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Flora and vegetation of the greenstone ranges of the Yilgarn Craton: Credo Station

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ABSTRACT

Credo Station is a former pastoral lease located within the Coolgardie IBRA (Interim Biogeographical Regionalisation for Australia) Bioregion in the Great Western Woodlands in the goldfields of Western Australia. This paper describes the flora and vegetation on the greenstone hills within the station and their relationships with environmental variables. A total of 186 taxa were recorded from the survey, including three priority flora and 62 annuals. Six communities were identified on the greenstones hills. We found a gradual change in the dominant taxa across the biogeographic boundary from *Eucalyptus*-dominated in the south to *Casuarina*-dominated woodlands in the north.

Keywords: floristic communities, Goldfields, greenstone, ranges, Yilgarn

INTRODUCTION

Previous surveys of greenstone ranges in south-west Western Australia have highlighted the significance of the greenstones within the South-Western Interzone as areas of high plant endemism (Gibson et al. 2012). The recent boom in exploration and mining has lead to a potential conflict between resource development and the 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. The objective of this study was to describe the flora and plant communities of the greenstone ranges on Credo Station and their relationships with environmental variables, and to provide baseline information for future management.

Credo Station is a former pastoral station situated approximately 70 km north-west of Coolgardie in the Great Western Woodlands, the world largest example of intact Mediterranean woodlands (Judd et al. 2008). Credo Station was run as a pastoral lease from 1906–07 until it was purchased by the (then) Department of Environment and Conservation in 2007 for the purpose of conservation and is currently listed as Unallocated Crown Land. The significant reserves of Rowles Lagoon Conservation Park and Clear and Muddy Lakes Nature Reserve are also within the station. These are the only freshwater wetland areas within the region reserved for nature conservation.

Gold was initially discovered in 1892 by Bayley and Ford near the current location of Coolgardie (Blatchford 1899). More gold discoveries were progressively made in the surrounding areas, with the next major find at the base of a low hill, Mount Charlotte, by Hannan, Flanagan and Shea (Quartermaine & McGowan 1979). There are many abandoned mines within Credo Station and several associated abandoned towns, with Callion and Davyhurst being the largest, both established in the early years of the gold rush in the 1890s and 1900s (Murray et al. 2011).

With the advent of goldmining in the district, the woodlands were heavily cut for mining, building timber and firewood (Beard 1978). The region is within the woodlines of Kalgoorlie, and the majority of the woodlands within Credo Station have been cutover in the past, with those areas surrounding abandoned mines especially degraded.

Geology

Credo Station spans two geological terranes, Barlee and Kalgoorlie, which are separated by the Ida Fault. The terranes occur within the larger part of the Yilgarn Craton, one of the largest intact parts of the ancient earth crust (Anand & Butt 2010). The greenstone belts within the terranes are composed of older Archaean basalts and komatiite units (types of volcanic rock), with the sequence topped by felsic volcanic and sedimentary rocks. On Credo Station, the basalts are mainly extrusive and mafic (high in magnesium and iron content) rocks that include amphibolites. Towards the eastern part of the station, ultramafic rocks are more common in the form of komatiite (low in silicon, potassium and aluminium, but high to extremely high magnesium content) and have undergone low- to medium-grade metamorphism (Wyche & Witt 1994). Tertiary weathering is evidenced by the presence of laterite units in the north-western part of Credo Station, where it forms a hard ferricrete crust from less than 1 m to a depth of about 60 m near Callion (Wyche

& Witt 1994). The greenstone belts on Credo Station are expressed as gentle, rolling hills and low rocky ridges, generally less than 50 m above the surrounding plains.

Climate

The climate of the region is classified as semi-desert mediterranean and characterised by hot, dry summers and mild winters (Beard 1990). Statistics are provided for the weather station at Kalgoorlie (c. 70 km south-east of Credo homestead). Significant rainfall events can occur in winter and summer, with the two highest mean monthly rainfalls on record occurring in February and June (31.3 mm and 28.4 mm respectively). The mean annual rainfall at Kalgoorlie is 265.2 mm, with large variation (151.2 mm, 1st decile; 412 mm, 9th decile; recorded 1939–2013). The highest maximum temperatures occur during summer, with January the hottest month (mean maximum temperature 33.7 °C and a mean of 3.7 days above 40 °C). Winters are mild, with the lowest mean maximum temperature of 16.7 °C recorded in July. Temperatures rarely fall below 0 °C in winter, with a mean minimum of 5 °C in July.

Vegetation

Credo Station lies within the Coolgardie IBRA (Interim Biogeographical Regionalisation for Australia) Bioregion (Department of Sustainability, Environment, Water, Population and Communities 2012), which occurs within the South-Western Interzone, a transitional rainfall and vegetation zone between the Southwest and Eremaean Botanical Regions. Credo Station covers approximately 202,000 ha with many different habitat types, including salmon gum (*Eucalyptus salmonophloia*) woodlands, banded ironstone ridges, granite inselbergs, mulga (*Acacia aneura*) woodlands and chenopod shrublands (Gibson & Langley 2012).

The vegetation of the greenstone hills on Credo Station has not been described in great detail. According to Beard (1978), the Credo Station greenstone hills lie within the Kununnuling System and are described broadly as medium woodland; salmon gum and goldfields blackbutt (*Eucalyptus lesouefii*). They have also similarly been described by Newbey & Hnatiuk (1985) as *Eucalyptus clelandii* low woodland on the shallow calcareous earths on the low stony ridges and *Eucalyptus salmonophloia* woodland and *Eucalyptus salubris* low woodland on the deep calcareous earths on the colluvial flats.

METHODS

The methods used in this survey follow the standard procedures used in previous vegetation surveys of other ironstone and greenstone ranges in Western Australia (e.g. Markey & Dillon 2008; Meissner & Caruso 2008). Fifty 20 × 20 m quadrats were established on the stony crests and slopes of the greenstone ranges of Credo Station during the spring of August and September 2011 (Fig. 1). Quadrats were located to cover the broader geographical and geomorphological variation found within the study area. The quadrats were placed stratigraphically 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 GPSMAP 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, height and cover were recorded for dominant taxa in each stratum (tallest, mid and lower). The qualitative data were used to describe the plant communities following McDonald et al. (1990). Nomenclature follows Western Australian Herbarium (1998–).

