae
Banksia cirsioides
Banksia nivea subsp. *nivea*
Grevillea concinna subsp. *lemanniana*
Grevillea dolichopoda
Grevillea huegelii
Grevillea oligantha
Grevillea patentiloba subsp. *patentiloba*
Grevillea pectinata
Grevillea rigida subsp. *distans*
Grevillea teretifolia
Hakea commutata
Hakea incrassata
Hakea laurina
Hakea lissocarpha
Hakea marginata
Hakea nitida
Hakea pandanicarpa subsp. *crassifolia*
Hakea verrucosa
Isopogon sp. Fitzgerald River (DB Foreman 813)
Persoonia striata
Petrophile seminuda
Synaphea interioris

Restionaceae
Desmocladus asper
Lepidobolus preissianus

Rhamnaceae
Cryptandra nutans
Cryptandra pungens
Pomaderris paniculosa subsp. *paniculosa*
Siegfriedia darwinioides
Spyridium cordatum
Trymalium elachophyllum

Rutaceae
Boronia inconspicua
Boronia inornata subsp. *inornata*
Boronia scabra subsp. *scabra*
Boronia subsessilis
Microcybe albiflora
Philotheca gardneri subsp. *gardneri*

Santalaceae
Choretrum glomeratum var. *glomeratum*
Exocarpos aphyllus
Exocarpos sparteus
Santalum acuminatum
Santalum spicatum

Sapindaceae
Dodonaea concinna
Dodonaea pinifolia
Dodonaea ptarmicaefolia

Scrophulariaceae
Eremophila decipiens subsp. *decipiens*
Glycocystis beckeri

Stylidiaceae
Stylidium albomontis
Stylidium involucratum
Stylidium piliferum

Thymelaeaceae
Pimelea brachyphylla
Pimelea erecta

Violaceae
Hybanthus floribundus subsp. *adpressus*