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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, florsitic 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

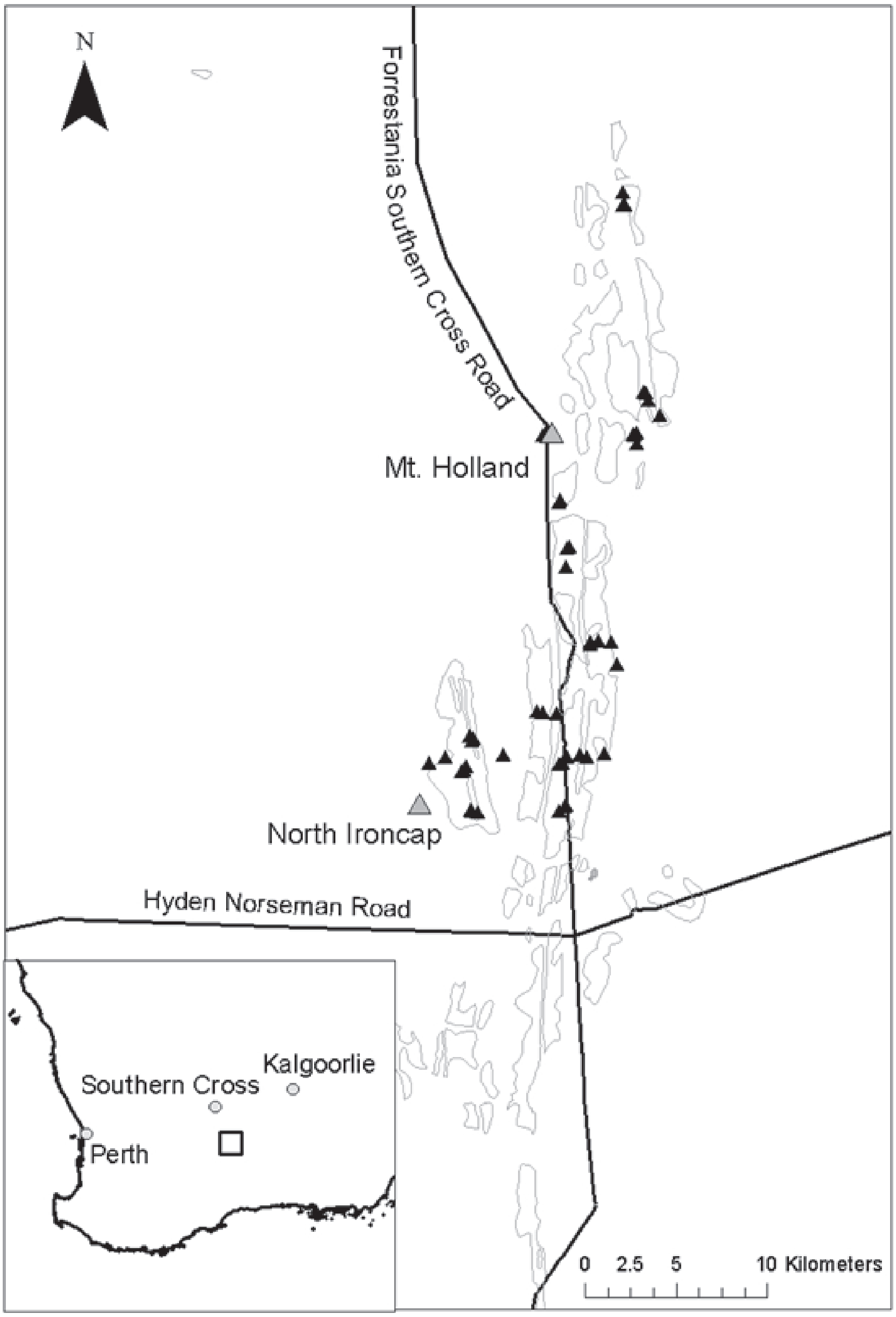

Figure 1. Map showing the location of the northern Forrestania Greenstone Belt survey area, with major landforms and landmarks indicated. The locations of the 50 permanent quadrats are marked by solid triangles (▲).

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 colluival 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 $CaCl_2$ (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 ± 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 × 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, *Hibbertia croninensis* ms, had previously been collected but was identified as *H.* aff. *oligantha* (PERTH 03033856).