Twenty soil samples were collected from four evenly spaced locations on five parallel transects, separated by 5 m, across the quadrat. The upper 10 cm of the soil profile within each quadrat was sampled. The samples were bulked and the <2 mm fraction was 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 carbon, total nitrogen and pH were determined using the methods described in Meissner and Wright (2010).

Quadrats were classified on the basis of similarity in species composition, using perennial species only and excluding singletons. This was done to remove any temporal variations in the abundance of annuals that may confound comparisons with other greenstone and banded ironstone ranges (Markey & Dillon 2008; Meissner & Caruso 2008). Species were classified into species groups according to their occurrence within the same quadrats. The quadrat and species' classifications were undertaken using the Bray–Curtis coefficient followed by hierarchical clustering (using group-average linking), using PRIMER v6 software (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). Community group circumscription closely followed SIMPROF results. Indicator species for community groups were determined following De Cáceres et al. (2010) using 'indicspecies' in the R language (De Cáceres & Legendre 2009).

Following the classification, the quadrats were 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).

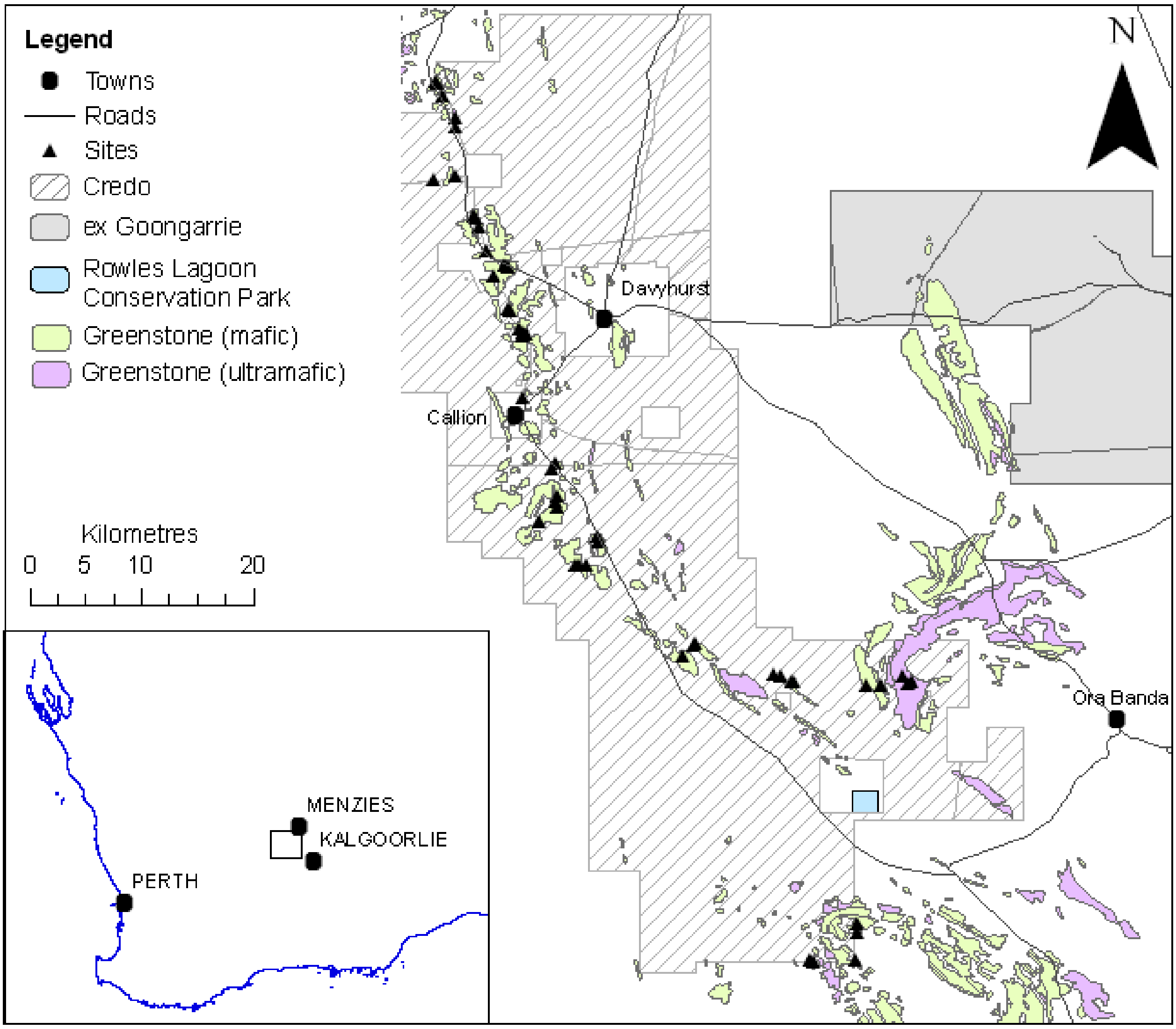

Figure 1. Location of the 50 quadrats (▲) established on the greenstone ranges on Credo Station (hashed areas) within the Coolgardie IBRA Bioregion. The Archaean mafic and ultramafic geology are shown in green and purple respectively.

To determine the environmental variables that best explained the community pattern, the BEST analysis using the 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, sodium and nickel 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 environmental variables were tried and the five best variables selected. The normalised environmental variables were then fitted to the MDS ordination and Pearson rank correlation values ($r > 0.6$) calculated to determine linear correlations between the variables and the vegetation communities.

RESULTS

Flora

A total of 186 taxa (species, subspecies and varieties) were recorded from the survey. The most speciose families were Asteraceae (15 taxa), Fabaceae (20), Chenopodiaceae (15) and Scrophulariaceae (15). The most common genera were *Eremophila* (15 taxa), *Eucalyptus* (10), *Acacia* (11) and *Ptilotus* (7). A total of 62 annuals and three introduced taxa were recorded (Appendix 1).

Priority flora

Three Priority Flora, as defined by Smith (2012), were collected during the survey:

- *Gnephosis intonsa* (shaggy Gnephosis) is a prostrate herb in the Asteraceae and is listed as Priority 1 . This species is known only from Western Australia and commonly occurs on red loam clays and is often associated with greenstone. It was found at a single site within the survey area.

