

# Flora and vegetation of greenstone formations of the Yilgarn Craton: the northern Forrestania Greenstone Belt (Mount Holland area)

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## ABSTRACT

A quadrat-based survey recorded the flora and associated environmental parameters in the northern portion of the Forrestania Greenstone Belt. A total of 312 taxa were identified, representing 47 families and 121 genera. Twelve taxa of conservation significance were recorded, including two declared rare flora (*Banksia sphaerocarpa* subsp. *dolichostyla* and *Eucalyptus steedmanii*). Three new taxa were identified, including two shrubs, a *Hibbertia* sp. and *Labichea rossii* (Priority 1), and a single grass species, *Austrostipa* sp. The two undescribed new taxa are proposed for conservation listing. The 50 quadrats were classified into eight community types. Topography and edaphic factors were influential in delineating community groups. Only five weed taxa were identified, despite the history of mining in the area. Only a small portion of the Forrestania Greenstone Belt belongs to the conservation estate. Based on the survey findings, expansion of the secure tenure is recommended to incorporate a more comprehensive representation of the vegetation and landforms of the greenstone belt.

Keywords: classification, Coolgardie, floristic diversity, mallee, vegetation patterns, ultramafics

## INTRODUCTION

Historically, the greenstone belts of the Yilgarn Craton have been the focus of pastoral settlement, agriculture and mining. Recent studies of flora and vegetation have highlighted their species richness (Gibson 2004a, 2004b; Gibson & Lyons 2001; Gibson et al. 2010; Markey & Dillon 2008a, 2008b, 2009; Meissner & Caruso 2008a, 2008b, 2008c; Meissner et al. 2009a, 2009b, 2009c) and the high beta-diversity of banded ironstone ranges and allied greenstone belts (Gibson et al. 2007; Gibson et al. 2012). This study is a continuation of the survey effort to document the flora, vegetation communities and associated environmental characteristics of the greenstone belts in the Yilgarn Craton.

## STUDY SITE

The northern portion of the Forrestania Greenstone Belt is situated in the south-central portion of the Coolgardie Bioregion, near the boundary of the Mallee Bioregion (Interim Biogeographic Regionalisation of Australia—IBRA; Thackway & Cresswell 1995) and is part of the Roe Botanical District (Beard 1990). The belt is located approximately 90 km south of Southern Cross and c.

85 km north east of Hyden (Fig. 1). The Forrestania Greenstone Belt trends north to south, and is c. 100 km in length and c. 15 km west to east. The focus of this study is the northern 40 km of the belt. The latitudinal and longitudinal boundaries of the study area are roughly 32° 00' S, 32° 25' S and 119° 40' E, 119° 50' E, respectively. The land tenure for this greenstone belt, located in the Yilgarn Shire, is unallocated crown land.

## Land use history

The area around Hyden primarily supports agricultural and pastoral activities (Chin et al. 1984). Mineral interests have focused on the Forrestania Greenstone Belt since gold was discovered in 1915 (Chin et al. 1984). Further exploration of the belt led to the discovery of nickel deposits, which were subsequently mined. At present, Western Areas NL operates nickel mines in the central portion of the belt.

## Climate

The northern Forrestania Greenstone Belt sits in the south-western portion of the Coolgardie Bioregion, which is defined as having a semi-arid climate with hot summers and mild winters (Thackway & Cresswell 1995). Rainfall events occur throughout the year, with a distinct increase in mean monthly rainfall during winter (May–August; Bureau of Meteorology 2010). Average annual rainfall at

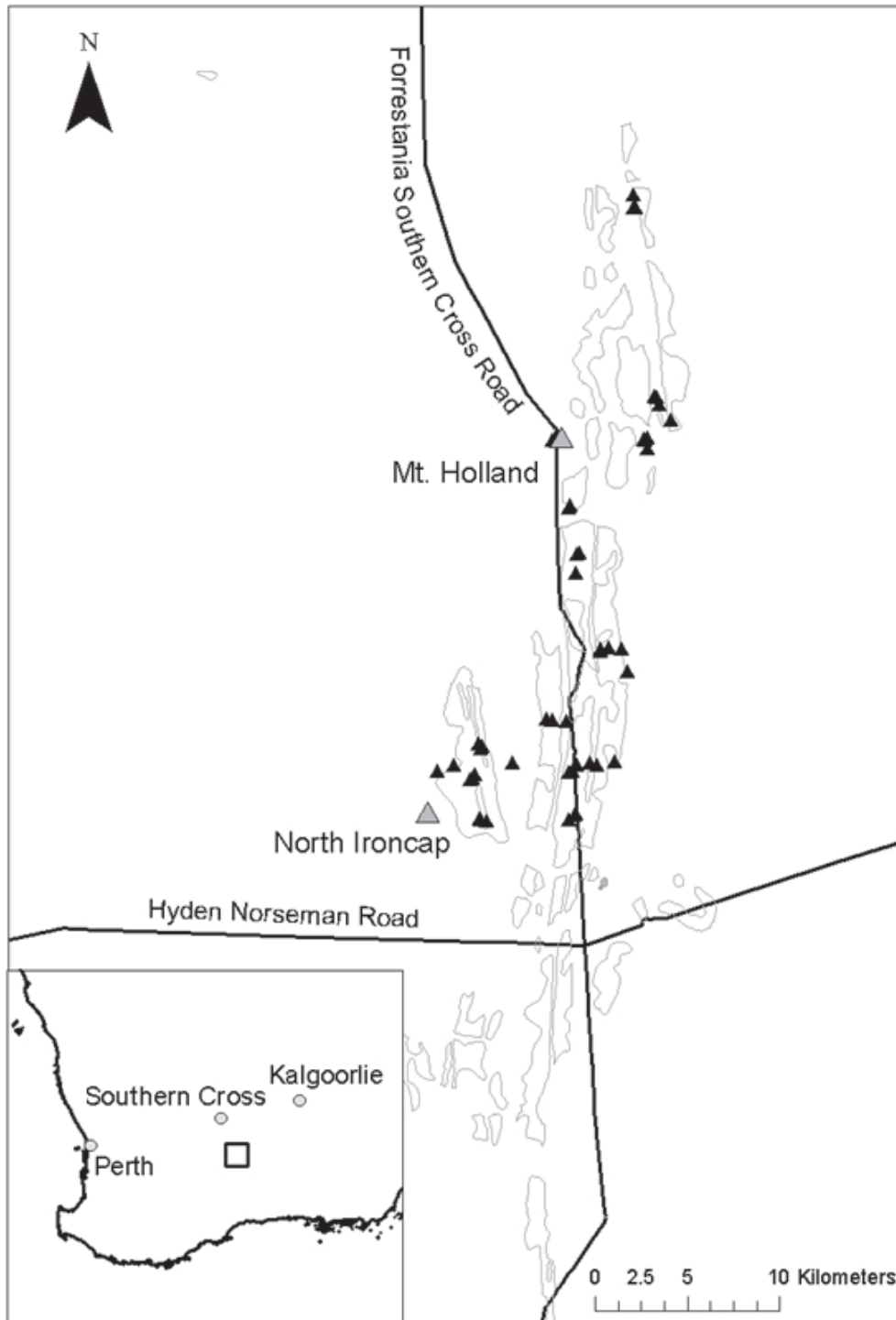


Figure 1. Map showing the location of the northern Forrestania Greenstone Belt survey area, with major landforms and landmarks indicated. The locations of the 50 permanent quadrats are marked by solid triangles (▲).

Hyden (c. 85 km south-west of the study area) is 343.3 mm, based on records from 1928 to 2010, with the months of June and December having the highest (50.6 mm) and lowest (13.7 mm) mean monthly rainfall, respectively. The average annual maximum is 24.8 °C and average annual minimum is 9.8 °C for the Hyden area, based on records from 1970–2009. The highest temperatures occur between December and March, with mean maximum temperatures

exceeding 29 °C. The lowest daily minimum temperatures occur between June and September, where mean minimum temperatures are below 6 °C.

### Geology

The geology of the northern portion of the Forrestania Greenstone Belt has been mapped and described on the

Hyden 1:250,000 geological sheet (Chin et al. 1984). Locally, greenstone refers to the outcropping of ultramafic and mafics associated with Archaean metavolcanic and meta-sedimentary rock sequences, often occurring as ranges positioned within vast areas of granitoid and gneiss (Cole 1992; Cassidy et al. 2006). The Forrestania Greenstone Belt is composed of low undulating hills and ranges, surrounded by sandplains interspersed with exposed duricrust (Chin et al. 1984). The northern portion of the belt sits between 400 and 450 m above sea level, with Mount Holland (477 m) and North Ironcap (454 m) as prominent features in the landscape. The southern boundary of the study area is the salt lake, Lake Cronin, a designated class 'A' nature reserve.