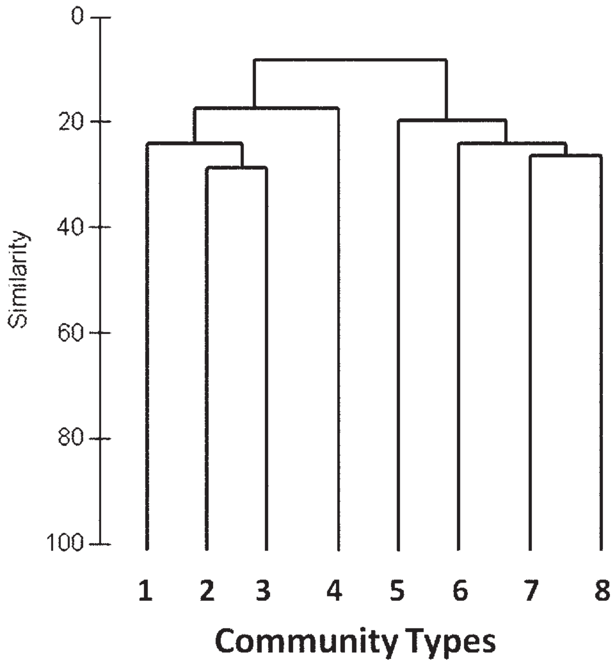

Figure 2. Summary dendrogram of community types for the northern Forrestania Greenstone Belt. The eight community types displayed in the dendrogram were derived from the classification analyses of the 176 taxa from 46 sites; the four sites excluded from the analyses are not displayed.

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	*Banksia sphaerocarpa var. dolichostyla*	R	COO, AW, MAL
Myrtaceae	*Eucalyptus steedmanii*	R	COO, ESP, MAL
Asteraceae	*Gnephosis intonsa*	P1	COO, MUR, AW, ESP, MAL
Fabaceae	*Labichea rossii*	P1	COO
Fabaceae	*Acacia asepala*	P2	COO, MAL
Fabaceae	*Acacia kerryana*	P2	COO
Stylidiaceae	*Stylidium sejunctum*	P2	COO, MAL
Myrtaceae	*Baeckea* sp. Parker Range (M Hislop & F Hort MH 2968)	P3	COO, AW
Fabaceae	*Eutaxia acanthoclada*	P3	COO, ESP, MAL
Fabaceae	*Eutaxia nanophylla*	P3	COO, JF, MAL
Proteaceae	*Grevillea dissecta*	P4	COO
Lamiaceae	*Microcorys* 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. *Cassytha 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. merralii*, 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 tuberculosum* 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