- *Menkea draboides*, listed as Priority 3, is a prostrate herb found only in Western Australia. The species may be widespread but poorly collected, with collections from northern Murchison to southern Coolgardie IBRA Bioregions.
- *Austrostipa blackii*, listed as Priority 3, is a grass with a disjunct distribution with populations in Western Australia and eastern Australia. This species was collected at one site from red brown sandy loam soils.

Plant communities

Six communities were determined from the cluster analysis (Table 1; Fig. 2). The first division in the dendrogram separated the vegetation occurring on laterised or ironstone geology (communities 5 and 6) from the vegetation on the more common basalt geology (communities 1 to 4). The first four communities demonstrate chaining within the dendrogram, indicating a gradational shift in species composition within the communities.

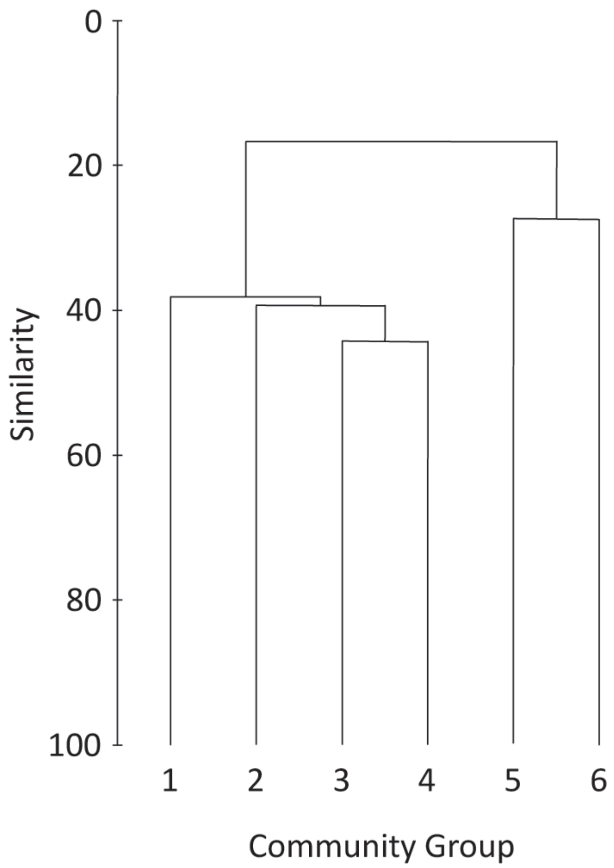

Figure 2. Dendogram of the classification of the 50 quadrats established on Credo Station into six community groups.

Community 1 was characterised by open woodlands (1–10% cover) to open forest (30–70% cover) of *Eucalyptus oleosa* subsp. *oleosa*, *Eucalyptus clelandii* or *Eucalyptus dundasii*, over open (10–30% cover) to sparse shrublands (1–10% cover) of *Eremophila* sp. Mt Jackson (GJ Keighery 4372) and *Senna artemisioides* subsp. *filifolia*, over low sparse shrublands (1–10% cover) of *Ptilotus obovatus*, *Acacia erinacea* and *Olearia muelleri* or isolated forb (<1% cover) of *Zygophyllum ovatum*. Quadrats characterised in this group (n = 5) were in the northern part of Credo Station, generally occurring on gentle or lower slopes of basalt hills. The species richness was 9.8 ± 0.8 SE taxa per quadrat. There were no indicator species found exclusively for this community; however, *Senna artemisioides* subsp. *filifolia*, *Austrostipa nitida* and *Eriochiton sclerolaenoides* were all indicator species for communities 1 to 4 (Table 1).

Community 2 was characterised by open woodlands of either *Eucalyptus griffithsii* or *Eucalyptus celastroides* subsp. *celastroides*, over sparse shrublands of *Eremophila* sp. Mt Jackson (GJ Keighery 4372) and other *Eremophila* spp. (*E. interstans* subsp. *interstans* or *Eremophila scoparia*), over low sparse shrubland of *O. muelleri*. Quadrats containing this community type (n = 2) were located on gentle slopes of basalt. The species richness was 12.5 ± 0.5 SE taxa per quadrat with three indicator species: *Eremophila interstans* subsp. *interstans*, *Exocarpos aphyllus* and *Eremophila scoparia* (Table 1).

Community 3 was characterised by open to sparse woodlands of *Casuarina pauper* or *Eucalyptus griffithsii*, over shrubland (30–70% cover) to open shrublands (1–10% cover) of *Dodonaea lobulata*, *Eremophila oldfieldii* subsp. *angustifolia*, *Senna artemisioides* subsp. *filifolia* and *Scaevola spinescens*, over open to sparse low shrublands of *Ptilotus obovatus*. Quadrats containing this community type (n = 12) were located on the crest and slopes of the basalt hills in the northern part of Credo Station. There was one indicator species, *Enchylaena tomentosa* (Table 1). Species richness was 16.8 ± 0.8 SE taxa per quadrat.

Community 4 was characterised as open forests to open woodlands of *Eucalyptus* spp. (*E. clelandii*, *E. celastroides* subsp. *celastroides*, *E. griffithsii*) and the occasional *Casuarina pauper*, over shrublands to sparse shrublands of *Eremophila* spp. (*E. oldfieldii* subsp. *angustifolia*, *E. interstans* subsp. *interstans* and *E. scoparia*), *Senna artemisioides* subsp. *filifolia* and *Dodonaea lobulata*, over open to sparse low shrublands of *Acacia erinacea*, *Olearia muelleri* and *Ptilotus obovatus* and isolated forb of *Zygophyllum ovatum*. Quadrats containing this community type (n = 24) were located in the southern part of Credo Station on the slopes and crests of the basalt hills. There were no indicator species confined to this community. Species richness was 17.6 ± 0.7 SE taxa per quadrat.

Community 5 was characterised by open forest to open woodland of several dominant taxa (*Acacia burkittii*, *Allocasuarina eriochlamys* subsp. *eriochlamys*, *Grevillea oligomera*, *Eucalyptus oleosa* subsp. *oleosa*) over shrublands to open shrublands of *Philotheca brucei* subsp. *brucei*, *Prostanthera grylloana* and *Dodonaea microzyga*

Table 1

Sorted two-way table of six community types determined from the classification of 50 quadrats established on Credo Station. Species groups were derived from the species classification. Taxa shaded black within a community are indicator species determined by 'indicspecies' (De Cáceres & Legendre 2009; $p < 0.05$).