Located in the central Archaean Yilgarn Craton, the greenstone belt is part of a tectonically stable region that occupies a substantial portion of Western Australia and was formed between c. 3000 and 2600 Ma (Myers 1993; Myers & Swagers 1997). The Forrestania Greenstone Belt trends northwards for most of its length, with a north-north-west trend at the southern extent. The belt is a complex series of folds and faults along a northerly syncline (Chin et al. 1984; Griffin 1990). Primary rock composition is fine- and medium-grained mafic amphibolites and metabasalts (Chin et al. 1984). Other dominant regolith types within the study area include banded chert, tremolite and talc schists and Tertiary laterite. A segment of metamorphosed shale and siltstone occurs in the western part of the belt. Adjacent to the greenstone belt are Quaternary colluvial deposits derived from the greenstone and substantial areas of remnant Tertiary sandplain, derived from the laterite. There are banded iron formations (BIF) within the greenstone belt, although not as substantial an element as other parts of the Yilgarn Craton. Within the northern portion of the belt, Mount Holland and North Ironcap are the dominant BIF features in the landscape (Chin et al. 1984). The ultramafic rocks of the greenstone belt are typically of economic interest, with nickel deposits associated with these geologies; however, there is limited surface exposure. Lacustrine and alluvial/aeolian deposits present in the area are generally associated with playa lakes (Chin et al. 1984).

The soils of the Forrestania area are primarily sands over clay (Beard 1990). Beard (1981) described the Forrestania Tableland, which includes the Forrestania Greenstone Belt, as principally brown and grey-brown calcareous earths. Soils from the Bounty gold deposit, in the northern part of the study area, are predominantly yellow-red brown clayey sands, with ferruginous gravel and red to light brown clay loams (Lintern 2004).

## Vegetation

The northern Forrestania Greenstone Belt is characterised by mallee communities, with *Eucalyptus eremophila* a significant element (Beard 1990). Beard (1981) classified the associated vegetation as the Forrestania System, part of the Swan 1:1,000,000 map sheet. The Forrestania System constitutes a mosaic of vegetation communities, primarily driven by the geology of the landscape (Beard

1981). The primary basaltic greenstones support eucalypt woodlands, where the communities of mallee, scrub heath and thicket are generally associated with the granite and quartzite geologies. Beard (1981) mapped the main portion of the Forrestania Greenstone Belt as *Eucalyptus salmonophloia* and *E. longicornis* on greenstone. The northern portion, encompassing the study area, also included *E. eremophila* scrub with pockets of heterogeneous scrub heath. Mount Holland supports a dense thicket of *Allocasuarina campestris* and *Calothamnus quadrifidus* (Beard 1981).

An extensive survey describing the flora and vegetation of the southern portion of the Forrestania Greenstone Belt, including Middle and South Ironcap, Diggers Rock and Hatter Hill, recorded 342 native taxa and three weed species (Gibson 2004a). Four vegetation community types were identified, which were strongly influenced by associated geology and edaphic factors. Vegetation communities included species-rich shrublands and mallee shrublands associated with BIF. Mallee shrublands and *Allocasuarina* thickets on skeletal soils were found in association with massive laterites. Colluvial deposits supported *Eucalyptus urna* – *E. salubris* woodlands with *Melaleuca* sp. understorey, with colluvial flats having species-depauperate mallee communities with *E. calycogona* and emergent *E. salmonophloia* (Gibson 2004a).

With known mineral deposits in the area, a history of mining and the high level of beta-diversity recorded between greenstone belts (Gibson et al. 2012), this study is a timely assessment of an area that has otherwise remained undocumented for plant species richness. This study aimed to record the floristic diversity, describe vegetation patterns and examine environmental variables associated with the northern section of the Forrestania Greenstone Belt.

## METHODS

Between the 22 September and 7 October 2009, fifty 20 × 20 m permanent quadrats were established throughout the northern portion of the Forrestania Greenstone Belt. The quadrat locations were chosen using an environmentally stratified but non-random method because of the extensive mineral exploration and mining-related disturbance in the area. The quadrats represented the topographical, geological and geomorphological variation across the length and breadth of the belt, and captured the associated vegetation communities that characterise the various geologies. The landscape positions of the sites encompassed a broad topological sequence from gentle hill crests to the colluvial deposits. 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). Quadrat locations were selected to represent areas subject to minimal disturbance or modification, although the whole region has been and still is the focus of mineral exploration. Thus sites were avoided where evidence of

disturbance (e.g. clearing, exploration, mining) was obvious.

The quadrats were marked by four steel fence droppers, and their locations recorded by 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 present and as part of a seven-point 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 dominant taxa to each stratum 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 31–70%; 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, which contributed to the overall species list for the survey area. Where sufficient representative plant material was available, it was lodged at the WA Herbarium. Nomenclature follows Florabase (Western Australian Herbarium 2010). For this study, the reference to weed taxa refers to invasive species categorised as alien or introduced to the area and corresponds with the Florabase classification.

Soil chemical attributes were analysed for each quadrat. Soil was collected from 20 regularly-spaced intervals across the quadrat, then bulked and sieved. The <2 mm fraction was analysed by a Inductively Coupled Plasma – Atomic Emission Spectrometer (ICP–AES) for B, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, 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<sub>2</sub> (method S3; Rayment & Higginson 1992). Organic carbon content was determined using a modified Walkley–Black method (method 6A1) and the calculation of total 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 176 perennial taxa occurring at more than a single site, which was consistent with previous greenstone belt studies (Gibson 2004a, 2004b; Gibson et al. 2012). The

dissimilarity between sites 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 relative abundance and compositional change (Legendre & Legendre 1998; Anderson & Robinson 2003), and provides quantitative output for similarity between samples (Faith et al. 1987). Using the Bray–Curtis similarity matrix, the sites were classified based on the flexible unweighted pair-group mean average method (UPGMA,  $\beta = -0.1$ ) using PATN v3.11 (Belbin 1989). The results provided the basis for grouping the taxa into ecological groups. A two-way table was derived from the classification for species grouping and the dendrogram of site grouping. The species–site similarity matrix was then subjected to Non-metric Multi-dimensional Scaling (NMS). An environmental data matrix that included soil chemical properties and site physical characteristics was created, which was then fitted to the NMS ordination using Spearman correlation values in Primer v6. The resulting figure displayed lines of best-fit in the NMS ordination. The continuous environmental variables were normalised prior to fitting the environmental vectors.

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 reported. Where no individual species contribution reached the 10% threshold, taxa constituting 50% cumulative contribution were included. When ties occurred at the 50% level, all taxa in the tie were reported.

Relationships between environmental variables were examined using the non-parametric Spearman rank correlation routine in Statistix 7.1 (Analytical Software, Tallahassee, Florida). The environmental variables were analysed using Kruskal–Wallis non-parametric one-way analysis of variance and post-hoc significance testing of means at  $\alpha = 0.05$  (Sokal & Rolf 1995) for differences between community groupings.

## RESULTS

### Summary information

A total of 305 taxa from 47 families and 121 genera were identified from the permanent quadrats in the northern area of the Forrestania Greenstone Belt (Appendix 1). An additional seven taxa were collected adjacent to the plots. The dominant families represented were Myrtaceae (63 taxa), Fabaceae (55 taxa), Proteaceae (25 taxa), Asteraceae (19 taxa) and Poaceae (14 taxa). The genera with the greatest number of species were *Acacia* (31 species), *Eucalyptus* (23 species), *Melaleuca* (23 species), *Grevillea* (9 species) and *Austrostipa* (8 species). There were five weed species

identified from the survey. Three new taxa were identified during the survey; two were the first collections of the taxa.

Species richness within the quadrats varied from 12 to 38 taxa, with an average richness of  $24.1 \pm 6.4$  (SD) taxa per quadrat. There was a high proportion of singleton specimens collected (94 taxa, including 11 annuals) and 26 annuals were identified during the survey. Fifteen taxa were amalgamated into seven species complexes for analysis. The resulting matrix used in the classification and ordination analyses comprised 176 species  $\times$  50 sites. All annuals, singletons and indeterminate specimens were excluded prior to analysis. The resulting dendrogram (Fig. 2) illustrated a clear separation of survey sites, grouped as floristic communities, and is discussed below.

### Rare and priority taxa

Two taxa classified as Declared Rare Flora (DRF) were collected during the survey (Table 1). Both populations of *Banksia sphaerocarpa* subsp. *dolichostyla* and *Eucalyptus steedmanii* were known in the WA Herbarium census. An additional 22 populations of ten priority taxa were recorded during the survey. Single collections of the annual *Gnephosis intonsa* (P1) and the perennial shrubs *Labichea rossii* (P1), *Acacia kerryana* (P2), *Baeckea* sp. Parker Range (M Hislop & F Hort MH 2968; P3), *Eutaxia nanophylla* (P3) and *Grevillea dissecta* (P4) were made.

Other priority taxa records included two new populations of both *Acacia asepala* (P2) and *Microcorys* sp. Forrestania (P4), and five populations of *Eutaxia acanthoclada* (P3). Seven populations of the perennial herb *Stylidium sejunctum* (P2) were recorded. Prior to this survey, there were 21 records on the WA Herbarium Florabase. We suggest that the priority status of *S. sejunctum* be changed to P3.