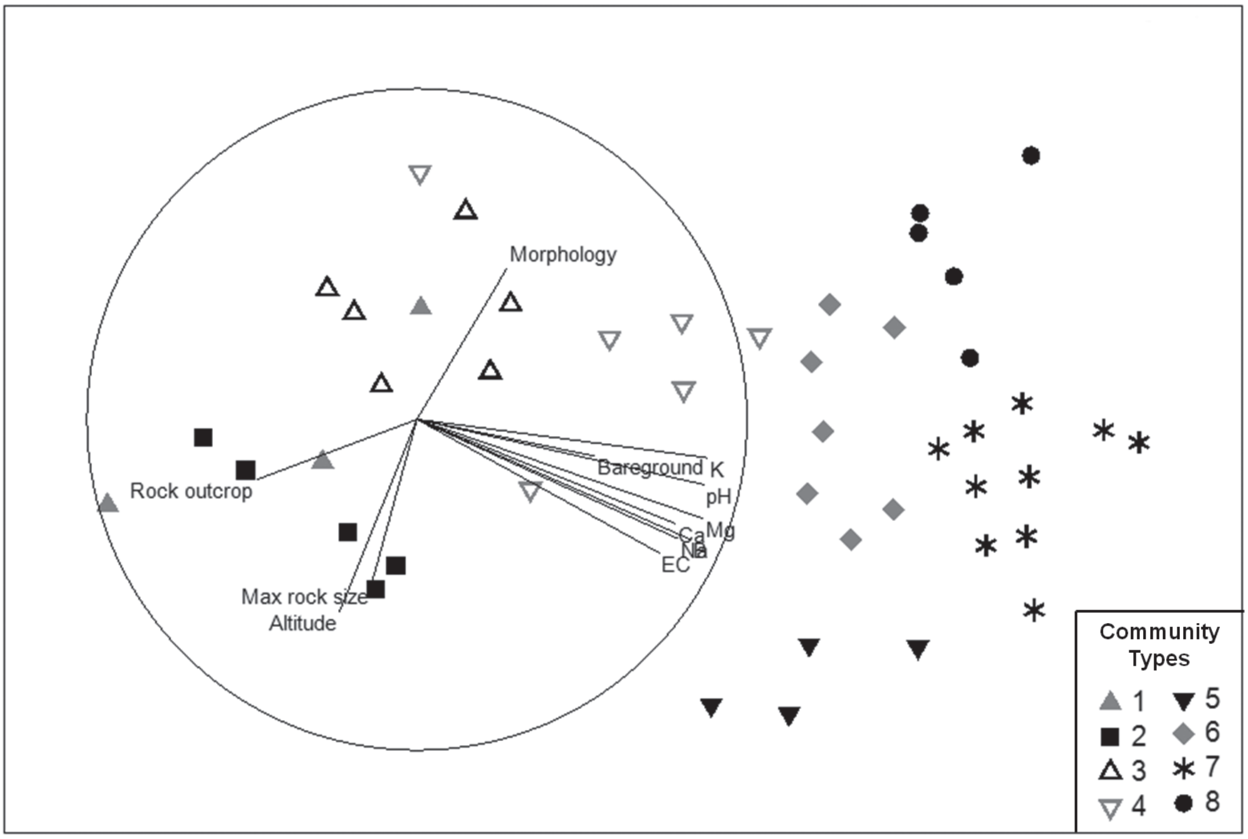

Figure 3. 2D graph of the first two axes of the NMS ordination of survey plots of the northern Forrestania Greenstone Belt (stress = 0.16). Survey plots are separated by community groups and are overlain with environmental vectors, using the lines of best-fit in multi-dimensional space. Vectors extending 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 acrociliata*.

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 *Drummondita 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 ± 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 ± 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 2

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

Group	Taxon	1	2	3	4	5	6	7	8
A	*Acacia asepala*								■
A	*Austrostipa elegantissima*		■					■	■
A	*Austrostipa hemipogon*							■	■
A	*Austrostipa nitida*							■	■
A	*Austrostipa scabra*								■
A	*Boronia inornata* subsp. *inornata*					■	■		
A	*Cryptandra wilsonii*						■		■
A	*Eremophila ionantha*						■	■	■
A	*Eucalyptus cylindrocarpa*				■				■
A	*Eucalyptus salmonophloia*			■			■	■	■
A	*Eucalyptus yilgarnensis*						■		■
A	*Grevillea huegelii*				■		■		■
A	*Melaleuca pauperiflora* subsp. *fastigiata*						■	■	■
A	*Melaleuca teuthidoides*				■		■		■
A	*Ptilotus holosericeus*							■	■
A	*Scaevola spinescens*								■
A	*Sclerolaena diacantha*						■	■	■
A	*Senna artemisioides* subsp. *filifolia*								■
A	*Templetonia sulcata*						■		■
B	*Acacia deficiens*						■	■	
B	*Acacia erinacea*			■		■	■	■	
B	*Acacia intricata*						■	■	
B	*Acacia merrallii*				■	■	■	■	■
B	*Acacia pachypoda*					■		■	
B	*Acacia rendlei*					■		■	
B	*Boronia fabianoides*					■	■		
B	*Daviesia articulata*							■	
B	*Daviesia benthamii* subsp. *acanthoclona*				■	■	■	■	
B	*Daviesia scoparia*			■	■	■	■	■	■
B	*Dodonaea stenozyga*				■	■	■	■	■
B	*Eremophila decipiens* subsp. *decipiens*				■	■	■	■	■
B	*Eremophila dempsteri*					■	■		
B	*Eremophila densifolia* subsp. *pubiflora*						■	■	
B	*Eucalyptus calycogona* subsp. *calycogona*				■		■	■	■