		Community Group					
	Species	1	2	3	4	5	6
Group a	*Olearia humilis*						
	Philotheca brucei subsp. *brucei*						
	Dodonaea microzyga var. *acrolobata*						
	Allocasuarina eriochlamys subsp. *eriochlamys*						
	Grevillea oligomera						
	Eremophila clarkei						
	Prostanthera grylloana						
	Amphipogon caricinus						
	Eucalyptus oleosa subsp. *oleosa*						
Group b	*Prostanthera althoferi* subsp. *althoferi*						
	Cheilanthes sieberi subsp. sieberi						
	Rhyncharrhena linearis						
Group c	*Thysanotus manglesianus*						
	Acacia ramulosa var. *ramulosa*						
	Eremophila latrobei subsp. *latrobei*						
	Brachychiton gregorii						
	Sida sp. dark green fruits (S. van Leeuwen 2260)						
	Allocasuarina dielsiana						
	Senna cardiosperma						
	Rhagodia drummondii						
	Acacia oswaldii						
	Eremophila alternifolia						
Group d	*Eucalyptus dundasii*						
Group e	*Acacia hemiteles*						
	Grevillea acuaria						
Group f	*Austrostipa platychaeta*						
	Sclerolaena fusiformis						
	Hybanthus floribundus subsp. *curvifolius*						
	Santalum spicatum						
Group g	*Eremophila parvifolia* subsp. *auricampa*						
	Atriplex vesicaria						
	Eremophila interstans subsp. *interstans*						
	Eucalyptus celastroides subsp. *celastroides*						
	Eremophila pustulata						
	Eremophila oppositifolia subsp. *angustifolia*						
	Eucalyptus clelandii						
	Austrostipa eremophila						
	Rytidosperma caespitosum						
	Solanum lasiophyllum						
	Austrostipa scabra						
	Chenopodium curvispicatum						
	Exocarpos aphyllus						
	Eremophila glabra subsp. *glabra*						
	Eremophila scoparia						
	Eremophila sp. Mt Jackson (G.J. Keighery 4372)						
	Sclerolaena diacantha						
	Austrostipa elegantissima						
	Acacia tetragonophylla						
	Eremophila oldfieldii subsp. *angustifolia*						
	Casuarina pauper						
	Austrostipa nitida						
	Olearia muelleri						
	Dodonaea lobulata						
	Scaevola spinescens						
	Ptilotus obovatus						
	Senna artemisioides subsp. *filifolia*						
	Eriochiton sclerolaenoides						
	Maireana trichoptera						
	Atriplex nummularia subsp. *spathulata*						
	Acacia erinacea						
	Maireana georgei						
	Acacia burkittii						
	Eucalyptus griffithsii						
	Maireana sedifolia						
	Sida spodochroma						
	Enchylaena tomentosa						
	Marsdenia australis						
Group h	*Eremophila decipiens* subsp. *decipiens*						
	Pittosporum angustifolium						
	Alyxia buxifolia						
	Solanum nummularium						

subsp. *acroblata*. Indicator species were *Eremophila clarkei*, *Grevillea oligomera*, *Prostanthera grylloana*, *Allocasuarina eriochlamys* subsp. *eriochlamys* and *Dodonaea microzyga* var. *acroblata* (Table 1). Quadrats with this community type (n = 5) were located on laterised basalt within the greenstone hills. This community had the lowest species richness of 9.5 ± 2.5 SE taxa per quadrat.

Community 6 was characterised as either open tall shrubland or woodland of *Acacia burkittii* or *Allocasuarina dielsiana*, over open to sparse shrublands of *Philotheca brucei* subsp. *brucei*, *Prostanthera althoferi* subsp. *althoferi*, over sparse to isolated forbland or grassland of *Ptilotus helipteroides* and *Aristida contorta*. Quadrats of this community type (n = 2) were located on ironstone geology. The species richness was 14.5 ± 0.5 SE, with a single indicator species, *Cheilanthes sieberi* subsp. *sieberi* (Table 1). In addition to individual species indicators, there were two indicator species, *Philotheca brucei* subsp. *brucei* and *Acacia burkittii,* common to both communities 5 and 6.

Environmental correlates

The two dimensional MDS (stress = 0.18; Figure 3) shows the separation of most of the communities determined from the classification (Fig. 2). Communities 5 and 6, occurring on ironstone and laterite substrates, are clearly distinct from the other communities. Community 1, the northern woodlands on lower or simple slopes, shows greater variability than the main communities of 3 and 4.

As communities 2 and 6 consisted of only two quadrats each, these communities were not analysed in the univariate post-hoc analysis. The nonparametric analysis of variance on the remaining four communities found that of the twenty soil parameters, Org C, pH, P, K, Mg, Al, B, Ca, Cd, Co, Cu, Mn, Na, S and Zn were significantly different between the four communities (Table 2), while of the 13 site attributes, latitude and morphology type were significantly different (Table 3). Community 5, on the laterite substrate, was the least fertile, apart from the significantly higher soil concentration of Al (Table 2). This community had more acidic soil and had lower conductivity. Communities 1, 3 and 4 were generally similar in terms of soil chemical properties but significantly differed in location within Credo, with communities 1 and 3 occurring in the northern part of Credo Station, mostly north of the abandoned mine of Callion. Community 1 also had a greater area of bare ground when compared with communities 3 and 4.