### New taxa

Three new taxa were identified during the survey. Single specimens of each taxon were collected. One taxon,

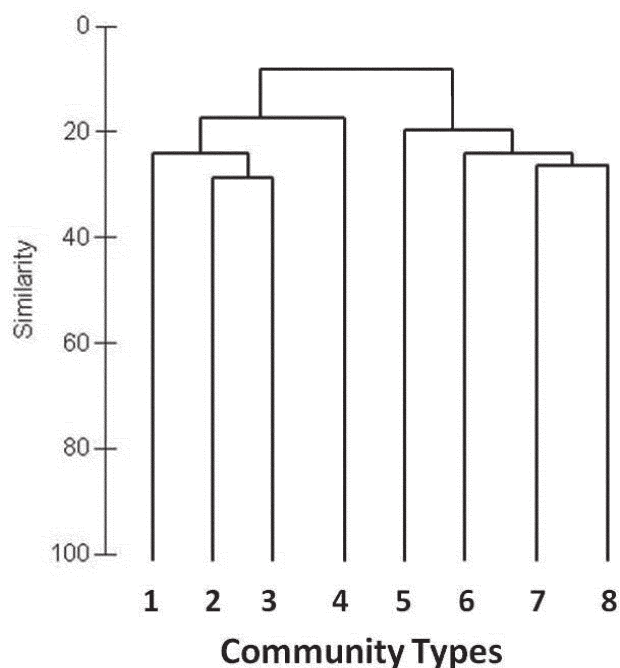


Figure 2. Summary dendrogram of community types for the northern Forrestania Greenstone Belt. The eight community types displayed in the dendrogram were derived from the classification analyses of the 176 taxa from 46 sites; the four sites excluded from the analyses are not displayed.

*Hibbertia croninensis* ms, had previously been collected but was identified as *H. aff. oligantha* (PERTH 03033856).

*Austrostipa* sp. Mount Holland (WA Thompson & J Allen 948; PERTH 07702833) is a perennial tussock grass with narrow, erect culms. The exserted nodes are distinct with dense retrorse hairs and ligules that have ciliate margins. The lemmas have margins inrolled onto the palea and short hairs near the apex (A Williams, pers. comm.). The characteristics of this taxon are unique to *Austrostipa* in Western Australia. Further investigation is required to

Table 1

Priority taxa recorded from the northern Forrestania Greenstone Belt. Bioregion abbreviations: COO = Coolgardie, MUR = Murchison, AW = Avon Wheatbelt, ESP = Esperance Plains, MAL = Mallee, JF = Jarrah Forest.

Family	Taxon	Conservation Status	Bioregion
Proteaceae	<i>Banksia sphaerocarpa</i> var. <i>dolichostyla</i>	R	COO, AW, MAL
Myrtaceae	<i>Eucalyptus steedmanii</i>	R	COO, ESP, MAL
Asteraceae	<i>Gnephosis intonsa</i>	P1	COO, MUR, AW, ESP, MAL
Fabaceae	<i>Labichea rossii</i>	P1	COO
Fabaceae	<i>Acacia asepala</i>	P2	COO, MAL
Fabaceae	<i>Acacia kerryana</i>	P2	COO
Stylidiaceae	<i>Stylidium sejunctum</i>	P2	COO, MAL
Myrtaceae	<i>Baeckea</i> sp. Parker Range (M Hislop & F Hort MH 2968)	P3	COO, AW
Fabaceae	<i>Eutaxia acanthoclada</i>	P3	COO, ESP, MAL
Fabaceae	<i>Eutaxia nanophylla</i>	P3	COO, JF, MAL
Proteaceae	<i>Grevillea dissecta</i>	P4	COO
Lamiaceae	<i>Microcorys</i> sp. Forrestania (V English 2004)	P4	COO, MAL

distinguish whether it is related to *A. setacea*, known from eastern Australia.

*Hibbertia croninensis* ms is a perennial shrub up to 45 cm in height, and is known from two collections in the northern Forrestania Greenstone Belt. The specimen collected during this survey has been lodged at the WA Herbarium (PERTH 08237166). The manuscript name stems from the proximity of the known individuals to Lake Cronin. The species is distinct for the combined characters of stamens on one side of glabrous carpels and short, tuberculate leaves (K Thiele, pers. comm.). It shares affinities to *Hibbertia oligantha*, which has glabrous carpels but longer leaves and a softer appearance. The two known localities do not occur on secure tenure; we propose a conservation status of Priority 1 for this species.

*Labichea rossii* (P1) was described based on the specimen from this survey (PERTH 07702841) and a subsequent collection made following the determination that it was a distinct, undescribed taxon (see Gibson 2011). It is a small sub-shrub to 50 cm in height. The specimen appears to have affinities to *Labichea punctata*, with equal size anthers and unifoliate leaves; however, examination of the WA Herbarium collection found there were no close matches. With regards to distribution, there is a large geographic disparity with *L. punctata*, which is only known at present on the coastal plain and Darling Scarp. *Labichea rossii*, collected to the north of Mount Holland on banded ironstone outcrop, has smaller inflorescences and flowers and it lacks the silvery sericeous hairs on the ovary of *L. punctata* (J Ross, pers. comm.). The specimen was collected from an outcrop of banded ironstone near a mine track. Given the lack of any prior material with similar affinities lodged with the WA Herbarium, and because of its restricted distribution, it has been designated Priority 1.

## Range extensions

A single significant range extension of c. 120 km was recorded during the survey, with a specimen of *Austrostipa* sp. Carlingup Road (S Kern & R Jasper LCH 18459) identified from the Mount Holland area. A minor geographic extension of c. 50 km was recorded for *Acacia pachypoda*, predominantly known from the central Coolgardie Bioregion south of Kalgoorlie. Three taxa were recorded for the first time within the Coolgardie Bioregion; all are widely distributed in other bioregions. *Melaleuca pungens* and *M. platycalyx* are both recorded in the adjacent Avon Wheatbelt and Mallee IBRA Regions. *Cassya aurea* var. *hirta* is primarily known from the Swan and Geraldton Sandplains IBRA Regions, with isolated records in the Mallee and Esperance Sandplains.

## Hybrids/integrades

Three interspecific hybrids were collected during the survey. Two of the hybrids, *Acacia* and *Dodonaea*, were matched with collections vouchered in the WA Herbarium, and the *Persoonia* hybrid is recognised in taxonomic description within Flora of Australia (Weston 1995). Five collections were made of the interspecific hybrid of *A.*

*poliochroa* × *A. merrallii*, which is known to occur in the vicinity of the Forrestania Greenstone Belt. Two subspecies of *D. viscosa* are known to intergrade; this survey identified two specimens of the *D. viscosa* subsp. *angustissima*/subsp. *spathulata* intergrade. A single collection was identified as a hybrid of *P. coriacea* × *P. helix*. This hybrid is a recognised entity, where the two taxa overlap in distribution. The taxonomic description also notes that there is uncertainty relating to the degree of twisting in the leaves and whether that is a natural variation or an indication of hybridization (Weston 1995).

## Floristic communities

Hierarchical clustering separated the taxa into 11 species groups (A–K; Table 2). Species group J contained the most ubiquitous taxa, with representation across all sites. Eight broad community types were defined from a modified SIMPROF output, with distinct separation of community types 1–4 from types 5–8 due to differences in soil pH (Fig. 2). Community types 1–4 had more acidic soils (pH 4.5–6), while types 5–8 had soils that were mildly acidic to more neutral and alkaline (pH 5.7–8). The two-way table highlights the relationship between the species and site associations (Table 2).

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). The environmental vectors overlain on the NMS ordination highlight the influence of edaphic factors on vegetation communities, with all the most highly correlated environmental parameters being soil characteristics. Vectors extending close to the edge of the circle indicate stronger correlation to those communities (Fig. 3). Strong correlations occurred between environmental vectors and community groups (Table 3). Soil chemical parameters, soil pH, electrical conductivity, B, Ca, K, Mg and Na exhibited the greatest intercorrelations ( $r_s \geq 0.8$ ).