B	*Eucalyptus extensa*					■	■	■	
B	*Eucalyptus longicornis*							■	■
B	*Eucalyptus polita*							■	
B	*Eucalyptus salubris*					■	■	■	
B	*Eucalyptus urna*						■	■	■
B	*Eutaxia acanthoclada*						■	■	
B	*Exocarpos aphyllus*				■	■	■	■	■
B	*Maireana marginata*						■	■	■
B	*Melaleuca adnata*						■	■	
B	*Melaleuca cucullata*					■		■	
B	*Melaleuca eleuterostachya*			■	■		■	■	■
B	*Melaleuca lanceolata*							■	■
B	*Melaleuca pauperiflora* subsp. *pauperiflora*				■		■	■	
B	*Melaleuca quadrifaria*							■	
B	*Microcybe multiflora* subsp. *multiflora*				■		■	■	
B	*Olearia muelleri*				■		■	■	■
B	*Pterostylis mutica*							■	■
B	*Scaevola bursariifolia*						■		■
B	*Senecio glossanthus*					■		■	■
B	*Senna artemisioides* subsp. x *artemisioides*					■		■	
B	*Styphelia exserta*					■			
B	*Templetonia battii*								■
B	*Trymalium myrtillus* subsp. *myrtillus*					■		■	
B	*Westringia rigida*				■		■	■	■
B	*Wilsonia humilis*						■	■	■
C	*Acacia hystrix* subsp. *hystrix*				■		■		
C	*Daviesia argillacea*				■		■		
C	*Eremophila rugosa*				■		■		
C	*Eucalyptus tenuis*			■	■		■		■
C	*Grevillea oncogyne*				■		■		
C	*Melaleuca phoidophylla*				■		■		
C	*Melaleuca scalena*			■	■				■
C	*Microcorys* sp. Forrestania (V. English 2004)						■		
C	*Olearia adenolasia*						■		
D	*Acacia* sp. narrow phyllode (B.R. Maslin 7831)					■			
D	*Allocasuarina helmsii*				■	■			
D	*Austrostipa acrociliata*							■	■
D	*Dianella revoluta* var. *divaricata*				■				
D	*Exocarpos sparteus*		■						
D	*Helichrysum leucopsideum*						■		
D	*Thysanotus manglesianus*				■				
	Acacia assimilis subsp. *assimilis*	■	■	■					
	Acacia castanostegia		■	■					
	Acacia steedmanii subsp. *steedmanii*		■		■				
	Acacia sulcata var. *platyphylla*	■	■	■					
	Allocasuarina campestris		■			■			
	Allocasuarina corniculata	■	■	■	■				
	Astroloma serratifolium		■	■					
	Baeckea crispiflora		■	■					
	Baeckea grandibracteata			■					
	Banksia purdieana		■	■					
	Beyeria minor	■		■					
	Beyeria sulcata	■		■					