The BEST analysis indicated that the best correlation was obtained with only two environmental variables: pH

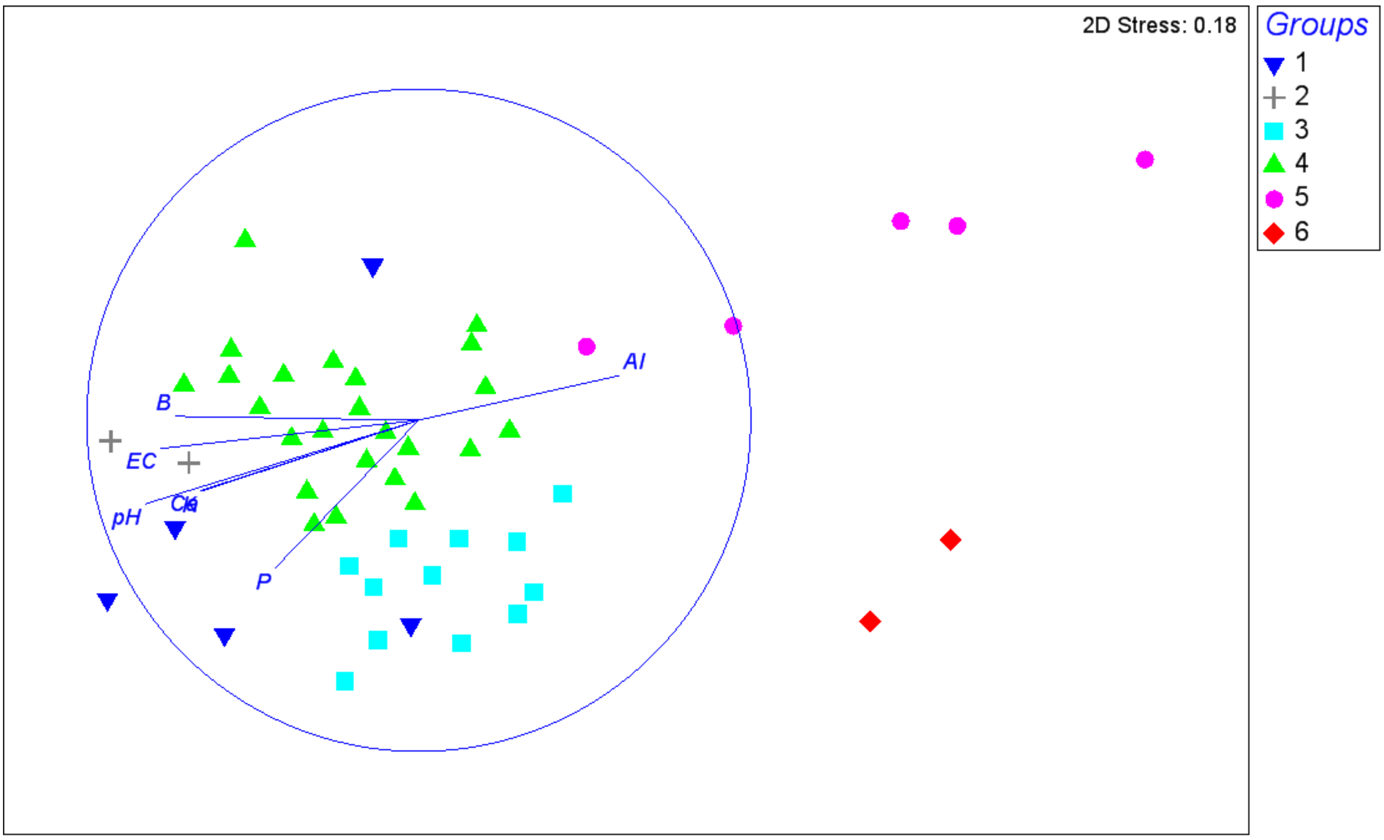

Figure 3. Two dimensional ordination of the 50 quadrats established on Credo Station. The six communities, as defined by the classification, are shown with the seven environmental variables correlated with the MDS using Pearson rank correlation (r > 0.6). The lines represent the seven environmental variables, a longer line and the direction indicates, respectively, a higher correlation and a higher value for the variable.

Table 2

Mean values for soil attributes, measured in mg.kg^{-1} except pH, EC (mS/m), organic carbon (%) and total N (%), by plant community type. Differences between ranked values tested using Kruskal–Wallis nonparametric analysis of variance and differences between communities determined using Dunn's post-hoc comparison. Standard error in parentheses. Significant differences between community types at $p < 0.05$ are indicated by superscript a and b (n = number of quadrats).

	Community 1	Community 2	Community 3	Community 4	Community 5	Community 6	P-value
n	5	2	12	24	5	2	
EC	12.4 (0.7)	10.0 (1.0)	10.8 (0.5)	12.5 (1.6)	5.2 (2.2)	3.0 (0.0)	0.069
Org C	2.07 (0.25)^{a}	1.54 (0.55)	1.17 (0.06)^{b}	1.39 (0.07)^{ab}	1.28 (0.15)^{ab}	0.75 (0.09)	0.0094
pH	7.9 (0.0)^{b}	8.1 (0.1)	7.8 (0.1)^{b}	7.7 (0.1)^{b}	5.6 (0.4)^{a}	5.5 (0.2)	0.0039
Total N	0.1244 (0.01779)	0.1115 (0.0385)	0.0941 (0.0066)	0.0978 (0.0052)	0.0722 (0.0079)	0.057 (0.015)\	0.0796
P	15.2 (3.3) b^{c}	13.0 (2.0)	13.4 (1.4)^{b}	8.4 (0.7)^{ac}	5.0 (0.8)^{a}	3.0 (0.0)	0.0002
K	294.0 (13.3)^{b}	240.0 (130.0)	275.8 (12.2)^{b}	276.7 (12.6)^{b}	115.6 (18.2)^{a}	160.0 (30.0)	0.0036
Mg	496.0 (67.9)^{ab}	675.0 (35.0)	408.3 (46.6)^{b}	632.5 (62.0)^{a}	89.0 (21.0)^{b}	215.0 (75.0)	0.0001
Al	400.0 (72.5)^{b}	220.5 (195.5)	501.7 (57.1)^{b}	517.9 (33.6)^{b}	868.0 (28.9)^{a}	785.0 (135.0)	0.0047
B	2.9 (0.4)^{b}	2.2 (1.2)	1.4 (0.2)^{ab}	1.7 (0.2)^{b}	0.3 (0.1)^{a}	0.3 (0.1)	0.0004
Ca	7500^{b}	7500	6300 (643.3)^{b}	5604 (486)^{b}	854 (229)^{a}	965 (235)	0.0003
Cd	0.01 (0.003)	0.005 (0)	0.019 (0.003)	0.0138 (0.002)	0.006 (0.001)	0.015 (0.005)	0.0303
Co	1.04 (0.31)	0.61 (0.13)	1.65 (0.16)	1.83 (0.21)	0.76 (0.26)	3.10 (0.8)	0.0269
Cu	3.70 (0.67)^{ab}	2.55 (1.35)	4.30 (0.42)^{b}	3.75 (0.33)^{b}	1.76 (0.44)^{a}	5.15 (1.85)	0.0164
Fe	39.4 (3.8)	48.0 (2.0)	43.8 (4.6)	54.3 (3.7)	50.2 (7.2)	52.5 (7.5)	0.1133
Mn	70.2 (20.6)	42.5 (8.5)	95.6 (7.2)	76.6 (6.7)	55.4 (13.8)	123.5 (46.5)	0.0457
Mo	0.005 (0)	0.005 (0)	0.005 (0)	0.0110 (0.002)	0.005 (0)	0.005 (0)	0.0617
Na	43.4 (6.5)^{ab}	41.0 (15.0)	39.3 (2.9)^{ab}	68.4 (19.1)^{a}	21.2 (3.5)^{b}	37.0 (1.0)	0.0157
Ni	0.96 (0.22)^{ab}	2.20 (1.10)	1.58 (0.46)^{ab}	3.90 (1.16)^{a}	1.00 (0.53)^{b}	0.90 (0.30)	0.0077
S	22.8 (3.7)^{a}	13.5 (3.5)	13.5 (1.9)^{ab}	12.0 (1.0)^{b}	10.2 (0.7)^{b}	7.5 (2.5)	0.0285
Zn	1.56 (0.13)^{ab}	0.80 (0.20)	1.96 (0.21)^{a}	1.21 (0.10)^{b}	0.90 (0.10)^{b}	0.90 (0.00)	0.001