Two groups of two quadrats were not incorporated into the formal description of community types due to the low number of representative quadrats. Additional surveys may clarify their status as a specific community group. The first pair, HLND 29 and 30, had red-brown sandy clay loam soils with basalt, ironstone gravel and quartz coarse fragments. Species richness was moderate (24 and 22 taxa, respectively). They had only minimal similarity to community group 4 (20%). The sites were predominantly shrublands. Typical taxa included *Allocasuarina campestris* with *Acacia neurophylla* subsp. *erugata*, *A. steedmanii* subsp. *steedmanii*, *A. sulcata* var. *platyphylla*, *Callitris canescens*, *Cryptandra minutifolia* subsp. *brevistyla*, *Dodonaea viscosa* subsp. *angustissima* – subsp. *spathulata* intergrade, *Gastrolobium melanocarpum*, *Grevillea acuaria*, *Lasiopetalum ferraricollinum*, *Melaleuca hamata*, *Phebalium tuberosum* and the climber *Comesperma volubile*. The second pair of quadrats, HLND 06 and 44, had red-brown sandy clay loam soils with moderate to high abundance of iron-enriched coarse fragments on the surface. Species

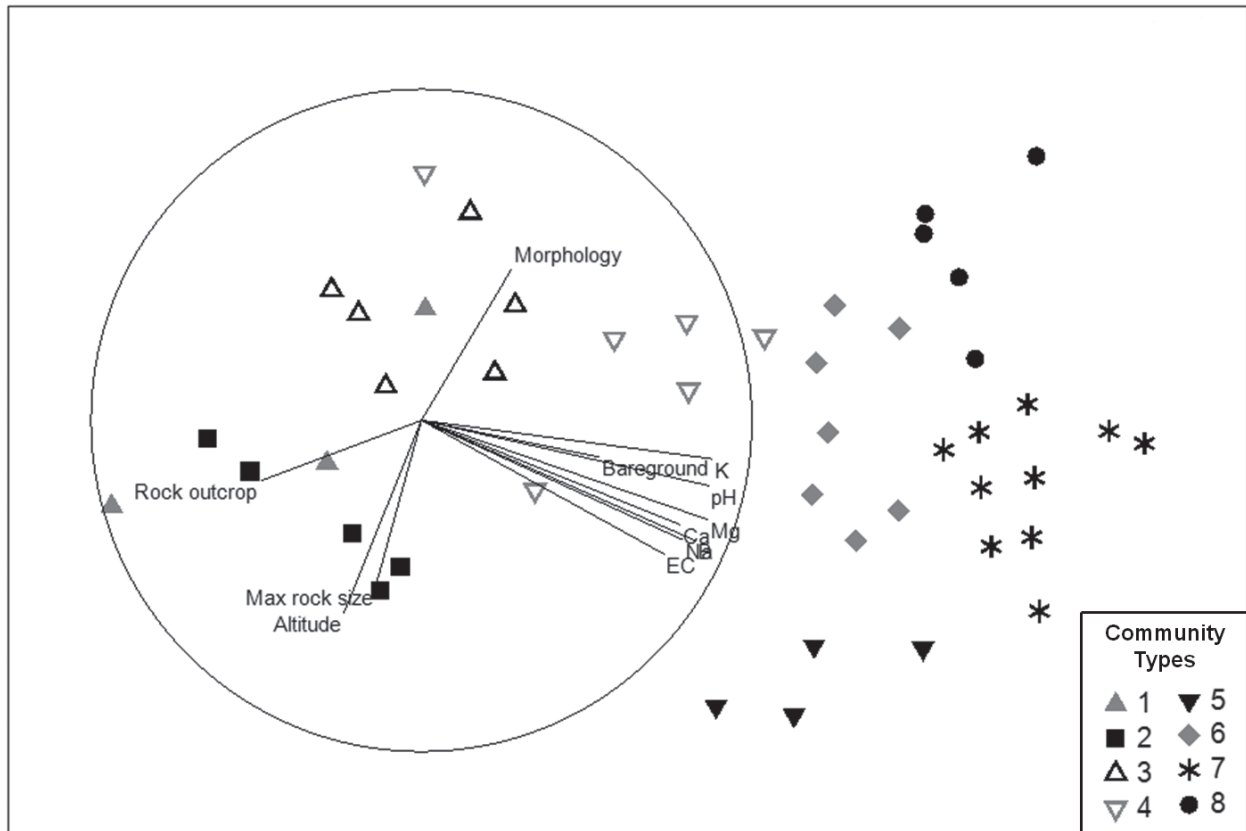


Figure 3. 2D graph of the first two axes of the NMS ordination of survey plots of the northern Forresteria Greenstone Belt (stress = 0.16). Survey plots are separated by community groups and are overlain with environmental vectors, using the lines of best-fit in multi-dimensional space. Vectors extending close to the edge of the circle indicate stronger correlation to those communities. Data were a matrix of 176 perennial species from 46 survey sites; the four sites excluded from analyses are not shown. Seven soil parameters (K, soil pH, Mg, Ca, B, Na and electrical conductivity) had the greatest correlation with community types ( $r_s \geq 0.8$ ). For comparison, the top five site physical characteristic vectors are shown (abundance of rock outcrop, maximum rock size, altitude, bareground and morphology), which were correlated at  $r_s \geq 0.5$ .

richness was relatively high, with 26 and 35 taxa per quadrat, respectively. Common taxa included *M. acuminata* subsp. *acuminata*, *Senna artemisioides* subsp. *filifolia*, *Thysanotus manglesianus*, *Westringia cephalantha* over *Dianella revoluta* var. *divaricata* and *Austrostipa acrocliliata*.

**Community type 1** was identified from predominantly upland basalt/laterite sites with gentle gradients. The community was associated with species groups E, G, I and J, with a complete absence of taxa from species groups A–D and F (Table 2). Species richness was high, ranging from 27 to 37 taxa per quadrat. Dominant taxa were *Allocasuarina acutivalvis* and *Acacia yorkrakinensis* subsp. *acrita* over *Melaleuca calyptroides*, *Thryptomene kochii*, *Hibbertia exasperata* and *Drummondia hassellii*.

Soils were highly acidic (pH 4.5–5.3) sandy loams and sandy clay loams. Concomitantly, Ca concentrations were low, but Fe content was relatively high (Table 3). Coarse rock fragments were variable in abundance, with only minor surface exposure of laterite bedrock detected at a single site.

**Community type 2** occurred on upland sites, and was characterised by granular or banded ironstone coarse fragments and moderate species richness (21–38 taxa per quadrat; mean  $26.2 \pm 6.9$  SD). This community type was associated with species groups E and H, with minor representation in group J (Table 2). There was a complete absence of taxa from groups B, C and G. Structure was generally defined by *Allocasuarina campestris* over *Calothamnus quadrifidus* subsp. *seminudus*, *Hakea subsulcata* and *Melaleuca cordata* over *Stenanthemum stipulosum* and *Stylidium sejunctum*.

Soils were moderately to highly acidic (pH 4.9–5.7) red-brown sandy loams and sandy clay loams. Coarse rock fragments were highly abundant and exposed bedrock of banded ironstone was generally present (Table 3). Leaf litter was variable, from sparse to moderate cover. Soil iron content was moderate to high.

**Community type 3** corresponded to upland laterite and weathered ironstone sites with moderate species richness (26–35 taxa per quadrat; mean  $30.5 \pm 3.3$  SD). The taxa were allied with species groups E, F and J, with an absence of taxa from group D and isolated







**Table 3**

Summary statistics for environmental variables, separated by community type for the northern Forrestania Greenstone Belt. Mean values with standard deviation are listed for community types. Differences were determined using Kruskal–Wallis non-parametric one-way analysis of variance. Significance values are shown by \* ( $p < 0.05 = *$ ;  $p < 0.01 = **$ ;  $p < 0.001 = ***$ ;  $p < 0.0001 = ****$ ) and the inclusion of + indicates no significant difference between mean values. 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 per quadrat.