Table 2 (cont.)

		1	2	3	4	5	6	7	8
E	*Callitris preissii*	■	■	■	■				
	Cassytha nodiflora	■	■	■					
	Comesperma volubile	■	■	■	■				
	Conostylis bealiana		■	■					
	Dampiera cf. *obliqua*		■	■					
	Drosera macrantha subsp. *macrantha*	■	■	■	■	■			
	Eucalyptus horistes	■	■	■					
	Eucalyptus rigidula		■	■					
	Gastrolobium spinosum		■	■					
	Grevillea pterosperma		■	■					
	Hakea meisneriana	■		■					
	Hakea multilineata	■	■	■	■				
	Hakea subsulcata	■	■	■					
	Hibbertia eatoniae		■	■					
	Hibbertia exasperata	■	■	■					
	Lepidosperma aff. *amantiferrum*			■					
	Lepidosperma sp. A2 Inland Flat (G.J. Keighery 7000)	■	■	■	■				
	Melaleuca calyptroides	■	■	■					
	Melaleuca cordata	■	■	■	■				
	Persoonia coriacea	■		■					
	Phebalium filifolium	■		■	■				
	Philotheca rhomboidea		■	■					
	Platysace maxwellii		■	■	■				
	Rinzia sessilis	■		■	■				
	Stenanthemum stipulosum	■	■	■					
	Stylidium sejunctum		■	■					
	Thysanotus patersonii		■	■	■	■	■		
	Westringia cephalantha	■		■	■				
F	*Acacia nigripilosa* subsp. *nigripilosa*		■	■					
	Allocasuarina spinosissima			■	■				
	Boronia ternata var. *ternata*			■					
	Lepidosperma sp. Bandalup Scabrid (N. Evelegh 10798)			■					
	Pimelea aeruginosa			■					
G	*Acacia yorkrakinensis* subsp. *acrita*	■							
	Baeckea elderiana	■							
	Grevillea didymobotrya subsp. *didymobotrya*	■		■					
	Hakea erecta	■							
	Hemigenia aff. *diplanthera*	■				■			
	Isopogon scabrisculus	■		■					
	Leucopogon cuneifolius	■	■						
	Leucopogon sulcatus	■		■					
	Melaleuca depauperata	■			■				
	Micromyrtus obovata	■		■					
H	*Alyxia buxifolia*		■						
	Austrodanthonia caespitosa	■	■						■
	Calothamnus quadrifidus subsp. *seminudus*		■						
	Ericksonella saccharata		■						
	Isopogon gardneri		■						
	Leptospermum ?erubescens		■		■				
	Thelymitra petrophila		■	■	■				
I	*Acacia beauverdiana*	■			■				
	Acacia mutabilis subsp. *mutabilis*				■				
	Acacia neurophylla subsp. *erugata*								
	Callitris canescens				■				
	Dampiera angulata subsp. *angulata*				■				
	Dodonaea viscosa ssp. *angustissima*- ssp. *spathulata*								
	Drummondita hassellii	■			■				
	Eucalyptus livida	■			■		■		
	Gastrolobium melanocarpum								
	Goodenia pinifolia		■		■				
	Lasiopetalum ferraricollinum	■							
	Leptosema daviesioides				■				
	Melaleuca condylosa	■			■				
	Rinzia carnosa				■				
	Thryptomene kochii	■	■	■	■				
J	*Acacia camptoclada*			■	■		■		■
	Allocasuarina acutivalvis	■	■	■	■				
	Cryptandra minutifolia subsp. *brevistyla*			■	■		■		
	Dodonaea bursariifolia		■	■	■		■		■
	Eucalyptus eremophila	■		■	■		■		
	Eucalyptus flocktoniae			■	■		■		
	Eucalyptus pileata			■	■		■		■
	Grevillea acuaria	■		■	■	■	■	■	■
	Melaleuca acuminata subsp. *acuminata*			■	■		■	■	■
	Melaleuca cliffortioides			■	■	■	■		
	Melaleuca hamata	■	■	■	■	■	■	■	
	Melaleuca johnsonii			■	■		■	■	
	Melaleuca lateriflora subsp. *lateriflora*	■			■		■		
	Melaleuca laxiflora	■		■	■				
	Phebalium tuberculosum		■	■	■				
	Santalum acuminatum	■	■	■	■	■	■	■	■
K	*Acacia densiflora*			■	■		■		
	Cassytha aurea var. *hirta*	■	■		■	■	■		
	Chamelaucium ciliatum				■				
	Cryptandra minutifolia subsp. *minutifolia*	■			■		■	■	
	Hakea scoparia subsp. *scoparia*	■			■				
	Halgania andromedifolia				■				■
	Hibbertia oligantha				■				
	Neurachne alopecuroidea			■	■				

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 α = 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.

	Community Types							
Soil Parameters	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
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]
Ca****	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]
Cd[NS]	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
Co****	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]
Cu****	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]
EC****	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]
Fe*	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]
K****	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]
Mg****	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]
Mn****	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]
N (total)****	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]
Na****	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]
Ni***	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]
Organic C (%)***	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]
P**	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]
pH****	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]
S**	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]
Zn[NS]	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
Site Physical Parameters								
Altitude (m)***	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]
Bare ground (%)[+]**	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
Abundance-fragments***	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]
Leaf litter (%)[NS]	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
Topographical position***	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]
Outcrop abundance*[+]**	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
Runoff*	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]
Species Richness	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
Number of quadrats:	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 multilineata*, *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 ± 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 ± 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 ± 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 erinacea* 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 ± 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 ± 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 Forrestania 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% ± 3.5 SD) and sparse cover of leaf litter (mean 22.4% ± 14.8 SD; Table 3).

Soils were typically mildly acidic with a mean pH of 6.32 ± 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^{-1}) and Mg levels (Mg >490 mg kg^{-1}). 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 Forrestania 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 Forrestania 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 Forrestania 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*, *Gastrolobium spinosum*, *Hakea subsulcata*, *Isopogon gardneri*, *Melaleuca cordata* and *Stylidum 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 Forrestania 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 Forrestania 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 Forrestania 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 Forrestania Greenstone Belt (Henry-Hall 1990; Gibson 2004a). The only part of the Forrestania 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
*Hypochaeris 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 gracilenta

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 Evelegh 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 viscifolia
Acacia yorkrakinensis 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. Forrestania (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
Lawrencia 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 teuthidoides
Micromyrtus erichsenii
Micromyrtus obovata
Rinzia carnosa
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 acrociliata
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 calyptrata
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 coricaea 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 involucratum
Stylidium sejunctum P2

Thymelaeaceae
Pimelea aeruginosa
Pimelea suaveolens subsp. *flava*

Violaceae
Hybanthus floribundus subsp. *floribundus*

Zygophyllaceae
Zygophyllum glaucum