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); land form (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 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). Differences between ranks tested using Kruskal–Wallis nonparametric analysis of variance. Standard error in parentheses (n = number of quadrats).

	Community 1	Community 2	Community 3	Community 4	Community 5	Community 6	P-value
n	5	2	12	24	5	2	
Latitude	-29.97 (0.04)	-30.26 (0.07)	-30.00 (0.04)	-30.32 (0.03)	-30.14 (0.05)	-30.04 (0.15)	<0.0001
Aspect	5.4 (1.0)	4.0 (1.0)	5.2 (0.9)	4.8 (0.5)	6.0 (1.4)	5.5 (0.5)	0.8277
Slope	1.9 (0.3)	2.0 (1.0)	1.4 (0.3)	1.7 (0.2)	0.7 (0.3)	2.5 (0.5)	0.1041
Morph	2.4 (0.4)	2.5 (0.5)	1.7 (0.3)	2.0 (0.2)	1.0 (0.0)	1.5 (0.5)	0.0454
Landform	1.8 (0.2)	2.0 (0.0)	1.6 (0.2)	1.6 (0.1)	1.0 (0.0)	1.5 (0.5)	0.0654
CFAbund	4.4 (0.4)	3.5 (0.5)	3.8 (0.2)	4.2 (0.2)	4.8 (0.4)	4.5 (0.5)	0.2476
CFMax	3.2 (0.2)	3.0 (0.0)	3.8 (0.2)	3.5 (0.2)	3.0 (0.0)	3.5 (0.5)	0.1574
ROAbund	0.0 (0.0)	0.0 (0.0)	0.2 (0.1)	0.2 (0.1)	0.0 (0.0)	1.0 (0.0)	0.5994
Soil	2.0 (0.0)	2.5 (0.5)	2.2 (0.2)	2.2 (0.1)	1.8 (0.2)	1.5 (0.5)	0.3616
Bare ground	4.0 (0.0)	3.5 (0.5)	3.3 (3.5)	3.5 (0.1)	2.8 (0.2)	3.5 (0.5)	0.0101
Leaf	3.2 (0.4)	2.0 (0.0)	1.8 (0.2)	2.3 (0.2)	2.0 (0.4)	1.5 (0.5)	0.0552

and B ($r = 0.642$). Six of the 31 environmental variables correlated with the MDS ($r > 0.6$; Fig. 3). Al was positively correlated with community 5, while B, conductivity, pH, Ca, K and P were negatively correlated with community 5 but positively with community 1, with communities 3 and 4 intermediate.

DISCUSSION

Flora

The flora on the greenstone ranges contains approximately 37% of the known flora recorded on Credo Station. The number of plant taxa recorded on the greenstones in this survey (186 taxa) was consistent with a concurrent survey of Kangaroo Hills and timber reserves south of Coolgardie, where 162 taxa were recorded (Meissner & Coppen 2013a). Similar families were recorded from Kangaroo Hills and Credo Station, with a similar number (albeit slight differences) in the dominant genera of *Eucalyptus* and *Acacia*. The dominant families of Asteraceae, Fabaceae, Chenopodiaceae and Myrtaceae are also consistent with other surveys in the eastern goldfields (Newbey & Hnatiuk 1985; Keighery et al. 1992).

Few priority taxa and no endemic taxa were recorded from the survey. The Credo Range is some distance from the South Western Australian Floristic Region (SWAFR) boundary (Hopper & Gioia 2004) and is consistent with the patterns found on more inland banded ironstone ranges, where species richness and the number of endemics decreased with increasing aridity (Gibson et al. 2012). Gibson et al. (2012) established that several ironstone ranges along this boundary were hotspots of endemism and may have acted as refugia during climatic oscillations in the geologic past. Such endemism is not restricted to ironstone, but also occurs on other greenstone ranges along this boundary, such as Ravensthorpe Range and the Warriedar Fold Belt (Craig et al. 2008; Meissner & Coppen 2013b). The lack of endemism at Credo may be due to the low relief of the basalt hills on Credo Station providing little habitat diversity for endemism to evolve. Additionally, the historical timber felling on Credo Station may have resulted in a poorer understorey, as Beard (1978) noted more open woodlands in areas recovering from clearfelling and commented that historical photographs of mining settlements showed the landscape was heavily cleared of all vegetation.

Plant communities

Credo Station traverses a major biogeographic boundary between the Coolgardie and Murchison IBRA Bioregions. This is illustrated by the change in dominant taxa in the tallest stratum from *Eucalyptus* (predominantly *Eucalyptus clelandii*, *E. celastroides* and *E. griffithsii*) in the woodlands of community 4 in the southern parts of Credo Station to *Casuarina pauper* in the woodlands of community 3 in the north. The soils of these two communities had similar soil fertility and chemistry, thus suggesting that climate is the main factor in the species turnover. Beard (1978) also noted the gradual shift in floristics with declining rainfall heading northward, specifically changes in the dominant *Eucalyptus*, such as the replacement of *E. torquata* from the greenstone ridges around Coolgardie with *Acacia* and *Allocasuarina* thickets further north. In addition, Keighery et al. (1992) noted the gradual change of *Eucalyptus* woodlands in the south to open low woodland of *Casuarina cristata* (syn. *C. pauper*) over low shrubs of *Maireana* in the north.