Soil Parameters	Community Types								
	1	2	3	4	5	6	7	8	
<b>B****</b>	0.13 ± 0.14 a	0.29 ± 0.27 a	0.18 ± 0.18 a	0.21 ± 0.13 a	1.20 ± 0.75 ab	0.81 ± 0.57 ab	2.68 ± 0.73 b	0.78 ± 0.28 ab	
<b>Ca****</b>	206.7 ± 73.7 a	902.0 ± 670.2 ab	670.0 ± 197.7 ab	543.3 ± 141.7 ab	4150.0 ± 1247.7 bc	2060.0 ± 1834.7 abc	5070.0 ± 942.9 c	2060.0 ± 1604.1 abc	
<b>Cd<sup>NS</sup></b>	0.010 ± 0.009	0.006 ± 0.002	0.005 ± 0.00	0.006 ± 0.002	0.005 ± 0.00	0.006 ± 0.002	0.006 ± 0.002	0.006 ± 0.002	
<b>Co****</b>	0.07 ± 0.06 a	0.24 ± 0.09 abc	0.22 ± 0.12 ab	0.42 ± 0.44 abc	1.48 ± 1.04 abc	1.56 ± 0.64 bc	1.21 ± 0.80 abc	1.92 ± 0.28 c	
<b>Cu****</b>	0.50 ± 0.44 ab	0.72 ± 0.44 a	0.97 ± 0.67 a	1.12 ± 0.55 abc	4.10 ± 1.07 abc	3.67 ± 1.75 abc	4.27 ± 1.10 bc	4.90 ± 1.08 c	
<b>EC****</b>	5.0 ± 5.2 ab	4.0 ± 2.0 ab	1.8 ± 0.4 a	2.7 ± 0.5 a	9.8 ± 6.1 ab	8.9 ± 5.9 ab	27.7 ± 20.2 b	6.2 ± 3.8 ab	
<b>Fe*</b>	98.7 ± 28.6 a	75.2 ± 27.1 ab	63.0 ± 17.8 ab	62.5 ± 23.8 ab	53.3 ± 14.8 ab	63.1 ± 13.6 ab	51.4 ± 19.2 b	66.0 ± 8.0 ab	
<b>K****</b>	64.0 ± 16.1 ac	139.6 ± 60.9 ac	83.3 ± 23.7 a	106.0 ± 30.1 ac	237.5 ± 135.3 abc	282.9 ± 124.3 abc	546.0 ± 12.6 b	448.0 ± 65.0 bc	
<b>Mg****</b>	48.3 ± 29.0 a	130.8 ± 82.1 ab	102.0 ± 49.1 a	174.7 ± 99.0 ab	1002.5 ± 195.0 bc	608.6 ± 291.1 abc	1100.0 ± 0.0 c	596.0 ± 139.6 abc	
<b>Mn****</b>	7.1 ± 7.7 a	22.0 ± 18.1 a	13.6 ± 4.7 a	24.8 ± 13.0 ab	49.0 ± 9.0 ab	52.3 ± 25.2 ab	80.2 ± 23.2 b	109.6 ± 44.9 b	
<b>N (total)****</b>	0.033 ± 0.003 a	0.090 ± 0.052 ab	0.051 ± 0.011 a	0.040 ± 0.024 a	0.099 ± 0.014 ab	0.049 ± 0.013 a	0.131 ± 0.036 b	0.066 ± 0.017 ab	
<b>Na****</b>	14.0 ± 20.8 a	16.1 ± 17.0 a	5.3 ± 3.4 a	15.3 ± 7.0 a	122.0 ± 110.2 ab	96.7 ± 111.1 ab	273.9 ± 203.7 b	43.0 ± 25.6 ab	
<b>Ni****</b>	0.17 ± 0.06 a	0.32 ± 0.22 a	0.42 ± 0.31 ab	0.65 ± 0.68 ab	2.53 ± 1.49 ab	2.07 ± 1.86 ab	3.70 ± 3.96 b	2.48 ± 0.78 b	
<b>Organic C (%)***</b>	0.99 ± 0.10 ab	2.01 ± 1.13 ab	1.30 ± 0.26 ab	1.02 ± 0.52 a	1.67 ± 0.21 ab	1.02 ± 0.30 a	2.22 ± 0.54 b	1.16 ± 0.26 ab	
<b>P**</b>	17.3 ± 28.3 ab	2.3 ± 1.6 ab	2.2 ± 0.8 a	2.3 ± 0.5 ab	2.5 ± 0.6 ab	3.1 ± 0.7 ab	6.1 ± 3.1 b	5.2 ± 1.6 ab	
<b>pH****</b>	4.9 ± 0.4 a	5.5 ± 0.3 a	5.5 ± 0.3 a	5.5 ± 0.3 a	7.1 ± 0.8 ab	6.6 ± 0.8 ab	7.7 ± 0.2 b	6.5 ± 0.7 ab	
<b>S**</b>	10.3 ± 6.5 ab	10.2 ± 6.1 ab	4.5 ± 0.8 a	4.5 ± 1.9 a	7.8 ± 6.2 ab	5.9 ± 3.2 a	36.8 ± 27.9 b	5.6 ± 1.5 ab	
<b>Zn<sup>NS</sup></b>	1.3 ± 1.1	1.1 ± 1.0	0.7 ± 0.6	1.1 ± 0.7	0.9 ± 0.3	1.0 ± 0.5	1.4 ± 0.8	1.6 ± 0.8	
<b>Site Physical Parameters</b>									
<b>Altitude (m)***</b>	434.3 ± 13.3 ab	443.6 ± 30.7 a	401.7 ± 4.7 bc	418.2 ± 12.6 abc	422.5 ± 6.5 abc	412.1 ± 12.5 abc	414.6 ± 6.1 abc	395.4 ± 6.2 c	
<b>Bare ground (%)***</b>	86.7 ± 1.2	88.2 ± 2.9	92.3 ± 2.1	89.2 ± 3.0	92.8 ± 5.3	92.4 ± 2.4	94.1 ± 2.6	94.2 ± 1.5	
<b>Abundance-fragments***</b>	3.3 ± 1.5 ab	5.8 ± 0.4 a	5.7 ± 0.5 a	3.3 ± 1.2 ab	5.5 ± 0.6 ab	3.1 ± 1.8 ab	4.5 ± 0.8 ab	2.2 ± 1.3 b	
<b>Leaf litter (%)<sup>NS</sup></b>	34.3 ± 22.9	31.6 ± 16.7	15.2 ± 6.2	32.2 ± 16.4	17.5 ± 14.5	19.7 ± 9.7	12.9 ± 8.9	25.8 ± 17.6	
<b>Topographical position***</b>	2.3 ± 1.2 ab	2.2 ± 0.8 ab	2.2 ± 0.8 a	3.2 ± 0.8 ab	1.8 ± 1.0 a	4.1 ± 0.7 ab	2.5 ± 1.3 ab	4.6 ± 0.5 b	
<b>Outcrop abundance****</b>	0.3 ± 0.6	2.2 ± 1.3	1.3 ± 0.8	0.0 ± 0.0	0.8 ± 1.0	0.0 ± 0.0	0.2 ± 0.6	0.0 ± 0.0	
<b>Runoff*</b>	1.2 ± 0.8 ab	2.3 ± 0.8 a	1.7 ± 0.8 ab	1.6 ± 0.7 ab	1.5 ± 0.6 ab	0.8 ± 0.3 b	1.7 ± 0.8 ab	0.7 ± 0.3 b	
<b>Species Richness</b>	32.0 ± 5.0	26.2 ± 6.9	30.5 ± 3.3	27.5 ± 4.6	16.3 ± 2.9	21.6 ± 3.0	19.8 ± 4.9	21.8 ± 6.4	
<b>Number of quadrats:</b>	3	5	6	6	4	7	10	5	

representation in other groups (Table 2). Vegetation was predominantly moderate in height. Principal species included *Eucalyptus eremophila*, *Acacia castanostegia*, *Baeckea crispiflora*, *Beyeria sulcata*, *Hakea multilinea*, *Melaleuca hamata* and *Stenanthemum stipulosum* over *Phebalium filifolium* and *Platysace maxwellii* over *Lepidosperma* sp. A2 Inland Flat.

Soils were typically strongly to moderately acidic (pH 5.1–6) yellow-brown sandy loams and sandy clay loams. Coarse rock fragments were highly abundant, with some surface exposure of bedrock, both composed principally of laterite and weathered ironstone. Ca concentrations were relatively low, as were other cation concentrations (K, Mg, Na; Table 3).

**Community type 4** encompassed five laterite and basalt sites with gentle slopes and moderate to high species richness (24–35 taxa per quadrat, mean  $27.5 \pm 4.6$  SD). Sites were associated with species groups B, J and K, with minor representation in C, D and I (Table 2). Community structure was *E. flocktoniae* and *Allocasuarina acutivalvis* over *Dodonaea bursariifolia*, *M. acuminata* subsp. *acuminata*, *M. hamata*, *M. lateriflora* subsp. *lateriflora* and *Grevillea acuaria*.

Soils were predominantly light- to red-brown, moderately to strongly acidic (pH 5.1–5.8) sandy loams and sandy clay loams. The abundance of coarse rock fragments, principally laterite and basalt, was variable, with no exposed bedrock recorded at any of the localities. Cation concentrations were predominantly low, with Ca consistently low across quadrats (Table 3).

**Community type 5** was recorded at four upland sites with relatively low species richness (13–20 taxa per quadrat, mean  $16.3 \pm 2.9$  SD). Taxa were principally associated with species group B, with minimal representatives recorded from groups D, E and J (Table 2). Community structure was generally *E. salubris* over *D. stenozyga*, *Trymalium myrtillus* subsp. *myrtillus* and *G. acuaria* with *Thysanotus patersonii*.

The sites were characterised by slightly acidic to mildly alkaline (pH 6.3–8), red-brown clay loams and sandy clay loam soils. Soil cation concentrations were notably high, particularly Ca and Mg (Table 3). The highest concentrations of Ca were concomitantly recorded at the sites with the highest soil pH values. Coarse rock fragments were predominantly basalt and undifferentiated greenstone and high in abundance. The slight presence of exposed bedrock was recorded as basalt.

**Community type 6** was typical of footslopes and pediments with little slope, recorded at seven sites with low to moderate species richness (16–25 taxa per quadrat, mean  $21.6 \pm 3.0$  SD). The strongest species associations were with groups A, B, C and J (Table 2). The vegetation structure was generally *E. calycogona* subsp. *calycogona*, *Exocarpos aphyllus* and *Santalum acuminatum* over *D. stenozyga*, *G. acuaria* over *Acacia crinacea* and *Wilsonia humilis*.

Soils were typically brown to red-brown sandy clay loams with variable acidic to neutral soil pH (5.7–7.6). Coarse rock fragments, primarily composed of undifferentiated greenstone, were variable in abundance,

with no bedrock exposed at any of the sites. Cation concentrations were relatively high, but also variable (Table 3).

**Community type 7** had the most widespread distribution and was identified from 10 sites, which were characterised by the presence of calcrete in the substrate. The sites had relatively low species richness (12–28 taxa per quadrat, mean  $19.8 \pm 4.9$  SD). Taxa were predominantly associated with species groups A and B, with minor representation in group J (Table 2). There was a complete absence of taxa from groups C and E to I. Community structure was dominated by *Eucalyptus extensa* over *A. merrallii*, *Daviesia articulata* and *Dodonaea stenozyga* with *W. humilis*.

Soils were generally brown to red-brown and neutral to moderately alkaline (pH 7.3–8), and of varying texture, including loam, clay loam and sandy clay loam. Soil cation concentrations were high; the highest Ca concentrations were associated with the highest soil pH values (Table 3). Other notable soil characteristics included relatively high electrical conductivity, organic carbon and S values for the groups. Coarse rock fragments, generally basalt, undifferentiated greenstone and mixed metasediments were abundant.

**Community type 8** was identified from five sites characterised by plains with little or no gradient. Species richness was variable, ranging from 17–32 taxa per quadrat (mean  $21.8 \pm 6.4$  SD). Species groups A and B were highly associated with these sites, with minimal representation from group J (Table 2). No taxa were present from groups E to G and I. Vegetation structure was dominated by *E. salmonophloia* over *Santalum acuminatum* over *A. merrallii*, *Daviesia scoparia*, *Eremophila ionantha* and *Olearia muelleri* with *Austrostipa elegantissima*.

Soils were typically red-brown sandy clay loams, mildly acidic to mildly alkaline (pH 6.1–7.7). No exposed bedrock was recorded, and surface rock fragments were generally moderate in abundance and size (large pebbles, up to 60mm). Cation concentrations were moderate to high, particularly K and Mg (Table 3).

## Environmental variables

The northern Forresteria Greenstone Belt was characterised by subtle topographic variation and gentle slopes, except for the isolated banded ironstone hills (Mount Holland and North Ironcap). Elevation ranged from 386–478 m. Variation in topographical position is highlighted on the NMS ordination in the form of topographical position (i.e. crest to outwash) and altitude (Fig. 3). Soils collected during the survey were skeletal to shallow in depth and typically light brown to red-brown sandy loams and sandy clay loams. Seven sites were classified as loam (1), clay loam sand (1) or clay loam (5). Coarse rock fragments were abundant at most survey sites, with an average cover category of 4.24, which corresponds to 20–50% cover (Table 3). The majority of sites lacked surface expression of bedrock, with only 14 sites having outcrops of bedrock, which were predominantly banded

ironstone. The sites typically had a high proportion of bare ground (mean  $91.8\% \pm 3.5$  SD) and sparse cover of leaf litter (mean  $22.4\% \pm 14.8$  SD; Table 3).

Soils were typically mildly acidic with a mean pH of  $6.32 \pm 1$  SD, ranging from 4.5 to 8 (Table 3). Twelve sites had alkaline pH values  $>7.5$  and 11 sites were characterised as having strongly acidic soils (pH  $<5.5$ ). Those sites with higher pH values (pH  $>7.4$ ) had high soil Ca concentrations (Ca  $>2800$  mg kg<sup>-1</sup>) and Mg levels (Mg  $>490$  mg kg<sup>-1</sup>). Levels of the most abundant exchangeable cations (Ca, K, Mg, Na) varied; the majority of sites were characterised by low Na concentrations and moderate to high K and Mg concentrations. There was an approximately even division between sites that had low or moderate calcium levels.

Strong intercorrelations existed between soil properties, as determined by the Spearman's rank correlation coefficient ( $r_s$ ). Soil pH, electrical conductivity, organic carbon and the soil nutrients B, Ca, Co, Cu, K, Mg, Mn, N, Na and P were all positively intercorrelated ( $p < 0.05$ ), except for organic carbon and Co ( $p > 0.05$ ), and all were negatively correlated with species richness ( $p < 0.05$ ). All of the aforementioned soil chemical properties, except organic carbon, were positively correlated with disturbance and bare ground and negatively correlated with rock outcrop abundance ( $p < 0.05$ ). Iron was negatively correlated with the soil chemical properties B, Ca, Cu, K, Mg, Mn and soil pH ( $p < 0.05$ ), but positively correlated with species richness ( $p < 0.05$ ). S and Zn were positively correlated with B, K, Mg, Mn and P ( $p < 0.05$ ), but not with one another ( $p > 0.05$ ). The strongest relationship between soil chemical properties was between Mg and Na ( $r_s = 0.92$ ,  $p < 0.0001$ ). For the site physical parameters, there were fewer significant relationships. Altitude, runoff and slope were positively intercorrelated ( $p < 0.05$ ), with the relationship between slope and runoff the strongest of any of the site physical characteristics ( $r_s = 0.67$ ,  $p < 0.0001$ ). There were no significant relationships between species richness and site physical parameters, except for the amount of bare ground ( $r_s = -0.37$ ,  $p < 0.01$ ).

Mean values for the environmental parameters were compared between the community types (Table 3). The Kruskal–Wallis statistics provided evidence that there were significant differences between types for environmental parameters. Community types 1–4 tended to have lower values for soil chemical properties than types 5–8; this was particularly evident with cation concentrations and soil pH. Mean values for community types 1 and 3 were significantly lower than those of community type 7 for Ca, K, Mg, Na and soil pH. Community types 2 and 4 also had statistically lower mean values for K, Na and soil pH, compared with community type 7. Community type 7, characterised by alkaline soils, also had significantly greater mean values for other soil chemical properties (Table 3), with the exception of community type 1 having the highest Fe concentrations. Differences amongst mean values for site parameters were less pronounced. Community type 8 was lower in the landscape, with significantly lower mean altitude than community types

1 and 2, which were identified as upland areas. Furthermore, community type 8 was less rocky (i.e. lowest abundance of coarse fragments) than communities types 2 and 3. Community type 2 had significantly greater mean runoff values compared with community types 6 and 8.

The two-way table (Table 2) highlights those species groups that were associated with specific soil pH values, as well those taxa that were more ubiquitous across the survey area (i.e. species group J). In particular, species groups A and B appeared strongly allied to neutral and alkaline soils, a characteristic of community types 5 to 8, with which the species groups are associated. Species groups E and F were linked to community types 1 to 4, which had moderate to strongly acidic soils.

## DISCUSSION

### Flora and vegetation communities

Surveys of flora and vegetation have focused on the central and southern portion of the Forrestania Greenstone Belt (Gibson 2004a), leaving the northern section of the belt primarily the subject of opportunistic collecting. A total of 312 taxa were identified from the quadrats and adjacent areas, which was lower than the 345 taxa identified by Gibson (2004a) further south in the belt. The area was dominated by perennial taxa, particularly shrubs. Only 26 taxa, identified as annuals, were removed from the species matrix. The sampling conditions were favourable, with above average rainfall recorded during the three months preceding the survey (159 mm, June–August 2009); typical rainfall during the same period is 139.5 mm (Bureau of Meteorology 2010).

The survey recorded 12 taxa of conservation significance, including two DRF taxa that were known populations in the WA Herbarium census. One of the DRF taxa, *Banksia sphaerocarpa* subsp. *dolichostyla*, was also recorded in the southern portion of the Forrestania Greenstone Belt (Gibson 2004a). *Stylidium sejunctum* was recorded from seven survey sites: we recommend changing the conservation status of this taxon from Priority 2 to Priority 3. Two new undescribed taxa identified during the survey are recommended for listing as Priority 1 conservation status until further study can provide information on population size, distribution and the security of land tenure. The identification of new and conservation-listed taxa is not surprising, given that the Forrestania Greenstone Belt has long been recognised as floristically significant (Gibson 2004a; Henry-Hall 1990).

Although the area has a history of exploration and mining, the number of weed taxa was relatively low compared with other greenstone belts with historical disturbance. The Bullfinch Greenstone Belt, which is the closest greenstone belt north of the survey area, has 38 weed taxa recorded from surveys in the central and southern portion (Gibson & Lyons 2001; Thompson & Allen 2013). The Forrestania Greenstone Belt has a noticeable lack of cattle, whereas cattle are commonly seen at Bullfinch, and they are likely to contribute to the spread

of weed taxa. There was only a single weed species, *Hypochaeris glabra*, common to this survey and Gibson's (2004a) southern Forresteria Greenstone Belt survey. All of the weed taxa recorded—*H. glabra*, *Pentaschistis airoides* subsp. *airoides*, *Rostraria cristata*, *Ursinia anthemoides* and *Vulpia myuros* forma *myuros*—are new records for the northern Forresteria Greenstone Belt; however, this is probably due to the lack of submission of specimens rather than to the novelty of the taxa to the area. The only weed taxon previously on record for the survey area was *Lysimachia arvensis*, which is also known from further south on the greenstone belt (Gibson 2004a).

Within the Forresteria Greenstone Belt, community types and species groups overlapped between this survey and Gibson (2004a). The analogous communities were recorded on similar landforms and substrate. Community types 2 and 3 were comparable to Gibson's (2004a) community types 1 and 2, respectively. All are relatively species rich, on rocky sites characterised by laterite and ironstone substrates. There was also an overlap of similar taxa within species groups associated with these communities. In particular, community type 2 and Gibson's community type 1 included the following taxa: *Astroloma serratifolium*, *Calothamnus quadrifidus*, *Gastrobium spinosum*, *Hakea subsulcata*, *Isopogon gardneri*, *Melaleuca cordata* and *Stylidium sejunctum*. Common taxa recorded both in this study's community type 3 and Gibson's community type 2 included *Allocasuarina acutivalvis*, *Dodonaea bursariifolia*, *Eucalyptus eremophila*, *Platysace maswellii* and *Santalum acuminatum*. *Eucalyptus salubris* – *E. urna*-dominated communities were recorded during both surveys of the Forresteria Greenstone Belt. However, they were rarely co-dominant in this survey as they were in Gibson (2004a), and only within *E. urna*-dominated communities (i.e. community type 7) were *Melaleuca* spp. an important understorey component. Community type 8 overlapped with Gibson's community type 4, with similar community structure of *E. salmonophloia* over *Olearia muelleri*. Further study of the central portion of the Forresteria Greenstone Belt will provide better context of the geographic distribution of these plant communities.