The soils of the greenstones were typically calcareous with some evidence of calcrete deposits of pedogenic origin on the surface. Soil pH was generally neutral to slightly alkaline, while in contrast the soils of the laterite and ironstone communities were acidic. These communities both had low soil fertility, which is consistent with other surveys that have sampled soils on highly weathered geologies (e.g. Meissner & Wright 2010). The more mobile elements are easily transported from the site, resulting in nutrient-poor soils (Britt et al. 2001).

Conservation

The greenstone communities described in this paper are well represented throughout Credo Station, which is currently Unallocated Crown Land proposed for conservation, after previously being managed as a pastoral lease since the early 20th century. The greenstone hills were not subjected to the same grazing pressures as the surrounding low-lying communities, as shown by the presence of very few weeds on the ranges. In contrast, the ranges have all been impacted by mining, primarily through the exploitation of the eucalypt woodlands for timber. While disturbance is evident in many areas, there is no baseline data for monitoring the recovery of the vegetation from grazing or clearfelling on the greenstone ranges.

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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.

Beard JS (1978) *The Vegetation of the Kalgoorlie Area Western Australia, Map and Explanatory Memoir 1:250,000 Series*. 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* **3**.

Britt AF, Smith RE, Gray DJ (2001) Element mobilities and the Australian regolith: a mineral exploration perspective. *Marine and 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.

Craig GF, Hickman EJ, McQuoid N, Newell J, Rick AM, Sandiford EM (2008) *Vegetation of the Ravensthorpe Range, Western Australia: Mt Short to Kundip, 1:10,000 scale.* Department of Environment and Conservation and South Coast Natural Resource Management Inc., Albany, Western Australia.

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, 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, Langley MA (2012) 'Vascular flora of Credo Station and adjacent reserves'. Unpublished report to the Bush Blitz Program, Australian Biological Resources Study.

Hopper SD, Gioia P (2004) The southwest Australian floristic region: evolution and conservation of a global hot spot of biodiversity. *Annual Review of Ecology and Systematics* **35**, 623–650.

Keighery GJ, Milewski AV, Hnatiuk RJ (1992) Vegetation and flora. In *The Biological Survey of the Eastern Goldfields of Western Australia Part 8. Kurnalpi–Kalgoorlie Study Area.* (eds NL McKenzie, NJ Hall). *Records of the Western Australian Museum* Supplement **41**, 18–36.

Judd S, Watson JEM, Watson AWT (2008) Diversity of a semi-arid, intact Mediterranean ecosystem in southwest Australia. *Web Ecology* **8,** 84–93.

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.

McDonald RC, Isbell RF, Speight JG, Walker J, Hopkins MS (1990) *Australian Soil and Land Survey: Field Hhandbook*, 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 (2013a) Flora and vegetation of greenstone ranges of the Yilgarn Craton: Kangaroo Hills and other timber reserves. *Conservation Science Western Australia* **8**, in press.

Meissner R, Coppen R (2013b) Flora and vegetation of greenstone ranges of the Yilgarn Craton: Warriedar Fold Belt. *Conservation Science Western Australia* **8**, in press.

Meissner R, Wright J (2010) Flora and vegetation of banded iron formations on the Yilgarn Craton: south Illaara Greenstone Belt. *Conservation Science Western Australia* 7, 605–616.

Murray I, Bianchi P, Bloomfield M, Bridge C (2011) *West Australian Gold Towns and Settlements Volume 1.* Hesperian Press, Carlisle, WA.

Newbey KR, Hnatiuk RJ (1985) Vegetation and flora. In *The Biological Survey of the Eastern Goldfields of Western Australia Part 3. Jackson–Kalgoorlie Study Area. Records of the Western Australian Museum* Supplement **23**, 11–38.

Quartermaine MK, McGowan E (1979) A historical account of the development of mining in Western Australia. In *Mining in Western Australia* (ed RT Prider), pp. 1–23. University of Western Australia Press, Nedlands WA.

Smith, M. (2012) 'Declared Rare and Priority Flora List for Western Australia'. Department of Environment and Conservation, Kensington.

Western Australian Herbarium (1998–). FloraBase—the Western Australian Flora. Department of Environment and Conservation. Available at http://florabase.dec.wa.gov.au [accessed 1 July 2012].

Wyche S, Witt WK (1994) *Geology of the Davyhurst 1:100,000 Sheet. Explanatory Notes.* Geological Survey of Western Australia, Perth.

APPENDIX 1

Flora list for the greenstone ranges on Credo Station, including all taxa from the sampling quadrats and adjacent areas.

Amaranthaceae
- *Ptilotus aervoides*
- *Ptilotus carlsonii*
- *Ptilotus exaltatus*
- *Ptilotus exaltatus* var. *villosus*
- *Ptilotus helipteroides*
- *Ptilotus holosericeus*
- *Ptilotus obovatus*

Apiaceae
- *Daucus glochidiatus*

Apocynaceae
- *Alyxia buxifolia*
- *Marsdenia australis*
- *Rhyncharrhena linearis*

Araliaceae
- *Trachymene cyanopetala*
- *Trachymene ornata*

Asparagaceae
- *Thysanotus manglesianus*
- *Thysanotus speckii*

Asteraceae
- *Actinobole uliginosum*
- *Asteridea athrixioides*
- *Brachyscome ciliaris*
- *Calotis hispidula*
- *Cephalipterum drummondii*
- *Chthonocephalus pseudevax*
- *Gnephosis arachnoidea*
- *Gnephosis intonsa* P1
- *Isoetopsis graminifolia*
- *Lawrencella rosea*
- *Lemooria burkittii*
- *Leucochrysum fitzgibbonii*
- *Millotia myosotidifolia*
- *Myriocephalus pygmaeus*
- *Olearia humilis*
- *Olearia muelleri*
- *Olearia pimeleoides*
- *Podolepis capillaris*
- *Rhodanthe laevis*
- *Rhodanthe oppositifolia* subsp. *oppositifolia*
- *Schoenia cassiniana*
- *Streptoglossa liatroides*
- *Triptilodiscus pygmaeus*
- *Vittadinia eremaea*
- *Waitzia acuminata* var. *acuminata*