### Environmental correlates

Edaphic factors were strongly correlated with species assemblages; this has been documented widely in the Yilgarn Craton (Gibson et al. 2012). Soils were predominantly light- to red-brown sandy loams and sandy clay loams, with almost equal number of sites defined as strongly acidic or neutral to alkaline. This is probably related to variations in underlying geology, rather than to lack of weathering, as other greenstone belts in the Yilgarn are characterised by highly acidic soils, which are indicative of heavily weathered regolith (Slattery et al. 1999).

The soil chemical parameters were highly intercorrelated, which has been documented in other greenstone belt studies in the Yilgarn Craton (Markey & Dillon 2008a, 2008b, 2009a, 2009b; Meissner & Caruso 2008a, 2008b, 2008c; Thompson & Sheehy 2011a,

2011b, 2011c). The positive relationship between Ca concentrations and other primary soil cations is not surprising given the characteristics of calcrete substrates. Calcrete accumulation has been allied with lower slopes and pediments (Anand et al. 1997) and calcretes are readily leached from the profile (Butt et al. 2000; Anand 2005). This is particularly evident in community type 7, where the soil chemical parameters indicated a strong presence of calcrete and the average concentrations of the soil cations were the highest of all communities. However, community type 8, which was characterised by low altitude and runoff (indicative of low surface gradients), had lower Ca concentrations. This may be indicative of variation in rates of weathering and different geologic sequences (i.e. ironstone or greenstone associations). Community type 8 had moderately high concentrations of both Mg and Fe and may represent an intergrade between underlying geologies (e.g. ironstone vs. greenstone). In comparison, community type 7 had the highest Mg concentration, indicative of the presence of greenstone, and the lowest Fe concentrations. This nutrient may have readily leached from the profile or originally been present in lower concentrations.

The influence of geology and soils on vegetation associations has been described in the southern part of the Forresteria Greenstone Belt (Gibson 2004b), as well as other greenstone belts in the Yilgarn Craton (Gibson & Lyons 2001; Markey & Dillon 2008a, 2008b, 2009; Meissner & Caruso 2008a, 2008b, 2008c; Thompson & Sheehy 2011a, 2011b, 2011c). The correlation between soil parameters and the species matrix was not surprising given the underlying geology of the greenstone belt. Soil pH strongly influenced the species groups, as well as separating community types. This was obvious in the summary dendrogram of community types, where communities with highly acidic soils separated from those with more moderately acidic to alkaline soils. In particular, the concentration of Mg was allied with the presence of ultra-mafic rocks (Le Bas 2000), a frequent geologic component of greenstone belts. Furthermore, sites with high Ca concentrations also had high Mg concentrations. Both elements are indicative of calcrete in the substrate, as the formation of calcrete involves their interaction (McQueen 2006). Overall, the variation in soil chemistry and site parameters and their association with vegetation patterns are similar to other greenstone belts in the Yilgarn Craton.

### Conservation significance

The importance of improving the representation of greenstone belts in the conservation estate has been raised repeatedly over the years (Chapman & Newbey 1995; Gibson & Lyons 2001; Gibson 2004b), and particularly for the Forresteria Greenstone Belt (Henry-Hall 1990; Gibson 2004a). The only part of the Forresteria Greenstone Belt that is part of the conservation estate is the Lake Cronin Nature Reserve (a class 'A' nature reserve), which lies south of the survey-area boundary. However, the reserve does not represent any of the banded ironstone

hills or laterite of the Forrestania Greenstone Belt (Gibson 2004a). Furthermore, recent papers have emphasised the greenstone belts, especially the banded ironstone formations, as hotspots for plant diversity and for the high beta-diversity associated with these landforms (Gibson et al. 2010; Gibson et al. 2012). The greenstone belt continues to be of interest for exploration and mining, with active and pending mining tenements covering much of the survey area. Expansion of the present reserve system in the greenstone belt remains an important imperative after more than two decades from the initial recommendation, particularly with regard to the newly discovered taxa.

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## APPENDIX 1

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

**Amaranthaceae**

*Ptilotus drummondii*  
*Ptilotus holosericeus*

**Apiaceae**

*Daucus glochidiatus*  
*Platysace maxwellii*

**Apocynaceae**

*Alyxia buxifolia*

**Araliaceae**

*Hydrocotyle pilifera* var. *glabrata*  
*Trachymene cyanopetala*

**Asparagaceae**

*Thysanotus manglesianus*  
*Thysanotus patersonii*

**Asteraceae**

*Actinobole uliginosum*  
*Asteridea athrixioides*  
*Blennospora drummondii*  
*Brachyscome perpusilla* var. *tenella*  
*Calotis hispidula*  
*Ceratogyne obionoides*  
*Gnephosis intonsa* P1  
*Helichrysum leucopsideum*  
*Hyalosperma demissum*  
\**Hypochoeris glabra*  
*Isoetopsis graminifolia*  
*Millotia tenuifolia* var. *tenuifolia*  
*Olearia adenolasia*  
*Olearia muelleri*  
*Rhodanthe laevis*  
*Rhodanthe pygmaea*  
*Senecio glossanthus*  
\**Ursinia anthemoides*  
*Waitzia acuminata* var. *acuminata*

**Boraginaceae**

*Halgania andromedifolia*

**Campanulaceae**

*Wahlenbergia gracilentia*

**Caryophyllaceae**

*Stellaria filiformis*

**Casuarinaceae**

*Allocasuarina acutivalvis*  
*Allocasuarina acutivalvis* subsp. *acutivalvis*  
*Allocasuarina campestris*  
*Allocasuarina corniculata*  
*Allocasuarina helmsii*  
*Allocasuarina spinosissima*

**Celastraceae**

*Psammomoya choretroides*

**Chenopodiaceae**

*Chenopodium desertorum* subsp. *microphyllum*  
*Maireana marginata*  
*Rhagodia preissii* subsp. *preissii*  
*Sclerolaena diacantha*

**Convolvulaceae**

*Wilsonia humilis*

**Crassulaceae**

*Crassula colligata* subsp. *lamprosperma*

**Cupressaceae**

*Callitris canescens*  
*Callitris preissii*

**Cyperaceae**

*Lepidosperma* aff. *amantiferrum*  
*Lepidosperma* aff. *fimbriatum*  
*Lepidosperma* sp. A2 Inland Flat (GJ Keighery 7000)  
*Lepidosperma* sp. Bandalup Scabrid (N Eveleigh 10798)

**Dilleniaceae**

*Hibbertia croninensis* ms  
*Hibbertia eatoniae*  
*Hibbertia exasperata*  
*Hibbertia gracilipes*  
*Hibbertia lepidocalyx* subsp. *lepidocalyx*  
*Hibbertia oligantha*  
*Hibbertia stowardii*

**Droseraceae**

*Drosera browniana*  
*Drosera macrantha* subsp. *macrantha*

**Ericaceae**

*Astroloma serratifolium*  
*Leucopogon cuneifolius*  
*Leucopogon hamulosus*  
*Leucopogon* sp. Coolgardie (M Hislop & F Hort MH 3197)  
*Leucopogon* sp. outer wheatbelt (M Hislop 30)  
*Leucopogon sulcatus*  
*Styphelia exserta*

**Euphorbiaceae**

*Beyeria minor*  
*Beyeria sulcata* var. *brevipes*  
*Beyeria sulcata* var. *gracilis*  
*Beyeria sulcata* var. *sulcata*

**Fabaceae**

*Acacia acutata*  
*Acacia asepala* P2  
*Acacia assimilis* subsp. *assimilis*  
*Acacia beauverdiana*  
*Acacia brachyclada*  
*Acacia camptoclada*  
*Acacia castanostegia*  
*Acacia deficiens*  
*Acacia densiflora*  
*Acacia erinacea*  
*Acacia hemiteles*  
*Acacia heteroneura*  
*Acacia hystrix* subsp. *hystrix*  
*Acacia intricata*  
*Acacia kerryana* P2  
*Acacia lasiocalyx*  
*Acacia merrallii*  
*Acacia mutabilis* subsp. *mutabilis*  
*Acacia neurophylla* subsp. *erugata*  
*Acacia nigripilosa* subsp. *nigripilosa*  
*Acacia nyssophylla*  
*Acacia pachypoda*  
*Acacia poliochroa* x *merrallii*  
*Acacia prainii*



- Acacia rendlei*  
*Acacia sclerophylla* var. *sclerophylla*  
*Acacia* sp. narrow phyllode (BR Maslin 7831)  
*Acacia steedmanii* subsp. *steedmanii*  
*Acacia sulcata* var. *platyphylla*  
*Acacia tetraptera*  
*Acacia viscidifolia*  
*Acacia yorkkrakinensis* subsp. *acrita*  
*Daviesia argillacea*  
*Daviesia articulata*  
*Daviesia benthamii* subsp. *acanthoclona*  
*Daviesia pachyloma*  
*Daviesia pachyphylla*  
*Daviesia scoparia*  
*Dillwynia divaricata*  
*Eutaxia acanthoclada* P3  
*Eutaxia nanophylla* P3  
*Eutaxia neurocalyx*  
*Gastrolobium melanocarpum*  
*Gastrolobium spinosum*  
*Gompholobium obcordatum*  
*Jacksonia nematoclada*  
*Labichea rossii* P1  
*Leptosema daviesioides*  
*Pultenaea* aff. *arida*  
*Senna artemisioides* subsp. *filifolia*  
*Senna artemisioides* subsp. x *artemisioides*  
*Senna stowardii*  
*Templetonia aculeata*  
*Templetonia battii*  
*Templetonia sulcata*  
*Templetonia sulcata*/smithiana
- Goodeniaceae**
- Dampiera angulata* subsp. *angulata*  
*Dampiera* cf. *obliqua*  
*Goodenia dyeri*  
*Goodenia pinifolia*  
*Scaevola bursariifolia*  
*Scaevola spinescens*
- Gyrostemonaceae**
- Codonocarpus cotinifolius*
- Haemodoraceae**
- Conostylis bealiana*
- Haloragaceae**
- Glischrocaryon flavescens*
- Hemerocallidaceae**
- Dianella revoluta* var. *divaricata*
- Lamiaceae**
- Hemigenia* aff. *diplanthera*  
*Hemigenia westringioides*  
*Microcorys* sp. Forresteria (V English 2004) P4  
*Westringia cephalantha*  
*Westringia cephalantha* var. *cephalantha*  
*Westringia rigida*
- Lauraceae**
- Cassytha aurea* var. *hirta*  
*Cassytha melantha*  
*Cassytha nodiflora*
- Loganiaceae**
- Logania judithiana*  
*Phyllangium* sp.
- Malvaceae**
- Keraudrenia cacaobrunnea* subsp. *cacaobrunnea*  
*Lasiopetalum ferraricollinum*  
*Lawrenzia glomerata*
- Myrtaceae**
- Baeckea crispiflora*  
*Baeckea elderiana*  
*Baeckea grandibracteata*  
*Baeckea* sp. Parker Range (M Hislop & F Hort MH 2968) P3  
*Calothamnus quadrifidus* subsp. *seminudus*  
*Calytrix sapphirina*  
*Chamelaucium ciliatum*  
*Chamelaucium pauciflorum* subsp. *pauciflorum*  
*Cyathostemon* sp. WA Thompson & J Allen 951  
*Eucalyptus burracoppinensis*  
*Eucalyptus calycogona* subsp. *calycogona*  
*Eucalyptus concinna*  
*Eucalyptus cylindrocarpa*  
*Eucalyptus eremophila*  
*Eucalyptus extensa*  
*Eucalyptus flocktoniae* subsp. *flocktoniae*  
*Eucalyptus flocktoniae* subsp. *hebes*  
*Eucalyptus horistes*  
*Eucalyptus livida*  
*Eucalyptus longicornis*  
*Eucalyptus oleosa* subsp. *oleosa*  
*Eucalyptus pileata*  
*Eucalyptus polita*  
*Eucalyptus rigidula*  
*Eucalyptus salmonophloia*  
*Eucalyptus salubris*  
*Eucalyptus steedmanii* R  
*Eucalyptus subangusta* subsp. *subangusta*  
*Eucalyptus tenera*  
*Eucalyptus tenuis*  
*Eucalyptus urna*  
*Eucalyptus yilgarnensis*  
*Euryomyrtus maidenii*  
*Leptospermum ?erubescens*  
*Leptospermum roei*  
*Melaleuca acuminata* subsp. *acuminata*  
*Melaleuca adnata*  
*Melaleuca calyptroides*  
*Melaleuca carrii*  
*Melaleuca cliffortioides*  
*Melaleuca condylosa*  
*Melaleuca cordata*  
*Melaleuca cucullata*  
*Melaleuca depauperata*  
*Melaleuca eleuterostachya*  
*Melaleuca hamata*  
*Melaleuca johnsonii*  
*Melaleuca lanceolata*  
*Melaleuca lateriflora* subsp. *lateriflora*  
*Melaleuca laxiflora*  
*Melaleuca pauperiflora* subsp. *fastigiata*  
*Melaleuca pauperiflora* subsp. *pauperiflora*  
*Melaleuca phoidophylla*  
*Melaleuca platycalyx*  
*Melaleuca pungens*  
*Melaleuca quadrifaria*  
*Melaleuca scalena*  
*Melaleuca teuthioides*  
*Micromyrtus erichsenii*  
*Micromyrtus obovata*  
*Rinzia carmosa*  
*Rinzia sessilis*  
*Thryptomene kochii*

## Appendix 1 (cont.)

**Orchidaceae**

*Caladenia microchila*  
*Ericksonella saccharata*  
*Pterostylis* aff. *nana*  
*Pterostylis mutica*  
*Pterostylis sargentii*  
*Thelymitra petrophila*

**Plantaginaceae**

*Plantago debilis*

**Poaceae**

*Austrodanthonia caespitosa*  
*Austrostipa acrocliliata*  
*Austrostipa elegantissima*  
*Austrostipa hemipogon*  
*Austrostipa nitida*  
*Austrostipa scabra*  
*Austrostipa* sp. Mt. Holland (WA Thompson & J Allen 948)  
*Austrostipa* sp. Carlingup Road (S Kern & R Jasper LCH18459)  
*Austrostipa trichophylla*  
*Neurachne alopecuroidea*  
*Pentaschistis airoides* subsp. *airoides*  
 \**Rostraria cristata*  
*Triodia* sp.  
 \**Vulpia myuros* forma *myuros*

**Polygalaceae**

*Comesperma volubile*

**Portulacaceae**

*Calandrinia calyprata*  
*Calandrinia eremaea* s.l.

**Proteaceae**

*Banksia elderiana*  
*Banksia purdieana*  
*Banksia sphaerocarpa* var. *dolichostyla* R  
*Grevillea acuaria*  
*Grevillea didymobotrya* subsp. *didymobotrya*  
*Grevillea dissecta* P4  
*Grevillea excelsior*  
*Grevillea hookeriana* subsp. *apiciloba*  
*Grevillea huegelii*  
*Grevillea oligantha*  
*Grevillea oncogyne*  
*Grevillea pterosperma*  
*Hakea erecta*  
*Hakea meisneriana*  
*Hakea multilineata*  
*Hakea scoparia* subsp. *scoparia*  
*Hakea subsulcata*  
*Isopogon gardneri*  
*Isopogon scabriusculus*  
*Isopogon scabriusculus* subsp. *pubifloris*  
*Persoonia angustiflora*  
*Persoonia coriacea*  
*Persoonia coriacea* x *helix*  
*Persoonia inconspicua*  
*Petrophile stricta*

**Pteridaceae**

*Cheilanthes sieberi* subsp. *sieberi*

**Rhamnaceae**

*Cryptandra minutifolia* subsp. *brevistyla*  
*Cryptandra minutifolia* subsp. *minutifolia*  
*Cryptandra myriantha*  
*Cryptandra wilsonii*  
*Stenanthemum stipulosum*  
*Trymalium myrtillus* subsp. *myrtillus*

**Rutaceae**

*Boronia fabianoides*  
*Boronia inornata* subsp. *inornata*  
*Boronia ternata* var. *ternata*  
*Drummondita hassellii*  
*Microcybe multiflora* subsp. *multiflora*  
*Phebalium ambiguum*  
*Phebalium filifolium*  
*Phebalium megaphyllum*  
*Phebalium tuberculosum*  
*Philotheca rhomboidea*

**Santalaceae**

*Exocarpos aphyllus*  
*Exocarpos sparteus*  
*Leptomeria pachyclada*  
*Santalum acuminatum*  
*Santalum murrayanum*

**Sapindaceae**

*Dodonaea adenophora*  
*Dodonaea bursariifolia*  
*Dodonaea ptarmicaefolia*  
*Dodonaea stenozyga*  
*Dodonaea viscosa* ssp. *angustissima* ssp. *spathulata* intergrade

**Scrophulariaceae**

*Eremophila decipiens* subsp. *decipiens*  
*Eremophila dempsteri*  
*Eremophila densifolia* subsp. *pubiflora*  
*Eremophila ionantha*  
*Eremophila rugosa*

**Stylidiaceae**

*Stylidium involucreatum*  
*Stylidium sejunctum* P2

**Thymelaeaceae**

*Pimelea aeruginosa*  
*Pimelea suaveolens* subsp. *flava*

**Violaceae**

*Hybanthus floribundus* subsp. *floribundus*

**Zygophyllaceae**

*Zygophyllum glaucum*