Brassicaceae
- *Arabidella chrysodema*
- *Menkea australis*
- *Menkea draboides* P3
- *Menkea sphaerocarpa*
- *Stenopetalum filifolium*

Campanulaceae
- *Wahlenbergia gracilenta*

Casuarinaceae
- *Allocasuarina dielsiana*
- *Allocasuarina eriochlamys* subsp. *eriochlamys*
- *Casuarina pauper*

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

Centrolepidaceae
- *Centrolepis cephaloformis*

Chenopodiaceae
- *Atriplex nummularia* subsp. *spathulata*
- *Atriplex vesicaria*
- *Chenopodium curvispicatum*
- *Enchylaena tomentosa*
- *Eriochiton sclerolaenoides*
- *Maireana georgei*
- *Maireana marginata*
- *Maireana sedifolia*
- *Maireana trichoptera*
- *Rhagodia drummondii*
- *Salsola australis*
- *Sclerolaena diacantha*
- *Sclerolaena drummondii*
- *Sclerolaena fusiformis*
- *Sclerolaena obliquicuspis*

Crassulaceae
- *Crassula colorata* var. *acuminata*
- *Crassula colorata* var. *colorata*
- *Crassula tetramera*

Cyperaceae
- *Schoenus nanus*

Droseraceae
- *Drosera macrantha* subsp. *macrantha*

Euphorbiaceae
- *Euphorbia drummondii* subsp. *drummondii*

Fabaceae
- *Acacia andrewsii*
- *Acacia burkittii*
- *Acacia caesaneura*
- *Acacia erinacea*
- *Acacia hemiteles*
- *Acacia ligulata*
- *Acacia oswaldii*
- *Acacia quadrimarginea*
- *Acacia ramulosa* var. *ramulosa*
- *Acacia tetragonophylla*
- *Acacia xerophila* var. *xerophila*
- *Dillwynia* sp. Coolgardie (VE Sands 637.3. 1)
- *Medicago minima*
- *Mirbelia microphylla*
- *Senna artemisioides* subsp. *filifolia*
- *Senna artemisioides* subsp. x *artemisioides*
- *Senna cardiosperma*
- *Senna glutinosa* subsp. *chatelainiana* x *charlesiana*
- *Senna stowardii*
- *Swainsona canescens*

Geraniaceae
- *Erodium aureum*
- *Erodium cygnorum*

Goodeniaceae
- *Brunonia australis*
- *Goodenia mimuloides*
- *Goodenia occidentalis*
- *Scaevola spinescens*
- *Velleia hispida*
- *Velleia rosea*

Haloragaceae
- *Haloragis trigonocarpa*

Lamiaceae
Prostanthera althoferi subsp. *althoferi*
Prostanthera althoferi/campbellii intergrade
Prostanthera grylloana

Loganiaceae
Phyllangium sulcatum

Loranthaceae
Amyema miquelii

Malvaceae
Abutilon cryptopetalum
Brachychiton gregorii
Keraudrenia velutina
Lawrencia diffusa
Sida calyxhymenia
Sida ectogama
Sida sp. dark green fruits (S van Leeuwen 2260)
Sida spodochroma

Myrtaceae
Eucalyptus celastroides subsp. *celastroides*
Eucalyptus clelandii
Eucalyptus dundasii
Eucalyptus griffithsii
Eucalyptus oleosa subsp. *oleosa*
Eucalyptus ravida
Eucalyptus salmonophloia
Eucalyptus transcontinentalis
Eucalyptus websteriana subsp. *websteriana*
Eucalyptus yilgarnensis
Melaleuca leiocarpa

Phyllanthaceae
Poranthera leiosperma
Poranthera microphylla

Pittosporaceae
Pittosporum angustifolium

Plantaginaceae
Plantago debilis

Poaceae
Amphipogon caricinus
Aristida contorta
Austrostipa blackii P3
Austrostipa elegantissima
Austrostipa eremophila
Austrostipa nitida
Austrostipa platychaeta
Austrostipa scabra
Austrostipa trichophylla
Enneapogon caerulescens
Eragrostis dielsii
Rostraria pumila
Rytidosperma caespitosum

Polygalaceae
Comesperma integerrimum

Portulacaceae
Calandrinia eremaea
Calandrinia sp. Blackberry (DM Porter 171)

Proteaceae
Grevillea acuaria
Grevillea nematophylla subsp. *nematophylla*
Grevillea oligomera
Hakea recurva subsp. *recurva*

Pteridaceae
Cheilanthes adiantoides
Cheilanthes sieberi subsp. *sieberi*

Rhamnaceae
Cryptandra aridicola

Rutaceae
Phebalium canaliculatum
Phebalium filifolium
Philotheca brucei subsp. *brucei*

Santalaceae
Exocarpos aphyllus
Santalum acuminatum
Santalum spicatum

Sapindaceae
Alectryon oleifolius subsp. *canescens*
Dodonaea lobulata
Dodonaea microzyga var. *acrolobata*
Dodonaea rigida
Dodonaea stenozyga

Scrophulariaceae
Eremophila aff. *ionantha*
Eremophila alternifolia
Eremophila clarkei
Eremophila decipiens subsp. *decipiens*
Eremophila georgei
Eremophila glabra subsp. *glabra*
Eremophila granitica
Eremophila interstans subsp. *interstans*
Eremophila latrobei subsp. *latrobei*
Eremophila oldfieldii subsp. *angustifolia*
Eremophila oppositifolia subsp. *angustifolia*
Eremophila parvifolia subsp. *auricampa*
Eremophila pustulata
Eremophila scoparia
Eremophila sp. Mt Jackson (GJ Keighery 4372)

Solanaceae
Solanum lasiophyllum
Solanum nummularium

Thymelaeaceae
Pimelea microcephala subsp. *microcephala*

Violaceae
Hybanthus floribundus subsp. *curvifolius*

Zygophyllaceae
Zygophyllum eichleri
Zygophyllum ovatum